Sort of document

D2.1 Application Specific Requirement Development Report

Dissemination Level (Security)

Public	☒	**Fully open, e.g. web**
Sensitive	☐	Sensitive, limited under the conditions of the Grant Agreement. Restricted to the consortium and including the European Commission Services

HORIZON-JTI-CLEANH2-2024-03-02

Classified		EU classified (EUCI) under Decision No 2015/444:
	☐	· R-UE/EU-R (EU Restricted)
	☐	· C-UE/EU-C (EU Confidential)
	☐	· S-UE/EU-S (EU Secret)

Dissemination Level (Security)

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Project

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23.05.2025	**The first review is conducted inside the FORD OTOSAN**	**FORD OTOSAN**
30.05.2025	**Second review is conducted with CMS-EPE, NLR and DAMEN**	**FORD OTOSAN, CMS-EPE, DAMEN, NLR**

Contents

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1. Executive Summary

In the context of the H2UpScale project, creating scalable fuel cell BOP systems for different applications is the main goal. Deliverable D2.1 presents a consolidated set of application-specific requirements developed collaboratively by the project partners Ford Otosan (FRD), Cummins LTD (CMS-LTD), Cummins Electrified Power Europe (CMS-EPE), Hydrogenics GMBH (CMS-HYD), Damen Research Development & Innovation BV (DAM), Stichting Koninklijk Nederlands Lucht- en Ruimtevaartcentrum (NLR), during months 1 to month 6 of the project.

The objective of this task is to identify and define the high-level specifications, performance targets, and environmental constraints for key application sectors, including on-highway transportation, maritime, and aviation. Sets of representative applications are selected as a reference for further technical development throughout the project.

For each selected application, the following parameters were quantified: required power and power density, system efficiency, voltage levels, mass and volume constraints, operational and environmental conditions, safety and compliance needs, hydrogen storage and supply characteristics, durability expectations, serviceability, and overall operating conditions. Special attention was given to identifying key challenges, potential bottlenecks, and trade-offs in implementing high-power fuel cell systems across these sectors.

The outcome of this task, detailed in this deliverable, forms the foundation for the design and development of Balance of Plant components and will directly inform subsequent technical work packages. By establishing a clear and consensus-based set of requirements, the project ensures alignment across partners and readiness for the next stages of system design and integration.

According to project documents, work package 2 will play a critical role for the project as shown in the scheme below (H2UpScale Eu Project, 2025). Outputs of work package 2 will be used in work package 3, work package 5, work package 6, work package 7, and work package 8 directly. This worksceheme is explained in Fig.1.

D2.1 report is public . Thus, requirement file can be found in section 6 Appendix. Also, it is available in the H2Upscale sharepoint (H2UpScale Sharepoint > General > WP2 > Deliverables WP2 > D2.1_H2upscale_DraftVersion_V2-Added Tables).

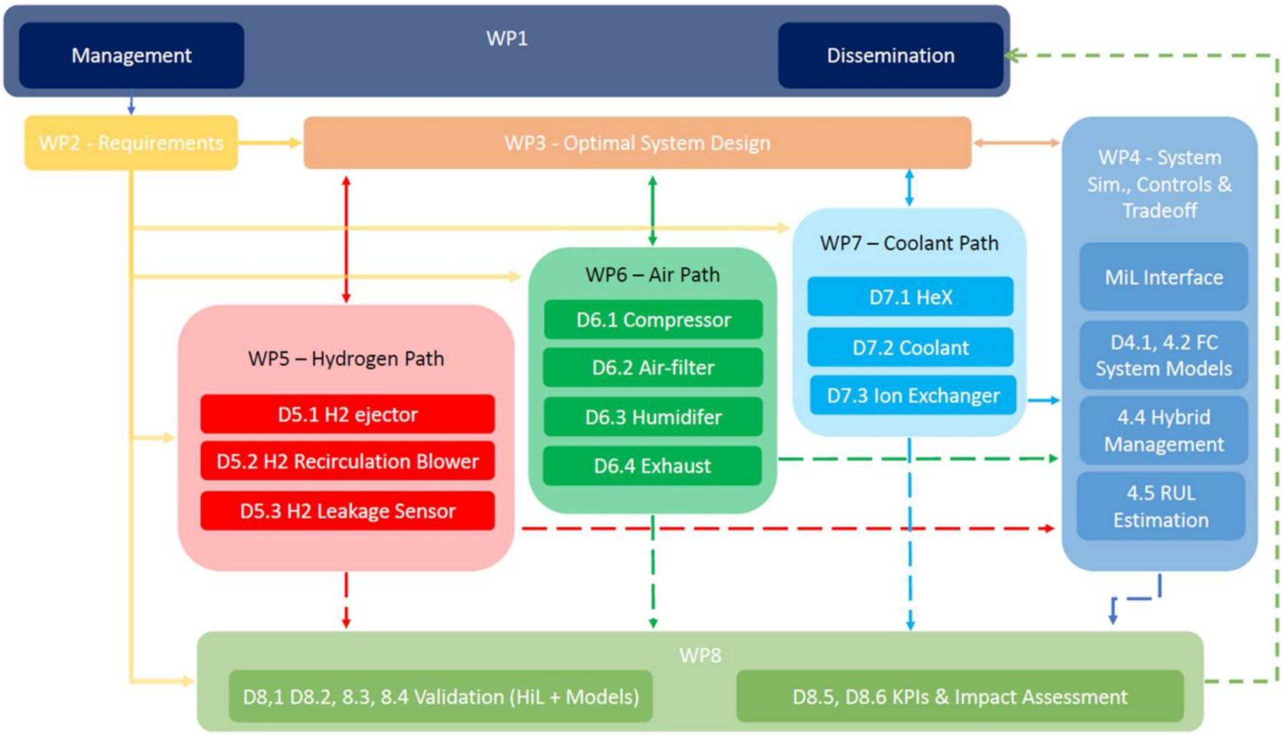

Figure 1 H2UpScale Workflow Diagram [i]

2. Introduction and Objectives

In this document, Ford Otosan has successfully carried out the activities with the critical support of partners outlined under WP2 in Task 2.1. In the scope of Task 2.1, application-specific requirements for heavy duty truck, marine and aviation applications are studied. The objective of this task is to create an application-specific requirement document. There are six different applications for these projects as follows.

- FRD focuses on Heavy Duty Truck, (One application)
- DAM focuses on marine, (Three applications)
- NLR focuses on aviation (Two applications).

2.1 Application Definitions

In this section, six main applications are explained, and images are ensured by the partners.

2.1.1 Heavy Duty Truck – T1

FRD focuses on high-level specifications for heavy duty trucks. F-MAX is selected as the target vehicle. This application is named T1. Images for this application are shown in Fig.2 (Ford F-MAX, 2025). Vehicle gross weight is 44 tons and axle configuration are 4x2. F-MAX is a long-haul heavy-duty truck. Currently, F-MAX version with internal combustion engine (diesel) is available and battery electric vehicle is in deployment. In the context of the H2UpScale, fuel cell integration is being targeted by FRD. Desired range with fuel cell application is 800km for target vehicle. Also, battery and powertrain requirements are determined and implemented in the H2UpScale project. Detailed requirements for the T1 application are listed in the excel file under Node#1 tab. Listed in appendix (section 6).

Figure 2 T1 Application Images

2.1.2 Marine

DAM focuses on high-level specifications in the marine industry. Damen has selected vessel types in the marine sector that are suitable for early adaptation of hydrogen. A fixed location, which makes a reliable supply of hydrogen more feasible, and a predictable range and profile which takes into account the volumetric energy density of hydrogen fuel. To supply accurate and precise information, existing hybrid vessels are taken as reference ships.

2.1.2.1 Urban Water Shuttle - M1

The first application is an urban water bus as shown in Fig.3 (Damen Urban Water Shuttle, 2025). The Waterbus 2907 HE3 is selected as the target vehicle. This application is named as M1. With a length of 28.6 m it can carry up to 150 passengers. The composite Waterbus 2907 is efficient in terms of weight, hull design and systems.Composite Waterbus is The waterbus is the type of vessel. The boat sails typically in a city or in between cities and provides transportation in a similar way as a bus. Composite is the main material used for the hull, which is strong and lightweight (which are both important for this application). The hydrogen version would be featuring a hybrid-electric arrangement, including batteries for peak-shaving. It is highly maneuverable and provides efficient boarding and disembarking. Sustainability is considered throughout. The interiors are completely circular, using natural materials such as wool and wood, as well as recycled materials. The hydrogen version would be capable of a full day sailing and bunkering overnight. Detailed requirements for M1 application are listed in the excel file under Node#2 tab or in the appendix (section 6).

Figure 3 M1 Application Image

2.1.2.2 Passenger Car Ferry - M2 & M3

The bigger marine applications are based on a RORO ferry, shown in the Fig.4 (DAMEN Passenger Car Ferry, 2025). This is the Road Ferry 8117 E3, which is a hybrid vessel combining diesel generators and battery power. With a length of 81.2 m it can carry up to 296 passengers and 44 cars. This kind of vessel has fixed routes between islands or ports. At least one of the ports would require hydrogen bunkering facilities.
In this project the applications are named as M2 and M3. For case M2 one diesel-generator would be replaced by a fuel cell, making a hybrid system with a fuel cell, batteries and a diesel generator. This setup would give maximum fuel (range) and bunkering flexibility, while having the possibility to have silent and clean sailing on hydrogen in particular areas. For case M3 all the main generators would be replaced by fuel cells. Creating a hybrid system of batteries and fuel cells, making the hydrogen system bigger and allowing sailing without carbon emissions.
Detailed requirements for M2 and M3 applications are listed in the excel file under Node#3 tab, or can be found in the appendix (Section 6).

Figure 4 M2 & M3 Applications Image

2.1.3 Aviation

In the H2UpScale project, Royal Netherlands Aerospace Centre (NLR) focuses on the specifications in the aviation industry. Aviation is not as far as the heavy duty truck and marine sector since there are no commercial applications yet, and the design standards are still under development. Considering NLR's role as a research institute that does not design its own applications, examples of aircraft manufacturers have been identified in literature to serve as illustrative applications. It is noteworthy that comprehensive certification specifications (CS) exist for various types of conventional aircraft. However, for the newly designed hydrogen fuel cell-powered aircraft, these standards are still in development, resulting in many requirements that remain to be fully defined. There are three different types of aviation applications identified as explained below.

2.1.3.1 Aviation Application - A1

The first aviation application is named A1 and includes Certification Specifications for Light Sport Aeroplanes (CS-LSA). These are relatively small aircraft with a maximum of six seats, which means they require a relatively low power output of less than 250 kW. Examples of current projects for this A1 aviation application are:

- Retrofit for a Britten Norman Islander led by Cranfield Aerospace Solutions [9];
- Pipistrel liquid hydrogen Range Extender, funded by Dutch Aviation in Transition and led by NLR [8];
- HyFLY's HY4 electric demonstrator aircraft powered by Liquid Hydrogen [6];
- ZeroAvia Piper M class aircraft [11];
- AeroDelft Phoenix powered by liquid hydrogen [1].

As all the examples are below 250 kW, it is decided that the A1 application is not considered further in H2UpScale project.

2.1.3.2 Aviation Application - A2

The target aircraft of the second application for aviation is the UNIFIER19 Miniliner and belongs to the Certification Specifications for Normal-Category Aeroplanes (CS-23) category. A picture of the UNIFIER19 Miniliner is shown in Fig.6 (UNIFIER19 Miniliner, 2025) and is named A2. It can carry up to 19 passengers. Detailed requirements for the A2 application are listed in the excel file under Node#3 tab or in the appendix (section 6).

Figure 5 A2 Application Image of the UNIFIER19 Miniliner as example

2.1.3.3 Aviation Application - A3

The target aircraft of the third application for aviation is the Airbus ZEROe (Airbus ZEROe, 2025) and the Certification Specifications for Large Aeroplanes (CS-25) is taken as reference. A picture of the Airbus ZEROe hydrogen-powered aircraft is shown in Fig.7 and this application is named A3. The aircraft contains four so-called pods under the wings, each with their own FC with BoP. The aircraft has a passenger capacity of 100 as well as a range of 1000 nautical miles. The fuel for the A3 application will be stored as liquid hydrogen, which will reduce the supply pressure compared to gaseous hydrogen storage. Detailed requirements for A3 application are listed in the excel file under Node#3 tab or in the appendix (section 6).

Figure 6 A3 Application Image of the Airbus ZEROe as reference

2.2 Requirement Determination

First of all, the initial requirement document is shared by FRD and this document is accepted as baseline. Important topics for the fuel cell system are defined and groups of the requirements are determined. After groups are created, requirements are implemented to the document. The importance of each requirement is determined. There are 13 main group for application – specific requirements:

- Application Description: Six main applications are targeted (1 HDV, 3 Marine, 2 Aviation). In this section, descriptions of each application are explained with duty cycles, weights and dimensions.
- Powertrain (Fuel Cell + Battery): The powertrain integrates fuel cells and batteries into a scalable system that is optimized for high power density, efficiency, and operational relability. Explained in the requirement to excel with power levels and control logics.
- Battery: Batteries are designed to support high transient power demands and system stability with different configurations. In this section, battery power levels and chemistry in the target applications are evaluated.
- Power and Efficiency (Fuel Cell): The fuel cell system aims for power level equal or higher than 350kW output for end of life condition. In this section, fuel cell intermittent and continuous power outputs, net efficiency values, and ramp up-down rates are studied.
- Electrical: EMC /EMI requirements, HV bus types and voltage levels and extra informations are explained.
- Packaging, Weight and Volume: Packaging is an important topic for fuel cell applications. Espacially trucks and aviation applications, weight and volume parameters are critical. In this section, Fuel cell and cooling system limitations are determined.
- Environment: Environmental conditions are defined considering humidity, high altitude, extreme temperatures, air quality.
- Operation: Operational conditions such as angularity, pitch up/down, roll left/right, vibration requirements are determined.
- Safety: The H2Upscale project prioritizes safety by integrating robust design principles and compliance with hydrogen-specific safety standards. Critical risks such as leaks, pressure hazards, and system malfunctions are addressed through preventive measures and continuous monitoring.
- Durability: Expected system of life is defined.
- Hydrogen: Hydrogen and storage specs are defined.
- Compliance: Important legislations are added.
- Service and Maintainability : Service intervals and maintenance requirements are defined.

After requirements are determined and finalized for a total of six applications, numeric values are added, and notes are created. A total of 122 different requirements in 13 groups are filled for applications. Find the requirement excel document in the link.
(H2UpScale Sharepoint > General > WP2 > Deliverables WP2 > D2.1_H2upscale_DraftVersion_V2-Added Tables)
Also, requirement document can be found in appendix (section 6).

2.3 Requirement Commonization for different Applications

The purpose of the project is not to create a FC Stack, it is to create a BOP system for different applications. It will be more efficient to work on different work packages if similar parts of the different applications are commonized. There are a total of 6 applications and the requirements of applications are commonized, based on the power requirements. For this reason, M2,M3, A2 and A3 requirements have been commonized. For the same purpose, T1 and M1 have been compared and commonized as much as possible. It is the intent of M1 application to use two of the fuel cell systems suitable for T1 with required changes for maritime use. Requirements that cannot be combined are marked in green, and an overall requirement sheet has been made for each case. Also, standalone versions of each application and commonized versions can be found in the requirement excel (see section 6 Appendix). Commonized versions of the applications are explained below:

- Node 1 includes T1,
- Node 2 includes M1,
- Node 3 includes M2, M3, A2 and A3.

3. Conclusion

The H2UpScale project aims to develop and validate innovative Balance-of-Plant (BoP) components for high-power PEM fuel cell (PEMFC) systems, targeting scalable and modular solutions capable of meeting the demands of heavy-duty transport applications, including road, maritime, and aviation. Motivated by the EU's climate targets and the need for zero-emission solutions across sectors, the project defines application-specific requirements for six distinct use cases—one for long-haul heavy-duty trucks, two for aviation, and three for maritime domains. These requirements serve as a foundation for the design, optimization, and validation of BoP components and system architectures at power levels ranging from 250 kW to 6 MW. During this work, a set of common requirements across all three application domains (road, maritime, aviation) was also identified. These shared specifications will help system development, enhance component compatibility, and modular upscaling.

In this report, application-specific requirements are presented and analyzed to guide system development in upcoming work packages. The complete requirements document is available both in the appendix and at the following directory: H2UpScale SharePoint > General > WP2 > Deliverables WP2 > D2.1_H2UpScale_DraftVersion_V1. Additionally, excel-based requirement documents are included in the appendix (Section 6) for quick reference.

4. Abbreviations

Term	Definition
BoP	Balance Of Plant
FC	Fuel Cell
HIL	Hardware in the Lopp
MIL	Model in the Loop
KPI	Key Project Indıcator
H2	Hydrogen
HeX	Heat Exchanger
WP	Work Package
CS-LSA	Certification Specifications and Acceptable Means of Compliance for Light Sport
CS	Cesrtification Specifications
T1	Truck Application
M1	First Marine Application
M2	Second Marine Application
M3	Third Marine Application
A1	First Aviation Application
A2	Second Aviation Application
A3	Third Aviation Application
NLR	Royal Netherlands Aerospace Centre
CS	Certification Specification
CS-LSA	Certification Specifications for Light Sport Aeroplanes
CS-23	Certification Specifications for Normal-Category Aeroplanes
CS-25	Certification Specifications for Large Aeroplanes
RORO	Roll on Roll off
FRD	Ford Otosan
DAM	Damen
-	-

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6. Appendix

This appendix contains the agreed Node Specific Requirements (6.1) and the Application Specific Requirements provided by the respective area experts (6.2, 6.3, 6.4).

In the Node Specific Requirements for Node N2, if a particular requirement is different from Node N1, then it is highlighted in green. An example is shown below:

180	575

In the Node Specific Requirements for Node N3A, if a particular requirement is different from Node N3M, then it is highlighted in green. An example is shown below:

50	55

In the Application Specific Requirements if a cell is blank then one or more of the following is true:

- The requirement is not relevant to the application being documented.
- The information on this requirement held by the application area subject matter expert is confidential and cannot be shared with the H2UpScale consortium.
- The application area subject matter expert does not have sufficient information to provide a clear requirement.

6.1 Node Specific Requirements (N1, N2, N3M, N3A)

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance				N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
							N1	N2	N3M	N3A					
Application Description														*None of this is compared or summarised. It is descriptive*	
H2US_APP_01	Machine Type	[-]	Truck	Urban Water Shuttle	Ro-Ro Passenger car, ferry										
H2US_APP_02	Application Description	[-]	Heavy Duty	Waterbus 2907, city water transport. Fixed route with stops	DRFe8117, car and passenger ferry, Fixed route with 2 stops										
H2US_APP_03	Environment Type	[-]	Asphalt	Inland	Offshore										*Road Type / Water type / Air*
H2US_APP_04	Duty Cycle	[-]	Cenevre - Barcelona Road Profile	PROVIDED	PROVIDED										*Can be road route, speed profile, power profile, or similar Provide description here, and detailed duty cycle in separate file(s) This can either be at the powertrain level, or (preferably) at the fuel cell level*
H2US_APP_05	Maximum vehicle speed	km/h	90	40	26										
H2US_APP_06	Vehicle Unladen Weight	kg	9000	48000	1820000										*including any fuel, but no passengers, cargo, or trailers*
H2US_APP_07	Vehicle Gross Weight	kg	44000	55000	2000000										*including any fuel, passengers, cargo, or trailers*
H2US_APP_08	Application Length	mm	4000	28650	80800										
H2US_APP_09	Application Width	mm	2500	7500	17000										
H2US_APP_10	Application Height	mm	4000	7900	18490										
H2US_APP_11	Desired Range	km	800	336	1019										*Range between tank filling on a declared or nominal duty cycle*
H2US_APP_12	On board hydrogen storage	kg	72	375	1020										
H2US_APP_13	Total hydrogen system weight	kg		8 500	25 000										*Includes fuel cell system, hydrogen storage, and cooling system*
Powertrain (Fuel Cell + Battery)														*Primarily for assisting with vehicle simulation*	
H2US_PWRTRN_01	Continuous Peak Power	kW	400	782	1980										*"Continuous" means power that could be needed indefinitely*
H2US_PWRTRN_02	Intermittent Peak Power	kW	550	832	2092										*"Intermittent" means power that isn't required full time but is required for certain operations. Please define intermittent for each application*
H2US_PWRTRN_02_DEF	Definition of intermittent if required	[-]	4% at 80 kph with full load for 5 minutes	intermediate speed engines and full hotel load (approx. 10 to 15 min)	intermediate speed engines and full hotel load (approx. 15 to 20 min)										

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance				N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
							N1	N2	N3M	N3A					
H2US_PWRTRN_03	Cruise Power	kW	120	740 - 575	1800										*"Cruise" is intended to be power vehicle could operate at for extended periods, such as truck running on flat at highway speed*
H2US_PWRTRN_04	Details on power split algorithm or strategy	[-]	rule based	rule based EMS, which is monitored, and input values are revised over time	rule based EMS, which is monitored, and input values are revised over time										*This information is helpful in determining the actual fuel cell duty cycle and performance requirements*
Battery														*Primarily for assisting with vehicle simulation*	
H2US_BATT_01	Battery Chemistry	[-]	NMC	LTO	LNMC										
H2US_BATT_02	Battery Size	kWh	120	168	600										
H2US_BATT_03	Continuous Discharge Power	kW or C		3C	1.25c										
H2US_BATT_04	Continuous Charge Power	kW or C		3C	1.75c										
H2US_BATT_07	Peak Charge Power	kW or C		1400 kW	3700 kW										
H2US_BATT_08	Max duration allowed at peak charge power	s		900	1 800										
H2US_BATT_09	Maximum allowed SOC	%	90	100	90										
H2US_BATT_10	Minimum allowed SOC	%	10	30	20										
Power and Efficiency (Fuel Cell)														*Efficiency is measured against LHV of Hydrogen i.e. 119.96 kJ/kg* *All powers and efficiencies referenced against EoL (End of Life)*	
H2US_PWREFF_01	Continuous Peak Net Power	kW	350	700	1050	1050	Critical	Critical	Critical	Critical	Power is EoL Set to Critical as these defines the Node	Power is EoL Set to Critical as this defines the Node Accept slight difference in power from initial request to make system more likely to be modular with Node #1	M3 and A3 intended to use multiple units to meet their power demand	M3 and A3 intended to use multiple units to meet their power demand	*"Continuous" means power that can be sustained indefinitely*
H2US_PWREFF_02	Continuous Peak Net Power Efficiency	%	50	50	50	50	Major	Major	Major	Major	This value might not be reached given the way fuel cell efficiency drops from cruise to rated power. A slightly smaller value is acceptable Set to Major as compromise acceptable	This value might not be reached given the way fuel cell efficiency drops from cruise to rated power. A slightly smaller value is acceptable Set to Major as compromise acceptable	This value might not be reached given the way fuel cell efficiency drops from cruise to rated power. A slightly smaller value is acceptable to both applications	This value might not be reached given the way fuel cell efficiency drops from cruise to rated power. A slightly smaller value is acceptable to both applications	
H2US_PWREFF_05	Idle Net Power	kW	35	70	105	105	Minor	Minor	Major	Major	Set idle power to 10% of peak power No great issue with values higher or lower	Set idle power to 10% of peak power No great issue with values higher or lower	10 % of continuous power for idle	10 % of continuous power for idle	*"Idle" means minimum power required with the fuel cell operating*
H2US_PWREFF_06	Idle Net Power Efficiency	%	>55	>55			Minor	Minor	Minor	Minor	Accept whatever value we get when targeting cruise efficiency	Accept whatever value we get when targeting cruise efficiency			
H2US_PWREFF_07	Cruise Net Power	kW	180	575	950	950	Critical	Major	Critical	Critical					*"Cruise" is intended to be point that fuel cell will operate at, or close to for long periods. An example would be required power for vehicle at highway speed on the flat*
H2US_PWREFF_08	Cruise Net Power Efficiency	%	55	50	50	55	Critical	Critical	Critical	Critical	55 chosen as better than 50 and allows potential to meet 50% at higher power on Marine	Upgraded to critical requirement as effectively defines the business case	Upgraded to critical requirement as effectively defines the business case	55 allows for smaller cooling system which has a large impact on weight and drag	

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance N1	Importance N2	Importance N3M	Importance N3A	N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
H2US_PWREFF_09	Net Power Ramp Rate - Up	kW/s	15	30	21	21	Major	Major	Major	Major	Battery will cover the power discrepancy between powertrain and fuel cell during ramp down	Increase to align requirements with Node #1	2 % per second i.e. 45s to peak power from idle	2 % per second i.e. 45s to peak power from idle	
H2US_PWREFF_10	Net Power Ramp Rate - Down	kW/s	15	30	21	21	Major	Major	Critical	Critical	Battery will cover the power discrepancy between powertrain and fuel cell during ramp down	Increase to align requirements with Node #1	2 % per second i.e. 45s to idle power from peak power	2 % per second i.e. 45s to idle power from peak power	
H2US_PWREFF_11	Net Power Ramp Rate - Down (Emergency)	kW/s	≥ 350	≥ 700	>1050	>1050	Critical	Critical	Critical	Critical	This is worst case requirement. Fuel cell would have a number of emergency response levels in service with associated severities and shut down times	This is worst case requirement. Fuel cell would have a number of emergency response levels in service with associated severities and shut down times	This is worst case requirement. Fuel cell would have a number of emergency response levels in service with associated severities and shut down times	This is worst case requirement. Fuel cell would have a number of emergency response levels in service with associated severities and shut down times	*Emergency Ramp Down is intended to document how fast the output power from the fuel cell is expected to drop during an emergency event.*
H2US_PWREFF_11_DEF	Definition of emergency if required	[-]	System leakage, fire etc	System leakage, fire etc	System leakage, fire etc	System leakage, fire etc	Critical	Critical	Critical	Critical					
Electrical															
H2US_ELEC_01	Minimum Fuel Cell System Output Voltage	V	600	600	1 000		Critical	Critical	Major			Decrease to 600 V to align with Node #1	Marine is seeing an increasing trend in voltages		*"Fuel Cell System Output Voltage" is voltage that the fuel cell is expected to create after its inbuilt DCDC*
H2US_ELEC_02	Maximum Continuous Fuel Cell System Output Voltage	V	850	850	1 250		Critical	Critical	Major		Increase to 850 V based on trend in heavy duty trucks	Increase to 850 V to align with Node #1	Marine is seeing an increasing trend in voltages		
H2US_ELEC_03	Maximum Intermittent Fuel Cell System Output Voltage	V				< 1000				Critical				Required to keep creepage and clearance at reasonable values Ensure that stack voltage does not exceed 1000V either	*"Intermittent" means voltage that isn't present full time but can occur in certain situations. Please define intermittent for each application*
H2US_ELEC_03_DEF	Definition of intermittent if required	[-]				Reduce voltage to make isolation easier				Critical					
H2US_ELEC_07	System HV bus type	[-]	DC	DC	DC	DC	Critical	Critical	Critical	Critical					*Is fuel cell system expected to output AC or DC voltage?*
H2US_ELEC_08	System HV bus AC details if required	[-]								Major					*If fuel cell is expected to output AC Voltage, include number of phases and frequency ranges here*
H2US_ELEC_04	Vehicle Isolation Resistance Requirement	Ω/V	500	500	500	500	Critical	Critical	Critical	Critical	In line with expectations from UNECE R134		Isolated DCDC expected on each fuel cell system	Isolated DCDC expected on each fuel cell system	
H2US_ELEC_05	Fuel Cell System Isolation Resistance Requirement	Ω/V	5 000	5 000	500	500	Critical	Critical	Critical	Critical	500 Ω/V is OK if isolated DCDC used 5000 Ω/V based on typical number of un-isolated devices on HV bus for vehicles	500 Ω/V is OK if isolated DCDC used 5000 Ω/V based on typical number of un-isolated devices on HV bus for vehicles	Isolated DCDC expected on each fuel cell system	Isolated DCDC expected on each fuel cell system	
H2US_ELEC_06	EMC/EMI Requirements	[-]	ECE R10	ECE R10	DO-160	DO-160	Critical	Critical	Critical	Critical			Use Aviation standard		*These can be legal standards, industry specific standards, and/or OEM requirements*
Packaging, Weight and Volume															
H2US_FIT_01	Ideal Weight of Fuel Cell System	kg	< 233	< 467	< 700	< 525	Critical	Critical	Critical	Critical	H2UpScale targets 1.5 kW/kg for marine and 2.0 kW/kg for aviation	H2UpScale targets 1.5 kW/kg for marine and 2.0 kW/kg for aviation	H2UpScale targets 1.5 kW/kg for marine and 2.0 kW/kg for aviation	H2UpScale targets 1.5 kW/kg for marine and 2.0 kW/kg for aviation	
H2US_FIT_02	Maximum Weight of Fuel Cell System	kg	< 389	< 778	< 1167	< 1167	Critical	Critical	Critical	Critical	Estimate as 0.9 kW/kg (DOE Ultimate target https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20005-automotive-fuel-cell-targets-status.pdf?Status=Master)	Estimate as 0.9 kW/kg (DOE Ultimate target https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20005-automotive-fuel-cell-targets-status.pdf?Status=Master)	Estimate as 0.9 kW/kg (DOE Ultimate target https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20005-automotive-fuel-cell-targets-status.pdf?Status=Master)	Estimate as 0.9 kW/kg (DOE Ultimate target https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/20005-automotive-fuel-cell-targets-status.pdf?Status=Master)	
H2US_FIT_05	Fuel Cell System Limiting Length	mm	1250	3000	7000		Major	Major	Major	Major		Should include space for maintenance	Should include space for maintenance	Separate values for Marine and Aviation	

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance				N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
							N1	N2	N3M	N3A					
H2US_FIT_06	Fuel Cell System Limiting Width	mm	1050	1150	6000		Major	Major	Major	Major		Should include space for maintenance	Should include space for maintenance	Separate values for Marine and Aviation	
H2US_FIT_07	Fuel Cell System Limiting Height	mm	700	2200	3000		Major	Major	Major	Major			Engine room height	Separate values for Marine and Aviation	
H2US_FIT_08	Fuel Cell System Location	[-]	Underbody	main deck, centre of vessel, in Fuel cell room	Above main deck, in fuel cell room		Major	Major	Major	Critical	Between chassis rails	Based on hydrogen storage and ship design			*Describe whereabouts on the vehicle the fuel cell system(s) would be placed*
H2US_FIT_09	Cooling System Type	[-]	Air to liquid	fresh water-cooled internal glycol/FW loop	Water/Glycol as primary cooling media	Water/Glycol as primary cooling media	Major	Minor	Critical	Critical			Both applications can have same coolant running through fuel cell/CAC Difference in how this heat is exchanged with environment	Both applications can have same coolant running through fuel cell/CAC Difference in how this heat is exchanged with environment	*A system generating turbulent flow could be a viable option, as this type of flow has been shown to enhance heat transfer and improve system efficiency. However, further studies will determine the type that best suits each application. HTF formulations will be evaluated according to each application.*
H2US_FIT_10	Cooling System Limiting Length	mm	968	NA	NA		Major			Minor		Cooling system is not space limited			
H2US_FIT_11	Cooling System Limiting Width	mm	1028	NA	NA		Major			Minor		Cooling system is not space limited			
H2US_FIT_12	Cooling System Limiting Height	mm	40	NA	NA		Major			Minor		Cooling system is not space limited			
H2US_FIT_13	Cooling System Location	[-]	Behind the Cabin		Engine room below waterline. Heat exchanger fuel cell room or in engine room	Ram air duct in pods/fuselage	Critical	Critical	Minor	Critical				Separate values for Marine and Aviation	*Describe whereabouts on the vehicle the fuel cell system(s) would be placed. Include whether cooling system will have access to ram air, or not*
Environment															
	Unrestricted Operation														
H2US_ENV_01	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-15 °C at 0 m -15 °C at 1500 m	-15 °C at 0 m	-15 °C at 0 m	-55 °C 7620 m	Major	Major	Critical	Critical				Worst case aviation	*Operating envelope of temperature and altitudes/pressures where full performance is expected*
H2US_ENV_02	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	40 °C at 0 m 40 °C at 1500 m	40 °C at 0 m	35 °C at 0 m	50 °C 7620 m	Major	Major	Critical	Critical		Increase to align requirements with Node #1		Worst case aviation	
	Restricted Operation														
H2US_ENV_03	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-15 °C at 0 m -15 °C at 1500 m	-15 °C at 0 m	-20 °C at 0 m		Major	Major	Critical		Only interested in no derate capability	Decrease to align requirements with Node #1		No derate allowed	*Operating envelope of temperature and altitudes/pressures where minimum performance is expected, and the minimum allowable performance*
H2US_ENV_04	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	40 °C at 0 m 40 °C at 1500 m	40 °C at 0 m	45 °C at 0 m		Major	Major	Critical		Only interested in no derate capability	Decrease to align requirements with Node #1		No derate allowed	
H2US_ENV_05	Minimum permissible power	kW	350	700	1 000		Major	Major	Critical				Only very minor decrease in power expected	No derate allowed	
H2US_ENV_06	Derate Curve(s)	kW at °C and/or m			Linear				Minor					No derate allowed	*If something other than a linear derate is expected, put that information here*
H2US_ENV_07	Ambient temperature range requirement during non-operation	°C	-15 to +40 °C	-15 to +40 °C	-20 to 45	DO-160	Major	Major	Minor	Minor			Worst case ambient temperature from restricted operation		*Storage, transport, etc* *Min and max temperature*

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance N1	Importance N2	Importance N3M	Importance N3A	N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
H2US_ENV_08	Relative humidity during operation	%	5 to 100	40 to 100	40 to 100	DO-160	Major	Major	Major	Major	Cummins application range	Cummins application range, unlikely to be seen in Marine environment			*Min and max humidity*
H2US_ENV_09	Maximum compartment temperature for Fuel Cell System location	°C	65	25	25	40	Major	Minor	Minor	Minor	65 chosen as an estimate of compartment if fuel cell cooling is behind cab on truck				*Compartment can get significantly hotter than ambient*
H2US_ENV_10	Time to full power from normal start	s	60	60	60	60	Major	Major	Major	Major				From marine	*Time to full power from request for fuel cell to start*
H2US_ENV_11	Unaided cold start temperature	°C	- 15	- 15	- 15	- 15	Minor	Minor	Minor	Minor				From marine	*Unaided would mean no preheating is carried out on the fuel cell system, but HV could be supplied for BoP*
H2US_ENV_12	Time to full power from unaided start	s	180	180	120	120	Major	Major	Minor	Minor				From marine	
H2US_ENV_13	Aided cold start temperature	°C	- 20	- 20	- 35	- 50	Major	Major	Critical	Critical				Worst case aviation	*Aided start involves preheating of fuel cell system prior to start*
H2US_ENV_14	Time to full power from beginning of aided start	s	180	180	< 300	< 300	Major	Major	Major	Major					
H2US_ENV_17	Restart time	s	25	25	25	25	Major	Major	Major	Major	Does not include ramp to full power. This is time to idle from start command	Does not include ramp to full power. This is time to idle from start command	Does not include ramp to full power. This is time to idle from start command Only major need if multiple stacks	Does not include ramp to full power. This is time to idle from start command Only major need if multiple stacks	*Restart time is time for fuel cell to get to provide power if starting during duty cycle e.g. stop/start, or multi-system power balancing*
H2US_ENV_15	Atmospheric pollutants expected during operation	ppm	based on air quality	based on air quality	2-50 µg/m³ salt		Critical	Critical	Critical	Critical	Expectation is that system would work in most polluted European city	Expectation is that system would work in most polluted European city or port			*Atmospheric pollutants are considered to be those that can poison the fuel cell either temporarily or permanently. Examples include ammonia and sulphates*
H2US_ENV_16	Air Quality	[-]	~150 AQI, city atmosphere	~150 AQI, city atmosphere			Critical	Critical	Critical	Critical	Expectation is that system would work in most polluted European city	Expectation is that system would work in most polluted European city or port			*Dust etc*
Operation															
	Angularity														
H2US_OP_12	Baseline Pitch	°	Up to 1.5	Up to 1.5	Up to 2	Up to 2	Critical	Critical	Critical	Critical	Marine is worst case	Marine is worst case	Chose aviation as worst case, but marine would find 2° useful	Chose aviation as worst case, but marine would find 2° useful	*Baseline pitch is what the fuel could be expected to see with no other inputs to the vehicle. For a truck this could be installation angle, for a ship this could be the expected angle with a full load and fully fuelled, for an aircraft this could be baseline trim Positive values indicate fuel cell is tilted upwards at the front*
H2US_OP_13	Baseline Roll	°	0	0	0	0	Major	Major	Critical	Critical	No baseline roll from applications	No baseline roll from applications	No baseline roll from applications	No baseline roll from applications	*Similar to Baseline Pitch, but for roll instead.* *No particular sign convention expected, but mention which way is positive in comments*
	Pitch Up/Down														
H2US_OP_1	Continuous	°	1.5	1.5	0	+5 to -5	Critical	Critical	Critical	Critical	Marine is worst case	Marine is worst case			*Angle at which fuel cell is expected to operate continuously. An example would be a digger which could be expected to be on a slope for hours at a time*
H2US_OP_2	Intermittent	°	+12 to -12	+12 to -12	+2 to -2	+8 to -8	Critical	Critical	Critical	Critical	Truck is worst case	Truck is worst case			
H2US_OP_2_DEF	Definition of intermittent if applicable	[-]	Hills and Waves	Hills and Waves	Sine wave from waves	1 min	Critical	Critical	Critical	Critical	Waves are short duration; hills are medium duration	Waves are short duration; hills are medium duration			
	Roll Left/Right														
H2US_OP_3	Continuous	°	0	0	0	+30 to -30	Major	Major	Critical	Critical	No baseline roll from applications	No baseline roll from applications			

Req. Number	Requirement	Units	N1	N2	N3M	N3A		Importance N1	Importance N2	Importance N3M	Importance N3A		N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
H2US_OP_4	Intermittent	°	+7 to -7	+7 to -7	+21 to -21	+45 to -45		Critical	Critical	Critical	Critical		Truck is worst case	Truck is worst case			
H2US_OP_4_DEF	Definition of intermittent if applicable	[-]	Hills and Waves	Hills and Waves	Sine wave from waves			Critical	Critical	Critical	Critical		Waves are short duration; hills are medium duration	Waves are short duration; hills are medium duration			
	Worst case combination of pitch/roll																
H2US_OP_5	Continuous	°	Max + Max	Max + Max	Max + Max	Max + Max		Critical	Critical	Critical	Critical		Marine could see both pitch and roll simultaneously. Truck is much less likely to do so	Marine could see both pitch and roll simultaneously. Truck is much less likely to do so			
H2US_OP_6	Intermittent	°	Max + Max	Max + Max	Max + Max	Max + Max		Critical	Critical	Critical	Critical		Marine could see both pitch and roll simultaneously. Truck is much less likely to do so	Marine could see both pitch and roll simultaneously. Truck is much less likely to do so			
H2US_OP_6_DEF	Definition of intermittent if applicable	[-]	Hills and Waves	Hills and Waves				Critical	Critical								
H2US_OP_7	What are the continuous vibration requirements?	g	ISO 16750-3	ISO 16750-3	ISO 16750-3	DO-160		Critical	Critical	Critical	Critical		Worst case	Worst case	Carry-over from smaller marine systems as no standard exists	Worst case as vibration environment likely to change as move from turbine to electromotors	*Separate answers for each axis (x,y,z)*
H2US_OP_8	What are the intermittent vibration requirements?	g	ISO 16750-3	ISO 16750-3	ISO 16750-3	DO-160		Critical	Critical	Critical	Critical		Worst case	Worst case	Carry-over from smaller marine systems as no standard exists	Worst case as vibration environment likely to change as move from turbine to electromotors	*Separate answers for each axis (x,y,z)*
H2US_OP_9	What is the shock load requirement (1 cycle)?	g	ISO 16750-3	ISO 16750-3	ISO 16750-3	DO-160		Critical	Critical	Critical	Critical		Worst case	Worst case	Carry-over from smaller marine systems as no standard exists	Worst case as vibration environment likely to change as move from turbine to electromotors	*Separate answers for each axis (x,y,z)*
H2US_OP_10	Is there a required vibration profile?	[-]	ISO 16750-3	ISO 16750-3	ISO 16750-3	DO-160		Critical	Critical	Critical	Critical		Worst case	Worst case	Carry-over from smaller marine systems as no standard exists	Worst case as vibration environment likely to change as move from turbine to electromotors	
H2US_OP_11	What chemical exposure resistance is needed?	[-]	ISO 16750-5	ISO 16750-5	ISO 16750-5	DO-160		Critical	Critical	Critical	Critical		Use automotive standards as this is the worst case	Use automotive standards as this is the worst case	Use automotive standards as this is the worst case		
Safety																	
H2US_SAFE_01	Legal safety requirements	[-]	ISO 23273	BV-classification: NR678 Hydrogen Fuelled Ships	BV-classification: NR678 Hydrogen Fuelled Ships	EASA, FAA, CAA		Major	Critical	Critical	Critical		No commonisation with Node #2	No commonisation with Node #1		Separate values for Marine and Aviation	*This would be any safety specific legislation for a fuel cell in the given application*
H2US_SAFE_02	Industry standards considered to be entry level	[-]	ISO 9001	IMO Interim guidelines for the safety of ships using fuel cell power installations	IMO Interim guidelines for the safety of ships using fuel cell power installations			Major	Critical	Critical	Critical		No commonisation with Node #2	No commonisation with Node #1		Separate values for Marine and Aviation	*What safety standards or codes are generally considered entry level for the industry that the application exists within*
H2US_SAFE_03	Additional standards that might be included	[-]			NA					Minor	Minor					Separate values for Marine and Aviation	*Any other standards that should be considered for this specific application*

Req. Number	Requirement	Units	N1	N2	N3M	N3A	Importance				N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
							N1	N2	N3M	N3A					
H2US_SAFE_04	Other safety expectations	[-]		double walled, boxed and inerted, A single point failure should not lead to dangerous situation	double walled, boxed and inerted, A single point failure should not lead to dangerous situation			Critical	Critical	Major		No commonisation with Node #1		Separate values for Marine and Aviation Aviation could need to handle multiple simultaneous failures prior to dangerous situation	*Examples could be a requirement for redundancy to allow for limited power to be supplied if one component fails*
Compliance															
H2US_COMP_01	European legislation for this application	[-]	UNECE R10 UNECE R100 UNECE R134 UNECE R155 UNECE R156	Type approval	Type approval	EASA, FAA, CAA	Critical	Critical	Critical	Critical	Initial list of known legislation that impacts design of fuel cell systems	No commonisation with Node #1		Separate values for Marine and Aviation	*Should include consideration for all applicable legislation, not just fuel cell specific. An example is fuel cell controllers need to comply with automotive Cybersecurity legislation*
H2US_COMP_02	Industry standards considered to be entry level	[-]	ISO 14687	unit certification, product approval	unit certification, product approval		Major	Major	Critical	Critical	No commonisation with Node #2	No commonisation with Node #1		Separate values for Marine and Aviation	
H2US_COMP_03	Additional standards that might be included	[-]			NA				Major	Major				Separate values for Marine and Aviation	
H2US_COMP_04	Maximum permissible noise	dB	70	NI			Major	Major	Major	Major	No commonisation with Node #2	No commonisation with Node #1		Separate values for Marine and Aviation	
H2US_COMP_05	How do you measure and define noise?	[-]	Noise inside the cabin, with 90kph speed at highway	dB(A) measurement	dB(A) measurements		Major	Major	Minor	Minor	No commonisation with Node #2	No commonisation with Node #1		Separate values for Marine and Aviation	
Durability															
H2US_DUR_01	Expected system life	hrs	30 000	15 000	30 000		Critical	Critical	Major	Major	System life is difficult to define exactly, as potential to replace/recondition components during the lifetime. Key factors are cost and time to replace Can be considered to be similar to combustion product		System life is difficult to define exactly, as potential to replace/recondition components during the lifetime. Key factors are cost and time to replace	System life is less of a concern as replacement expected more frequently than existing power sources	
H2US_DUR_02	Expected uptime	%		85	85			Major	Major	Major					
Service and Maintainability															
H2US_SER_01	Minimum service intervals (for any component)	h		100	500		Major	Major	Minor	Major	Equivalent to 50 000 km at 50 km/h average speed	Service no more than once a week	Try and match diesel capability, but acceptable if shorter		
H2US_SER_02	Service access expectations/restrictions	[-]	Service shouldn't require fuel cell removal or disassembly	No splitting of any hydrogen seals during maintenance	No splitting of any hydrogen seals during maintenance		Critical	Critical	Critical	Critical		Standard service/maintenance should be capable to be done by technician without hydrogen or high voltage qualifications	Standard service/maintenance should be capable to be done by technician without hydrogen or high voltage qualifications		*Examples include expected maximum time to service fuel cell, service access only possible to a limited section of the fuel cell envelope, etc*
Hydrogen															

Req. Number	Requirement	Units	N1	N2	N3M	N3A		Importance					N1 Comments	N2 Comments	N3M Comments	N3A Comments	Explanatory Notes
								N1	N2	N3M	N3A						
H2US_HY_01	Hydrogen type	[-]	Compressed	Compressed	Compressed	Liquid		Critical	Critical	Critical	Critical						*Compressed / Cryo Compressed / Liquid*
H2US_HY_02	Expected hydrogen quality	[-]	ISO 14687:2025 Type I; Grade D	ISO 14687:2025 Type I; Grade D	ISO 14687:2025 Type I; Grade D	99.999 % pure H_2		Critical	Critical	Critical	Critical		From standard, Type I is gas, Grade D is for PEM FC road vehicles.	From standard, Type I is gas, Grade D is for PEM FC road vehicles. Can be used with Marine			
H2US_HY_03	Maximum storage pressure	bar (abs)	750	750	700	5		Critical	Major	Major	Major			Taken from automotive		Higher than this will reduce hydrogen density	
H2US_HY_04	Storage temperature range	°C	-40 to +85	-40 to +85	-40 to +85	- 253		Critical	Critical	Major	Major		ISO 19881 - Gaseous Hydrogen - Land Vehicle Fuel Containers Allowable temperature range	ISO 19881 - Gaseous Hydrogen - Land Vehicle Fuel Containers Allowable temperature range			
H2US_HY_05	Supply pressure range	bar (abs)	<20	<20	<20	2 to 3		Critical	Critical	Critical	Critical		20 bar is a threshold between low and high pressure on marine certification. Less than this number is acceptable at any level based on hydrogen sub-system development	20 bar is a threshold between low and high pressure on marine certification. Less than this number is acceptable at any level based on hydrogen sub-system development			*Supply means supply to the fuel cell system*
H2US_HY_06	Supply temperature range	°C	-40 to +85	-40 to +85	-40 to +85	- 253		Critical	Critical	Critical	Critical		ISO 19881 - Gaseous Hydrogen - Land Vehicle Fuel Containers Allowable temperature range	ISO 19881 - Gaseous Hydrogen - Land Vehicle Fuel Containers Allowable temperature range		Expectation of H_2 heating using stack coolant, electrical heater, or combination of both	
Additional Comments or Information																	
H2US_INF_01	Additional Comments or Information	[-]															*Include anything else that should be considered for the particular application in question*

6.2 Application Specific Requirements – Heavy-Duty Truck (T1)

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
Application Description							*None of this is compared or summarised. It is descriptive*
H2US_APP_01	Machine Type	[-]					
H2US_APP_02	Application Description	[-]	Heavy Duty	Exact Value	Critical		
H2US_APP_03	Environment Type	[-]	Asphalt	Exact Value	Critical		*Road Type / Water type / Air*
H2US_APP_04	Duty Cycle	[-]	Cenevre - Barcelona Road Profile	Estimated Value	Minor		*Can be road route, speed profile, power profile, or similar Provide description here, and detailed duty cycle in separate file(s) This can either be at the powertrain level, or (preferably) at the fuel cell level*
H2US_APP_05	Maximum vehicle speed	km/h	90	Exact Value	Critical		
H2US_APP_06	Vehicle Unladen Weight	kg	9 000	Exact Value	Major		*including any fuel, but no passengers, cargo, or trailers*
H2US_APP_07	Vehicle Gross Weight	kg	44 000	Exact Value	Major		*including any fuel, passengers, cargo, or trailers*
H2US_APP_08	Application Length	mm	4 000	Exact Value	Major		
H2US_APP_09	Application Width	mm	2 500	Exact Value	Major		
H2US_APP_10	Application Height	mm	4 000	Exact Value	Major		
H2US_APP_11	Desired Range	km	800	Estimated Value	Major		*Range between tank filling on a declared or nominal duty cycle*
H2US_APP_12	On board hydrogen storage	kg	72	Estimated Value	Critical		
H2US_APP_13	Total hydrogen system weight	kg					*Includes fuel cell system, hydrogen storage, and cooling system*
Powertrain (Fuel Cell + Battery)							*Primarily for assisting with vehicle simulation*
H2US_PWRTRN_01	Continuous Peak Power	kW	400	Exact Value	Critical		*"Continuous" means power that could be needed indefinitely*
H2US_PWRTRN_02	Intermittent Peak Power	kW	550	Exact Value	Critical		*"Intermittent" means power that isn't required full time but is required for certain operations. Please define intermittent for each application*
H2US_PWRTRN_02_DEF	Definition of intermittent if required	[-]	4% at 80 kph with full load for 5 minutes	Exact Value	Critical		
H2US_PWRTRN_03	Cruise Power	kW	120	Exact Value	Critical	Depends on the control logic	*"Cruise" is intended to be power vehicle could operate at for extended periods, such as truck running on flat at highway speed*
H2US_PWRTRN_04	Details on power split algorithm or strategy	[-]	rule based				*This information is helpful in determining the actual fuel cell duty cycle and performance requirements*
Battery							*Primarily for assisting with vehicle simulation*
H2US_BATT_01	Battery Chemistry	[-]	NMC	Estimated Value	Unknown		
H2US_BATT_02	Battery Size	kWh	120	Exact Value	Critical		
H2US_BATT_03	Continuous Discharge Power	kW or C					
H2US_BATT_04	Continuous Charge Power	kW or C					
H2US_BATT_05	Peak Discharge Power	kW or C					
H2US_BATT_06	Max duration allowed at peak discharge power	s					
H2US_BATT_07	Peak Charge Power	kW or C					
H2US_BATT_08	Max duration allowed at peak charge power	s					
H2US_BATT_09	Maximum allowed SOC	%	90	Estimated Value	Major		
H2US_BATT_10	Minimum allowed SOC	%	10	Estimated Value	Major		
Power and Efficiency (Fuel Cell)							*Efficiency is measured against LHV of Hydrogen i.e. 119.96 kJ/kg All powers and efficiencies referenced against EoL (End of Life)*

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
H2US_PWREFF_01	Continuous Peak Net Power	kW			Minor	*"Continuous" means power that can be sustained indefinitely*	*"Continuous" means power that can be sustained indefinitely*
H2US_PWREFF_02	Continuous Peak Net Power Efficiency	%	> 50		Critical		
H2US_PWREFF_03	Intermittent Peak Net Power	kW	350	Exact Value	Critical	*"Idle" means minimum power required with the fuel cell operating*	
H2US_PWREFF_04	Intermittent Peak Net Power Efficiency	%					
H2US_PWREFF_04_DEF	Definition of intermittent if required	[-]				*"Cruise" is intended to be point that fuel cell will operate at, or close to for long periods. An example would be required power for vehicle at highway speed on the flat*	
H2US_PWREFF_05	Idle Net Power	kW	50	Exact Value			*"Idle" means minimum power required with the fuel cell operating*
H2US_PWREFF_06	Idle Net Power Efficiency	%	> 50	Exact Value	Major		
H2US_PWREFF_07	Cruise Net Power	kW	180	Exact Value	Critical		*"Cruise" is intended to be point that fuel cell will operate at, or close to for long periods. An example would be required power for vehicle at highway speed on the flat*
H2US_PWREFF_08	Cruise Net Power Efficiency	%	> 50	Exact Value	Critical	*Emergency Ramp Down is intended to document how fast the output power from the fuel cell is expected to drop during an emergency event.*	
H2US_PWREFF_09	Net Power Ramp Rate - Up	kW/s	15	Estimated Value	Major		
H2US_PWREFF_12	Net Power Ramp Rate - Up (Emergency)	kW/s	15	Estimated Value	Minor	*Efficiency is measured against LHV of Hydrogen i.e. 119.96 kJ/kg* *All powers and efficiencies referenced against EoL (End of Life)*	*Emergency Ramp Up is intended to document how fast the output power from the fuel cell is expected to rise during an emergency event such as an airplane 'go around'*
H2US_PWREFF_12_DEF	Definition of emergency if required	[-]				*"Continuous" means power that can be sustained indefinitely*	
H2US_PWREFF_10	Net Power Ramp Rate - Down	kW/s	15	Estimated Value	Major		
H2US_PWREFF_11	Net Power Ramp Rate - Down (Emergency)	kW/s	15	Estimated Value	Minor	*"Idle" means minimum power required with the fuel cell operating*	*Emergency Ramp Down is intended to document how fast the output power from the fuel cell is expected to drop during an emergency event.*
H2US_PWREFF_11_DEF	Definition of emergency if required	[-]					
Electrical							
H2US_ELEC_01	Minimum Fuel Cell System Output Voltage	V	600	Exact Value	Critical		*"Fuel Cell System Output Voltage" is voltage that the fuel cell is expected to create after its inbuilt DCDC*
H2US_ELEC_02	Maximum Continuous Fuel Cell System Output Voltage	V	720	Exact Value	Critical		
H2US_ELEC_03	Maximum Intermittent Fuel Cell System Output Voltage	V					*"Intermittent" means voltage that isn't present full time but can occur in certain situations. Please define intermittent for each application*
H2US_ELEC_03_DEF	Definition of intermittent if required	[-]					
H2US_ELEC_07	System HV bus type	[-]	DC	Exact Value	Critical		*Is fuel cell system expected to output AC or DC voltage?*
H2US_ELEC_08	System HV bus AC details if required	[-]					*If fuel cell is expected to output AC Voltage, include number of phases and frequency ranges here*
H2US_ELEC_04	Vehicle Isolation Resistance Requirement	Ω/V	No Info				
H2US_ELEC_05	Fuel Cell System Isolation Resistance Requirement	Ω/V	No Info				
H2US_ELEC_06	EMC/EMI Requirements	[-]	ECE R10				*These can be legal standards, industry specific standards, and/or OEM requirements*
Packaging, Weight and Volume							

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
H2US_FIT_01	Ideal Weight of Fuel Cell System	kg					
H2US_FIT_02	Maximum Weight of Fuel Cell System	kg					
H2US_FIT_03	Ideal Volume of Fuel Cell System	l					
H2US_FIT_04	Maximum Volume of Fuel Cell System	l					
H2US_FIT_05	Fuel Cell System Limiting Length	mm	1 250	Estimated Value	Major		
H2US_FIT_06	Fuel Cell System Limiting Width	mm	1 050	Estimated Value	Major		
H2US_FIT_07	Fuel Cell System Limiting Height	mm	700	Estimated Value	Major		
H2US_FIT_08	Fuel Cell System Location	[-]	Underbody	Exact Value	Major		*Describe whereabouts on the vehicle the fuel cell system(s) would be placed*
H2US_FIT_09	Cooling System Type	[-]				Turbulent flow of the cooling fluid	*A system generating turbulent flow could be a viable option, as this type of flow has been shown to enhance heat transfer and improve system efficiency. However, further studies will determine the type that best suits each application. HTF formulations will be evaluated according to each application.*
H2US_FIT_10	Cooling System Limiting Length	mm	968	Estimated Value	Major		
H2US_FIT_11	Cooling System Limiting Width	mm	1 028	Estimated Value	Major		
H2US_FIT_12	Cooling System Limiting Height	mm	40	Estimated Value	Major		
H2US_FIT_13	Cooling System Location	[-]	Behind the Cabin	Exact Value	Critical		*Describe whereabouts on the vehicle the fuel cell system(s) would be placed. Include whether cooling system will have access to ram air, or not*
Environment							
	Unrestricted Operation						
H2US_ENV_01	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-15 °C at 0 m -15 °C at 1500 m	Estimated Value	Major		*Operating envelope of temperature and altitudes/pressures where full performance is expected*
H2US_ENV_02	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	40 °C at 0 m 40 °C at 1500 m	Estimated Value	Major		
	Restricted Operation						
H2US_ENV_03	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-15 °C at 0 m -15 °C at 1500 m	Estimated Value	Major	power derate is not desired, thus same as with 78th line.	*Operating envelope of temperature and altitudes/pressures where minimum performance is expected, and the minimum allowable performance*
H2US_ENV_04	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	40 °C at 0 m 40 °C at 1500 m	Estimated Value	Major	power derate is not desired, thus same as with 78th line.	
H2US_ENV_05	Minimum permissible power	kW	350	Estimated Value	Major		
H2US_ENV_06	Derate Curve(s)	kW at °C and/or m					*If something other than a linear derate is expected, put that information here*
H2US_ENV_07	Ambient temperature range requirement during non-operation	°C	-15 to +40 °C	Estimated Value	Major		*Storage, transport, etc* *Min and max temperature*
H2US_ENV_08	Relative humidity during operation	%	40 to 80	Estimated Value	Major		*Min and max humidity*
H2US_ENV_09	Maximum compartment temperature for Fuel Cell System location	°C	No Info				*Compartment can get significantly hotter than ambient*
H2US_ENV_10	Time to full power from normal start	s	No Info				*Time to full power from request for fuel cell to start*
H2US_ENV_11	Unaided cold start temperature	°C	- 15	Estimated Value	Minor		*Unaided would mean no preheating is carried out on the fuel cell system, but HV could be supplied for BoP*

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
H2US_ENV_12	Time to full power from unaided start	s	180	Estimated Value	Major		
H2US_ENV_13	Aided cold start temperature	°C	- 20	Exact Value	Major		*Aided start involves preheating of fuel cell system prior to start*
H2US_ENV_14	Time to full power from beginning of aided start	s	180	Estimated Value	Major		
H2US_ENV_15	Atmospheric pollutants expected during operation	ppm	Average Eu Condition	Estimated Value	Minor		*Atmospheric pollutants are considered to be those that can poison the fuel cell either temporarily or permanently. Examples include ammonia and sulphates*
H2US_ENV_16	Air Quality	[-]	No Info				*Dust etc*
Operation							
	Angularity						
H2US_OP_12	Baseline Pitch	°	No Info				*Baseline pitch is what the fuel could be expected to see with no other inputs to the vehicle. For a truck this could be installation angle, for a ship this could be the expected angle with a full load and fully fuelled, for an aircraft this could be baseline trim* *Positive values indicate fuel cell is tilted upwards at the front*
H2US_OP_13	Baseline Roll	°	No Info				*Similar to Baseline Pitch, but for roll instead.* *No particular sign convention expected, but mention which way is positive in comments*
	Pitch Up/Down						
H2US_OP_1	Continuous	°	0	Estimated Value			*Angle at which fuel cell is expected to operate continuously. An example would be a digger which could be expected to be on a slope for hours at a time*
H2US_OP_2	Intermittent	°	12	Estimated Value			
H2US_OP_2_DEF	Definition of intermittent if applicable	[-]					
	Roll Left/Right						
H2US_OP_3	Continuous	°	0	Estimated Value			
H2US_OP_4	Intermittent	°	7	Estimated Value			
H2US_OP_4_DEF	Definition of intermittent if applicable	[-]					
	Worse case combination of pitch/roll						
H2US_OP_5	Continuous	°	0	Estimated Value			
H2US_OP_6	Intermittent	°	12	Estimated Value			
H2US_OP_6_DEF	Definition of intermittent if applicable	[-]					
H2US_OP_7	What are the continuous vibration requirements?	g	ISO 16750-3	Exact Value			*Give separate answers for each axis (x,y,z)*
H2US_OP_8	What are the intermittent vibration requirements?	g	ISO 16750-3	Exact Value			*Give separate answers for each axis (x,y,z)*
H2US_OP_9	What is the shock load requirement (1 cycle)?	g	ISO 16750-3	Exact Value			*Give separate answers for each axis (x,y,z)*
H2US_OP_10	Is there a required vibration profile?	[-]	ISO 16750-3	Exact Value			
H2US_OP_11	What chemical exposure resistance is needed?	[-]	No Info				
Safety							
H2US_SAFE_01	Legal safety requirements	[-]	ISO 23273	Exact Value			*This would be any safety specific legislation for a fuel cell in the given application*

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
H2US_SAFE_02	Industry standards considered to be entry level	[-]	ISO 9001	Exact Value			*What safety standards or codes are generally considered entry level for the industry that the application exists within*
H2US_SAFE_03	Additional standards that might be included	[-]					*Any other standards that should be considered for this specific application*
H2US_SAFE_04	Other safety expectations	[-]					*Examples could be a requirement for redundancy to allow for limited power to be suppled if one component fails*
Compliance							
H2US_COMP_01	European legislation for this application	[-]					*Should include consideration for all applicable legislation, not just fuel cell specific. An example is fuel cell controllers need to comply with automotive Cybersecurity legislation*
H2US_COMP_02	Industry standards considered to be entry level	[-]	ISO 14687	Exact Value	Major		
H2US_COMP_03	Additional standards that might be included	[-]					
H2US_COMP_04	Maximum permissible noise	dB	70	Exact Value	Major		
H2US_COMP_05	How do you measure and define noise?	[-]	Noise inside the cabin, with 90kph speed at highway	Estimated Value	Major		
Durability							
H2US_DUR_01	Expected system life	hrs	30 000	Estimated Value	Critical		
H2US_DUR_02	Expected uptime	%					
	Continuous Power Durability						
H2US_DUR_03	Allowable drop in power	kW					
H2US_DUR_04	Allowable drop in efficiency	%					
H2US_DUR_05	Allowable increase in heat rejection	kW					
	Intermittent Power Durability						
H2US_DUR_06	Allowable drop in power	kW					
H2US_DUR_07	Allowable drop in efficiency	%					
H2US_DUR_08	Allowable increase in heat rejection	kW					
	Cruise Power Durability						
H2US_DUR_09	Allowable drop in power	kW					
H2US_DUR_10	Allowable drop in efficiency	%					
H2US_DUR_11	Allowable increase in heat rejection	kW					
Service and Maintainability							
H2US_SER_01	Minimum service intervals (for any component)	h	30,000	Major			
H2US_SER_02	Service access expectations/restrictions	[-]	restricted during operations	Critical			*Examples include expected maximum time to service fuel cell, service access only possible to a limited section of the fuel cell envelope, etc*
Hydrogen							
H2US_HY_01	Hydrogen type	[-]	Compressed	Exact Value	Critical		*Compressed / Cryo Compressed / Liquid*
H2US_HY_02	Expected hydrogen quality	[-]					

Requirement Number	Requirement	Units	T1	Requirement Status	Importance	Comments	Explanatory Notes
H2US_HY_03	Maximum storage pressure	bar (abs)	750	Exact Value	Critical		
H2US_HY_04	Storage temperature range	°C	-30 to +60	Estimated Value	Critical		
H2US_HY_05	Supply pressure range	bar (abs)	2 - 3.5	Exact Value	Major		*Supply means supply to the fuel cell system*
H2US_HY_06	Supply temperature range	°C	60	Exact Value	Major		
Additional Comments or Information							
H2US_INF_01	Additional Comments or Information	[-]					*Include anything else that should be considered for the particular application in question*

6.3 Application Specific Requirements – Marine (M1, M2, M3)

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
Application Description									*None of this is compared or summarised. It is descriptive*
H2US_APP_01	Machine Type	[-]	Urban Water Shuttle	Ro-Ro Passenger car, ferry	Ro-Ro Passenger car, ferry				
H2US_APP_02	Application Description	[-]	Waterbus 2907, city water transport. Fixed route with stops	DRFe8117, 1 generator replacement	DRFe8117, car and passenger ferry, Fixed route with 2 stops				
H2US_APP_03	Environment Type	[-]	Inland	Offshore	Offshore			Sea conditions	*Road Type / Water type / Air*
H2US_APP_04	Duty Cycle	[-]	PROVIDED	PROVIDED	PROVIDED				*Can be road route, speed profile, power profile, or similar Provide description here, and detailed duty cycle in separate file(s) This can either be at the powertrain level, or (preferably) at the fuel cell level*
H2US_APP_05	Maximum vehicle speed	km/h	40	26	26				
H2US_APP_06	Vehicle Unladen Weight	kg	48 000	1820 000	1820 000			approximation	*including any fuel, but no passengers, cargo, or trailers*
H2US_APP_07	Vehicle Gross Weight	kg	55 000	2000 000	2000 000			approximation	*including any fuel, passengers, cargo, or trailers*
H2US_APP_08	Application Length	mm	28 650	80 800	80 800				
H2US_APP_09	Application Width	mm	7 500	17 000	17 000				
H2US_APP_10	Application Height	mm	7 900	18 490	18 490			including underwater + appendages (antenna's)	
H2US_APP_11	Desired Range	km	336	510	1 019			one full day of sailing	*Range between tank filling on a declared or nominal duty cycle*
H2US_APP_12	On board hydrogen storage	kg	375	575	1 020				
H2US_APP_13	Total hydrogen system weight	kg	8 500	12 500	25 000	Estimated Value	Major	based on removal of (1 or 2) generators	*Includes fuel cell system, hydrogen storage, and cooling system*
Powertrain (Fuel Cell + Battery)									*Primarily for assisting with vehicle simulation*
H2US_PWRTRN_01	Continuous Peak Power	kW	782	1 000	1 980	Exact Value	Critical	maximum power propulsion engines	*"Continuous" means power that could be needed indefinitely*
H2US_PWRTRN_02	Intermittent Peak Power	kW	832	1 050	2 092	Exact Value	Critical	intermediate power of propulsion engines	*"Intermittent" means power that isn't required full time but is required for certain operations. Please define intermittent for each application*
H2US_PWRTRN_02_DEF	Definition of intermittent if required	[-]	intermediate speed engines and full hotel load (approx. 10 to 15 min)	intermediate speed engines and full hotel load (approx. 15 to 20 min)	intermediate speed engines and full hotel load (approx. 15 to 20 min)				
H2US_PWRTRN_03	Cruise Power	kW	740 - 575	900	1 800	Exact Value	Critical	upstream - downstream, based on actual data	*"Cruise" is intended to be power vehicle could operate at for extended periods, such as truck running on flat at highway speed*
H2US_PWRTRN_04	Details on power split algorithm or strategy	[-]	rule based EMS, which is monitored, and input values are revised over time	rule based EMS, which is monitored, and input values are revised over time	rule based EMS, which is monitored, and input values are revised over time				*This information is helpful in determining the actual fuel cell duty cycle and performance requirements*

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
Battery									*Primarily for assisting with vehicle simulation*
H2US_BATT_01	Battery Chemistry	[-]	LTO	LNMC	LNMC				
H2US_BATT_02	Battery Size	kWh	168	600	600	Estimated Value	Minor	is not optimized, depends on capabilities of fuel cell system	
H2US_BATT_03	Continuous Discharge Power	kW or C	3C	1.25c	1.25c	Estimated Value		based on chemistry	
H2US_BATT_04	Continuous Charge Power	kW or C	3C	1.75c	1.75c	Estimated Value		based on chemistry	
H2US_BATT_05	Peak Discharge Power	kW or C							
H2US_BATT_06	Max duration allowed at peak discharge power	s							
H2US_BATT_07	Peak Charge Power	kW or C	1400 kW	3700 kW	3700 kW	Exact Value		based on current technology	
H2US_BATT_08	Max duration allowed at peak charge power	s	900	1 800	1 800				
H2US_BATT_09	Maximum allowed SOC	%	100	90	90				
H2US_BATT_10	Minimum allowed SOC	%	30	20	20			based on redundancy (safety requirement)	
Power and Efficiency (Fuel Cell)									*Efficiency is measured against LHV of Hydrogen i.e. 119.96 kJ/kg* *All powers and efficiencies referenced against EoL (End of Life)*
H2US_PWREFF_01	Continuous Peak Net Power	kW	740	1 000	2 100	Estimated Value	Major	End of life power, determined by profile to make sure full profile can be done on hydrogen. Can be trade-off between battery and fuel cell	*"Continuous" means power that can be sustained indefinitely*
H2US_PWREFF_02	Continuous Peak Net Power Efficiency	%	50	50	50	Estimated Value	Major	maximum speed is critical selling point	
H2US_PWREFF_03	Intermittent Peak Net Power	kW					Minor	is a result of the fuel cell not leading	
H2US_PWREFF_04	Intermittent Peak Net Power Efficiency	%							
H2US_PWREFF_04_DEF	Definition of intermittent if required	[-]							
H2US_PWREFF_05	Idle Net Power	kW	18	180	180		Minor	This is the power of just the hotel, if more is required batteries can be charged.	*"Idle" means minimum power required with the fuel cell operating*
H2US_PWREFF_06	Idle Net Power Efficiency	%					Minor	To be provided by Fuel cell supplier	
H2US_PWREFF_07	Cruise Net Power	kW	575	950	1 900	Estimated Value	Major	M1 (waterbus, this is downstream power)	*"Cruise" is intended to be point that fuel cell will operate at, or close to for long periods. An example would be required power for vehicle at highway speed on the flat*
H2US_PWREFF_08	Cruise Net Power Efficiency	%	50	50	50	Estimated Value	Major	as large as possible for business case (including converters to switchboard)	
H2US_PWREFF_09	Net Power Ramp Rate - Up	kW/s	25	15	15		Minor	For crew, similar response as diesel is preferred.	
H2US_PWREFF_12	Net Power Ramp Rate - Up (Emergency)	kW/s							*Emergency Ramp Up is intended to document how fast the output power from the fuel cell is expected to rise during an emergency event such as an airplane 'go around'*
H2US_PWREFF_12_DEF	Definition of emergency if required	[-]							
H2US_PWREFF_10	Net Power Ramp Rate - Down	kW/s	25	15	15		Minor	For crew, similar response as diesel is preferred.	

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_PWREFF_11	Net Power Ramp Rate - Down (Emergency)	kW/s	50	50	50		Major	To be checked by Damen	*Emergency Ramp Down is intended to document how fast the output power from the fuel cell is expected to drop during an emergency event.*
H2US_PWREFF_11_DEF	Definition of emergency if required	[-]	crash stop	crash stop	crash stop				
Electrical									
H2US_ELEC_01	Minimum Fuel Cell System Output Voltage	V	750	1 030	1 030		Major	Voltage of DC switchboard	*"Fuel Cell System Output Voltage" is voltage that the fuel cell is expected to create after its inbuilt DCDC*
H2US_ELEC_02	Maximum Continuous Fuel Cell System Output Voltage	V	750	1 030	1 030		Major	Voltage of DC switchboard	
H2US_ELEC_03	Maximum Intermittent Fuel Cell System Output Voltage	V							*"Intermittent" means voltage that isn't present full time but can occur in certain situations. Please define intermittent for each application*
H2US_ELEC_03_DEF	Definition of intermittent if required	[-]							
H2US_ELEC_07	System HV bus type	[-]	DC	DC	DC		Major		*Is fuel cell system expected to output AC or DC voltage?*
H2US_ELEC_08	System HV bus AC details if required	[-]	NA	NA	NA				*If fuel cell is expected to output AC Voltage, include number of phases and frequency ranges here*
H2US_ELEC_04	Vehicle Isolation Resistance Requirement	Ω/V	500	500	500				
H2US_ELEC_05	Fuel Cell System Isolation Resistance Requirement	Ω/V	500	500	500	Estimated Value	Critical	No strict minimum, the expected value is an indication, but this is a critical concern, Galvanically isolated DC/DC converters might be a solution	
H2US_ELEC_06	EMC/EMI Requirements	[-]							*These can be legal standards, industry specific standards, and/or OEM requirements*
Packaging, Weight and Volume									
H2US_FIT_01	Ideal Weight of Fuel Cell System	kg	750	1 050	2 100	Estimated Value	Critical	As small as possible, Important as small as possible. Weight is most important for waterbus. M1	
H2US_FIT_02	Maximum Weight of Fuel Cell System	kg	1 125	1 575	3 150	Estimated Value	Critical	addition of 50%	
H2US_FIT_03	Ideal Volume of Fuel Cell System	l	NA	NA	NA		Minor	as long as it fits in limits	
H2US_FIT_04	Maximum Volume of Fuel Cell System	l	NA	NA	NA		Minor	as long as it fits in limits	
H2US_FIT_05	Fuel Cell System Limiting Length	mm	3 000	7 000	7 000	Exact Value	Major	(maintenance space to be deducted from this number)	
H2US_FIT_06	Fuel Cell System Limiting Width	mm	1 150	6 000	6 000	Exact Value	Major	(maintenance space to be deducted from this number)	
H2US_FIT_07	Fuel Cell System Limiting Height	mm	2 200	3 000	3 000	Exact Value	Major	engine room height (if it doesn't fit in floater, we can place it on top of deck)	
H2US_FIT_08	Fuel Cell System Location	[-]	main deck, centre of vessel, in Fuel cell room	above main deck, in fuel cell room	above main deck, in fuel cell room		Major	based on hydrogen storage and ship design	*Describe whereabouts on the vehicle the fuel cell system(s) would be placed*
H2US_FIT_09	Cooling System Type	[-]	fresh water-cooled internal glycol/FW loop	sea water cooled internal glycol/FW loop	sea water cooled internal glycol/FW loop		Minor		*Describe the cooling system e.g. fan cooled air-to-liquid radiator* *A system generating turbulent flow could be a viable option, as this type of flow has been shown to enhance heat transfer and improve system efficiency. However, further studies will determine the type that best suits each application. HTF formulations will be evaluated according to each application.*
H2US_FIT_10	Cooling System Limiting Length	mm	NA	NA	NA		Minor	There is space in floaters	
H2US_FIT_11	Cooling System Limiting Width	mm	NA	NA	NA		Minor	There is space in floaters	

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_FIT_12	Cooling System Limiting Height	mm	NA	NA	NA		Minor	There is space in floaters	
H2US_FIT_13	Cooling System Location	[-]	floater, pump overboard. Heat exchanger fuel cell room or in floater	Engine room below waterline. Heat exchanger fuel cell room or in engine room	Engine room below waterline. Heat exchanger fuel cell room or in engine room	Estimated Value	Minor		*Describe whereabouts on the vehicle the fuel cell system(s) would be placed. Include whether cooling system will have access to ram air, or not*
Environment									
	Unrestricted Operation								
H2US_ENV_01	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-15 °C at 0 m	-15 °C at 0 m	-15 °C at 0 m	Exact Value	Major		*Operating envelope of temperature and altitudes/pressures where full performance is expected*
H2US_ENV_02	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	35 °C at 0 m	35 °C at 0 m	35 °C at 0 m	Exact Value	Major		
	Restricted Operation								
H2US_ENV_03	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-20 °C at 0 m	-20 °C at 0 m	-20 °C at 0 m	Exact Value	Major		*Operating envelope of temperature and altitudes/pressures where minimum performance is expected, and the minimum allowable performance*
H2US_ENV_04	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	45 °C at 0 m	45 °C at 0 m	45 °C at 0 m	Exact Value	Major		
H2US_ENV_05	Minimum permissible power	kW	750	1 000	1 900	Estimated Value	Minor	schedule should be met. Missing average power can be covered with batteries	
H2US_ENV_06	Derate Curve(s)	kW at °C and/or m	lin.	lin.	lin.				*If something other than a linear derate is expected, put that information here*
H2US_ENV_07	Ambient temperature range requirement during non-operation	°C	-15 to 35	-15 to 35	-15 to 35				*Storage, transport, etc* *Min and max temperature*
H2US_ENV_08	Relative humidity during operation	%	100	100	100				*Min and max humidity*
H2US_ENV_09	Maximum compartment temperature for Fuel Cell System location	°C	25 degrees	25degree	25degree			Fuel cell room can be cooled /heated to optimal temperature	*Compartment can get significantly hotter than ambient*
H2US_ENV_10	Time to full power from normal start	s	60	60	60		Major	same as unaided	*Time to full power from request for fuel cell to start*
H2US_ENV_11	Unaided cold start temperature	°C	ambient	ambient	ambient			Ambient matches operation range above	*Unaided would mean no preheating is carried out on the fuel cell system, but HV could be supplied for BoP*
H2US_ENV_12	Time to full power from unaided start	s	120	120	120		Minor	Initial startup from fully cold	
H2US_ENV_13	Aided cold start temperature	°C	20	20	20				*Aided start involves preheating of fuel cell system prior to start*
H2US_ENV_14	Time to full power from beginning of aided start	s	25	25	25			as little as possible will determine the necessary size of battery for similar performance as diesel, especially important if more than 1 fuel cell is necessary	
H2US_ENV_15	Atmospheric pollutants expected during operation	ppm	based on air quality	0	0	Estimated Value	Critical	Water bus is city atmosphere, RoRo ferry is salt atmosphere PPM is salt only on M2/M3. SEE paper for more info	*Atmospheric pollutants are considered to be those that can poison the fuel cell either temporarily or permanently. Examples include ammonia and sulphates*
H2US_ENV_16	Air Quality	[-]	~150 AQI, city atmosphere	salt environment, rest ~100AQI	salt environment, rest ~100AQI	Estimated Value	Critical		*Dust etc*
Operation									
	Angularity								

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_OP_12	Baseline Pitch	°	2	0	0	Estimated Value	Critical	depending on loading, can be positive or negative	*Baseline pitch is what the fuel could be expected to see with no other inputs to the vehicle. For a truck this could be installation angle, for a ship this could be the expected angle with a full load and fully fuelled, for an aircraft this could be baseline trim Positive values indicate fuel cell is tilted upwards at the front*
H2US_OP_13	Baseline Roll	°	0	0	0	Estimated Value	Major	depending on loading (in general tanks are filled symmetrical) should be around 0	*Similar to Baseline Pitch, but for roll instead. No particular sign convention expected, but mention which way is positive in comments*
	Pitch Up/Down								
H2US_OP_1	Continuous	°	2	0	0		Critical	same as baseline	*Angle at which fuel cell is expected to operate continuously. An example would be a digger which could be expected to be on a slope for hours at a time*
H2US_OP_2	Intermittent	°	0 to 3	-2 to 2	-2 to 2		Critical		
H2US_OP_2_DEF	Definition of intermittent if applicable	[-]	sinus wave around baseline	sinus wave around baseline	sinus wave around baseline				
	Roll Left/Right								
H2US_OP_3	Continuous	°	0	0	0				
H2US_OP_4	Intermittent	°	-4 to 4	-6 to 6 normal operation. 21 degree for class	-6 to 6 normal operation, 21 degree for class			(max measured over 2 weeks 8 degrees singular event)	
H2US_OP_4_DEF	Definition of intermittent if applicable	[-]	sinus wave around baseline	sinus wave around baseline	sinus wave around baseline				
	Worse case combination of pitch/roll								
H2US_OP_5	Continuous	°	Max + Max	Max + Max	Max + Max				
H2US_OP_6	Intermittent	°	Max + Max	Max + Max	Max + Max				
H2US_OP_6_DEF	Definition of intermittent if applicable	[-]							
H2US_OP_7	What are the continuous vibration requirements?	g	(4,4,4)	(3,3,3) mm/s RMS	(3,3,3) mm/s RMS	Estimated Value	Critical	mm/s RMS NOT G! at maximum speed based on measurements	*Give separate answers for each axis (x,y,z)*
H2US_OP_8	What are the intermittent vibration requirements?	g	NA	NA	NA				*Give separate answers for each axis (x,y,z)*
H2US_OP_9	What is the shock load requirement (1 cycle)?	g	0.2,0.2,1.2	0.1,0.1,1.1	0.1,0.1,1.1	Estimated Value	Critical	maximum (in z direction including 1g of gravity)	*Give separate answers for each axis (x,y,z)*
H2US_OP_10	Is there a required vibration profile?	[-]						If necessary, can be shared, but is ship dependant	
H2US_OP_11	What chemical exposure resistance is needed?	[-]	none	salt environment	salt environment			cleaning agents and cooling agents can be prescribed by fuel cell supplier	
Safety									
H2US_SAFE_01	Legal safety requirements	[-]	BV-classification: NR678 Hydrogen Fuelled Ships	BV-classification: NR678 Hydrogen Fuelled Ships	BV-classification: NR678 Hydrogen Fuelled Ships			pdf file document provided	*This would be any safety specific legislation for a fuel cell in the given application*

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_SAFE_02	Industry standards considered to be entry level	[-]	IMO Interim guidelines for the safety of ships using fuel cell power installations	IMO Interim guidelines for the safety of ships using fuel cell power installations	IMO Interim guidelines for the safety of ships using fuel cell power installations				*What safety standards or codes are generally considered entry level for the industry that the application exists within*
H2US_SAFE_03	Additional standards that might be included	[-]	NA	NA	NA				*Any other standards that should be considered for this specific application*
H2US_SAFE_04	Other safety expectations	[-]	double walled, boxed and inerted, A single point failure should not lead to dangerous situation	double walled, boxed and inerted, A single point failure should not lead to dangerous situation	double walled, boxed and inerted, A single point failure should not lead to dangerous situation			Class certified system, type approval, or project approval	*Examples could be a requirement for redundancy to allow for limited power to be supplied if one component fails*
Compliance									
H2US_COMP_01	European legislation for this application	[-]	Type approval	Type approval	Type approval				*Should include consideration for all applicable legislation, not just fuel cell specific. An example is fuel cell controllers need to comply with automotive Cybersecurity legislation*
H2US_COMP_02	Industry standards considered to be entry level	[-]	unit certification, product approval	unit certification, product approval	unit certification, product approval				
H2US_COMP_03	Additional standards that might be included	[-]	NA	NA	NA				
H2US_COMP_04	Maximum permissible noise	dB	NI					Not an issue will be quieter than ICE, annoying frequencies to be avoided	
H2US_COMP_05	How do you measure and define noise?	[-]	dB(A) measurement	dB(A) measurement	dB(A) measurement				
Durability									
H2US_DUR_01	Expected system life	hrs	15 000	45 000	45 000			as high as possible for business case	
H2US_DUR_02	Expected uptime	%	85	85	85				
	Continuous Power Durability								
H2US_DUR_03	Allowable drop in power	kW					Critical		
H2US_DUR_04	Allowable drop in efficiency	%					Major	based on load profile (H2 required based on end of life) Cost is the driver	
H2US_DUR_05	Allowable increase in heat rejection	kW					Major	based on load profile (cooling to be sized based on end of life) Cost is the driver	
	Intermittent Power Durability								
H2US_DUR_06	Allowable drop in power	kW					Critical	based on load profile (end of life) cost is the driver	
H2US_DUR_07	Allowable drop in efficiency	%					Major	based on load profile (H2 required based on end of life) cost is the driver	

Requirement Number	Requirement	Units	M1	M2	M3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_DUR_08	Allowable increase in heat rejection	kW					Major	based on load profile (cooling to be sized based on end of life) cost is the driver	
	Cruise Power Durability								
H2US_DUR_09	Allowable drop in power	kW					Critical	based on load profile (end of life) cost is the driver	
H2US_DUR_10	Allowable drop in efficiency	%					Major	based on load profile (H2 required based on end of life) cost is the driver	
H2US_DUR_11	Allowable increase in heat rejection	kW					Major	based on load profile (cooling to be sized based on end of life) cost is the driver	
Service and Maintainability									
H2US_SER_01	Minimum service intervals (for any component)	h	100	500	500	Estimated Value	Major	not critical concern, but components which are near hydrogen to be as maintenance free as possible. Maintenance check expected every 3 to 6 months (or different based on suppliers). maintenance interval for small components	
H2US_SER_02	Service access expectations/restrictions	[-]	restricted during operations	restricted during operations	restricted during operations	Estimated Value	Critical	fuel cell module to be inerted, no maintenance access to fuel cell room and fuel preparation room in operation. Around this access is possible for technicians and possibly crew.	*Examples include expected maximum time to service fuel cell, service access only possible to a limited section of the fuel cell envelope, etc*
Hydrogen									
H2US_HY_01	Hydrogen type	[-]	compressed	compressed	compressed				*Compressed / Cryo Compressed / Liquid*
H2US_HY_02	Expected hydrogen quality	[-]						indication only, to be specified by fuel cell provider	
H2US_HY_03	Maximum storage pressure	bar (abs)	350	700	700		Major		
H2US_HY_04	Storage temperature range	°C	ambient	ambient	ambient		Major		
H2US_HY_05	Supply pressure range	bar (abs)	1-5	1-5	1-5			indication only, to be specified by fuel cell provider	*Supply means supply to the fuel cell system*
H2US_HY_06	Supply temperature range	°C	45	60	60			indication only, to be specified by fuel cell provider	
Additional Comments or Information									
H2US_INF_01	Additional Comments or Information	[-]							*Include anything else that should be considered for the particular application in question*

6.4 Application Specific Requirements – Aviation (A1, A2, A3)

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
Application Description									*None of this is compared or summarised. It is descriptive*
H2US_APP_01	Machine Type	[-]	TBD	TBD	TBD	Unknown / TBD	Unknown		
H2US_APP_02	Application Description	[-]	1 to 6 passengers	Up to 19 passengers	< 100 passengers		Minor	CS-LSA, CS-23 type A, and CS-23 type B. Modulair 250 kW FCS for A2 and A3.	
H2US_APP_03	Environment Type	[-]	Air	Air	Air		Minor	From sea level (runway) up to flight altitude	*Road Type / Water type / Air*
H2US_APP_04	Duty Cycle	hrs	1-2	1-3	2-4		Critical	Normally take-off, cruise, and landing. Cruise length depends on application of the aircraft. A1: ENFICA-FC effective flight time, 2.8 hrs block time for A2: typical flight 1-2 hour, but with reserve mission phases up to 3 hours (Hypotrade)	*Can be road route, speed profile, power profile, or similar Provide description here, and detailed duty cycle in separate file(s) This can either be at the powertrain level, or (preferably) at the fuel cell level*
H2US_APP_05	Maximum vehicle speed	km/h	135 - 180	400	600		Critical	Air speed is relevant for Ram-air heat exchanger design & drag optimization A1: ENFICA-FC steady flight speed -- max diving speed A2. Hypotrade info	
H2US_APP_06	Vehicle Unladen Weight	kg	500	4600-8000	17500-21000		Minor	A2. Hypotrade info A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	*including any fuel, but no passengers, cargo, or trailers*
H2US_APP_07	Vehicle Gross Weight	kg	600	6600-10000	25000-29000		Minor	A2. Hypotrade info A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	*including any fuel, passengers, cargo, or trailers*
H2US_APP_08	Application Length	mm	7	14-22	25-27		Minor	A2. Jetstream 32 https://www.mdpi.com/2226-4310/6/10/107 A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	
H2US_APP_09	Application Width	m	10	16-21	31-36		Minor	A2. wing span Jetstream 32 https://www.mdpi.com/2226-4310/6/10/107 A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	
H2US_APP_10	Application Height	m	3	5	2.5-3.5		Minor	A2. fus height Jetstream 32 https://www.mdpi.com/2226-4310/6/10/107 A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	
H2US_APP_11	Desired Range	km	200-400	500-1000	1000-2000		Major	Range estimation based on current practices for CS-LSA/CS-23 type A/CS-23 type B A1. ENFICA-FC max tested range A2. 600 km found for Hypotrade A3. 1000 NM (1800 km) for EXACT	*Range between tank filling on a declared or nominal duty cycle*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_APP_12	On board hydrogen storage	kg	~5-10	~100 - 460	~550		Minor	Depends on application; amount of stored fuel depends on the requested output power (FCS efficiency) and the desired range and/or duty cycle. A1. ENFICA-FC 2 tanks of 1.2 kg, one is spare A2. 92 kg LH2 found for Hypotrade	
H2US_APP_13	Total hydrogen system weight	kg	~150	~1000 - 2000	~ 500		Minor	Limited by aircraft MTOW. The system weight largely depends on the application (FC & HX size), the power density (PD) and energy density (ED). The PD is related to the FCS and the ED is related to the size of the tank (= range) and its Gravimetric Index (GI=Fuel_ mass/Full_tank_mass; typically, GI=5-40%) and how hydrogen is stored: LH2 or GH2. A2. Hypotrade info A1: ENFICA-FC, A2: Vonhoff (2021)-> Do, A3: DLR Exact, FlyZero	*Includes fuel cell system, hydrogen storage, and cooling system*
Powertrain (Fuel Cell + Battery)									*Primarily for assisting with vehicle simulation*
H2US_PWRTRN_01	Continuous Peak Power	kW		~1000		Unknown / TBD	Minor	Occurrence of continuous peak power seems unlikely for aircraft A2. Hypotrade info, climb and cruise electric power provided by FC	*"Continuous" means power that could be needed indefinitely*
H2US_PWRTRN_02	Intermittent Peak Power	kW	40-100	~1250	3000-8000		Critical	For fuel cell-powered aircraft peak power will be provided for short durations only during take-off & climb or emergency cases (at sea level) and will most likely be a combination of FCS + battery power. Emergency case could be an aborted landing or diversion Take-off/Climb/Diversion power ratios TBD A1: Max power FC + bat in ENFICA-FC A2. Hypotrade info, take-off and go-around electric power provided by FC +batt	*"Intermittent" means power that isn't required full time but is required for certain operations. Please define intermittent for each application*
H2US_PWRTRN_02_DEF	Definition of intermittent if required	[-]	Diversion (Aborted landing)	Go-around (Aborted landing) and take-off	Diversion (Aborted landing)		Critical	Go-around, Diversion and take-off	
H2US_PWRTRN_03	Cruise Power	kW	< 20-50	~1000	3 000		Critical	FCS will be mostly used to provide continuous power during cruise to provide thrust, Non-Propulsive Loads (NPL) and (optionally) for recharging the batteries for the duration of the mission. Cruise power ratios TBD A1: FC can deliver max 20 kW, cruise power not given in ENFICA-FCA2. Hypotrade info, climb and cruise electric power provided by FC A3. EXACT 70-seater	*"Cruise" is intended to be power vehicle could operate at for extended periods, such as truck running on flat at highway speed*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_PWRTRN_04	Details on power split algorithm or strategy	[-]	50/50 in TO	take-off ~30% bat (1 min) climb ~0% bat (16 min) cruise -1% to -20% bat (22 min) descend 100% bat (16 min)	no info		Major	NLR: initial estimations for the durations and required power ratios. Battery assisted take-off is considered. A1: ENFICA-FC splits battery and FC power 50/50 during take-off (18 min), after that battery is drained A2. Hypotrade info, battery power percentages: support during take-off (and go-around), charging during cruise, battery during descend. Remark: Initial version, such schemes need mission optimization!	*This information is helpful in determining the actual fuel cell duty cycle and performance requirements*
Battery									*Primarily for assisting with vehicle simulation*
H2US_BATT_01	Battery Chemistry	[-]	Lithium Polymer	no info	no info		Minor	Li-ion Pipistrel Velis Electro as certified example for batteries A1: ENFICA-FC Li-Po batteries (high C-rate, often used in small UAVs)	
H2US_BATT_02	Battery Size	kWh	5.8-6.2	170	no info		Major	A1: ENFICA-FC A2. derived from Hypotrade mission info Depends on FC/BAT power ratios for take-off & climb and emergency cases TBD	
H2US_BATT_03	Continuous Discharge Power	kW	20	500	no info	Unknown / TBD	Major	TBD for ground level operations without FCS power A1: ENFICA-FC battery is drained at 20 kW for 18 min during TO. Peak power is potentially higher A2. derived from Hypotrade mission info (descend power)	
H2US_BATT_04	Continuous Charge Power	kW	no info	- 200	no info	Unknown / TBD	Major	TBD. power ratios during cruise A2. derived from Hypotrade mission info (during cruise charge)	
H2US_BATT_05	Peak Discharge Power	kW	>20	700	no info	Unknown / TBD	Major	TBS. power ratios for take-off & climb and emergency cases A1: ENFICA-FC A2. derived from Hypotrade mission info, last go-around on batt	
H2US_BATT_06	Max duration allowed at peak discharge power	s	1 080	300	no info	Unknown / TBD	Major	TBD Take-off/climb/emergency durations A1: ENFICA-FC A2. derived from Hypotrade mission info, last go-around on batt	
H2US_BATT_07	Peak Charge Power	kW	no info	no info	no info	Unknown / TBD	Major	TBD. ground level/airport charging capabilities	
H2US_BATT_08	Max duration allowed at peak charge power	s	no info	no info	no info	Unknown / TBD	Major	TBD. ground level/airport charging speed/turn-around	
H2US_BATT_09	Maximum allowed SOC	%	80	80	80		Major	EASA/Velis requirements	
H2US_BATT_10	Minimum allowed SOC	%	20	20	20		Major	EASA/Velis requirements	
Power and Efficiency (Fuel Cell)									*Efficiency is measured against LHV of Hydrogen i.e. 119.96 kJ/kg All powers and efficiencies referenced against EoL (End of Life)*
H2US_PWREFF_01	Continuous Peak Net Power	kW	20	1 000	3000-8000		Critical	Occurrence of continuous peak power seems unlikely for aircraft under nominal operations. Continuous power = cruise power	*"Continuous" means power that can be sustained indefinitely*
H2US_PWREFF_02	Continuous Peak Net Power Efficiency	%	no info	47	no info		Minor	Efficiency may not be relevant for emergency cases A2. derived from Hypotrade mission info	

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_PWREFF_03	Intermittent Peak Net Power	kW	20	N.A. (peak only with batt)	no info		Critical	Required for take-off/climb and emergency cases such a a diversion A1: ENFICA-FC fuel cell is rated at max 20 kW	*"Intermittent" means power that isn't required full time but is required for certain operations. Please define intermittent for each application*
H2US_PWREFF_04	Intermittent Peak Net Power Efficiency	%	< 50	< 50	< 50 (47)		Minor	Efficiency may not be relevant during take-off/climb and emergency cases such a diversion A3: Assumed TO efficiency in DLR EXACT	
H2US_PWREFF_04_DEF	Definition of intermittent if required	[min]	15-20	N.A. (peak only with batt)	20-30		Critical	Durations=take-off + climb	
H2US_PWREFF_05	Idle Net Power	kW	~10%	~10%	~10%		Major	TBD, FCS, idle power 10%? May be used for airport operations or on board NPL or charging batteries?	*"Idle" means minimum power required with the fuel cell operating*
H2US_PWREFF_06	Idle Net Power Efficiency	%	> 50	> 50	> 50		Minor	At low output powers a FC is relatively more efficient A2. in Hypotrade no FC idle power found	
H2US_PWREFF_07	Cruise Net Power	kW	350 (<20)	1000 - 1157	10 x 300		Critical	A1: exact cruise power not given in ENFICA-FC, A2: Vonhoff (2021) for FC Do228 with current technology values	*"Cruise" is intended to be point that fuel cell will operate at, or close to for long periods. An example would be required power for vehicle at highway speed on the flat*
H2US_PWREFF_08	Cruise Net Power Efficiency	%	> 50	47	> 50 (54)		Critical	TBD. An oversized FCS (=above cruise power) delivers an improved nominal efficiency during cruise that allows for less heat rejection (smaller radiator) and longer flight distances. Another advantage is the availability of access FCS power in case of emergencies - potential downside is less payload A3: Assumed cruise efficiency in DLR EXACT	
H2US_PWREFF_09	Net Power Ramp Rate - Up	kW/s	1	10	no info		Major	TBD Max 10 kW/s is standard for industrial FCS? If battery assisted, the battery will do the ramps A1: from FC power/time curve ENFICA-FC	
H2US_PWREFF_12	Net Power Ramp Rate - Up (Emergency)	kW/s	no info	no info	no info	Unknown / TBD	Critical	TBD Max 10 kW/s is standard for industrial FCS If battery assisted, the battery will do the ramps	*Emergency Ramp Up is intended to document how fast the output power from the fuel cell is expected to rise during an emergency event such as a crash stop*
H2US_PWREFF_12_DEF	Definition of emergency if required	[-]	no info	no info	no info	Unknown / TBD	Major	TBD If battery assisted, battery charge can be used as power dump	
H2US_PWREFF_10	Net Power Ramp Rate - Down	kW/s	20	no info	no info	Unknown / TBD	Critical	TBD, Charge batteries with excess FCS power in case of emergencies? A1: from FC power/time curve ENFICA-FC	
H2US_PWREFF_11	Net Power Ramp Rate - Down (Emergency)	kW/s	no info	no info	no info	Unknown / TBD	Major	TBD Diversion, FCS failure in cruise, battery failure during take-off	*Emergency Ramp Down is intended to document how fast the output power from the fuel cell is expected to drop during an emergency event.*
H2US_PWREFF_11_DEF	Definition of emergency if required	[-]					Major	Diversion, FCS failure in cruise, battery failure during take-off	
Electrical									
H2US_ELEC_01	Minimum Fuel Cell System Output Voltage	V	182	no info	no info		Major	DCDC efficiencies and battery voltages A1: ENFICA-FC P_max / I_max	*"Fuel Cell System Output Voltage" is voltage that the fuel cell is expected to create after its inbuilt DCDC*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_ELEC_02	Maximum Continuous Fuel Cell System Output Voltage	V	300-400	< 1000	< 1000		Critical	Roadmap towards high-voltage (540 -1000 V). Or increase battery voltage via DC/DC converters? Voltage limitations due to partial discharge at higher altitude levels	
H2US_ELEC_03	Maximum Intermittent Fuel Cell System Output Voltage	V	300-400	< 1000	< 1000		Critical	Emergency cases	*"Intermittent" means voltage that isn't present full time but can occur in certain situations. Please define intermittent for each application*
H2US_ELEC_03_DEF	Definition of intermittent if required	[-]	no info	no info	no info	Unknown / TBD	Minor	TBD Emergency cases	
H2US_ELEC_07	System HV bus type	[-]	no info	no info	no info	Unknown / TBD	Critical	TBD Redundancy concepts	*Is fuel cell system expected to output AC or DC voltage?*
H2US_ELEC_08	System HV bus AC details if required	[-]	no info	no info	no info	Unknown / TBD	Major	TBD AC bus design	*If fuel cell is expected to output AC Voltage, include number of phases and frequency ranges here*
H2US_ELEC_04	Vehicle Isolation Resistance Requirement	Ω/V	no info	no info	no info		Critical	TBD, depends on mounting location in aircraft. See DO-160 for specs aviation equipment. No requirements for FCS available.	
H2US_ELEC_05	Fuel Cell System Isolation Resistance Requirement	Ω/V	no info	no info	no info		Critical	TBD, depends on mounting location in aircraft. See DO-160 for specs aviation equipment. No requirements for FCS available.	
H2US_ELEC_06	EMC/EMI Requirements	[-]	DO-160	DO-160	DO-160		Critical	TBD, depends on mounting location in aircraft. See DO-160 for specs aviation equipment. No requirements for FCS available.	*These can be legal standards, industry specific standards, and/or OEM requirements*
Packaging, Weight and Volume									
H2US_FIT_01	Ideal Weight of Fuel Cell System	kg	no info	10% of H2US_APP_07 i.e. 862kg	no info	Unknown / TBD	Unknown	TBD As light as possible for an aircraft. There is a maximum take-off weight (MTOW)	
H2US_FIT_02	Maximum Weight of Fuel Cell System	kg	< 150 (100)	841 (1610)	< 2400 per POD (178/POD)		Critical	Based on > 2kW/kg target A2. Hypotrade sizing -> 1.2 kW/kg, Vonhoff (2021) with current technology indicators A3: total weight / n_pods DLR EXACT	
H2US_FIT_03	Ideal Volume of Fuel Cell System	l	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_04	Maximum Volume of Fuel Cell System	l	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_05	Fuel Cell System Limiting Length	m	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_06	Fuel Cell System Limiting Width	m	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_07	Fuel Cell System Limiting Height	m	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_08	Fuel Cell System Location	[-]	Behind front prop	in fuselage	Under-wing pods (10)		Critical	POD below the wings / fuselage A1: ENFICA-FC fuel cell replaces front piston engine A3: DLR EXACT FC concept	*Describe whereabouts on the vehicle the fuel cell system(s) would be placed*
H2US_FIT_09	Cooling System Type	[-]	Liquid/water	Liquid/water	Liquid/water		Critical	TBD Usually liquid/water cooling or two-phase mechanically pumped cooling A system generating turbulent flow could be a viable option, as this type of flow has been shown to enhance heat transfer and improve system efficiency. However, further studies will determine the type that best suits each application. HTF formulations will be evaluated according to each application. A1: ENFICA-FC features IE fuel cells, which probably use liquid cooling	*Describe the cooling system e.g. fan cooled air-to-liquid radiator*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_FIT_10	Cooling System Limiting Length	mm	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_11	Cooling System Limiting Width	mm	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_12	Cooling System Limiting Height	mm	no info	no info	no info	Unknown / TBD	Unknown	TBD. Depends on application and installation area	
H2US_FIT_13	Cooling System Location	[-]	In ram air duct behind front prop	RAM air duct in fuselage	Ram air duct in pods		Critical	TBD Location Ram air HX depends on application. From the FC stack towards a ram air heat exchanger. Drag optimization needed, large influence on aerodynamic performance. A1: ENFICA-FC fuel cell replaces front piston engine A3: DLR EXACT FC concept	*Describe whereabouts on the vehicle the fuel cell system(s) would be placed. Include whether cooling system will have access to ram air, or not*
Environment									
	Unrestricted Operation								
H2US_ENV_01	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-40 °C 4572 m	-40 °C 7620 m	-55 °C 7620 m		Critical	Based on ISA+15 Use this to create operational envelope to target altitude Altitude based on CS-23 type A, CS-23 type B	*Operating envelope of temperature and altitudes/pressures where full performance is expected*
H2US_ENV_02	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	50 °C 4572 m	50 °C 7620 m	50 °C 7620 m		Critical	Based on ISA+15 Use this to create operational envelope to target altitude Altitude based on CS-23 type A, CS-23 type B	
	Restricted Operation								
H2US_ENV_03	Min. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	-40 °C 4572 m	-40 °C 7620 m	-55 °C 7620 m		Critical	Equal values applied for unrestricted and restricted	*Operating envelope of temperature and altitudes/pressures where minimum performance is expected, and the minimum allowable performance*
H2US_ENV_04	Max. Ambient Temperature vs Altitude/Pressure	°C at m ° at kPa	50 °C 4572 m	50 °C 7620 m	50 °C 7620 m		Critical	Equal values applied for unrestricted and restricted	
H2US_ENV_05	Minimum permissible power	kW	no info	no info	no info	Unknown / TBD	Critical	TDB, depends on application	
H2US_ENV_06	Derate Curve(s)	kW at °C and/or m	no info	no info	no info	Unknown / TBD	Minor	TDB, depends on application	*If something other than a linear derate is expected, put that information here*
H2US_ENV_07	Ambient temperature range requirement during non-operation	°C	DO-160	DO-160	DO-160		Minor	TBD Depends on application	*Storage, transport, etc* *Min and max temperature*
H2US_ENV_08	Relative humidity during operation	%	DO-160	DO-160	DO-160		Major	TBD Depends on application	*Min and max humidity*
H2US_ENV_09	Maximum compartment temperature for Fuel Cell System location	°C	no info	no info	no info	Unknown / TBD	Minor	TDB, depends on application and cooling system design	*Compartment can get significantly hotter than ambient*
H2US_ENV_10	Time to full power from normal start	s	no info	no info	no info	Unknown / TBD	Minor	TDB, depends on application	*Time to full power from request for fuel cell to start*
H2US_ENV_11	Unaided cold start temperature	°C	no info	no info	no info	Unknown / TBD	Minor	TDB, depends on application	*Unaided would mean no preheating is carried out on the fuel cell system, but HV could be supplied for BoP*
H2US_ENV_12	Time to full power from unaided start	s	no info	no info	no info	Unknown / TBD	Minor	TDB, depends on application	
H2US_ENV_13	Aided cold start temperature	°C	-35 -50	-35 -50	-35 -50		Critical		*Aided start involves preheating of fuel cell system prior to start*
H2US_ENV_14	Time to full power from beginning of aided start	s	< 300	< 300	< 300		Major		
H2US_ENV_15	Atmospheric pollutants expected during operation	ppm	no info	no info	no info	Unknown / TBD	Critical	TBD On ground pollutants could be critical (combustion exhaust other aircraft). FCS may be more sensitive than GT	*Atmospheric pollutants are considered to be those that can poison the fuel cell either temporarily or permanently. Examples include ammonia and sulphates*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_ENV_16	Air Quality	[-]	no info	no info	no info	Unknown / TBD	Major	TBD Pollutants in air could be critical. FCS may be more sensitive than GT	*Dust etc*
Operation									
	Angularity							Meaning ??	
H2US_OP_12	Baseline Pitch	°	~8	2	2		Critical	A1: Pipistrel Velis Electro flight data	*Baseline pitch is what the fuel could be expected to see with no other inputs to the vehicle. For a truck this could be installation angle, for a ship this could be the expected angle with a full load and fully fuelled, for an aircraft this could be baseline trim Positive values indicate fuel cell is tilted upwards at the front*
H2US_OP_13	Baseline Roll	°	~3	0	0		Critical	A1: Pipistrel Velis Electro flight data	*Similar to Baseline Pitch, but for roll instead. No particular sign convention expected, but mention which way is positive in comments*
	Pitch Up/Down								
H2US_OP_1	Continuous	°	8 - 10 °	5	5		Critical	A1: Pipistrel Velis Electro flight data	*Angle at which fuel cell is expected to operate continuously. An example would be a digger which could be expected to be on a slope for hours at a time*
H2US_OP_2	Intermittent	°	16	8	8		Critical	A1: Pipistrel Velis Electro flight data	
H2US_OP_2_DEF	Definition of intermittent if applicable	[-]	5 sec	1 min	1 min		Critical	A1: Pipistrel Velis Electro flight data	
	Roll Left/Right								
H2US_OP_3	Continuous	°	3 - 5 °	~30	~30		Critical	A1: Pipistrel Velis Electro flight data	
H2US_OP_4	Intermittent	°	20	~45	~45		Critical	A1: Pipistrel Velis Electro flight data	
H2US_OP_4_DEF	Definition of intermittent if applicable	[-]	5 sec	no info	no info		Critical	A1: Pipistrel Velis Electro flight data	
	Worse case combination of pitch/roll								
H2US_OP_5	Continuous	°	60	no info	no info		Critical	A1: Pipistrel Velis Electro max bank angle (flight manual)	
H2US_OP_6	Intermittent	°	60	no info	no info		Critical	A1: Pipistrel Velis Electro max bank angle (flight manual)	
H2US_OP_6_DEF	Definition of intermittent if applicable	[-]	N/A			Unknown / TBD	Unknown		
H2US_OP_7	What are the continuous vibration requirements?	g	+4.0g / -2.0g	DO-160	DO-160		Critical	A1: Pipistrel Velis Electro flight load factor limits	*Give separate answers for each axis (x,y,z)*
H2US_OP_8	What are the intermittent vibration requirements?	g	N/A	DO-160	DO-160		Critical	See D0-160	*Give separate answers for each axis (x,y,z)*
H2US_OP_9	What is the shock load requirement (1 cycle)?	g	N/A	DO-160	DO-160		Critical	See D0-160	*Give separate answers for each axis (x,y,z)*
H2US_OP_10	Is there a required vibration profile?	[-]	N/A	DO-160	DO-160		Critical	See D0-160	
H2US_OP_11	What chemical exposure resistance is needed?	[-]	no info	no info	no info	Unknown / TBD	Critical	TBD May be critical at airports. FC are known to be more sensitive for pollutions then GT	
Safety									
H2US_SAFE_01	Legal safety requirements	[-]	EASA, FAA, CAA	EASA, FAA, CAA	EASA, FAA, CAA		Critical	A permit is needed by the aviation authorities (EASA, FAA, CAA) to use hydrogen systems for aircraft. Allowance needed to charge batteries in-flight	*This would be any safety specific legislation for a fuel cell in the given application*

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_SAFE_02	Industry standards considered to be entry level	[-]	TBD	TBD	TBD	Unknown / TBD	Critical	There are no hydrogen-powered aircraft standards yet. EUROCAE WG80 is working on new (not yet published) standards for hydrogen storage and hydrogen fuel cell powered aircraft. Generic safety documentation ED-79B & ED-135 for civil aircraft design may be partly applicable	*What safety standards or codes are generally considered entry level for the industry that the application exists within*
H2US_SAFE_03	Additional standards that might be included	[-]	TBD	TBD	TBD	Unknown / TBD	Minor	Other industrial standards and safety methods may be useful to apply for GSE and test facilities	*Any other standards that should be considered for this specific application*
H2US_SAFE_04	Other safety expectations	[-]	TBD	TBD	TBD	Unknown / TBD	Major	Design limitations, redundancy concepts depending on application etc	*Examples could be a requirement for redundancy to allow for limited power to be suppled if one component fails*
Compliance									
H2US_COMP_01	European legislation for this application	[-]	EASA, FAA, CAA	EASA, FAA, CAA	EASA, FAA, CAA		Critical	Permit is needed from the aviation authorities, for example the European Union Aviation Safety Agency (EASA). CAA from the UK and FAA from US.	*Should include consideration for all applicable legislation, not just fuel cell specific. An example is fuel cell controllers need to comply with automotive Cybersecurity legislation*
H2US_COMP_02	Industry standards considered to be entry level	[-]	TBD	TBD	TBD	Unknown / TBD	Critical	There are no hydrogen-powered aircraft standards yet. EUROCAE WG80 is working on new (not yet published) standards for hydrogen storage and hydrogen fuel cell powered aircraft. Generic safety documentation ED-79B & ED-135 for civil aircraft design may be partly applicable	
H2US_COMP_03	Additional standards that might be included	[-]	TBD	TBD	TBD	Unknown / TBD	Major	Other industrial standards and safety methods may be useful to apply for GSE and test facilities	
H2US_COMP_04	Maximum permissible noise	dB	TBD	TBD	TBD	Unknown / TBD	Major	Potential noise level requirements from airports, it is expected that hydrogen-electric propulsion will produce less noise than conventional aircraft	
H2US_COMP_05	How do you measure and define noise?	[-]	TBD	TBD	TBD	Unknown / TBD	Minor	Noise models and measurements	
Durability									
H2US_DUR_01	Expected system life	hrs	TBD	TBD	TBD	Unknown / TBD	Major	TBD, Depends on application and operations. All power requirements above are End of Life	
H2US_DUR_02	Expected uptime	%	TBD	TBD	TBD	Unknown / TBD	Major	TBD, Depends on application and operations. All power requirements above are End of Life	
	Continuous Power Durability								
H2US_DUR_03	Allowable drop in power	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_DUR_04	Allowable drop in efficiency	%	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_DUR_05	Allowable increase in heat rejection	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
	Intermittent Power Durability								
H2US_DUR_06	Allowable drop in power	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	

Requirement Number	Requirement	Units	A1	A2	A3	Requirement Status	Importance	Comments	Explanatory Notes
H2US_DUR_07	Allowable drop in efficiency	%	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_DUR_08	Allowable increase in heat rejection	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
	Cruise Power Durability								
H2US_DUR_09	Allowable drop in power	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_DUR_10	Allowable drop in efficiency	%	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_DUR_11	Allowable increase in heat rejection	kW	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
Service and Maintainability									
H2US_SER_01	Minimum service intervals (for any component)	h	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	
H2US_SER_02	Service access expectations/restrictions	[-]	TBD	TBD	TBD	Unknown / TBD	Major	TBD, no experience available with FCS for aviation. May be comparable with automotive FCS	*Examples include expected maximum time to service fuel cell, service access only possible to a limited section of the fuel cell envelope, etc*
Hydrogen									
H2US_HY_01	Hydrogen type	[-]	high-pressure gaseous	high-pressure gaseous or liquid	Liquid		Critical	It is expected that liquid hydrogen from a cryotank is already purified (all air constituents will be hard frozen) until the tank runs empty and warms up.	*Compressed / Cryo Compressed / Liquid*
H2US_HY_02	Expected hydrogen quality	[-]	5	5	5		Critical	Purity, 99,997% is critical for the operation of a FC	
H2US_HY_03	Maximum storage pressure	bar (abs)	700	700 or 5	5		Minor	Related to tank design	
H2US_HY_04	Storage temperature range	°C	-40 towards 50	-40-50 or -253	- 253		Major	Related to tank design	
H2US_HY_05	Supply pressure range	bar (abs)	2-3	2-3	2-3		Critical	For liquid hydrogen a low tank and Fuel Cell Stack inlet pressures are to be expected	*Supply means supply to the fuel cell system*
H2US_HY_06	Supply temperature range	°C	Above ambient < 100C	Above ambient < 100C	Above ambient < 100C		Critical	Fuel Cell Stack inlet temperature range needs to be higher than BOP inlet temperature. 40-85 for stack inlet and may be lower for BOP inlet	
Additional Comments or Information									
H2US_INF_01	Additional Comments or Information	[-]							*Include anything else that should be considered for the particular application in question*

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