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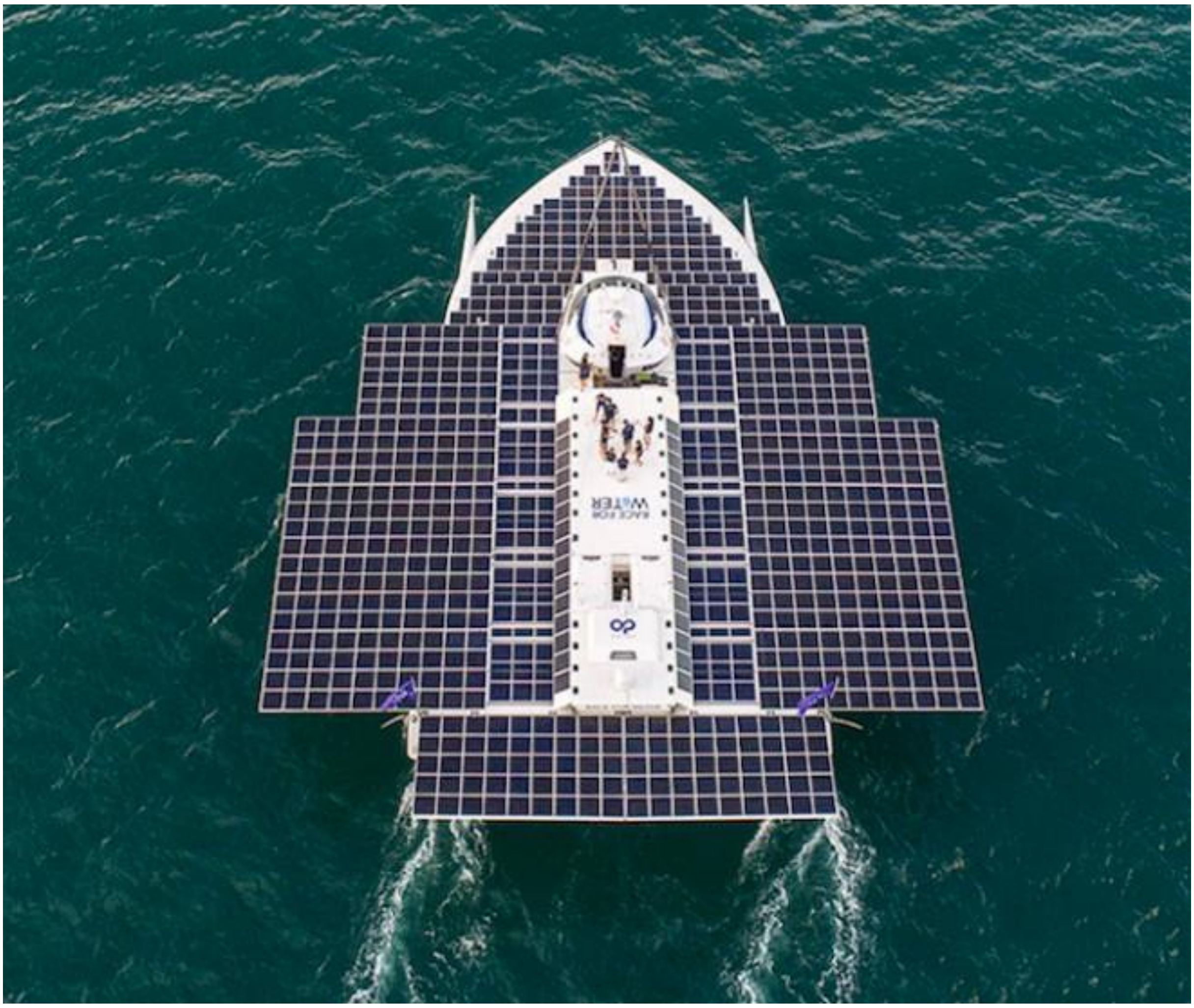
Energy Research and Cleantech

Final report

Hydrogen production, storage and conversion into electricity as range extender on the world largest solar catamaran (ex PlanetSolar)



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Pilot and demonstration Research Programme
CH-3003 Bern
www.bfe.admin.ch
energieforschung@bfe.admin.ch

Agent :
Swiss Hydrogen SA
Passage du Cardinal 1, CH-1700 Fribourg
www.swisshydrogen.ch

Authors :
Pascal Goulpié, Swiss Hydrogen SA, pascal.goulpie@plasticomnium.com
Alexandre Closset, Swiss Hydrogen SA, alexandre.closset@plasticomnium.com

SFOE head of domain: Stefan Oberholzer, stephan.oberholzer @bfe.admin.ch
SFOE programme manager: Men Wirz, men.wirz@bfe.admin.ch
SFOE contract number: SI/501514-01

Summary

The existing solar boat, which concluded in 2012 the first PV-powered round-the-world trip, was adapted with a range extender system based on hydrogen and fuel cell technology. The main objective was to massively increase the energy storage capacity of this zero emissions vessel, thanks to state-of-the-art technologies without significantly increasing its total weight.

This project was designed and carried out in close collaboration with the international class society in charge of the complete system certification. This class society's early involvement greatly facilitated the definition of the safety concept and the final equipment choice.

All main components were installed in a hydrogen equipment container located on the solar deck of the vessel. The hydrogen system has been monitored and improved over a period of 3 years during 28'000 nautical miles of open-sea navigation. The system was last upgraded in Hong Kong at the end of 2019. The final certification was accorded at the beginning of 2020 by the DNVGL. This certification, awarded by the world's largest classification society, represents a prestigious and valuable reference in this sector.

This operational and certified project demonstrates that hydrogen can successfully complement batteries as an energy storage solution for renewable energy systems. Systems such as this one can also be successfully deployed even in relatively low-power systems. Their compactness permits integration even with tight dimensional constraints. Among the valuable lessons learned, each subsystem interface should be carefully optimized. In this way the global system efficiency will be as close as possible to that expected based on the specifications of the individual components and subsystems.

The global circumnavigation provided a demanding test environment with a large range of weather conditions, including constant humidity, salty air and significant temperature swings. Operating such a system over months has provided unique and valuable experience, which can be applied in various energy projects for a wide range of applications, not only in the marine sector.

Résumé

Le bateau solaire qui a réalisé le premier tour du monde à l'énergie photovoltaïque a été modifié pour recevoir un système de prolongateur d'autonomie basé sur l'hydrogène et la pile à combustible. Le principal objectif était d'augmenter massivement la capacité de stockage d'énergie de ce vaisseau 'zéro émissions', en intégrant une technologie émergente sans affecter déraisonnablement sa masse totale.

Ce projet fut conçu et mené à bien en étroite collaboration avec la société internationale en charge de la certification du système dont l'implication dès la phase de présélection des composants, a facilité l'établissement du concept de sécurité et la définition des équipements associés.

Tous les composants principaux ont été installés et regroupés dans un container ventilé, logé sur le pont supérieur du navire solaire. Le système hydrogène, monitoré et amélioré tout au long d'une navigation océanique de presque 28'000 mile nautique, a profité d'une dernière mise à niveau fin 2019 à Hong Kong. La certification par la DNVGL, la plus grande société de classification au monde, fut obtenue début 2020, ce qui constitue une référence pour le secteur.

Ce projet, opérationnel et certifié, démontre que l'hydrogène est une solution concrète de stockage complémentaire aux batteries pour les systèmes d'énergie renouvelable. Un tel système peut aussi être adapté à des équipements de petites puissances et remplir de difficiles contraintes dimensionnelles. Du à l'interdépendance des sous-systèmes, les interfaces doivent faire l'objet de soins particuliers afin d'atteindre pour le système global, le rendement prévisible sur la base des données des fournisseurs respectifs.

La navigation autour du globe a offert un large éventail de conditions météorologiques dans un environnement exigeant, doté d'humidité constante, d'air salin et d'amplitudes de température élevées.

Opérer un tel système pendant des mois a généré de nombreux enseignements et un retour d'expérience unique qui peut être appliqué dans divers projets énergétiques pour toute une gamme d'applications, et pas seulement dans le secteur maritime.

Zusammenfassung

Der solar angetriebene Katamaran, welcher 2012 die erste Weltumrundung mit Solarenergie erfolgreich absolvierte, wurde mit einem System zur Reichweiten Verlängerung mit Wasserstoff ergänzt. Das Hauptziel des Projekts bestand darin, die aufkommende Technologie um den Energievektor Power-To-Gas auf diesem «zero emission» Katamaran zu integrieren. Damit konnte die Energiespeicherkapazität des Gesamtsystems massiv zu erhöhen, ohne dabei zu viel Gewicht hinzu zu fügen.

Durch die enge Zusammenarbeit mit der Zertifizierungsstelle DNVGL, gelang es frühzeitig die richtigen Elemente für die Integration auszuwählen und ein geeignetes Sicherheitskonzept für die Installation auf dem Schiff auszuarbeiten.

Alle Hauptelemente des Systems sind in einem belüfteten und massgefertigten Container auf dem Deck des Schiffes installiert. Das Wasserstoffsystem wurde während der Weltumrundung dauernd überwacht und verbessert. Bisher hat das Schiff 28’000 nautische Meilen zurückgelegt und ende 2019 wurden in Hong Kong letzte Verbesserungen am System ausgeführt. Die Zertifizierung durch den DNVGL wurde anfangs 2020 erlangt. Dieser Schritt markiert einen wichtigen Meilenstein. Die DNVGL ist die grösste internationale Klassifikationsgesellschaft für die Schifffahrt.

Dieses Projekt veranschaulicht, dass die Wasserstofftechnologie eine konkrete Ergänzung für die Speicherung der erneuerbaren Energie darstellt. Solche Systeme im tieferen kW-Bereich können einfach integriert werden und in anfordernden Platzverhältnissen installiert werden. Eine der wichtigsten Erkenntniss aus diesem Projekt ist, dass die Schnittstellen zwischen den einzelnen Subsystemen sorgfältig analysiert werden müssen damit im Endresultat ein möglichst hoher Wirkungsgrad des gesamten Systems erreicht werden kann.

Dieses funktionsfähige und zertifizierte System veranschaulicht das Funktionsprinzip eines autonomen Systems zur Erzeugung, Speicherung und Umwandlung von «grüner» Energie. Die Navigation rund um den Globus bot eine Vielzahl von Wetterbedingungen in einer anspruchsvollen Umgebung mit konstanter Luftfeuchtigkeit, salzhaltiger Luft und hohen Temperaturbereichen. Mit dem monatelangen Betrieb eines solchen Systems konnten viele Erfahrungen gewonnen und ein einzigartiges Feedback generiert werden, das in verschiedenen Energieprojekten für ein breites Spektrum von Anwendungen, nicht nur im maritimen Bereich, angewendet werden kann.

1 Contents

List of abbreviations

ATEX	Explosive Atmosphere
ALARP	As Low As Reasonably Practicable
BMS	Battery Management System
CAN	Controller Area Network Bus
DI-Water	De-Ionized Water
DNVGL	Det Norsk Veritas Germanischer Lloyd
DPS	Differential Pressure Sensor
ESD	Emergency Shut Down
ETH	Ethernet Bus
ELY	Electrolyser
FAT	Factory Acceptance Test
FMEA	Failure Mode and Effects Analysis
FCS	Fuel Cell System
FTE	Full Time Equivalent
H2	Gaseous Hydrogen
HMI	Human Machine Interface
HP	High Pressure
HSL	Hard-wired Security Layer
LHV	Lower Heating Value
INV	Inverter, controlled motor drive
kWh	1000 Watt hours
LEL	Lower Explosive Level
MPPT	Maximum Power Point Tracker
MWh	Mega-Watt-hour
NIST	National Institute of Standard and Technology
NLPH	Norm Litre Per Hour
OTV	On Tank Valve
PEM	Proton Exchange Membrane
PLC	Programmable Logic Controller
PV	Photovoltaic
R4W	Race for Water Foundation
SAT	Site Acceptance Test
SHSA	SwissHydrogen SA
SOC	State of Charge
STO	Hydrogen storage
TPRD	Temperature Pressure Release Device
VFD	Variable Frequency Drive

1 Introduction

This final report includes 6 main sections. Following a short brief on the European energy supply trend and global emissions generated by transport and in particular marine sector and some latest innovative projects in this field, the second main section (section 3, page 13 and on) deals with project organisation and targets.

Section 4 draws from page 15, system design such as ventilation and control systems (respectively sections 4.3 and 4.5) and safety concepts including hydrogen and fire safeties and hardwired security layers (HSL). This section deals as well with the results of the failure mode and effects analysis (FMEA) conducted by the international class society (page 25).

The next section (section 5, from page 26 on) gives some general information on the selected components in order to carry out the integration of zero emission hydrogen energy system on an open sea vessel. Section 6 shortly describes main achievements from the component integration in Lorient, first tests and runs, system improvements along the navigation route (Figure 34, page 36) and last system upgrade conducted in Hong Kong on December 2019.

Section 7 discusses main results related to hydrogen production and electrical system efficiencies. The international certification work for this system is presented in section 7.1, page 40. Conclusions, following 3 years of work and more than 28'000 nautical miles of navigation are presented on page 47.

2 Context

2.1 Background

As part of the energy transition in Europe and the current and planned development of renewable energy plant fleet (see Figure 2), hydrogen as long term solution for energy storage is nowadays gaining attention for stationary and mobile applications.

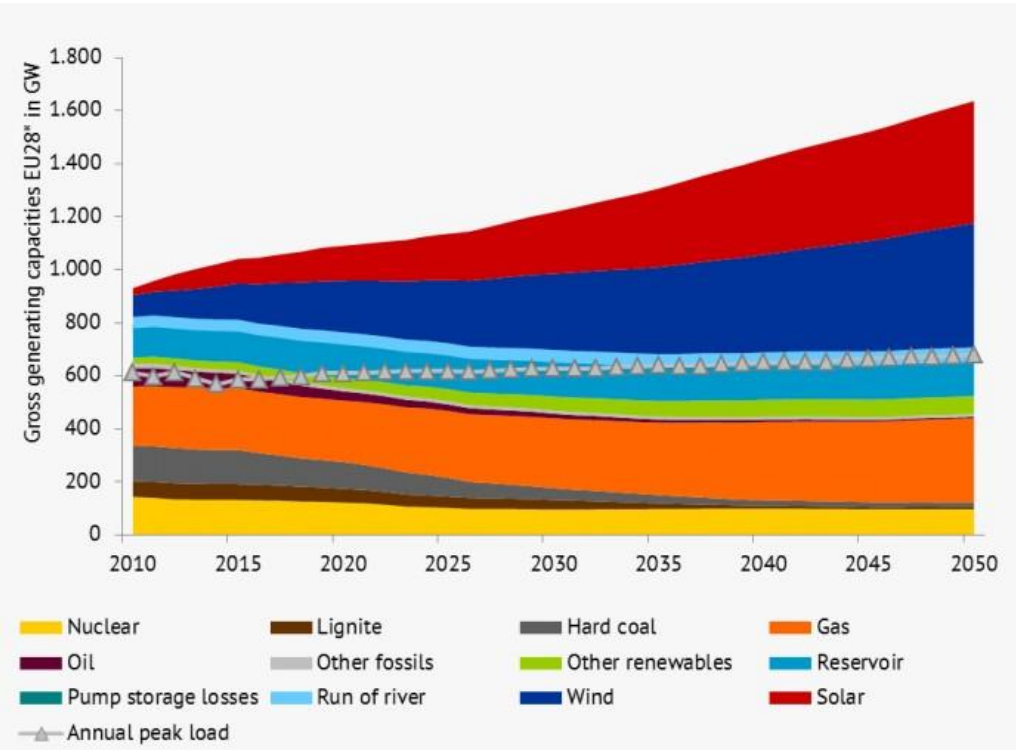

Figure 1: installed generation capacities in EU 28 (incl. NO and CH) by energy carrier; Source: Energy Brainpool, "Energy, transport and GHG emissions Trends to 2050 – Reference Scenario 2016 [4]

The development of renewable energy in the national or European energy mix contributes to reduce environmental impact and to modify the electricity market.

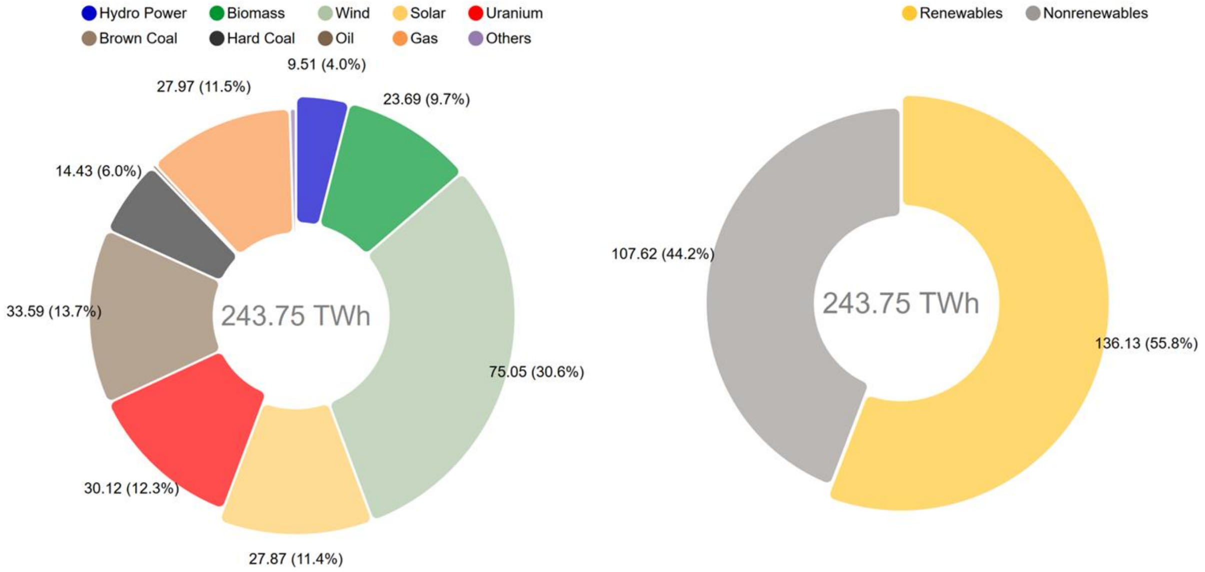

Figure 2: Net public electric generation in Germany for 2020 first semester. Source: Fraunhofer ISE [5]

Some countries like Germany (Figure 2), Portugal or Spain cover over several days, large parts of their electricity consumption with their local renewable energy production. In order to absorb energy over production, mechanical or chemical storage solutions are more and more frequently associated to wind and photovoltaic farms.

2.2 Mobility environmental impacts and current marine hydrogen projects

In the mobility sector, CO_2 emissions have increased by more than 70% from 1990 to 2016 and those from the marine sector are close to aviation sectors about 0.75 Gt compared to 0.9 Gt in 2016, see Figure 3, right). In addition, emissions of sulphur dioxide of a big liner are 350’000 times higher than those of a personal car (seeFigure 3, left).

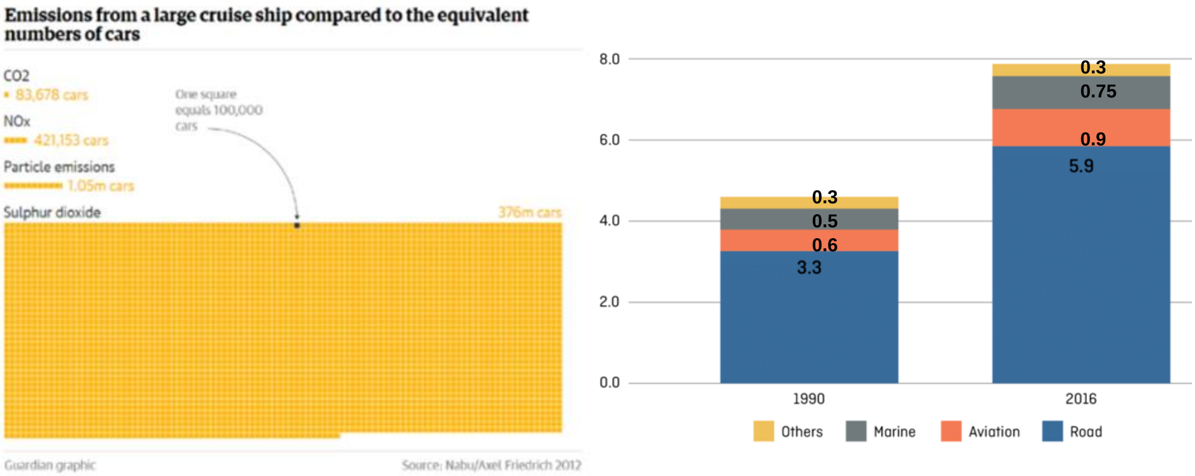

Figure 3: Comparison of SOx emissions for maritime and road transportation (left); CO_2 emission for transport acc. OECD/IEA, 2016 (right).

These observations have motivated the development by the private sector and support from national institutions of many hydrogen projects, to demonstrate the technical and economic feasibility of low or no carbon hydrogen production, hydrogen storage and propulsion for shipping and to identify the conditions for successful market entry for the technology. Among others, here is below such running projects:

- Amsterdam: [6] :
  The 20 meter long vessel will operate both in urban areas (Amsterdam's canals) as well as in the seaport area between Amsterdam and IJmuiden. The vessel will be completely emission-free and silent, operating with a battery and a fuel cell.
- Belgium [6] :
  The objective of this pilot is to develop and test a modular plug and play hydrogen bunkering system that can be used in marine conditions.
- Norway [7]:
  In January 2019, Norled and the Norwegian Public Roads Administration signed an agreement for the world’s first hydrogen-electric ferry. The contract includes the development, construction and operation of the vessel where at least 50 percent of the energy requirement is covered by hydrogen.
- France [8]:
  Barillec Marine, a VINCI Energies Business Unit specialised in energy conversion and management on ships, is working on an innovative project: using a hydrogen electrolyser to store the electric energy generated by renewable energy sources and to redistribute this energy in a seagoing ship.
- USA [9]:
  On April 1st 2020, the boat builder All American Marine and the investment platform SW / TCH Maritime announced their teaming up to build a hydrogen-powered aluminium e-ferry to be operated in San Francisco Bay. Called the "Water-Go-Round Project" for now, this ferry will be the first of its kind in the United States. Able to accommodate 84 passengers without emitting any particles, it has been developed to prove that a path towards the commercialization of marine zero emission technologies is possible.

Figure 4: Some current illustration design for hydrogen application in marine sector (top left: Amsterdam, top right: San Francisco, bottom left: Norway, bottom right: France)

2.3 Tûranor PlanetSolar energy chain

The Swiss flag solar vessel Tûranor PlanetSolar (renamed in 2015 Race for Water) achieved the first world tour with solar energy in 2012 (https://www.planetsolar.swiss). Thanks to more than 500m² of 20% efficiency solar panels and a large battery storage, the solar vessel was able to conclude her world tour and to reach more than 50 stopovers around the globe on time. This relies on the very abundant solar energy yield along the navigation route close to the equator line and the high reliability of the complete energy chain.

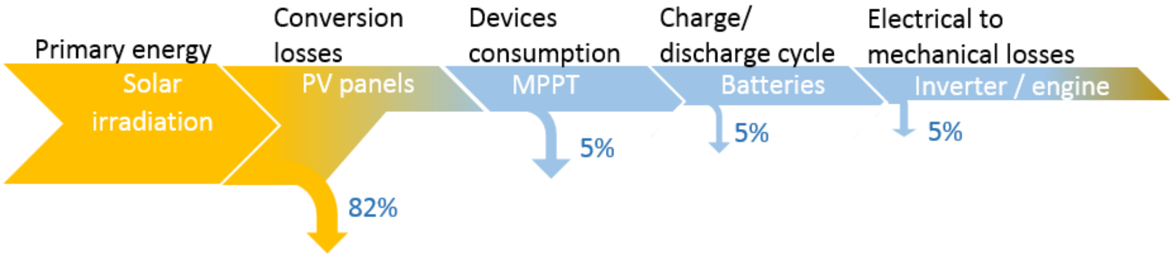

Figure 5: Transformation losses in the Tûranor PlanetSolar energy chain

The Sankey diagram (Figure 5) illustrates the energy chain efficiency without considering the propellers one and indicates around 85% of losses in the various transformation processes. However thanks to the 120kWp of installed PV power, 400kWh was daily generated during the world tour and allowed all along the route an average speed of 5 knot.

2.4 Goals

In order to be able to face bad weather and to go on navigating at night, Tûranor PlanetSolar was fitted with more than 1.1 MWh of electrical storage thanks to 6 battery packs located in the hulls of the catamaran. The complete energy storage was more than 11 tons of weight, including cells chassis and battery management systems.

In order to extend the navigation range, this project aimed at the integration of a complete hydrogen chain on this vessel, able to produce green hydrogen with PV energy and electricity with zero emission Fuel Cell System (FCS) as illustrated in Figure 6.

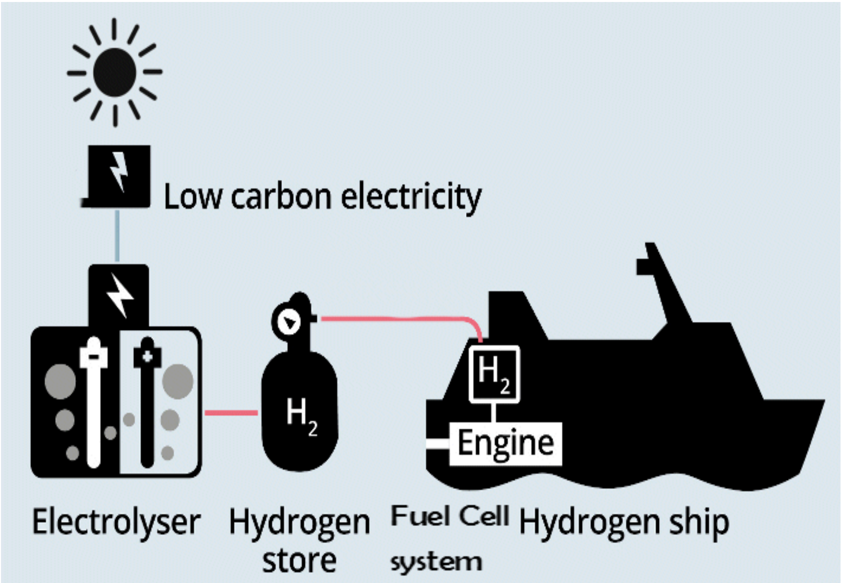

Figure 6: Concept of hydrogen system for energy storage and generation

This system allows to considerably increase energy storage capacity, without significantly increasing the load balance. Indeed, by removing 2 on the 6 battery packs and adding the hydrogen system, the global weight of the boat increases of 2.7 tons for 1.8 MWh of additional storage capacity. The equivalent weight of additional batteries for such an energy storage increase would have been closed to 18 tons (see details, in Table 1).

		Turanor PlanetSolar	Race for Water
Battery	Number of packs	6	4
	Capacity [kWh]	1'131	754
	Weight	11'160	7440
Hydrogen	Stored mass [kg]	0	180
	Eq. capacity [kWh]	0	2'200
	Weight	0	6'440
Total	Capacity [kWh]	1'131	2'954
	Weight [kg]	11'160	13'880
	Mass energy density [Wh/kg]	101	213

Table 1: Comparison of energy storage capacity and weight before and after the hydrogen installation, respectively Tûranor PlanetSolar and Race for Water named vessel.

The added energy storage largely extends the range of navigation of this zero emission vessel, even in low irradiation level environment without compromising her cruise speed. Advantages of the system on the different operation modes are schematized in Table 2, function of day and night situation and for harbour and navigation conditions (in parallel of this project, the solar vessel was upgraded with a kite sail to take advantage of winds when appropriate heading during navigation).

			Navigation mode		
		Harbor mode	*1. Sunny*	*2. Windy*	*3. Cloudy*
Turanor PlanetSolar	Day	Batteries charge	Batteries charge and vessel cruise speed		Vessel speed adapted to battery level
	Night	Batteries discharge by life on board	Batteries discharge by life on board and vessel cruise speed		
		Harbor mode	*1. Sunny*	*2. Windy (kite sail traction)*	*3. Cloudy (or low batteries)*
Race for Water	Day	Batteries charge and Hydrogen production	Batteries charge and vessel cruise speed	Batteries charge and hydrogen production	Batteries charged by FCS and vessel at cruise speed
	Night	Batteries discharge by life on board and hydrogen production	Batteries discharge by life on board and vessel cruise speed	Batteries discharge by life on board	

Table 2 : Operating modes of the solar vessel before and after the hydrogen system installation respectively Tûranor PlanetSolar and Race for Water named vessel

More favourable operation modes are highlighted in Table 2, typically in cloudy or low batteries level conditions during navigation. Hydrogen system allow as well to largely extend energy storage capacities, when hydrogen is produced at full capacity, mainly in harbor mode.

In addition to an innovative valorisation of the solar generator, this full scale demonstrator represents a new first world premiere for this emblematic vessel, some opportunities of worldwide visibility and a unique return of experience in a rash environment for an innovative system developed and assembled in Switzerland.

Finally, this project aims to illustrate the reliability and maturity of hydrogen solutions in the sector of long term energy storage in addition to battery systems dedicated for the day and night cycles.

3 System overview and organisation

In navigation, the electricity energy balance of the PlanetSolar catamaran was exclusively covered by solar energy stored in lithium batteries. Battery packs were generally full after 3 days of stopover and there was then, no more way to store the PV energy.

The current project proposes to illustrate at real scale the use of compressed hydrogen as an energy vector to store excess of PV electricity production and then to convert on demand, by a PEM FCS this stored energy into electricity to power the solar catamaran, when solar irradiation yield is poor.

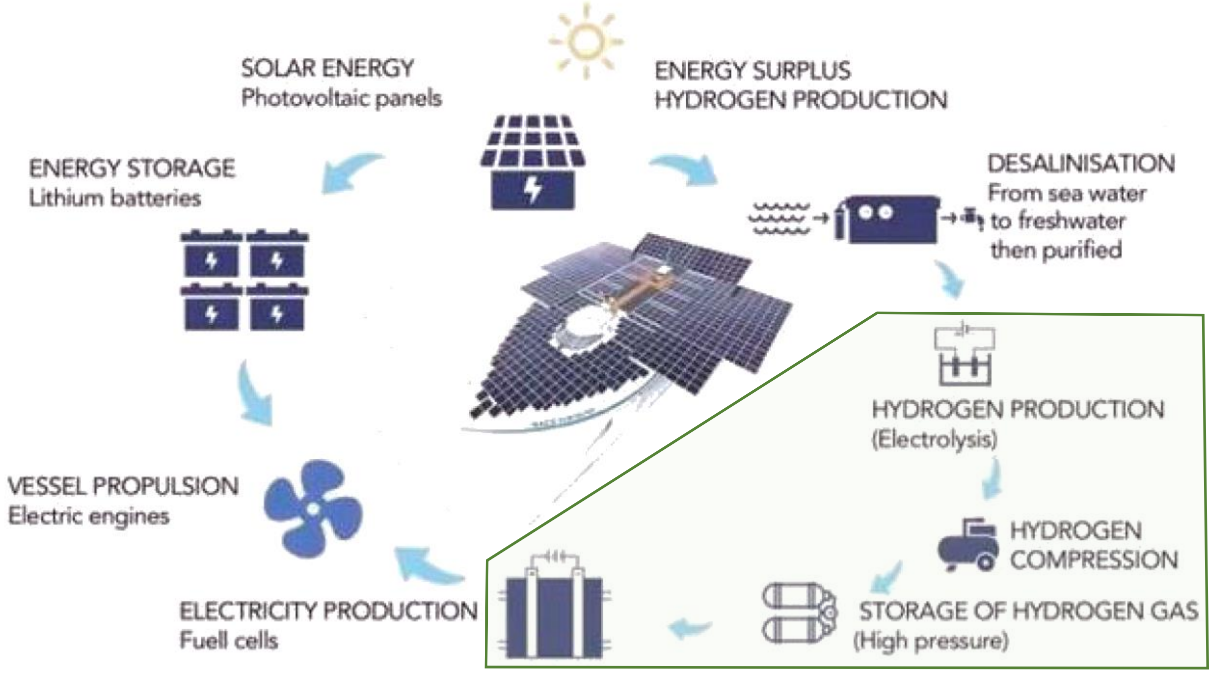

Figure 7: Energy chain components on the vessel with existing equipment (solar panels, Lithium ion batteries, electrical propulsion engines and sea water maker) and added H_2 system (highlighted)

Figure 7 illustrates PlanetSolar energy working principle and highlights the added hydrogen system on Race for Water catamaran.

3.1 Definition and system processes

The hydrogen system (H_2 system) is composed of the equipment presented in Figure 7 and described in detail in section 5, while hydrogen container is used to designate the complete system including its dedicated and specially designed structure made of carbon fibre (see Figure 11). The reasons to gather all components in a single container are given in section 4.1.

The main processes achieved by the H_2 system are illustrated on Figure 8.

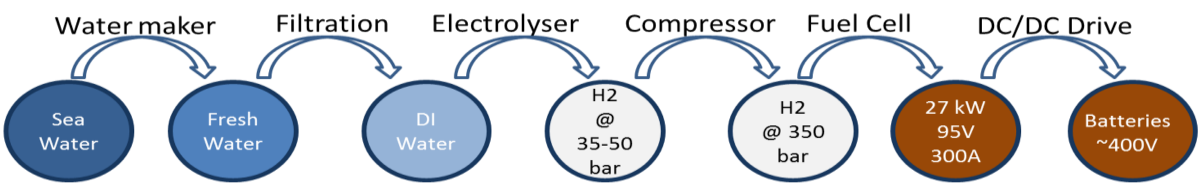

Figure 8 : Schematic description of the process sequences

A simplified view of the 3 sub-systems is provided in Figure 9.

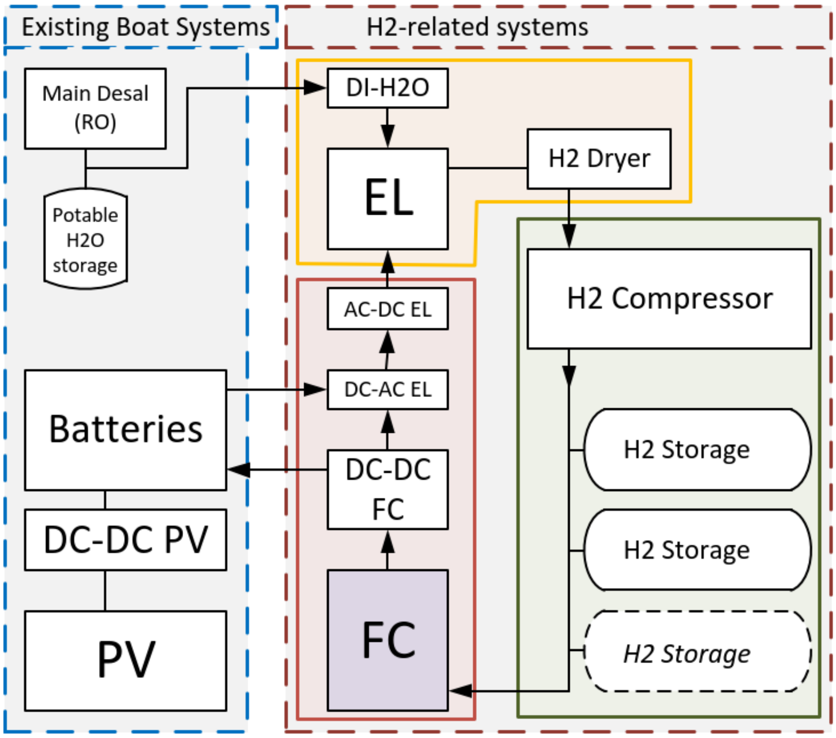

Figure 9: Schematic system description and integration on existing system on board (existing systems surrounded by blue rectangle, and new ones by brown rectangle).

1. Hydrogen production (highlighted in yellow)
   Potable water is produced on board by an existing fresh water maker based on reverse osmosis principle. This fresh water is then stored and purified on demand by a deionizer system (DI-H_2O) when supplying electrolysers and dryer (ELY and H_2 Dryer), which are producing a dry hydrogen (see section 5.3, for details).
2. Hydrogen compressor and storage (highlighted in green).
   A compressor (described in section 5.4) is used to increase the produced hydrogen pressure from about 45 bar to the storage pressure (up to 350 bar maximum, see section 5.2).
3. Electricity production (highlighted in purple)
   The energy supply of the system is stored in the battery packs, which can be recharged through DC/DC converters by the FCS (Fuel Cell System) upon captain's decision. A double stage of DC/AC and AC/AC converters are used to supply the electrolysers, dryer and auxiliary from the main battery packs.

3.2 Organisation

The customer and final user of the hydrogen system is the Race for Water Foundation, based in Lausanne and boat owner. The system conception, its assembly and integration of the components and qualification tests of the system on board is led by Swiss Hydrogen SA (SHSA), based in Fribourg.

The design and building of the hydrogen container that contains most of the components and the required boat modifications are managed by Multi One Design SA (MOD), a Swiss company in charge of the boat administration, maintenance and operations.

SHSA has subcontracted many suppliers for the H_2 system realisation, some of them are Swiss based, like Shiptec AG, Fischer Engineering AG, and Celeroton AG. Historical engineer companies and suppliers of the solar catamaran like Drivetek AG, Wago Schweiz and Schaefer Power GmbH are involved as well. The project organisation is illustrated in the following figure:

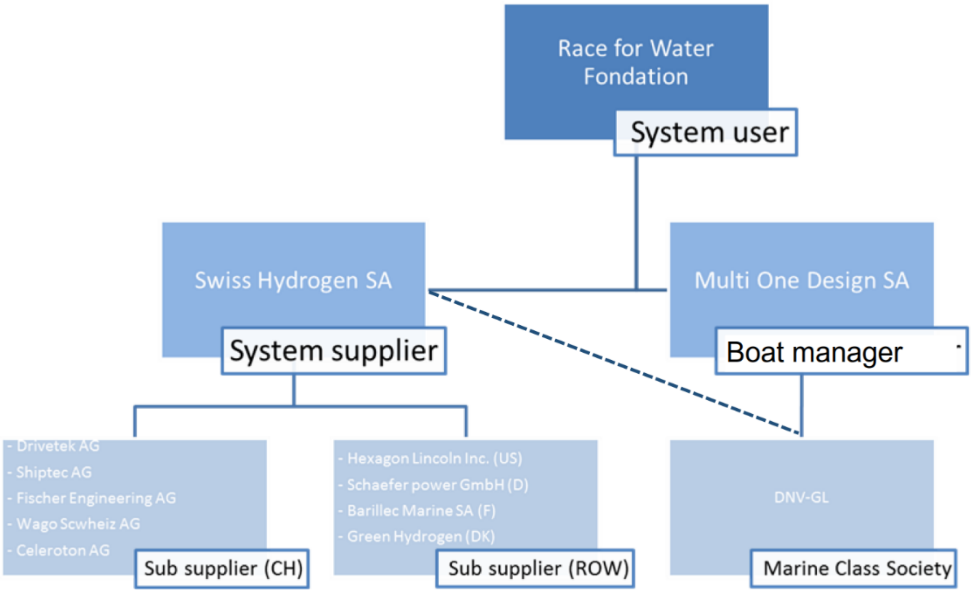

Figure 10: Project organisation

4 System design and safety

4.1 Predesign

Following a meeting with the international class society of the vessel (see section 4.6.4), it was decided to integrate all hydrogen components in a ‘hydrogen container’ located on the solar deck of the vessel (see Figure 11) for the following reasons:

- to reduce the risk of a direct impact into the hydrogen tanks in case of a collision;
- to minimize the number of interfaces with the solar vessel;
- to reduce the risks associated to the hydrogen system. For example, the hydrogen pipes are kept to a minimum length and do not go through any rooms within the vessel

Figure 11: Integrated hydrogen container (highlighted in green)

The main drawback of the hydrogen container of following dimensions 15 x 3,8 x 1,0 m^3, located on the solar deck is the required removal of 30 m^2 of solar panels (about 6kW_p). The stability booklet of the vessel was updated and showed no deviation from marine standards stability criteria.

4.2 Components integration

The hydrogen container highlighted in Figure 11 is divided into 3 main compartments where the systems component are gathered (see Figure 12, bottom), i.e.:

1. Storage and compressor (STO compartment)
2. Electrolysers and dryer (ELY compartment), and
3. Fuel cells (FCS compartment).

For safety reasons, in order to avoid any hydrogen accumulation in case of leak in the tubing or any equipment, each compartment of the hydrogen container is ventilated by its own system. Ventilation strategies depend on their functionality:

- The hydrogen storage and compressor compartment is permanently ventilated (refer to sections 5.2, and 5.4)
- The electrolysers and the dryer (see section 5.3) are located in the portside compartment, which is ventilated when hydrogen or electricity is being produced
- The fuel cell systems (see section 5.5) are located in a starboard compartment, which is ventilated when hydrogen or electricity is being produced. This compartment includes a fire suppression system, which covers all compartments

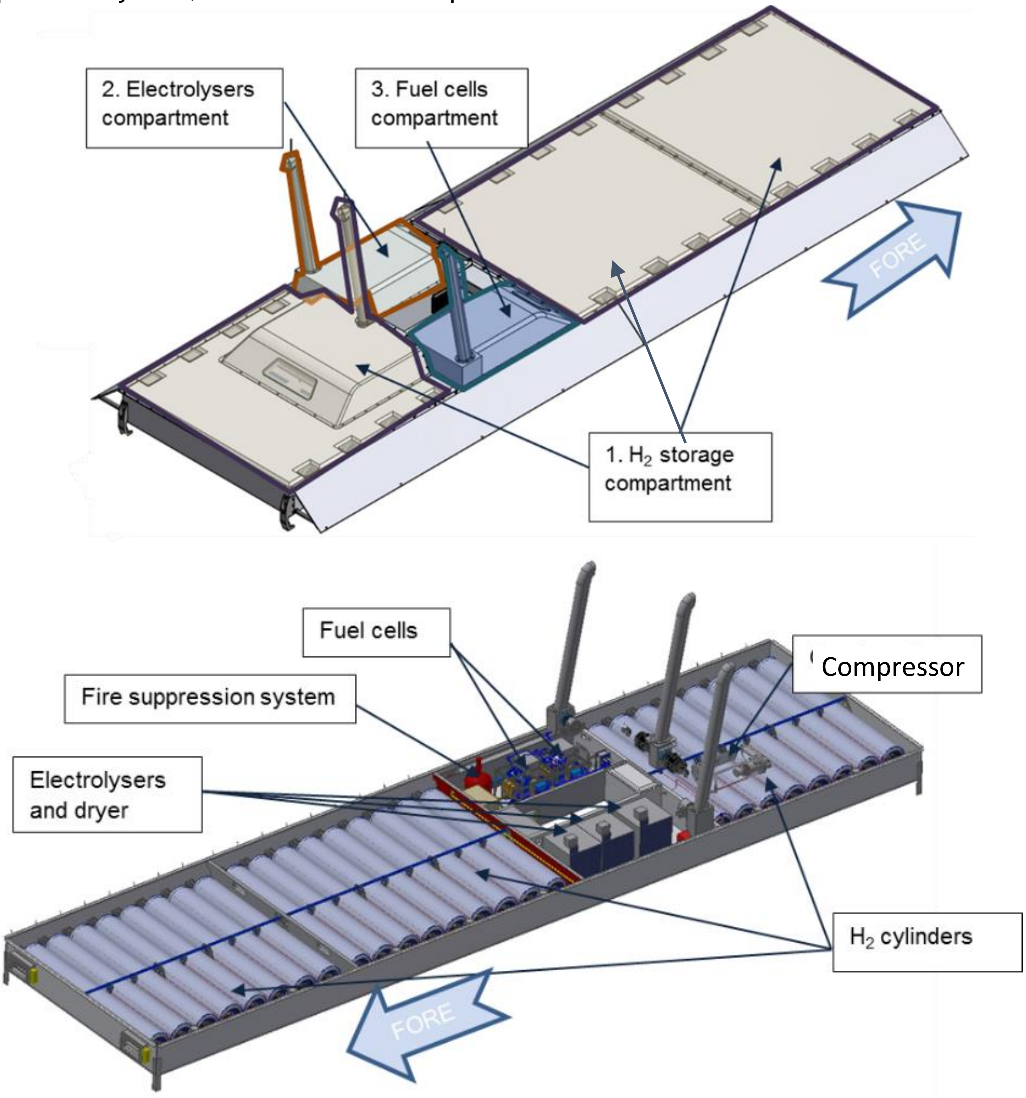

Figure 12: Perspective view of the H_2 container with coloured covers (top) and without covers (bottom)

As visible on Figure 12, each compartment is fitted with its own chimney, whose functions are described in the following section.

4.3 Ventilation concept

The air flux are indicated on Figure 13. In Yellow are the airflow for storage and in green the airflow for ELY and FCS compartments. The ventilators extracting the air in three different chimneys are symbolized in red (2 ventilators for STO compartment, for redundancy concept). In blue are represented the 4 fire dampers for air inlet.

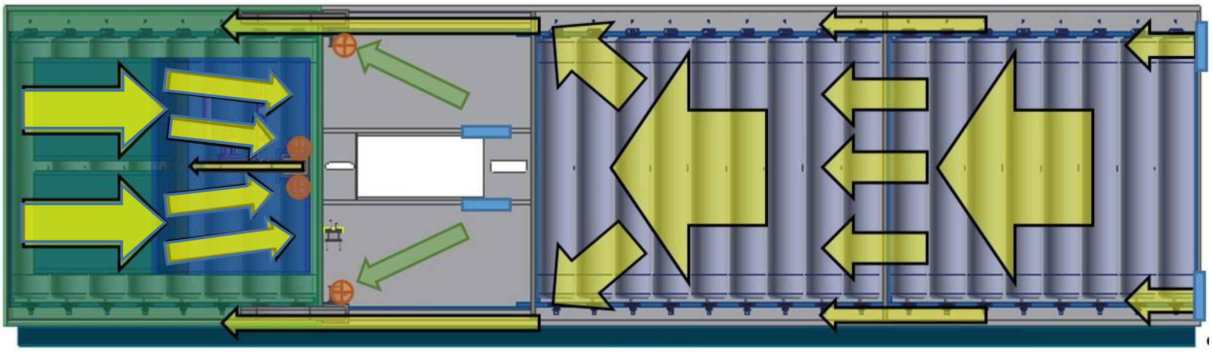

Figure 13: Ventilation fluxes overview (yellow arrows: storage ventilation, green arrows: ELY and FCS ventilation, blue rectangle: air inlets, and red crossed circle: air outlets)

The ventilated air exits hydrogen, oxygen and/or air from the container via 3 different chimneys connected with each compartment. Produced oxygen by the electrolyser is released via the ELY chimney (see Figure 14). A vertical distance of 3 meters has been kept between the outlets of the chimney and the solar panels, which complies with the rules of the certification body to keep all gas system exhaust at a minimum distance to any potential source of ignition.

The chimney fans are chosen to be ATEX (EXplosive ATmosphere) compliant and selected according to the net volume of each compartment and its potential H_2 release rate by taking a margin of safety regarding the H_2 concentration to LEL. (Low Explosive Level). In case of an electrical black out, the storage ventilation will be supplied by the 24V emergency battery pack of the vessel.

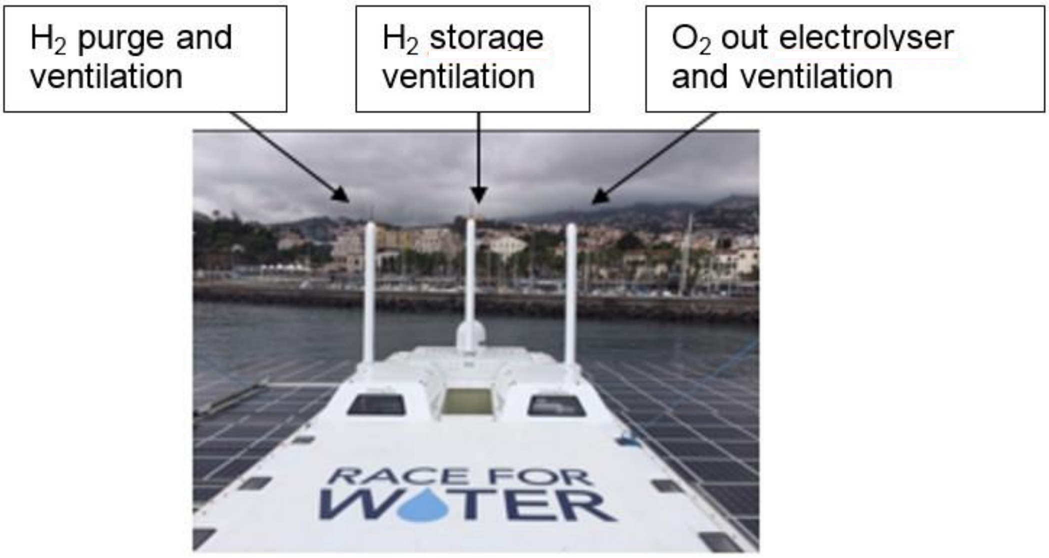

Figure 14: Hydrogen container chimneys for ventilated air, H_2 purge and produced oxygen (looking aft)

It should be noted that the 3 chimneys made of carbon fibber serve as lighting rods thanks to copper wires connected from each chimney housing to the sea water surface.

4.3.1 Ventilation monitoring

In each chimney, there are two air flow sensors, according to required redundancy principle. The air-flow monitoring system detects a sensor disconnection or a cable break. Disconnection or cable break is signalized as “no air flow”. A “no air flow” or “insufficient air flow” detection is triggering an ESD (Emergency Shut Down) and lead to audio and visible alarms.

4.3.2 Redundant flow monitoring for storage compartment

This is a second control to check the proper functioning of the ventilation, which applies for the storage compartment only, due to the large stored quantities and to natural permeation of the composite tanks. The differential pressure sensor (DPS) measures with two small tubes the relative pressure difference between the ambient and the inside pressure of the storage compartment. This setup is implemented in double in order to comply with redundancy requirement for system certification.

4.4 Electrical system and power regulation

DC/DC converters of the fuel cell systems and DC/AC power supplies of electrolysers are installed remotely in a dedicated electrical room on the main deck of the vessel (Figure 15).

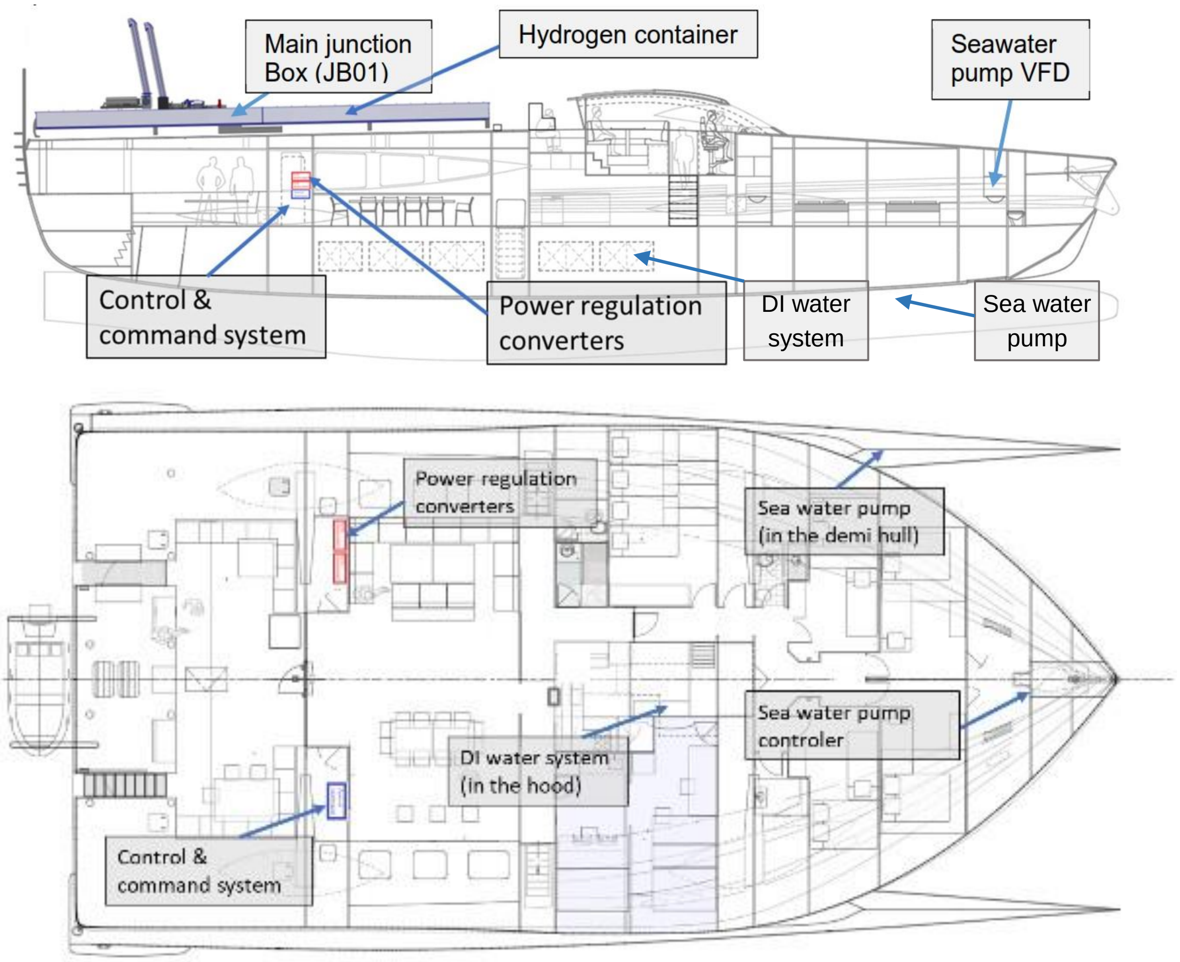

Figure 15: Location on the system electrical equipment on the main deck of the vessel

Most of power regulation devices are supplied by the company Schaefer power based in Germany. Some Schaefer products have been installed from the building phase of the boat and have proven to be robust and stable. A major criteria in this field is to have a galvanic separation in order to physically isolate main battery packs from the hydrogen system electrical components, one drawback is the much higher weight and lower efficiency compared to transformer-less products fully electronically controlled.

On the main deck, is installed the sea water pump controller located at the forward compartment of the vessel (Figure 15). On the lower deck (in the hold) is also located a small electrical panel related to the DI water system.

Power supplies of the system are summarized in Figure 16.

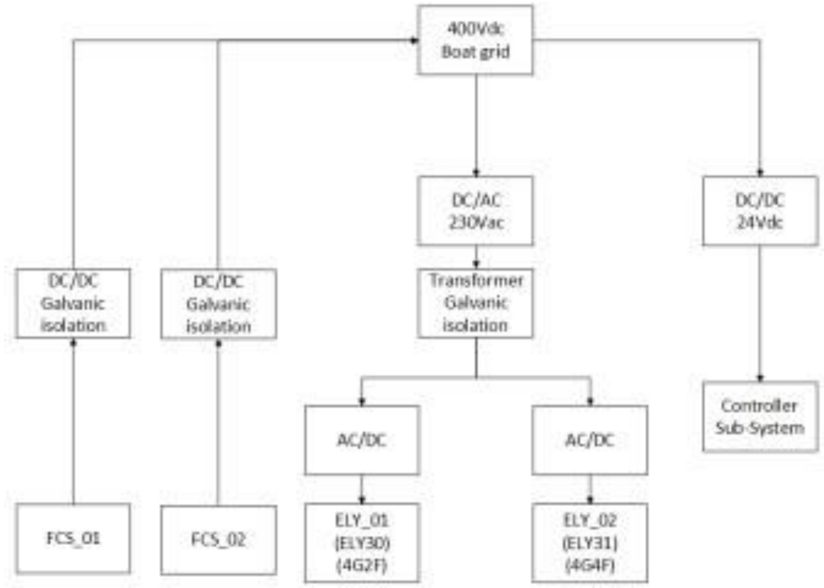

Figure 16: Main power supplies of H_2-System

4.5 Control system

The control system is distributed and divided in different level of control. There is a global installation's control (H_2 system control), assumed by a hardwired safety layer (HSL) for safety function and a programmable logic controller (PLC) for the non-safety function (see sections 4.5.1 and 4.6.3).

The figure below shows a conceptual structure of the control.

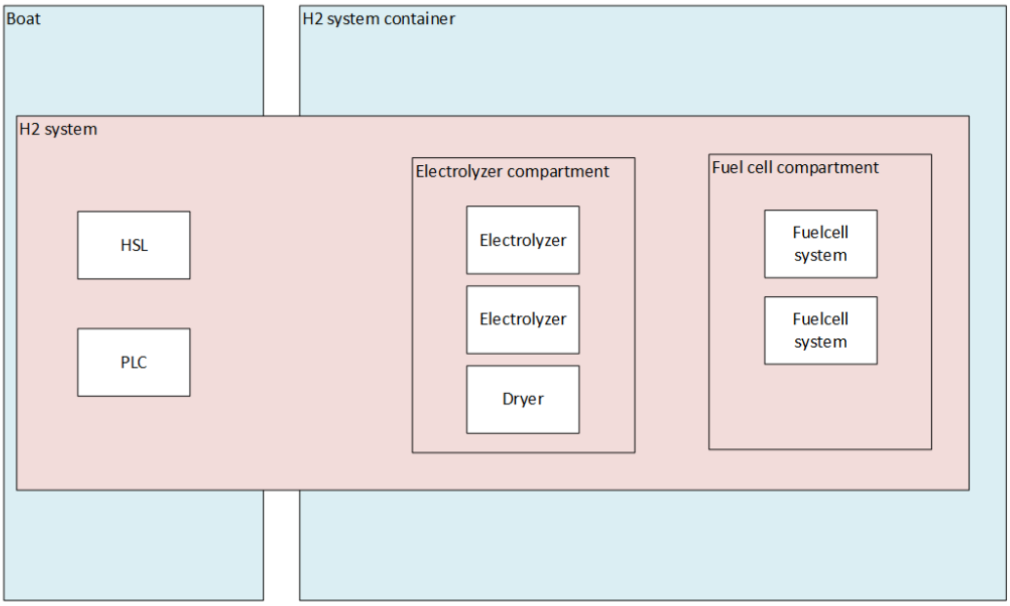

Figure 17: Conceptual distribution of system and controllers

4.5.1 Hardwired Safety Layer (HSL) and Programmable Logic Controller (PLC)

The HSL is supervising the system (see section 4.6.3, for details). In case of malfunction (e.g. major H_2 leak) the HSL interrupts all supply to the relays with cables connected to an area potentially containing hydrogen (storage, fuel cell and electrolysis).

The command and control system is based on different interfaces, all managed by a main PLC controller.

Figure 18 shows a simplified state-event diagram of the control system for the hydrogen system. This state-event is running on the Wago PLC, which is the top level controller of the hydrogen system. The sub-systems FCS01. FCS02, ELY01 and ELY02 have their own controller and are connected to the top level controller PLC.

The program is mainly structured in a state machine. There is a main state-machine that calls some sub state-machine. All the state machines run at the same time.

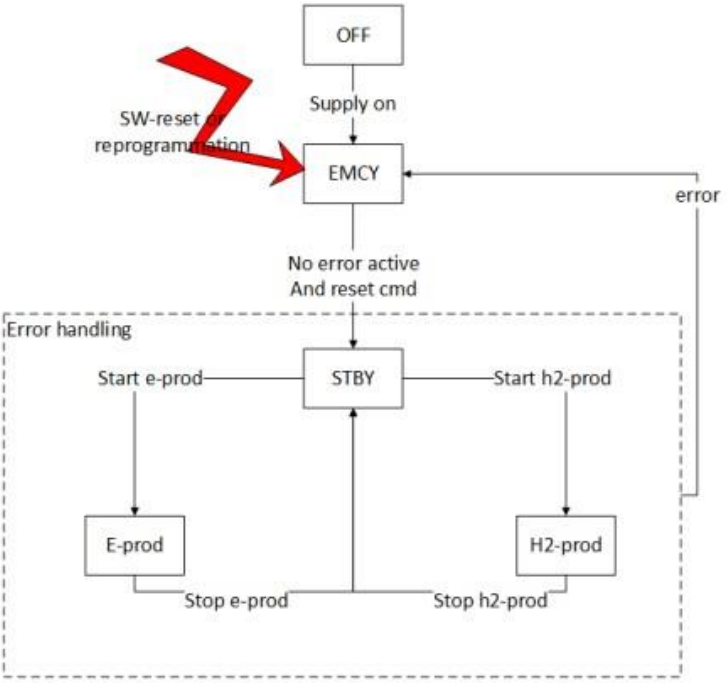

Figure 18: Simplified state-event diagram of the hydrogen system

Main system states are listed in the table below:

State	Remarks
Vessel Blackout (only 24V emergency)	Complete vessel blackout (main high voltage batteries disconnected), only supply from 24V emergency batteries. Ventilation can run with these backup up to 24h.
24V Failure / Main Switch Off	Power failure of 24V converter 1T10A (vessel side). System is offline. Ventilation is supplied from 230V and activated for each compartment. An UPS is implemented to supply a buzzer/alarm in cockpit.
Fire	Fire alarm system triggered.
H2 detected or storage vent. airflow error or ESD	H2 detection or storage insufficient airflow or ESD bouton pushed
Standby	System is OK and waiting for command from HMI
H2-Production	System is starting, producing or stopping H2 production
Ely comp. vent. airflow error	insufficient airflow in electrolyser compartment
E-production	System is starting, producing or stopping electricity production
FC comp. vent. airflow error	insufficient airflow in fuel cell compartment

Table 3 : Main states of the H_2 system

A control panel displays all the main control values of the hydrogen system and allows to diagnose and control it (see ‘Overview’ window interface on Figure 19).

4.5.2 Human machine interface (HMI)

The HMI is provided by a touch-screen display installed on the bridge. All the H_2 system is operated by this interface, in normal operation and for basic maintenance operation.

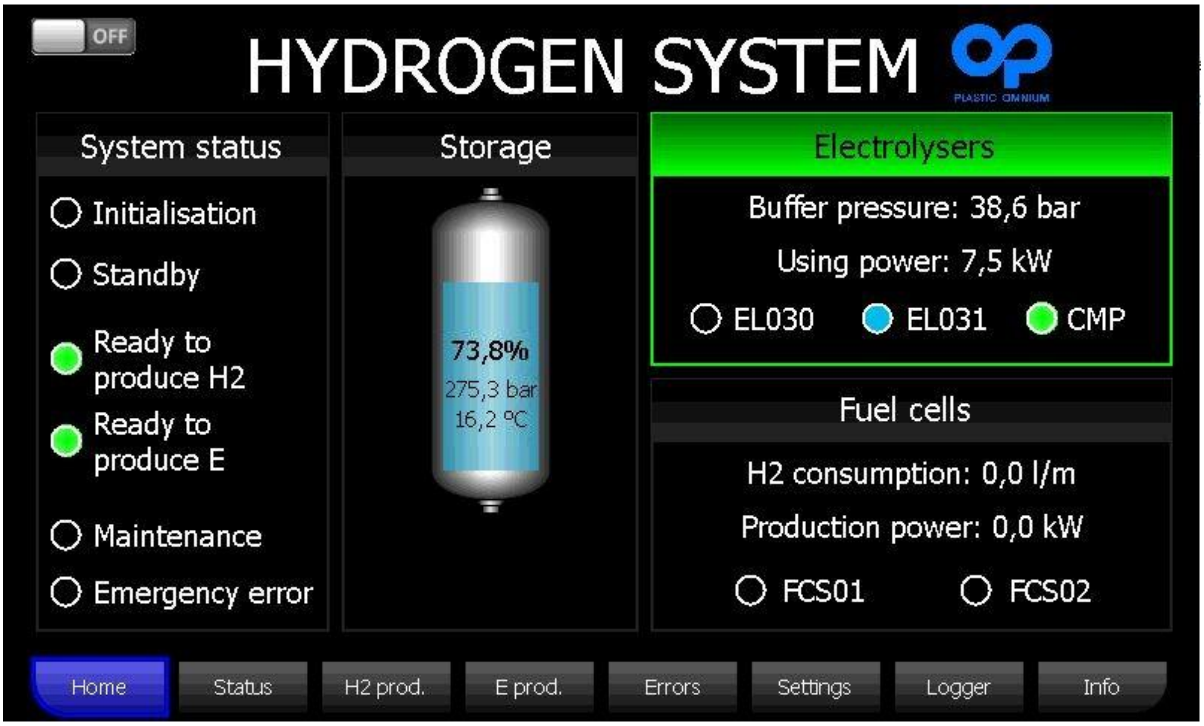

Figure 19: Overview menu of the system command interface

The different first level screen can be accessed by tab navigation:

- *Overview* gives an overview of the present system state
- *Status* gives more detailed information on the present system state, typically a complete overview of the storage state (pressure of each individual tank, mean and deviation, and two temperature measurements)
- *H2 prod*. gives detailed information on the electrolysers and compressor and provide the command interface to start and stop electrolyser
- *E prod.* is similar to H2 prod, but for electricity production
- *Errors* shows active and acknowledged error with a short description, including some statistics on errors
- *Settings* provides access to some parameters like defining electrolyser master, or some special function like activating some pumps, test of fire damper. There is as well a sub menu 'Maintenance', which gives access to some maintenance procedure.
- *Logger* gives access to histogram of recorded variables
- *Info* gives some general information about memory and CPU usage, and PLC software version among others.

The complete navigation system is illustrated in Figure 20.

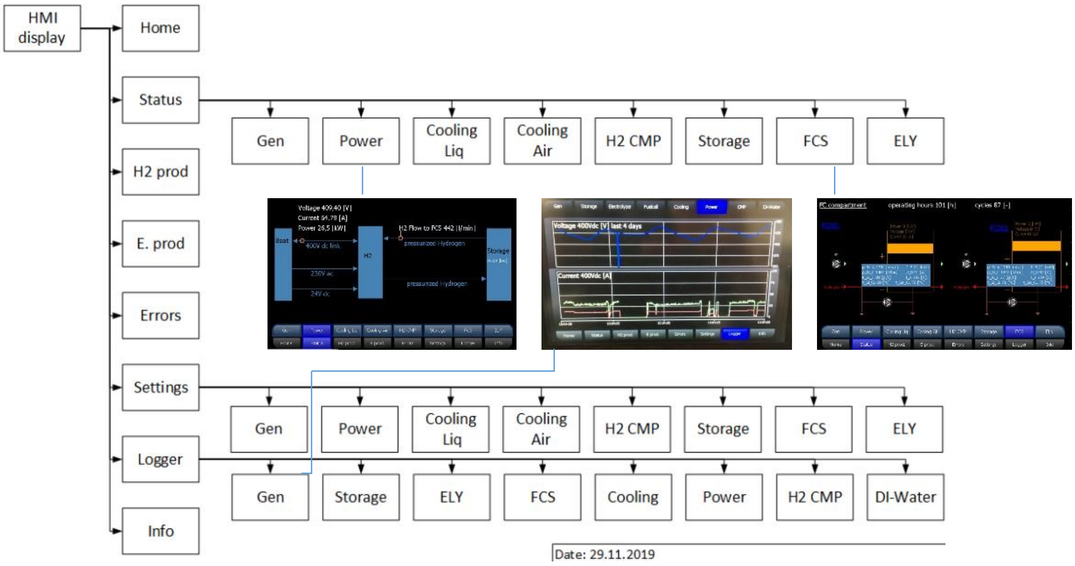

Figure 20: HMI navigation overview

4.5.3 Self-diagnostics and alarming functionalities

The following are monitored by the HSL.

- No active fire alarm on boat
- No H2 detection alarm in H2-System, ESD buttons are not pushed and signal line is not broken
- Ventilation of storage compartment is sufficient and no signal fault from airflow sensors
- Ventilation of fuel cell compartment is sufficient and no signal fault from airflow sensors
- Ventilation of electrolyser compartment is sufficient and no signal fault from airflow sensors requested

The PLC is monitoring the following signals, in case of inconsistency an alarm is displayed on the HMI a red light appears on the Control box:

- ✓ Ventilation breakers (distribution's, motor's and fire damper's breakers)
- ✓ 400V supply to FCs breakers
- ✓ 230V to electrolyser's controllers breakers
- ✓ 230V distribution to electrolyser is coherent with HSL state
- ✓ DI water conductivity is good
- ✓ Fresh water tank is not empty
- ✓ 230V supply to compressor breakers
- ✓ HSL is supplied
- ✓ 24V supply to FC compartment is coherent with command from PLC
- ✓ 24V supply to ELY compartment is coherent with command from PLC
- ✓ 24V supply to OTV is coherent with command from PLC
- ✓ Isolation of OTV supply line is good
- ✓ Isolation of 230V distribution and fuel cell power output lines are good
- ✓ Pressure sensor signal fault
- ✓ Storage pressure low warning and fault
- ✓ Storage pressure high warning and fault
- ✓ Buffer pressure high warning and fault

- ✓ Compressor leak pressure high warning and fault
- ✓ Fuel cell in state warning, request stop or emergency stop
- ✓ Electrolyser in state error
- ✓ Floor water in FC compartment
- ✓ Low temp. cooling temperature too high
- ✓ Low temp. and high temp. cooling level low
- ✓ Sea water valve don't open or don't close as requested

4.6 Safety concept

The design of the security system was carried out with the following rules in mind:

- In case of fire or emergency shutdown (ESD) all the system have to be de-energized and ventilation have to be shutdown
- In all other case, compartments with pressurized H_2 have to be always ventilated (section 4.3)
- Non ventilated compartment with potential H_2 distribution have to be de-energized and equipped only with approved ATEX equipment

These safety rules were part of the main outputs of the FMEA (see section 4.6.5). Furthermore, hydrogen and smoke detectors and an active firefighting system are installed in the H_2 container.

4.6.1 Hydrogen safety

The hydrogen system has been designed using best practices in order to minimize the risk of hydrogen leaks and accumulation. When the system is not in use, very little gas remains in fuel cell and electrolyser compartments. During installation and maintenance, the system was tested for leakage at each connection of the hydrogen piping (typically at 1.5 times the nominal pressure).

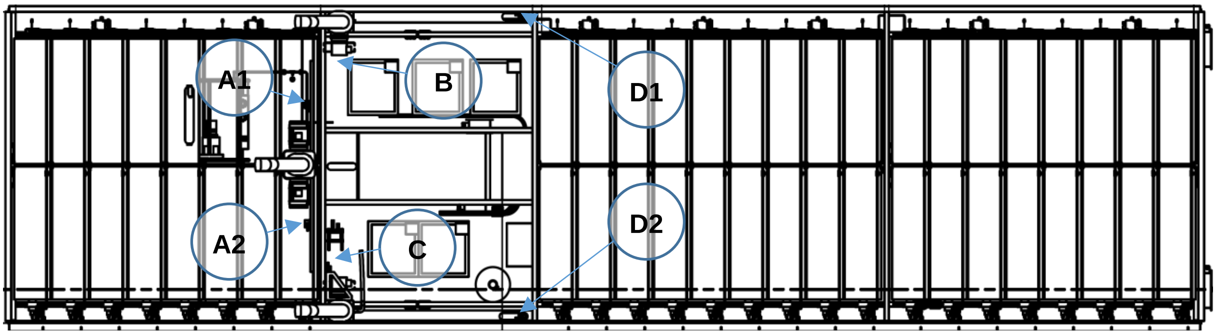

Figure 21: Top view zone hydrogen detectors

Six hydrogen sensors are installed as visible on Figure 21: 1 in the fuel cell compartment (C), 1 in the electrolyser compartment (B), 4 in the storage (D1 and D2) plus compressor compartment (A1 and A2).

A hydrogen detection would result in the several actions to keep the system in a safe mode:

- Immediate in-tank valves shut off
- Emergency shutdown of electrolyser and fuel cells systems
- Forced ventilation to ensure no accumulation of gas
- De-energizing of all potential ignition sources

4.6.2 Fire safety

This safety is firstly preserved by a passive layer insured by fire resistance of the storage compartment (below and on its sides).

The material used for the hydrogen container is made of epoxy with a composite foam to improve the fire resistance properties. Fire resistance tests have been conducted by the accredited company Currenta GmbH in Germany according to International Code for Application of Fire Test Procedures, 2010 (FTP Code) part 1.

Fire safety is also provided by active measures consisting of 4 smoke detectors distributed in each compartment of the hydrogen system (Figure 22). These detectors are connected to the boat main fire central alarm.

A fire detection would result in the several actions to keep the system in a safe mode:

- Shut off storage tank hydrogen valves
- Close the storage damper
- Emergency shutdown of electrolyser or fuel cells systems
- Stop all compartment ventilation

.

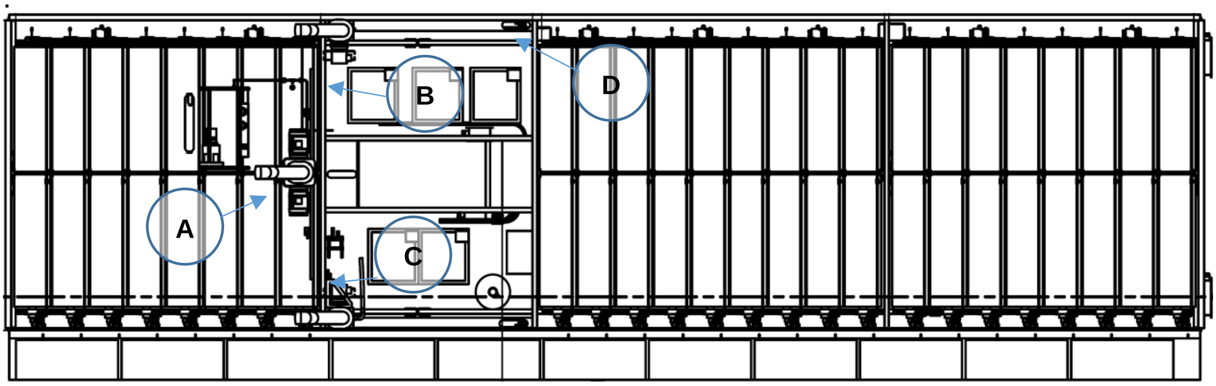

Figure 22: Top view zone smoke detectors

A fire suppression system is installed in the FCS compartment. This system consists of fire extinguish product that can be manually released from the cockpit.

In case of fire, in addition to TPRDs (3 per tank), structural fire resistance is defined to resists during 20 minutes for crew evacuation in case of vessel abandon.

4.6.3 Hardware safety layer (HSL) and cascade strategy

The general overview of the HSL is given on Figure 23. As input, the HSL verifies the state of different alarm, switches and sensors and as output it controls some relays in power distribution and 24V distribution, and gives some information signal to the main controller (PLC, see 4.5.1), which is based on a I/O-IPC product.

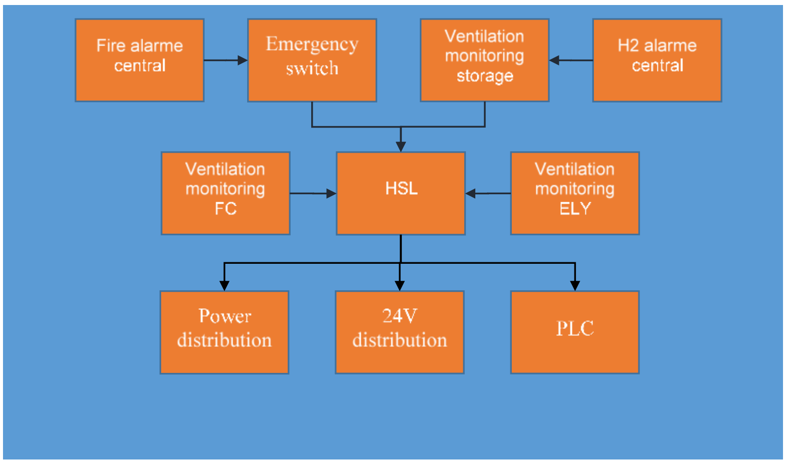

Figure 23: Hardware Security Layer overview

The H_2 system HSL is implemented by security relays. It is structured in three stage in cascade, which are the following:

1. First stage: checking fire alarm activation.
2. Second stage: checking ESD, H_2 concentration and STO ventilation
3. Third stage: checking FCS and ELY compartments ventilation

4.6.4 Preliminary meetings with international class society

The vessel Race for Water has been certified by a marine international class society the Germanischer Lloyd (GL based in Hamburg) from her launching date on March 31st, 2010. This society merged in 2012 with the Det Norsk Veritas (DNV based in Norway) to become the DNVGL.

DNVGL is now the world's largest classification society, providing services for 13'175 vessels and mobile offshore units, which represents a global market share of 21%. It is also the largest technical consultancy and supervisory to the global renewable energy (particularly wind, wave, tidal and solar) and oil and gas industry — 65% of the world's offshore pipelines are designed and installed to DNVGL's technical standards.

An objective of the project is to get an international certification for the hydrogen system. It was then straightforward to contact the DNVGL for preliminary discussions. In order to compare feedbacks from such an organisation, the French class society Bureau Veritas was also contacted.

Main outputs of the first assessment phase with DNVGL were the following:

a. DNVGL rules for ship classification integrates the dedicated sections for hydrogen storage and fuel cells aspects (see [10] and [11])
b. DNVGL was interested in a contribution to confront classification rules under running revision.
c. DNVGL has special concerns with the hydrogen bunkering

It was also required to carry out a FMEA (Failure modes and effects analysis) in an early phase of the project (see next section)

4.6.5 Failure Mode and Effect Analysis (FMEA)

The FMEA involves reviewing as many components, assemblies and subsystems as possible to identify failure modes, causes, and effects of such failures.

For each component the failure modes and their effects on the rest of the system are documented on specific FMEA work sheets. Analyses have been carried out by considering for each potential risk, coming from one unique system failure.

The basic FMEA procedure involves the following steps (see Figure 24):

- Define system boundaries and assumptions;
- Decomposition of the system into functional blocks;
- Describe function and interfaces of each block (consider different operational modes);
- Definition of possible failure scenarios;
- Identification of failure effects on the component and the system (local and global effect);
- Identification of failure cause;
- Assessment of the effect regarding its consequence (severity), likelihood (occurrence) and detectability of the failure;
- Provision of recommendations for control measures and necessary actions.

The FMEA method is described by different technical standards, e.g. [12]

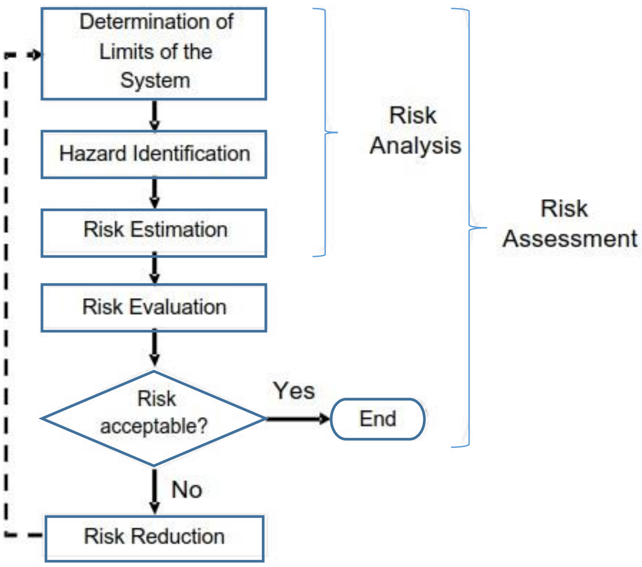

Figure 24: Flowchart for the risk assessment

The risk matrixes before and after the FMEA are illustrated in Table 4

Table 4 illustrates the impact of corrective actions on the risk matrix.

		Occurrence Oi				
		1	2	3	4	5
Severity Si	1		2	6	1	1
	2		2	8	6	
	3		6	8	3	
	4		2	1		
	5					

		Occurrence Or				
		1	2	3	4	5
Severity Sr	1		3	6	1	
	2	1	3	8	5	
	3		7	8	3	
	4					
	5					

Table 4 : Risk matrix (initial and revised assessment, resp. left and right table)

4.6.6 Fire numerical simulation

The Swiss based company Shiptec AG, has been contracted as shipbuilding specialist by SHSA to check the strength of the hydrogen container in case of fire.

Shiptec AG performed a linear strength and deformation test using a Finite Element simulation of the hydrogen tank storage chamber. Based on the 3D data and information from SHSA, a simplified Solid-Works Finite Element Analysis model was built.

Please refer to section 4.6.2, for additional details on fire safety concept.

5 Main components description

5.1 Sizing of the system

As the hydrogen production should be generally operated during stopover (or during sail traction phases by kite), a large part of the available solar power could be assigned to this process. Considering a relatively low daily produced energy by the PV plant of 300kWh for usual navigation latitude, it was then proposed to install a hydrogen production system of an average consumption power of 10kW.

In parallel, the hydrogen storage was expected to be the heaviest component of the hydrogen system. There was a trade off in the storage capacity design between the potential stored energy in the tanks and their impact on the total mass balance of the vessel (see section 5.7). It was decided to limit the maximum mass of stored hydrogen to 180kg (165 kg usable). This hydrogen mass corresponds to an electrical energy capacity of 2.5 MWh by considering a global efficiency of the FCS of 45%.

The third main component is the FCS it-self. The total averaged energy consumption of the vessel in navigation is about 20 kW. It was decided to install two FCs of 28kW$_p$ each in order to comply with redundancy concept recommended by DNVGL safety general guideline.

5.2 Hydrogen tanks

To be the heaviest component of the H_2 system, and to limit the impact on the global weight of the vessel, the lightest tank technology (of Type IV, made of carbon fibre with polymer liner inside) has been chosen.

The production and testing of the tank have to comply with actual Standard EC 79/2009 [13] and EU 406/2010 [14], which relies on a good implementation of a Quality Program and third party test reports:

- Burst test: the pressure at which the tank bursts, typically more than 2x the working pressure.
- Proof pressure: the pressure at which the test will be executed, typically 1.5 times the working pressure.
- Leak test or permeation test, in NmL/h/L
- Fatigue test, typically several thousand cycles of charging/emptying.
- Bonfire test where the tank is exposed to an open fire.
- Bullet test where live ammunition is fired at the tank.

The specifications of the tanks DP 240283-002 supplied by HEXAGON can be found below:

Working pressure (NWP)	350 bar @15 degree C
Max. Pressure (MEOP)	437,5 bar
Water volume @ NWP	312 l
Weight (unpressurzied)	101 kg
nominal Diameter @ MEOP	410 mm
nominal Length @ MEOP	3172 mm
Stored H2 mass @ NWP	7.5 kg
Certification	according to EC-79
Number of ports	2 (front and back)
Port size	1 1/8-12UN
No. of solenoid valves/cylinder	1
No. of PRDs/cylinder	3 (front/middle/back)

Table 5: specifications of the type IV Hexagon Lincoln DP 240283-002 cylinder

As defined during the FMEA with the class society (see Section 4.6.5), each tank is equipped with 3 thermal pressure relief devices (TPRDs). When the TPRD reaches 110°C in the case of fire, the compressed hydrogen is released though the TPRD.

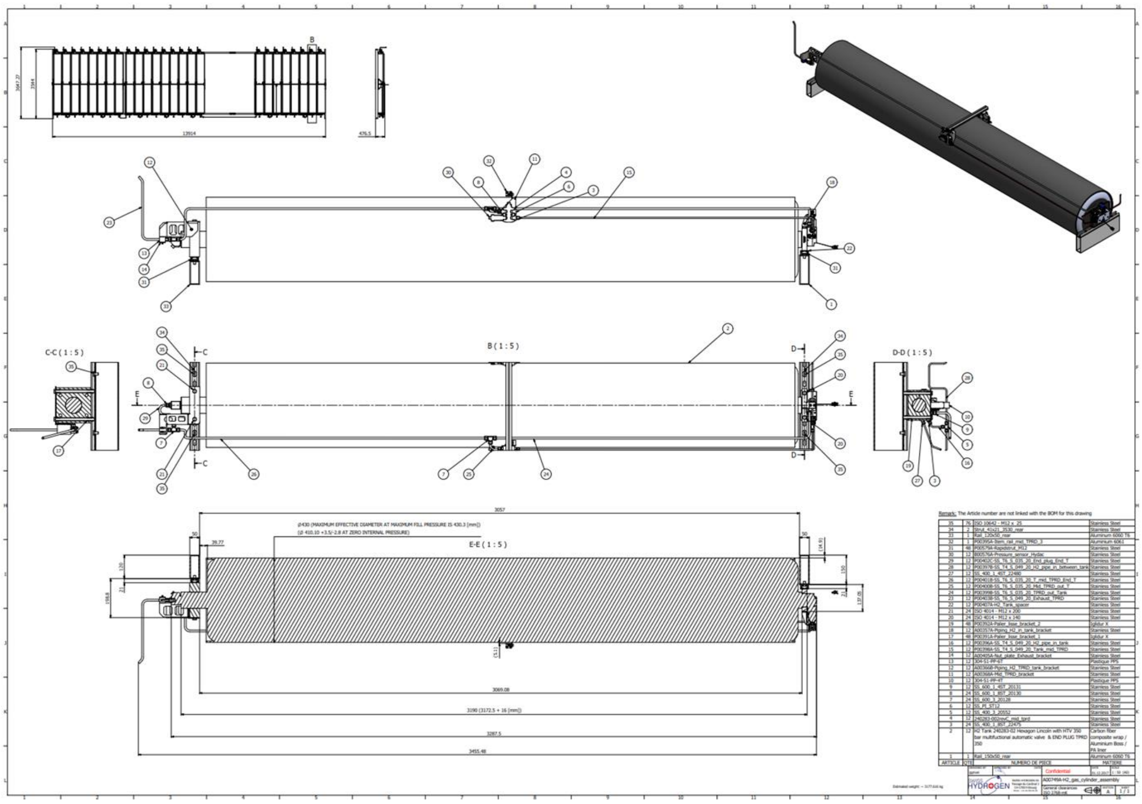

Figure 25: Cylinder assembly

The tank support solution has been designed by SHSA (see Figure 25) to allow longitudinal and radial expansion when the cylinder is fully pressurized. The high pressure H_2 piping has been supplied by the US based company Swagelok.

Figure 26: Type IV Hexagon Lincoln hydrogen cylinders, fixation and piping (3 TPRD outputs are visible with a yellow cap at right)

5.2.1 Tank DNVGL Certification

The following documents have been provided to DNVGL from the tank supplier:

- TÜV Test Report according to EC 79/2009 [13] and EU 406/2010 [14]

- EC Type Approval Certification
- Report of Manufacturer and Certification of Conformance
- Batch and production Test report by third party

According to the provided documentation, the torque test for the On Tank Valves (OTV) based on US standards was achieved at 220 Nm instead of 420 Nm as required by European regulation. It was then requested by DNVGL to complete the certification process with a 420 Nm torque test, followed by a pressure cycling test and a leak test, to be achieved by an independent laboratory. Before the successful completion of these complementary tests, the pressure in the tank were limited to 200 bar.

5.3 Electrolysers and H_2 dryer

Compared to alkaline products, PEM electrolysers were selected for

- their compactness for a given installed power
- the availability of small unit (alkaline technology is in the >100kW range)
- the high purity gas they are producing without any output filtering system
- the higher gas output pressure they can offer (up to 50 bar, currently)
- and no required environmental protection (alkaline solution must be fitted with retention tray).

A requirement was its ability to work in slightly inclined position and with a relative high output pressure to limit the effort from the gas compressor.

A visit was organized at the Danish company Green Hydrogen Systems and this company was then selected to provide the electrolysers and dryer solutions.

As a 10kW electrolyser was not part of Green Hydrogen catalogue, it was decided to install two electrolysers, which offers the advantage of system redundancy for H_2 production and to reach a global production capacity of 2 Nm^3/h.

The technical characteristics of the electrolyser can be found in the table below:

Technical data characteristics	Value	Units
Electrical power input: 400V, 3 phases + N + E	 400 50 16 Max. 5.5	 V (AC) Hz A kW
Water input: De-mineralized water Water quality Water inlet pressure	5 <2 1.5 to 10	l/h µS/cm ASTM type II barg
Hydrogen production capacity Hydrogen purity Max. Hydrogen pressure	1 High purity (saturated with water) 5 (50)	Nm3/h MPa (bar)
Heat power Water temp. to heat circulation	1.3 max. 70	kW °C
Oxygen out: Waste – not used, purged to environment	0.5	Nm3/h
Durability, life time	> 2.500	h
Dimension: - Height - Width - Depth	 101 60 60	 cm cm cm
Weight system only Weight system and packing mat.	130 150	kg kg

Table 6: Green Hydrogen Electrolyser model E1050 Product specifications

The ELY require high quality water to work properly and to comply with their expected lifetime of 2'500h (water conductivity inferior to 2 µS/cm). A DI water system has been designed by SHSA, to supply the ELY in high quality water.

The dryer system consists of 2 reactors containing a molecular sieve desiccant to purify the gaseous hydrogen before compression. One dryer has a drying capacity of up to 2 Nm^3/h, its main features are illustrated in the table, below:

Technical data characteristics	Value	Units
Electrical power input: 230V, 1 phases N + E	 230 50 13 Normal 0.4 Start-up 1,8	 V (AC) Hz A kW kW
Hydrogen capacity * One dryer has the drying capacity for drying two Nm3/h eith reduced dewpoint	1,0 (2,0*)	Nm3/h
H2 pressure	5 (50)	MPa (bar)
H2 dewpoint	< -70	°C
H2 dewpointAmbient temperature	+2 to +40	°C
Durability, life time	> 50.000	h
Dimension: - Height - Width - Depth	 63 60 50	 cm cm cm
Weight system only Weight system and packing mat.	45 55	kg kg

Table 7: Green Hydrogen Dryer model HyDry Product specifications

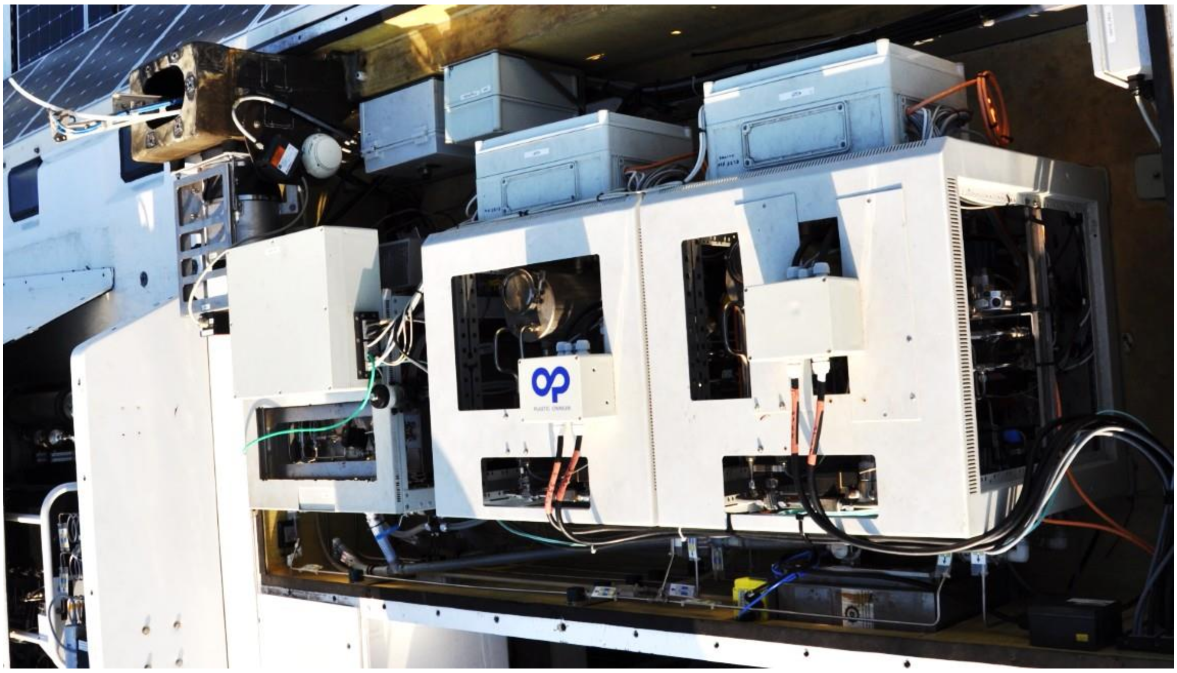

Figure 27: Top view of the ELY compartment, dryer on the left, both electrolysers at right (ELY chimney base and smoke detector are visible on top left corner)

5.4 Hydrogen compressor

The main criteria were to, first of all, be oil free type, but compact and light as well, with an acceptable level of noise emission.

A California based company Hydraulic International Incorporation (HII) delivered a two-stage electrically driven product (see Table 8). Some modifications have been achieved at SHSA to comply with the certification requirements, such as:

- The Variable Frequency Drive and most controls are to be remote, since non ATEX devices.
- For explosive-area compatibility, all components on the compressor chassis must be approved for operation in such an area (ATEX Zone 2).
- PED-approved pressure-relief valve must be used

The specifications of the compressor can be found below:

Motor rating	2	HP
Current @ 230 VAC, 1-phase, 60-Hz, VFD	10.4	Amps
Speed: Cycles per minute	0-70	cpm
Weight	155	Pounds
Noise level @ 3 ft	65	dB(A)
Cooling air provided	176	CFM
Delta temperature (gas outlet vs. ambient)	15-25	°F
Operational ambient temperature range	-40 to +350	°F
Inlet pressure range	350-1900	Psi
Operating pressure range	350-5220	Psi
Low Pressure limit switch	350	Psi
High Pressure limit switch	5220	Psi
Pressure reducing regulator with bypass	350-1900	Psi
Inlet & outlet ports	¼"	37-deg Flare
Overall dimensions (L x W x H)	32x22x11	Inches
Cooling method	Air-Cooled	
Number of Stages	2	

Table 8: Hydraulics International Inc. Model PG2-21282 specifications

The Pressure Equipment Directive (PED) 2014/68/EU (formerly 97/23/EC) of the EU sets out the standards for the design and fabrication of pressure equipment like pressure vessels, piping, safety valves and other components and assemblies subject to high pressure.

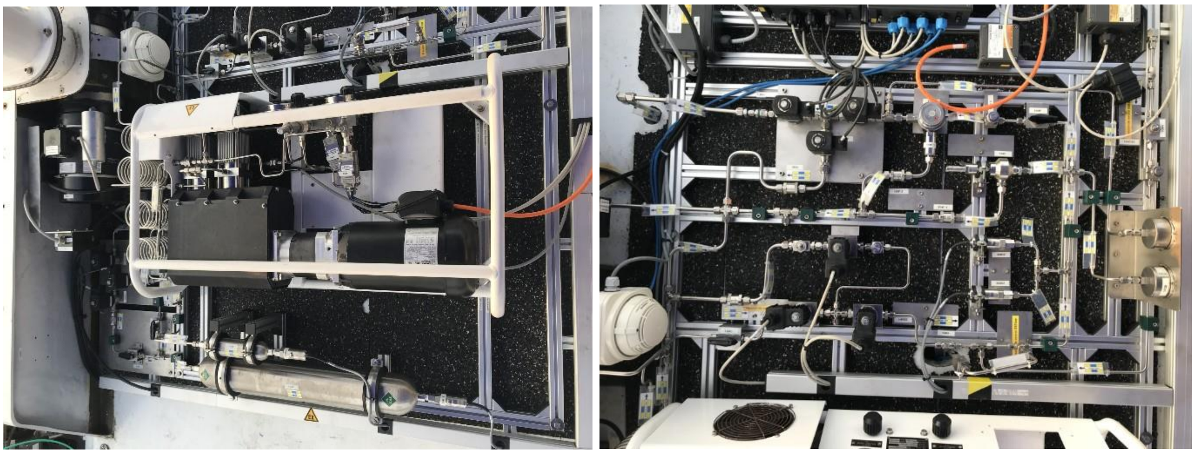

Figure 28: Top views of compressor unit and hydrogen buffer (left), and its hydrogen distribution piping system (right)

5.5 Fuel cells

The fuel cell systems of 28 kW of peak power each have been designed and assembled by Swiss Hydrogen.

The stacks are supplied by Powercell based in Sweden. The advantages of this product is to have a competitive efficiency and a high energy volumetric density (3 kW/L). The stack is made out of 143 metallic bipolar plates.

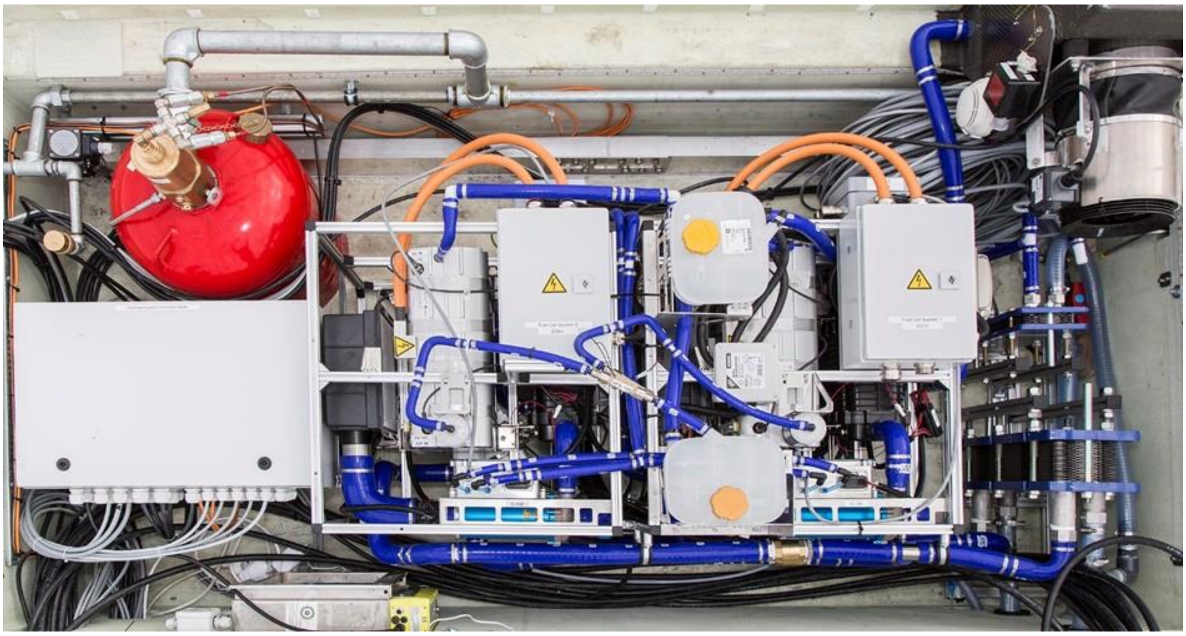

Figure 29: Top view of the fuel cell system

The specifications of the fuel cell system are shown below:

FC system technical data	Specification
Number of cells	143
Max. continuous net power	28 kW
DC electric supply	95V, 300 A
System pressure	1.8 bar_{abs}
Voltage range (Peak Power EOL .. OCV BOL)	78 .. 157 V
Coolant flow (pump integrated)	65 l/min
Coolant outlet temperature	80°C
Coolant waste heat	24 kW
System efficiency (LHV H2 in to DC stack out)	50 %
Dimensions (H x W x D) [1)]	427 x 647 x 408 mm

Table 9: Swiss hydrogen fuel cell specifications

The FCS compartment includes:

- the 2 fuel cells system (including air booster, low and high temperature cooling systems, and control boxes)
- the fire suppression system
- The H_2 alarm central unit

5.5.1 FCS Factory Acceptance Test

Before delivery on board, the 2 FCS have been submitted to several tests to check their safety and correct function. The conducted test concerns the following:

- Leakage rate on anode and cathode of the FCS
- Coolant leakage test
- Gas strength pressure test
- Full operation test

Figure 30: Experimental set-up for the FCS01 for Factory Acceptance Test (FAT)

The full operation test was limited in time and in power (to approx. 25 kW) due to the limitation of heat removal in the laboratory. However, main electrical parameters were measured during the Factory Acceptance Test (FAT), like stack generated current and voltage, corresponding power and coolant output temperature (see Figure 31).

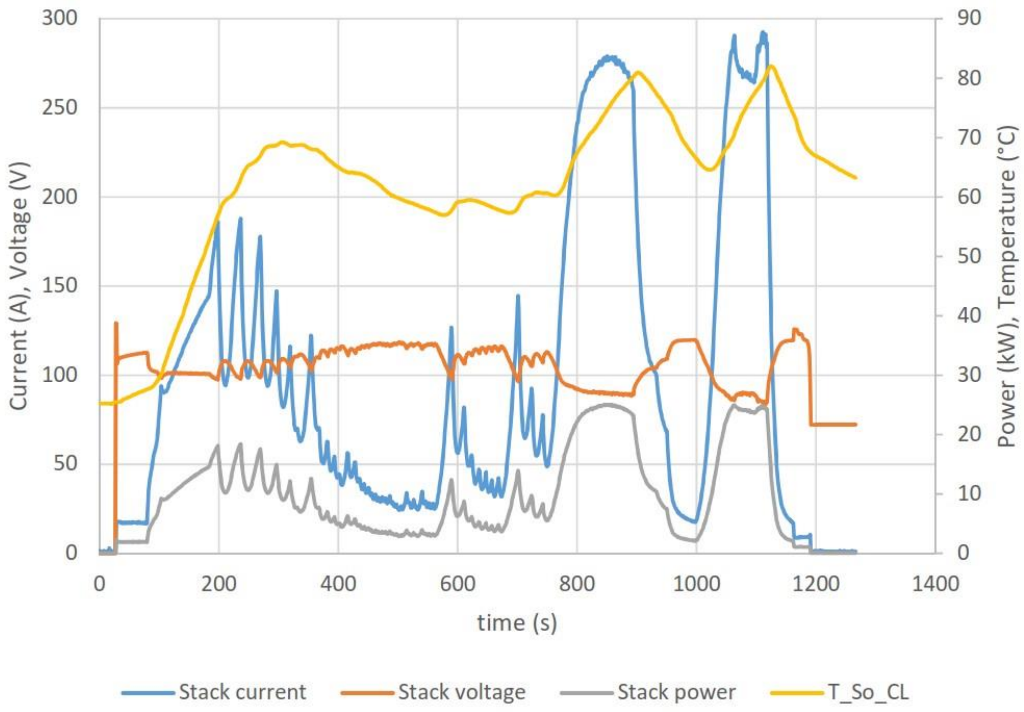

Figure 31: Typically main FCS parameters recorded during the FAT

Several testing sequences were carried at up to 300 A, which represent the maximum current acceptable for the DC/DC converter system (see Section 5.6). All tests have been successfully conducted for the 2 FCS before their commissioning.

5.6 Power electronics

Cabling installation and supply were subcontracted to an electrical marine company Barillec, based in Concarneau (F), close to Lorient.

The power injection for the fuel cells into the main 400 V-DC grid of the vessel is provided by 4 DC/DC converters with galvanic separation which offer an input voltage range of 80 to 160 VDC, an a maximum output current of 100 A.

The supply of the 2 electrolysers is achieved by a DC/AC converter of 15 kVA (visible on Figure 32, left) to feed AC/DC converters of the electrolyser (source of efficiency loss).

FCS auxiliaries (coolant pumps and solenoid valves) are supplied in 12V by a 1.25 kW DC/DC one with galvanic separation for safety reasons.

Figure 32: View of power cabinet (power distribution 400Vdc, left and 230Vac, right)

5.7 System weight

The total weight of the hydrogen system, including its container is of 6.4 tons, which remains a relative small increase of the weight of the vessel of about 100 tons.

#	Components	Supplier	Quantitiy	Weigth [kg]
1	**H2 piping and tanks (50 %)**			
1.1	312 L tank and OTV	Hexagon Lincoln Inc	25	2'800
1.2	Piping H2 & TPRD & bracket	Swagelok Switzerland	25	250
1.3	Auxiliary and others (fire damper, ventilation,..)			150
	Subtotal: 3200 kg			
2	**FCS, fire suppression system and HSL (6%)**			
2.1	FCS01 and FCS02 (incl air blower, coooling loop , filter)	SwissHydrogen SA	2	150
2.2	Heat exchangers & cooling	Alfa Laval	2	25
2.3	Fire suppression system tank	Novec		67
2.4	Auxiliary & control systems			120
	Subtotal: 362 kg			
3	**Compressor (2%)**			
3.1	H2 compressor	HII	1	98
3.2	Auxiliary & control systems			52
	Subtotal: 150kg			
4	**Electrolysers (5 %)**			
4.1	Electrolysor E-1050	GreenHydrogen	2	260
4.2	Dryer 50 bar	GreenHydrogen	1	45
4.3	Auxiliary			8
	Subtotal: 313 kg			
5	**Power converters (9%)**			
5.1	DC/DC C5858, 15 kW (injection)	Schäfer Elektronik GmbH	4	260
5.2	DC/AC IT 5978, 15 kW, electrolyser supply	Schäfer Elektronik GmbH	1	200
5.3	DC/DC, C3772 1.1 kW	Schäfer Elektronik GmbH	1	10
5.4	Electrical cabinet & cables		6	95
	Subtotal: 565 kg			
6	**H2 container (29%)**			
6.1	Walls, structure, covers, chimneys, stairs & auxialiary	MOD70	1	1'850
			TOTAL:	6'440

Table 10 : Decomposition of the total weight of the system.

It could be pointed out that the H_2 storage and piping represent 50% of the total system weight, while the container and auxiliaries are close to 30%.

6 Installation and upgrade phases

Most of system components are installed in a H_2 container, which was assembled in Lorient (F), the technical base of the R4W catamaran. The approach was to install the main components inside the container and to use a crane to install the whole equipped container onto the vessel.

The component integration phase was launched on February 20th, 2017 when 5 SwissHydrogen SA (SHSA) employees started working in Lorient.

Due to the imperative boat departure on the April 7th for her world tour and a strict navigation planning including partners events at most of stopovers, it was not possible to complete all the system tests in Lorient. One SHSA engineer took part to the navigation in order to support the crew with the H_2 system and to carry out a continuous reporting of actions and results. He stayed on board until Concep-tion in Chile stopover at the end of July 2018 (see Figure 34).

Figure 33: Installation of the H_2 container on the R4W vessel with a crane

SHSA sent to 9 different stopovers in total, electrical and mechanical engineers and some sub-suppliers in order support our colleagues on board. It took finally close to 3 years to make all the system upgrades and to obtain final DNVGL system certification.

Figure 34: Navigation route of the R4W vessel and intervention location (yellow dotted line: navigation with one SHSA representative on board)

The installation process was also slowed down by scarce reactivity from some sub-suppliers in providing technical support or adequate documents for the certification.

The progress in the system installation, tests and fine tuning along the time including durations of intervention and involved FTE on board are synthetized in Table 11.

			2017			2018			2019		
			1. Lorient	2. Hamilton	3. Pointe-à-Pitre	4. Lima	5. Concepción	6. Papeete	7. Noumea	8. Jakarta	9 Hong Kong
		FTE :	3.5	1	4	2	2	2	2	2.5	4.5
#	Component	Duration [Week]:	6	2	3	2	3	2	3	4	3
A	DI Water	1. Installation/Testing			✓						
		2. Troubleshooting/improvment			✓	✓	✓	✓	✓	✓	
		3. Maintenance						✓			✓
B	Electrolysers	1. Installation/Testing	✓		✓						
		2. Troubleshooting/improvment				✓	✓	✓	✓	✓	✓
		3. Maintenance				✓		✓	✓	✓	✓
C	Dryer	1. Installation/Testing	✓		✓						
		2. Troubleshooting/improvment						✓	✓	✓	✓
		3. Maintenance							✓		
D	Compressor	1. Installation/Testing			✓						
		2. Troubleshooting/improvment					✓				✓
		3. Maintenance			✓			✓	✓	✓	✓
E	Fuel Cell Systems	1. Installation/Testing	✓	✓							
		2. Troubleshooting/improvment		✓			✓		✓	✓	✓
		3. Maintenance									✓
F	H_2 storage	1. Installation/Testing	✓		✓	✓					
		2. Troubleshooting/improvment				✓			✓		
		3. Maintenance							✓		✓
G	Electronics & command	1. Installation/Testing	✓		✓						
		2. Troubleshooting/improvment			✓	✓			✓	✓	✓
		3. Maintenance									✓

Table 11: Work packages over time for all SHSA intervention locations (including duration and FTE)

Following sections are dealing with the main achievements of each intervention.

6.1 Lorient (France)

The main achieved tasks in Lorient were:

a. Production and assembly of the H2 container
b. Tanks and HP piping installation validated by a 200 bar pressure test on the piping
c. ELYs and dryer and FCS installation
d. Installation of the H2 containers on the vessel with a crane (Figure 33)
e. Start of the power electronics installation and cabling by Barrilec SA.

6.2 Hamilton (Bermuda)

Vessel anchored at Bermuda Island during the America Cup to take part to the race observation fleet. Despite the stopover was rather long from May 23rd to July 7th, the hospitality program was dense and only minor operations on the H_2 system have been carried out.

6.3 Pointe-à-Pitre (Guadeloupe)

For this important technical campaign, a 20 ft. container workshop with machineries has been shipped to Guadeloupe. This container was including a compactable structure to protect the H_2 system in case of bad weather events during the operations (Figure 35). In order to achieve the leak safety test on the HP piping and tank standard procedure for their commissioning, a second container was designed to store nitrogen, hydrogen and helium bottles.

The main achieved tasks in Guadeloupe were:

a. Final commissioning of the tanks.
b. Completion of DI water system and cooling water piping.
c. Completion of the O_2 and H_2 piping, including tightness tests
d. Safety functional tests: flow monitoring, H_2 detection, fire detection, fire suppression system, fire dampers.
e. Test runs of the ELYs and dryer with the support of Green Hydrogen on site
f. Test runs of the ATEX compressor
g. Completion of the electrical connections by Barillec

h. 5 days DNVGL survey, which lead to preconditions for H_2 production and to connection of the H_2 supply to the FCS.

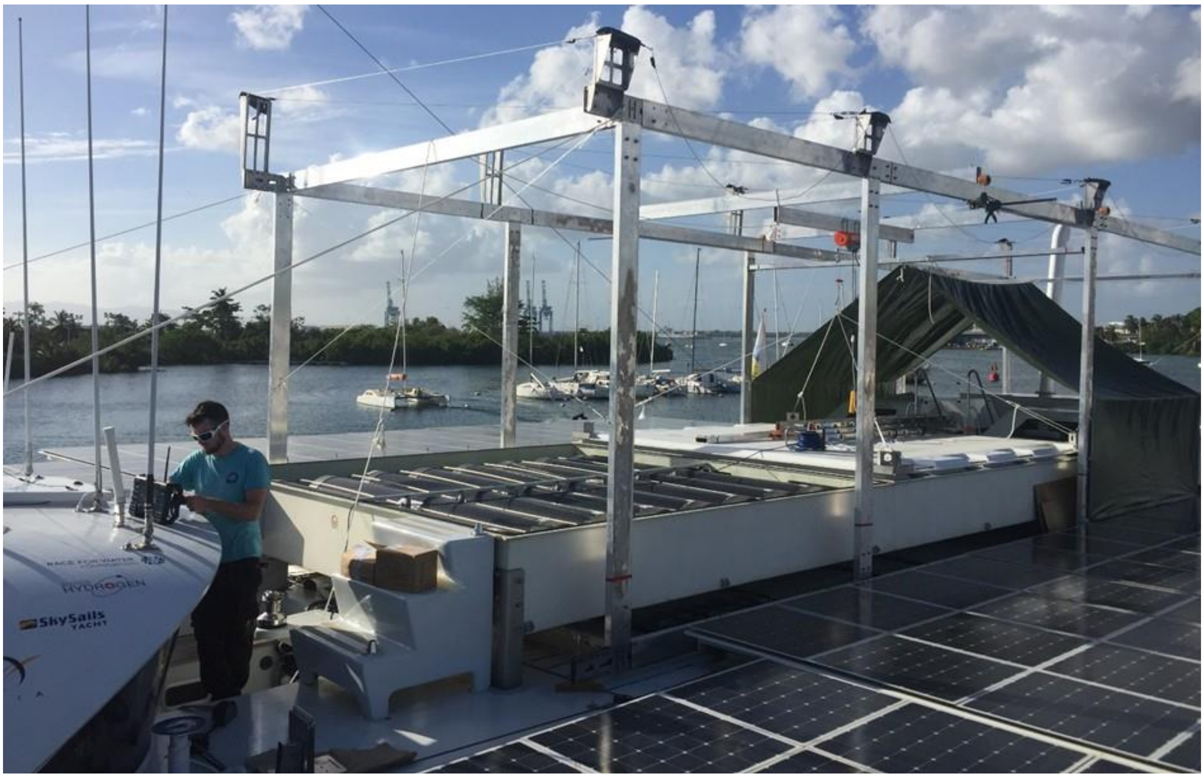

Figure 35: Compactable structure to protect the H_2 system from bad weather, fitted with a hoist for heavy load

A pressure limitation to 100 bar in the H_2 tanks was imposed by DNVGL due to lacking documents from the tank supplier regarding EC79, [13].

In order to complete the DNVGL precondition tasks (see above, bullet list –h-), a SHSA command & control engineer took part to the navigation to Panama, in addition to the design engineer already on board.

First runs of H_2 production have been done in navigation to Panama. Successful FCS runs were done during Panama stopover (February 19th to 27th) and the canal crossing to Pacific Ocean. Our control and command engineer left then the vessel.

6.4 Lima (Peru)

Main achievements in Lima were:

a. Installation of degassing ELY output water system
b. Removal of tank N°:3539 -026 for passing additional DNVGL tests
c. Installation of a replacement tank N°:3577-005
d. DNVGL SAT from May 14th to 17th by a local surveyor

6.5 Concepción (Chili)

The main achieved tasks in Concepción were:

a. Troubleshooting on H_2 production: DI Water, ELYs, CMP
b. Tuning of the FCS01 and 02 to reach stable operation even in a cold environment
c. DNVGL decisions:
    - Increase of pressure limit in the 24 tanks (lot 3539), up to 200 bar
    - 25th tank (lot 3577) not to be connected before complete reviewing of the Type Approval.
    - Agreement to operate the system without any SHSA representative on board.

The command and control engineer who stayed 2 weeks in Chili and the design engineer who navigated on board went back to Switzerland after boat departure for her Pacific crossing.

6.6 Papeete (French Polynesia)

The main achieved tasks there were consisting in improving the H_2 production equipment, as:

a. Compressor maintenance (seal kit replacement)
b. Electrolysers fixing, maintenance and fine tuning
c. Dryer fixing and maintenance

6.7 Nouméa (New Caledonia)

As electrolysers and dryer performances were still not convincing, a technical representative from GreenHydrogen.DK joined SHSA for this intervention.

The main achieved tasks were:

a. Improvement of the DI water system
b. Reliability improvement, fixing and maintenance of H_2 production equipment by the supplier
c. Fixing of H_2 piping components, among defective pressure sensors on H_2 cylinder
d. Decommissioning of tank lot 3577 due to unsatisfactory cycling test on tank lot sample

6.8 Jakarta (Indonesia)

Green Hydrogen DK Service Engineer attends again to this intervention for ten days. A delivery of spare parts was also organized on board for system maintenance.

The main achieved tasks there were:

a. DI water system upgrade
b. Reliability improvement and maintenance of H_2 production equipment by the supplier
c. Intensive run tests of FCSs following PLC firmware update
d. Training of the board engineers for the compressor maintenance

6.9 Last system upgrade in Hong Kong (China)

The main achieved tasks there were:

a. Periodical H_2 tanks inspections by Hexagon Maintenance Service (every 36 months, following production date)
b. Reliability improvement of H_2 production equipment
c. Compressor maintenance
d. Update of FCS HV boxes
e. Yearly system maintenance

Main outputs of this final commissioning are:

- Successful visual inspection of the 24 tanks by Hexagon
- H_2 production runs operated from the HMI interface, only
- Stable and reliable FCSs run.
- Improvement of user interface
- Yearly complete system maintenance successfully conducted

7 Discussion of results

After 3 years following the kick off meeting of the project, and more than 28'000 nautical miles of navigation, the H_2 system has been certified by the international classification society DNVGL and illustrates the working principle for producing and storing green hydrogen on a circumnavigating vessel and being able to produce clean electricity on demand.

The first section in this chapter deals with the work and requirements involved in the certification process while the second one is dealing with log files analyses, which show systems efficiency and storage content behaviour along the time.

7.1 DNVGL certification

Two DNVGL visits have been organized on board (in Guadeloupe and Lima). Final system certification has been delivered beginning 2020. It states that the hydrogen system installation meets the DNVGL's requirements based on their Rules for Classification Part 6, C.2 Section 3 (Fuel Cell installation –FC, January 2016, [11]) regarding the safety of the installed system.

The documentation package consists mainly in the following:

- DNVGL standard documents (see Table 12) sorted by categories
- Drawings and piping and instrumentation diagrams (Table 13, numbered A to G)
- Complementary SHSA documents which consists in sub-system descriptions and procedures for the crew (Table 13, numbered 22 to 39)

Table 12 and Table 13 illustrate the complete documentation package that was prepared and submitted for review and approval to DNVGL, through an iterative process. The documents are sorted by discipline like Electrical, Safety, or Instrumentation. The grey marked documents in the tables are not required for this specific project.

#	Discipline	File name	Final Rev.
1	Electrical	E170_Electrical_schematic_drawing	07
2	Safety	G060_Structural_fire_protection_drawing	04
3		G080_Hazardous_area_classification_drawing	13
4		G170_Safety_philosophy	07
5		G200_Fixed_fire_extinguishing_system_documentation	07
6	General	GlobalConceptDescription	07
7	Hull and structure	H030_Tank_and_capacity_plan	13
8	Intrumentation	I010_Control_system_philosophy	03
9		I020_Control_system_functional_description	07
10		I140_Software_quality_plan	02
11	Material	BOM002_BoM_SHA-30BS_E2 & Material certificate	11
12	Piping	S012_Ducting_diagram	10
13	Multidiscipline	Z030_Arrangement_plan	07
14		Z071_Failure_mode_and_effect_analysis_(MRGDE717 2016.132, Rev. 1.0)	01
15		Z161_Operation_manual	06
16		Z163_Maintenance_manual	08
17		Z252_Test_procedure_at_manufacturer	03
17a		TEST011_FAT_FC_SYTEM1_BLUESEA	02
17b		TEST011_FAT_FC_SYTEM2_BLUESEA	03
18		Z252_TEST014_FAT_electrical_R05	05
18a		QC014_FAT_electrical_Report_FCS1	04
18b		QC014_FAT_electrical_Report_FCS2	04
19		Z253_BlueSea_SAT	06
20		Z253_TEST015_SAT_electrical	04

Table 12: Standard DNVGL document listed by discipline

According to the maintenance plan (document #16 in Table 12), an annual visit has to be achieved on board for maintenance and system checking.

	Topic	File name	
21	SAT Lima follow up	DOC026_BlueSea_evidences_SAT	07
22	System description	DOC022 DI_system	06
23		DOC023 Fuel Cell System	03
24		DOC024 H2 production system	04
25		DOC027_H2_Compression_Storage_Interface	02
26		DOC032_Safety measures related to Hydrogen System	01
27	Procédures	PR019_Closing_H2_tank	01
28		PR021_Maintenance_seal_HII_H2_gaz_booster (SH)	02
29		PR022_Remplacement_compression_unit	04
30		PR023_Test relief valve (PRVs)	03
31		PR024_Pressure_Test (36 months period)	02
32		PR025_Safety_Devices_maintenance and functional test	05
33		PR027_Annually_check_of_electical_equipment	03
35		PR030_Changement_pressure_sensor	03
36		PR031 Quality Control piping compressor & storage compartment	01
37		PR033 Quality Control piping FCS	01
38		PR034 Quality Control piping compressor internal	01
39		PR035 Quality Control piping electrolyser & Dryer	01
A	Drawing	A00749revA-H2_gas_cylinder_assembly.pdf	A
B		A00568revA-H2_Storage_Compartment_assembly.pdf	A
C		A00567revA-Caisson_global_assembly	A
D		A00567B-Caisson_global_assembly_H2_sensor_new_positionning.pdf	B
E	PID	PID005_BlueSea_piping_spec_WSCAD	17
F		PID011_BlueSea_electrolysers_and_dryer	01
G		PID006_BlueSea_FCS_WSCAD	03

Table 13: PID, drawing, procedures and system description document list

7.2 System performances

System performances concern both H_2 and electricity productions. Analyses mainly relies on log files, which are generated and stored on board with different time stamps for short and long term assessments. This log files system gives numerous physical information and states of most of H_2 system components.

7.2.1 H_2 storage

The storage is monitored by a pressure measurement on each tank and a temperature measurement on tank #5 and #21, respectively in front and back storage compartment (Figure 12).

In order to visualize a stored mass of H_2 in the storage and its corresponding SOC (State Of Charge), the hydrogen density is calculated based on these recorded values. This relies on tables of H_2 density function of pressure and temperature provided by NIST [15].

As tanks pressure is affected by ambient temperature, SOC of H_2 storage is added on pressure temporal plot in Figure 36. SOC of H_2 storage corresponds to 0% when storage contains a H_2 mass pressurized at 20 bar at 15°C (12.5 kg in total), which is the minimum storage pressure to be consumed and 100% when storage contains 179.7 kg of H_2 (in 24 tanks at 350 bar and 15°C).

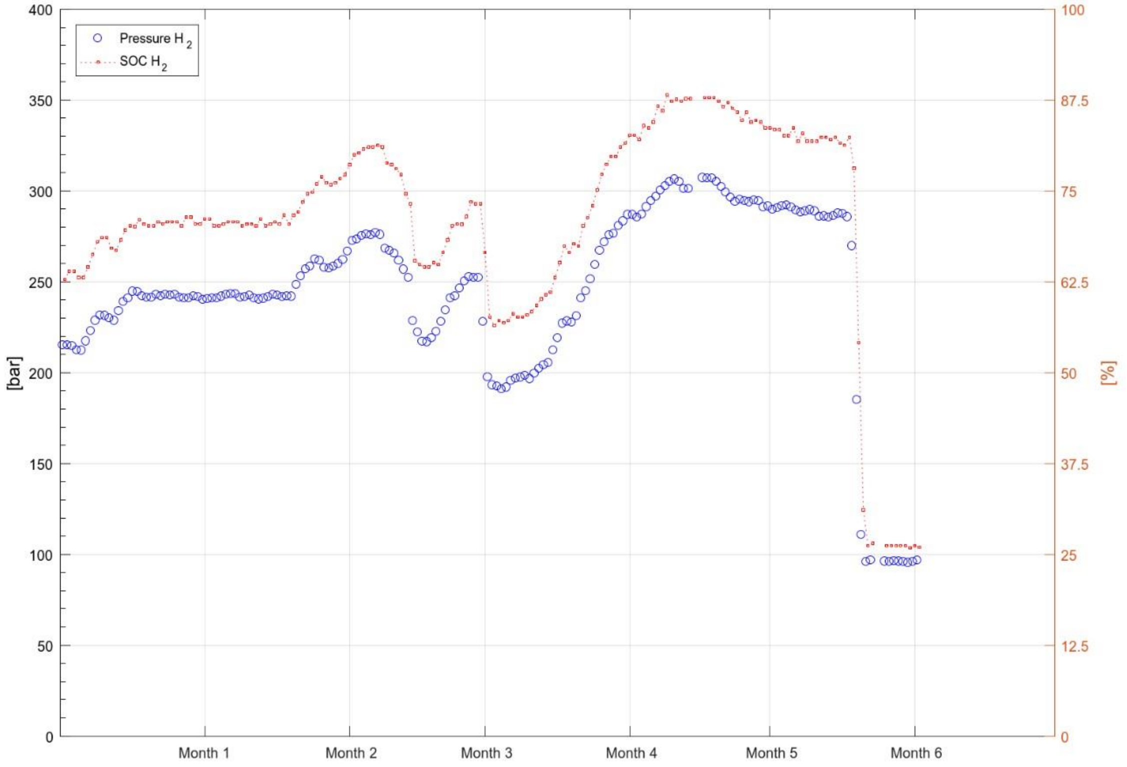

Figure 36: Daily averaged pressure and state of charge of H_2 storage

Figure 36 shows a zoom of averaged pressure and equivalent SOC of H_2 storage over 6 months. The current mass of stored H_2 is at the end of the temporal series of 44 kg.

SOC reflects H_2 production runs when SOC is increasing and electricity production runs when SOC is decreasing. Theses phases respectively correspond to periods of over solar production which was used to produce H_2 and to periods of needs of additional power for electrical navigation under cloudy sky, for instance. A 3 days energy production run on Figure 36 (see month 6th) consumed more than 90 kg of H_2 (see section 7.2.3, for details).

7.2.2 H_2 production

Based on the H_2 produced mass derived from temperature and pressure measurements and the consumed energy by H_2 production system (which is composed of the DI water system, 2 electrolysers, one dryer, one compressor and power electronics, safety devices and ventilators, see sections 5.3 and 5.4), a global efficiency of the complete process is evaluated.

The diagram below illustrates the approximate losses that are to be considered in this evaluation:

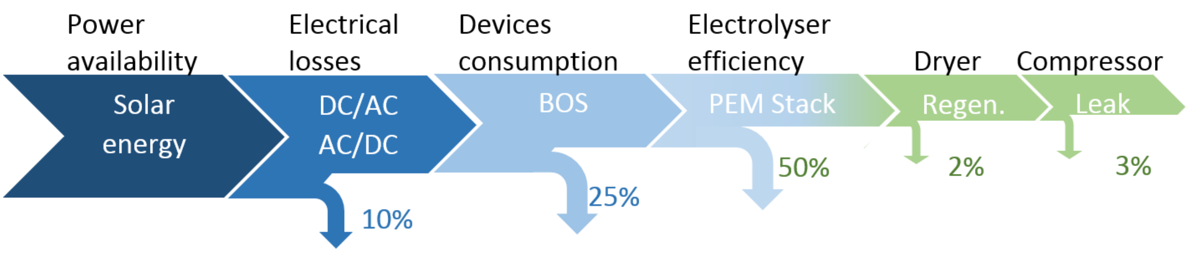

Figure 37: Electrical (blue) and process losses (green) in the H_2 production chain

Figure 37 shows that only 67.5 % of the Initial PV power goes to the electrolysers stack themselves. A double stage of power electronics DC to AC and then AC to DC absorbs 10% of the power while BOS made of DI water system pumps, compressor, dryer, ventilators, pumps and controllers consume 25% of the remaining power.

When producing H_2, the PEM stacks are also generating heat and only 50% of the electrical input power to the fuel cell stacks is transformed into H_2 and O_2. The dryer is consuming another 2% of the produced hydrogen, according to the supplier, for the regeneration of the drying columns, which is a process lasting 4 hours every 2 weeks approximately. Finally, some measurements done on board have shown that the oil free compressor presents a hydrogen leak of 3% after 500h of operation due to wear and tear of dry seal kit. In this context, depending on operating condition, global system efficiency can be around 32%.

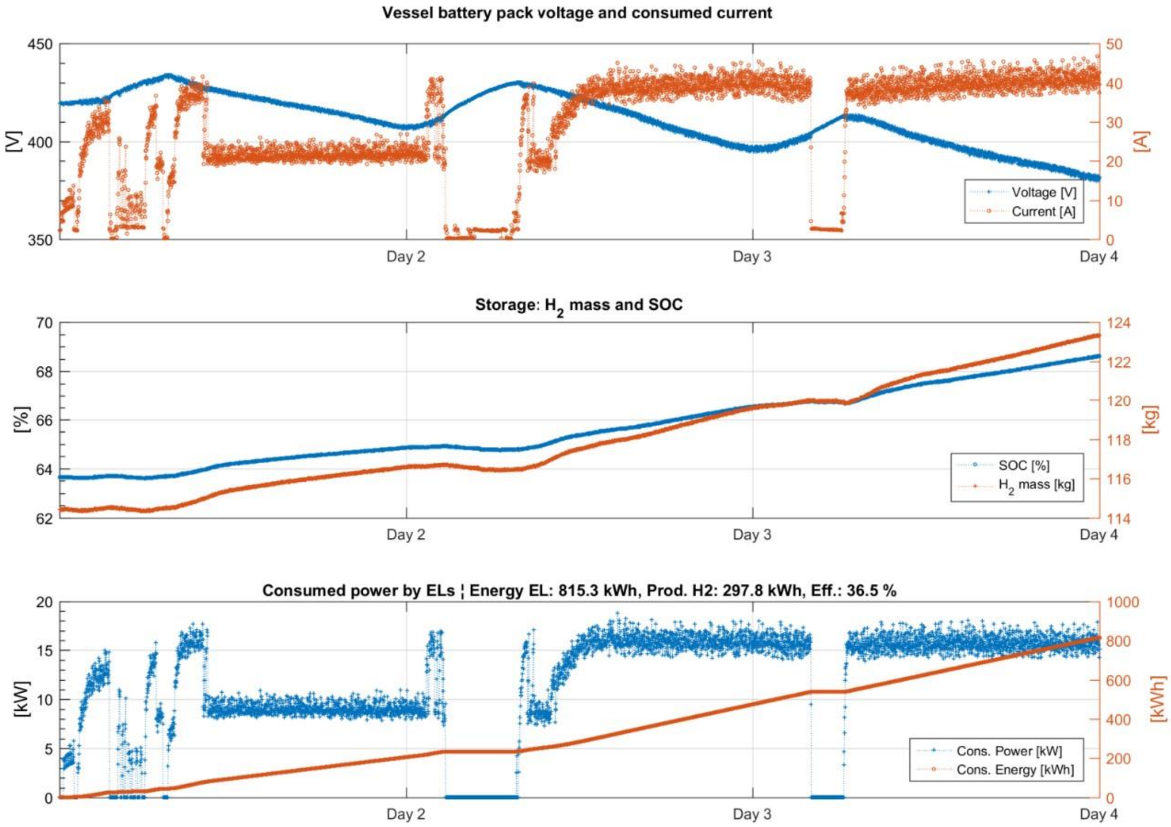

Figure 38: Efficiency calculation on a 3 days long H_2 production run

In Figure 38, a H_2 production run is illustrated over 3 days. Consuming an electrical energy of 815 kWh and producing and compressing at about 240 bar close to 9 kg of H_2, the global efficiency appears to be of 36.5% over the total period.

It could be noted that a regular compressor maintenance was just completed and it can be assumed that the H_2 leak of the seal kit was at this period less than estimated in average on Figure 37.

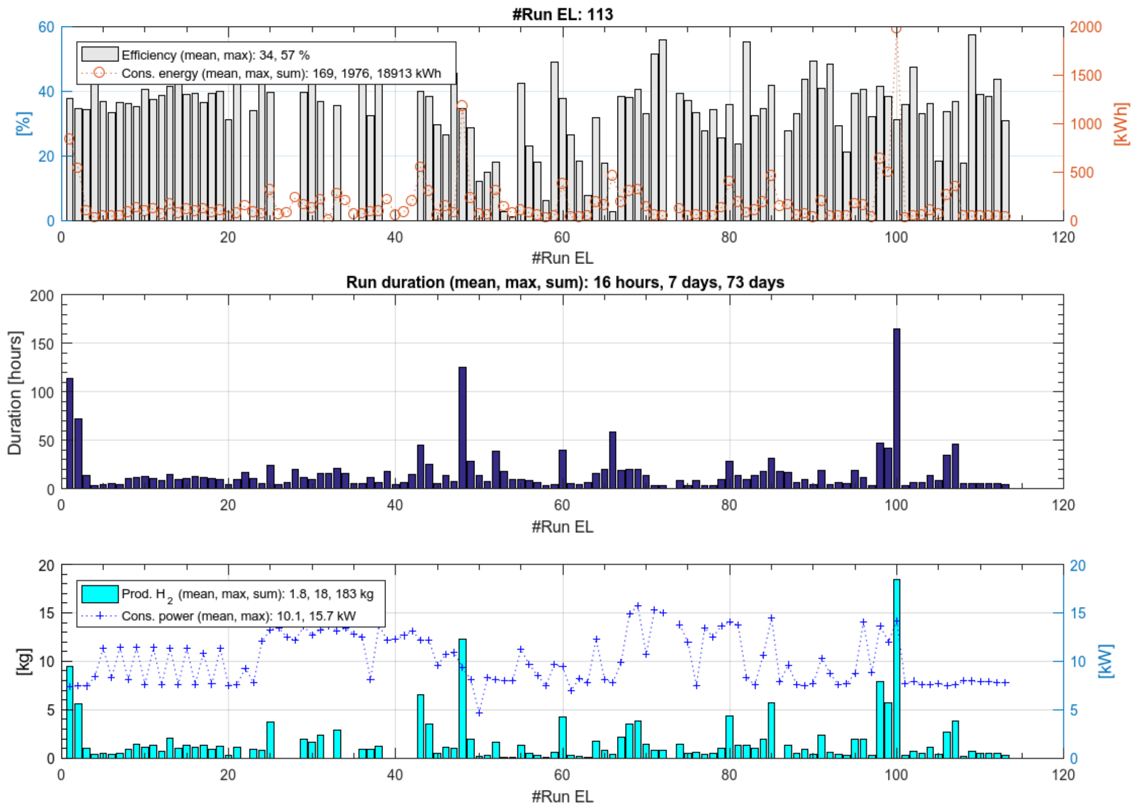

Figure 39: EL run analyse over 14 months

Figure 39 shows a systematical H_2 production run analysis over 14 months. This presents a total of 113 runs of 16 hours duration each (on average), which leads to 73 days of H_2 production over the period. The total produced mass of H_2 was 183 kg with an average process efficiency of 34% and a maximal efficiency of 57%.

7.2.3 Electricity production

Before considering the complete system chain efficiency, some efficiency calculations are done on the PEM stack themselves.

1. *FCS stacks*

Stacks performance could be derived from different sources

1. Polarisation curves from the stack supplier. However, these curves are established at 2 bar gas mixture pressure for a content of 70% H_2 and 30% N_2 on the anode side, which is not representative of real conditions cases, with up to 10% N_2 only and a pressure inlet of 1.6 bar.
2. Factory Acceptance Tests achieved in SHSA laboratory before FCS delivery. However these tests were dedicated to insure no stack leak and stack proper functioning and no H_2 flow rate was recorded.
3. Through the HMI interface where global FCS H_2 flowrate is given in real time and power, voltage and current of each stacks, as well.

This stack efficiency (including purge) could be obtained from the hydrogen flow meter at the stacks entry and power measurements on the stack themselves. On Figure 40, the screen shot shows both FCS generating 21 kW each. Global efficiency of the FCS based on produced power and hydrogen consumption is at 45%.

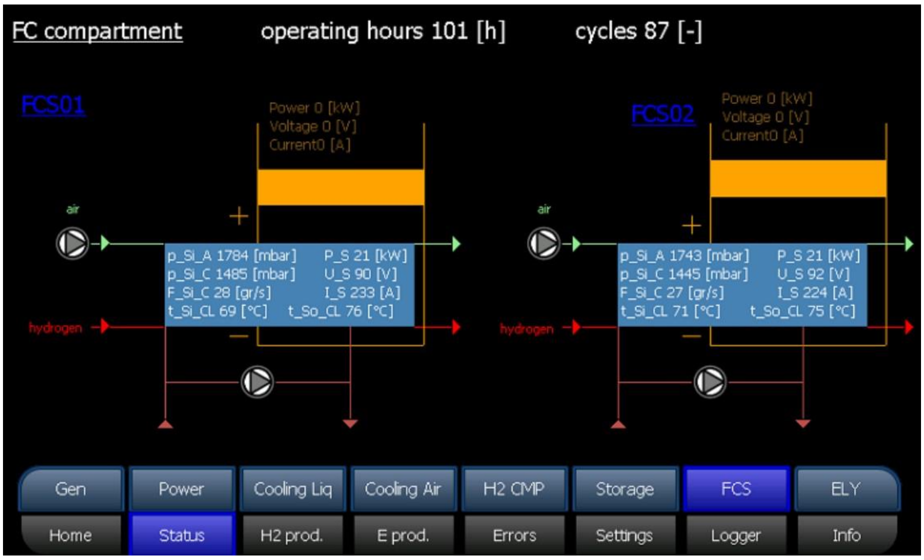

Figure 40: HMI interface when FCS in operation and main parameters

According to measurements achieved in December 2019, FC02 efficiency varies from 43% at 27kW, to 50% at 20 kW. Average efficiency is of 46% in the power range from 15 to 27kW.

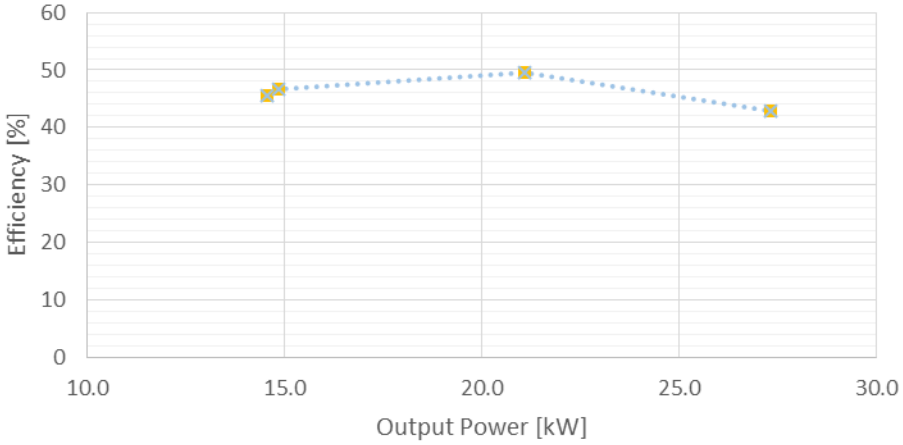

Figure 41: FCS02 efficiency function of output power

2. Complete electrical production chain

The diagram below illustrates the approximate losses that are to be considered for electrical production efficiency evaluation.

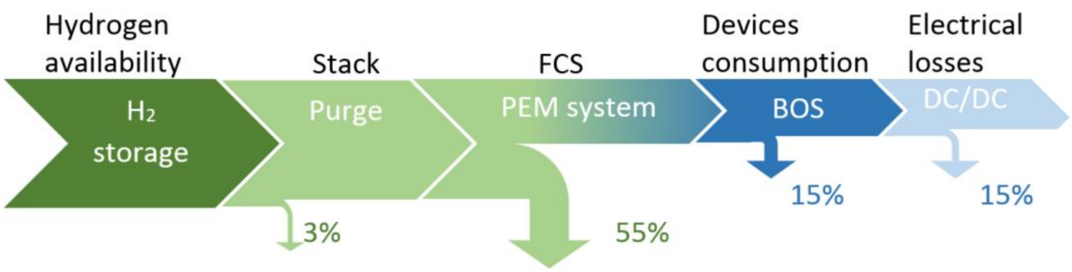

Figure 42: Process (green) and electrical (blue) losses in the electrical production chain

Figure 42 considers 3% of losses by FCS H_2 purges and an averaged stack efficiency of 45% (Figure 41). The air compressor is directly supplied by the FCS and consumes between 1.5 and 3 kW. Electrical consumptions of the cooling systems of FCS and OTV of the tanks represent 15% of additional losses. The DC/DC converters with transformer for galvanic insulation works with an efficiency greater than 85% according to the supplier. In this context, depending of operating conditions, theoretical efficiency of the global electrical production chain can be around 32%.

Based on the H_2 consumed mass and the injected energy by the FCS, efficiency of the complete process is evaluated.

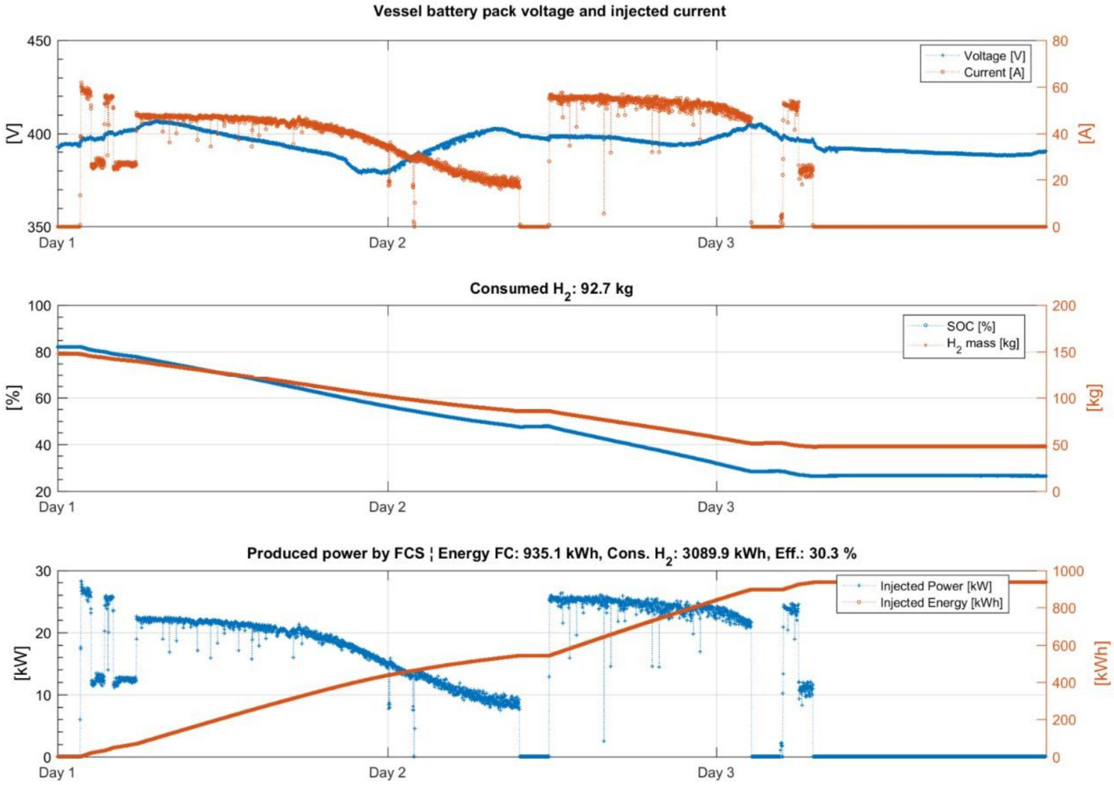

Figure 43: Efficiency calculation on a 3 days long electrical production run

Figure 43 illustrates a 3 days long electrical production run. By producing an electrical energy of 935 kWh while consuming 93 kg of H2, global efficiency appears to be of 30% on the period, which is a bit lower than estimated global efficiency in Figure 42.

Figure 44 shows a systematically electrical production run analysis over one year. This represents a total of 63 runs of 92 minutes in average, cumulating 97 hours of electrical production over the period.

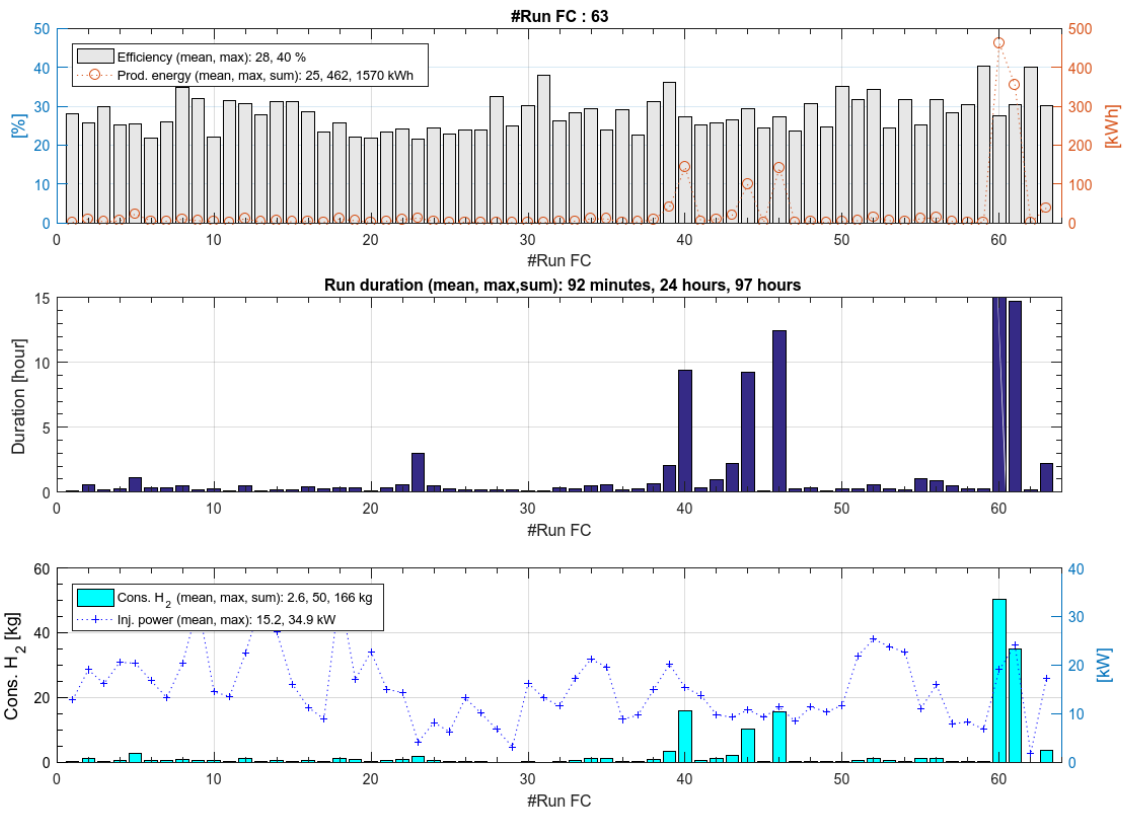

Figure 44: FCS runs analyses over one year

The total produced energy was 1’570 kWh with an average process efficiency of 28%, which is lower than losses estimation illustrated in Figure 42. Lower efficiency runs could be explained by more frequent purge in case of high humidity content in the ambient air and warm ambient temperature leading to lower efficiency of the converters, for instance.

8 Conclusions and outlook

This project was the opportunity to develop, install and certify an innovative and compact system for production, storage and conversion of energy, based on hydrogen and applied in maritime sector, as range extender for a stand-alone application.

Combined with battery packs that offer high efficiency for short term storage, hydrogen illustrates typical advantages of long term green energy storages with a high mass energy density (Table 14):

	Electrical storage capacity [kWh]	System weight [kg]	Mass energy density [Wh/kg]
Battery system	754	7'440	101
Hydrogen system	2'200	6'440	342

Table 14: Battery and hydrogen system mass density comparison (H_2 System weight includes both H_2 production system and FCS) for the solar catamaran (for 40% H_2 system efficiency, and 165kg of usable H_2 mass)

This system represents a clean range extender of 3 times the electrical battery capacity, to be used on demand, to increase vessel speed, or to face low irradiation weather during a certain period, which could lead to an earlier Estimated Time for Arrival.

DNVGL international certification is an achievement, which required an extended cooperation with various suppliers and a substantial compilation work of test references, system documentation and detailed procedures. It appeared very effective to collaborate with the class society upfront the design phase of the project.

The completion of the project was longer than expected due mainly to scarce stopovers for system adjustments and to working conditions not so appropriate during navigation. In addition, some sub suppliers delivered products showing lack of maturity, which required several upgrade steps. In this context, the complete system has not been optimized and its global efficiency is below than expectations. Detailed efficiency analyses show major losses which could have been overcome by optimizing different features, notably sub-systems interfaces, and various control and command strategies. Typically, double stage of power conversion devices should have been avoided, by directly supplying them from the main DC grid. All OTVs are open when using FCS, it would have been optimal to consume hydrogen from one tank only, at the same time and to balance the pressure between all the tanks at the end of FCS run. It was also not possible to drastically reduce length of power cablings due to the large distance between FCS, power electronics and main battery packs. Complex hydrogne piping geometry and equipment resulted in higher pressure drop than expected, as well.

By gathering sub-systems from Swiss, European, and US companies and complying with diverse requirements, Swiss Hydrogen achieved a major work in system design and integration. A unique return of experience has been gained all along the project phases that could be applied not only in marine sector, but more largely in green mobility and off-grid applications as well. Operating such a FCS system that produced more than 1.7 MWh over 14 months during a world tour navigation, offered real case conditions for quality check in a rash and diversified meteorological environment, which lead to numerous equipment improvements and fine tuning.

As a perspective, the European Hydrogen and Fuel Cell Association compiled recently optimal zero emission solution for marine sector where hydrogen appears best appropriate for small ferries, fishing, cruise and tug boats when bunkering is nearby (Figure 45).

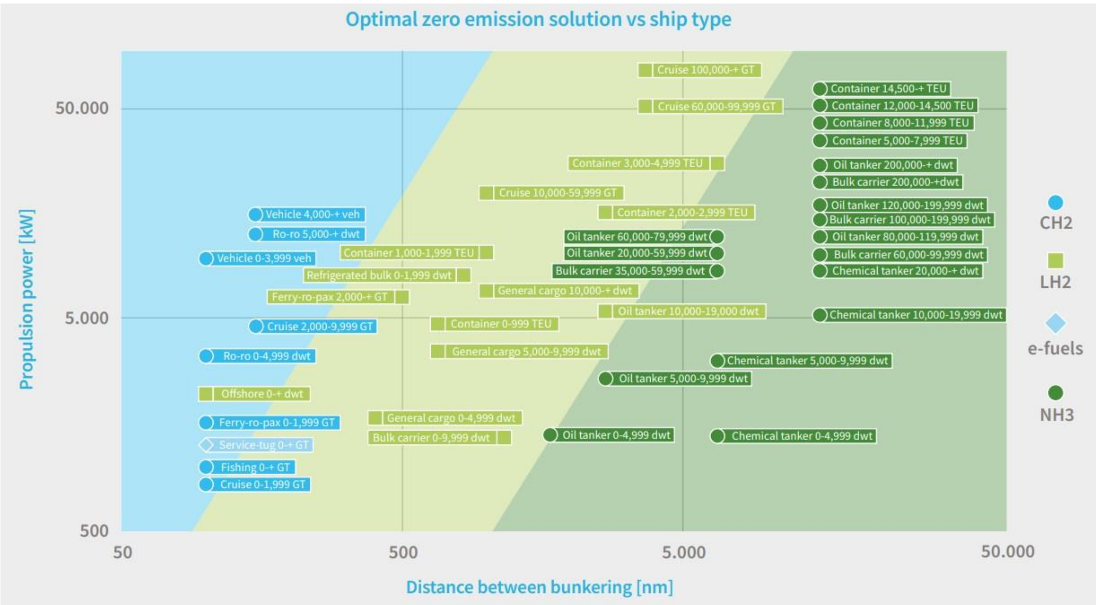

Figure 45 : Optimal zero vessel emissions versus ship type and distance between bunkering (Source: Hydrogen Europe, annual report 2019, [16])

9 References

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