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D6.6 Upscale and replication feasibility study in FHA

WP6 – Techno-economic and environmental assessment

WP LEADER	RINA Consulting
DELIVERABLE RESPONSIBLE	FHA
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1 INTRODUCTION

This report assesses the feasibility of integrating the SPOTLIGHT prototype in FHA's facilities, as integral part of the WP6 - **Techno-economic and environmental assessment.**

The work presented in this deliverable has been carried out in the framework of **Task 6.4.2 – Upscale and replication feasibility study in FHA**, led by FHA, with the contribution of RINA and ACEA partners.

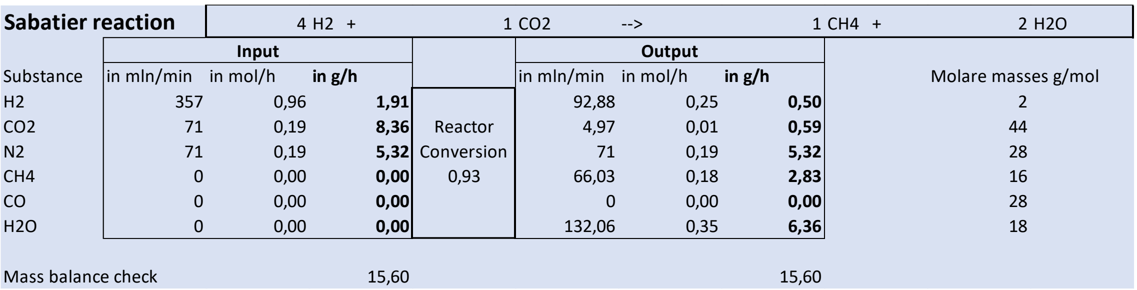
The FHA's upscale study is based on SPOTLIGHT's final specifications of the system developed during WP2 and mass balance data gathered during validation of the system in WP5. It is also based on FHa's current facilities, their constraints and opportunities.

In this respect FHA assesses the utilities required, identifying the best location, evaluating the modifications required in mechanical, electrical and civil specialties, and also considering the process to obtain the required permits for integrating such plant. Also, various sources of biogenic CO2 have been examined and included in the feasibility study.

2 CURRENT SCALE OF SPOTLIGHT PROCESS

As a starting point for the analysis, preliminary data have been collected from the SPOTLIGHT process in the pilot plant validation in WP5. Characterising the mass balances of this process will allow us to assess the current scale of the process and subsequently analyse the options for scaling up the FHA facilities, depending on different factors and constraints.

For the Sabatier reaction, we consider 1.91 g/h of H2, 8.36 g/h of CO2 and 5,32 g/h of N2:

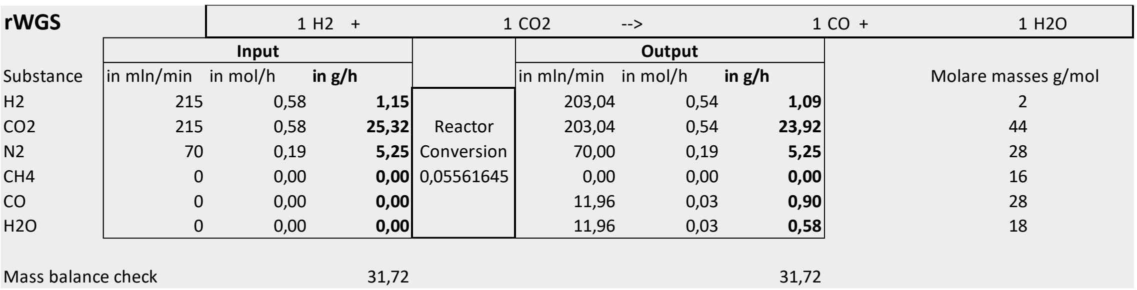


Sabatier reaction 4 H2 + 1 CO2 --> 1 CH4 + 2 H2O

	Input				Output			
Substance	in mln/min	in mol/h	in g/h		in mln/min	in mol/h	in g/h	Molare masses g/mol
H2	357	0,96	**1,91**		92,88	0,25	**0,50**	2
CO2	71	0,19	**8,36**	Reactor	4,97	0,01	**0,59**	44
N2	71	0,19	**5,32**	Conversion	71	0,19	**5,32**	28
CH4	0	0,00	**0,00**	0,93	66,03	0,18	**2,83**	16
CO	0	0,00	**0,00**		0	0,00	**0,00**	28
H2O	0	0,00	**0,00**		132,06	0,35	**6,36**	18
Mass balance check			15,60				15,60	

Figure 1. Preliminary mass balance for Sabatier reaction

For rWGS reaction, we consider 1.15 g/h of H2, 25.32 g/h of CO2 and 5,25 g/h of N2:



rWGS 1 H2 + 1 CO2 --> 1 CO + 1 H2O

	Input				Output			
Substance	in mln/min	in mol/h	in g/h		in mln/min	in mol/h	in g/h	Molare masses g/mol
H2	215	0,58	**1,15**		203,04	0,54	**1,09**	2
CO2	215	0,58	**25,32**	Reactor	203,04	0,54	**23,92**	44
N2	70	0,19	**5,25**	Conversion	70,00	0,19	**5,25**	28
CH4	0	0,00	**0,00**	0,05561645	0,00	0,00	**0,00**	16
CO	0	0,00	**0,00**		11,96	0,03	**0,90**	28
H2O	0	0,00	**0,00**		11,96	0,03	**0,58**	18
Mass balance check			31,72				31,72	

Figure 2. Preliminary mass balance for rWGS reaction

In terms of green hydrogen production, which FHa is producing locally, if we run processes at the pilot plant for 24 hours with the current configuration, under Sabatier reaction we will need 46 g/day of H2 and 28 g/day of H2 in the case of rWGS reaction.

H2	g/h	g/day	g/week	g/month
SABATIER	1,91	45,84	320,88	1375,2
rWGS	1,15	27,6	193,2	828

Table 1. H2 needs of the SPOTLIGHT pilot plant

In addition to hydrogen production, the current footprint of the reactor assembly, the solar and LED flux guide, and the gas storages serving the pilot plant process are relevant. This assembly is estimated to be less than 3 x 3 metres in size.

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3 SCALING UP SPOTLIGHT PROCESS: FHA FACILITIES CONSTRAINTS AND ASSUMPTIONS

To evaluate the scaling-up options of the process developed during the SPOTLIGHT project, it is first necessary to analyse the possibilities and constraints of the current FHa installations.

The following possible restrictions are identified:

- The H2 production capacity limit at FHa. FHa's hydrogen needs are diverse: refuelling its own vehicles, generators and small fuel cells, European research projects such as SPOTLIGHT and its own development and innovation initiatives.
- Available space close to the main FHa building, with existing utilities, to install the process developed in the project and the primary optics.
- Electricity consumption and need for air conditioning and protection of equipment from inclement weather.

It is assumed that scaling up the Spotlight process does not involve multiplying the size of the plant by that scale. Although the size of the reactor would increase or several reactors would be installed simultaneously, the gas supply and the solar energy collection and concentration facilities would be sized appropriately, but it is estimated that the ratio of this sizing would not be directly proportional and that the facilities serving the process could be optimised.

These restrictions will be analysed in detail in the following sections, to evaluate which would be the most restrictive and which would finally condition the possibilities of scaling up the process.

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4 DEVELOPMENT OF UPSCALE AND REPLICATION FEASIBILITY STUDY IN FHA

4.1 POTENTIAL LOCATION AND AVAILABILITY OF SPACE

Aragon Hydrogen Foundation (FHa) facilities are composed of a 1200 square metres building, which includes offices and laboratories. The main area of the building is 8.5 metres in height area, fully prepared with safety equipment and devices, which permits working with different hydrogen production systems and other hydrogen applications.

Moreover, two Hydrogen Refilling Station (HRS) are located outside the building. The first HRS (HRS350), launched at 2010 in the scope of the ITHER project, is allowed to refill Fuel Cell Electrical Vehicles (FCEV) at a maximum pressure of 350 bars. On the other hand, the second HRS (HRS700), which is under commissioning now of preparing this report, will refill FCEV up to 700 bars.

Next to the building, there is a plot in which the upscaling of the Spotlight pilot plant is going to be discussed. In this field (see Figure 3) there is a 62kWp photovoltaic field and different pilot plants. In this plot there is availability of different auxiliaries (water, electricity, compressed air…) and it is connected to both the HRS and the main building by a tubing system for different gases (H2, N2 and H2 vent).

Figure 3: Plot next to FHa facilities

In this Figure, two different options to install the upscaling plant at FHa within this plot are remarked. Both of them are concrete surface areas of 9x9 metres.

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4.2 ENERGY SYSTEM: PV PRODUCTION

For the Spotlight pilot plant energy requirements, a solar concentrator structure (SOF) is required as a primary optics, aiming at concentration solar irradiation to efficiently use the terrestrial sunlight for the Spotlight photonic device. A solar concentrator structure is a design which main objective is increasing the flux density of the solar radiation and so raising the irradiance to a specific point.

Moreover, as it has been explained in Deliverable 2.3, a secondary optics is needed to convert the non-uniform obtained from this SOF structure into the desired uniform distribution direct to the Spotlight reactor. Figure 4 shows in a schematic way the process of collecting and directing the solar irradiation to the reactor, and the main Boundary Conditions defined in this previous report.

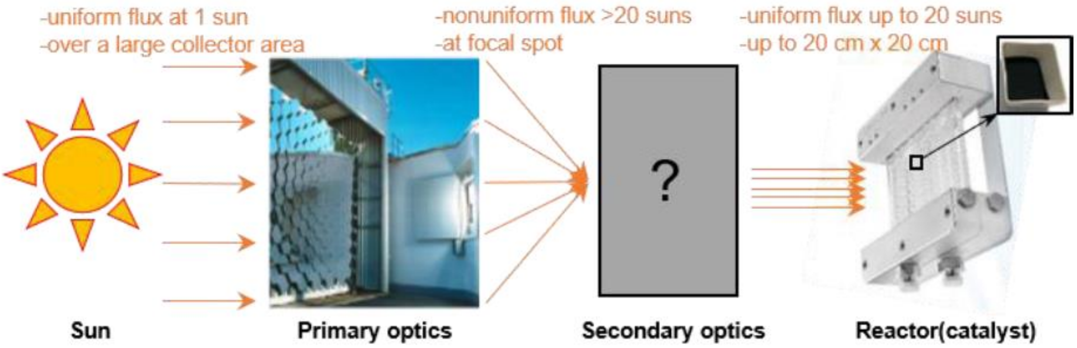

Figure 4: Schematic of beam shaping optics required from the sun to the reactor.

This combination of both the primary and secondary optics previously commented was the final solution installed at DLR facilities in Cologne, where the Spotlight pilot plant was located. However, in the Deliverable 2.3 a review of the State of Art of different solar concentrating systems was performed, aiming at finding the most feasible solution for the plant requirements. For the Spotlight process, the suggested development route to the commercial scale is based on adapting the well-stablished linear Fresnel reflector (LFR) technology with an appropriate strategy for scaling purpose (Figure 5).

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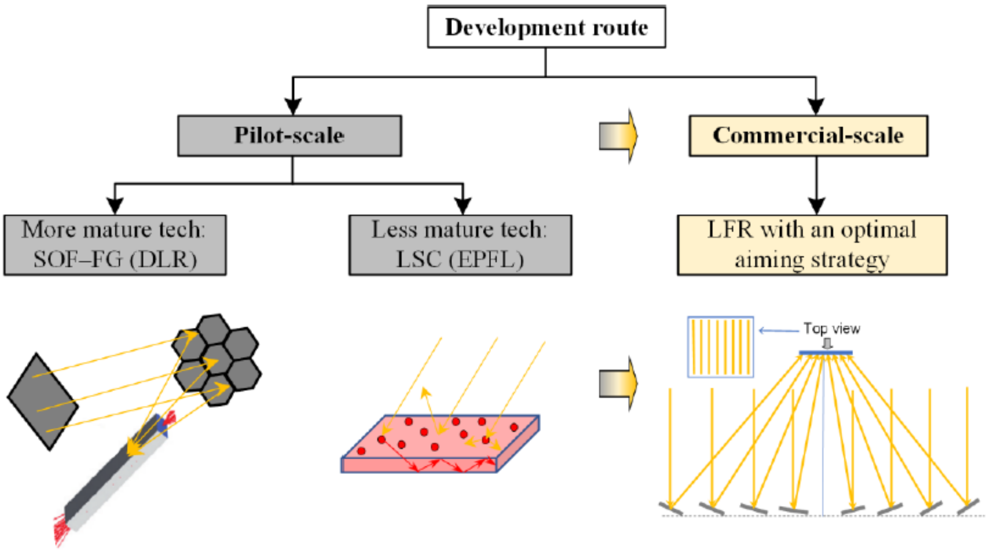

Figure 5: Schematic of the development route for the Spotlight project

Table 5 of the Deliverable 2.3 (Figure 7) provides the main specifications of the LFR system aiming at coupling between this system and the reactor at commercial scale.

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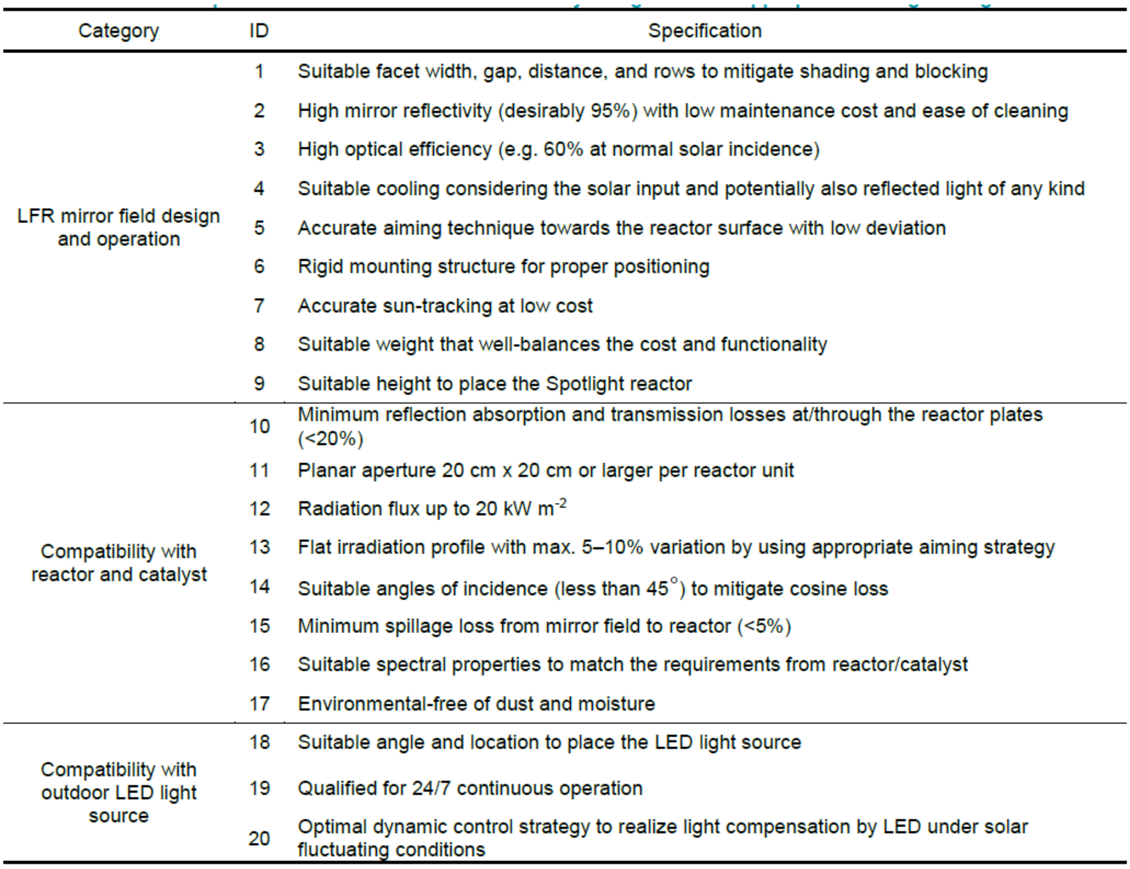
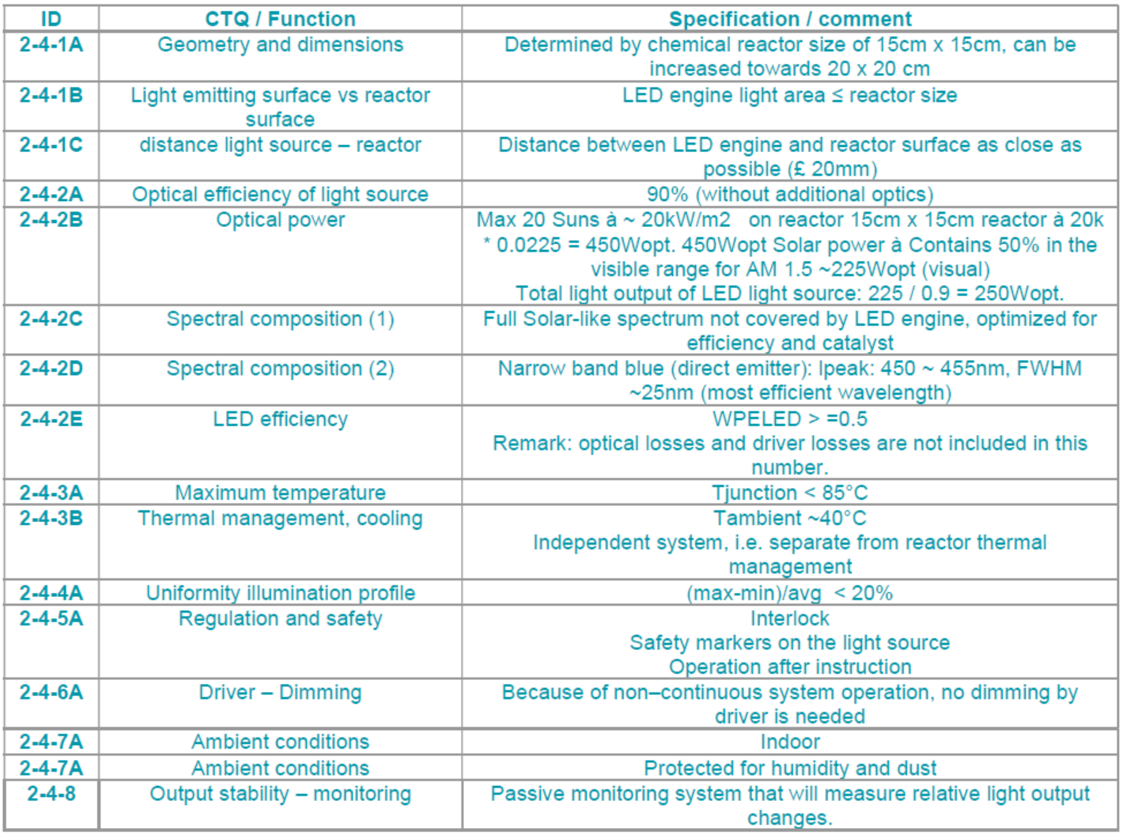


Category	ID	Specification
LFR mirror field design and operation	1	Suitable facet width, gap, distance, and rows to mitigate shading and blocking
	2	High mirror reflectivity (desirably 95%) with low maintenance cost and ease of cleaning
	3	High optical efficiency (e.g. 60% at normal solar incidence)
	4	Suitable cooling considering the solar input and potentially also reflected light of any kind
	5	Accurate aiming technique towards the reactor surface with low deviation
	6	Rigid mounting structure for proper positioning
	7	Accurate sun-tracking at low cost
	8	Suitable weight that well-balances the cost and functionality
	9	Suitable height to place the Spotlight reactor
Compatibility with reactor and catalyst	10	Minimum reflection absorption and transmission losses at/through the reactor plates (<20%)
	11	Planar aperture 20 cm x 20 cm or larger per reactor unit
	12	Radiation flux up to 20 kW m^{-2}
	13	Flat irradiation profile with max. 5–10% variation by using appropriate aiming strategy
	14	Suitable angles of incidence (less than 45°) to mitigate cosine loss
	15	Minimum spillage loss from mirror field to reactor (<5%)
	16	Suitable spectral properties to match the requirements from reactor/catalyst
	17	Environmental-free of dust and moisture
Compatibility with outdoor LED light source	18	Suitable angle and location to place the LED light source
	19	Qualified for 24/7 continuous operation
	20	Optimal dynamic control strategy to realize light compensation by LED under solar fluctuating conditions

Figure 6: User requirements for the commercial route by using LFR

Aiming at ensuring a continuous operation during dark or light-poor conditions, an energy-efficient light emitting diode (LED) system was installed at the demonstration pilot plant. In the report D2.4 “User Requirements of Light Source”, main characteristics of this light source for the Spotlight prototype are fully described. In Figure 7 those requirements are gathered.



ID	CTQ / Function	Specification / comment
2-4-1A	Geometry and dimensions	Determined by chemical reactor size of 15cm x 15cm, can be increased towards 20 x 20 cm
2-4-1B	Light emitting surface vs reactor surface	LED engine light area ≤ reactor size
2-4-1C	distance light source – reactor	Distance between LED engine and reactor surface as close as possible (£ 20mm)
2-4-2A	Optical efficiency of light source	90% (without additional optics)
2-4-2B	Optical power	Max 20 Suns à ~ 20kW/m2 on reactor 15cm x 15cm reactor à 20k * 0.0225 = 450Wopt. 450Wopt Solar power à Contains 50% in the visible range for AM 1.5 ~225Wopt (visual) Total light output of LED light source: 225 / 0.9 = 250Wopt.
2-4-2C	Spectral composition (1)	Full Solar-like spectrum not covered by LED engine, optimized for efficiency and catalyst
2-4-2D	Spectral composition (2)	Narrow band blue (direct emitter): Ipeak: 450 ~ 455nm, FWHM ~25nm (most efficient wavelength)
2-4-2E	LED efficiency	WPELED > =0.5 Remark: optical losses and driver losses are not included in this number.
2-4-3A	Maximum temperature	Tjunction < 85°C
2-4-3B	Thermal management, cooling	Tambient ~40°C Independent system, i.e. separate from reactor thermal management
2-4-4A	Uniformity illumination profile	(max-min)/avg < 20%
2-4-5A	Regulation and safety	Interlock Safety markers on the light source Operation after instruction
2-4-6A	Driver – Dimming	Because of non–continuous system operation, no dimming by driver is needed
2-4-7A	Ambient conditions	Indoor
2-4-7A	Ambient conditions	Protected for humidity and dust
2-4-8	Output stability – monitoring	Passive monitoring system that will measure relative light output changes.

Figure 7: LED light source requirements

4.3 H_2 PRODUCTION

As it has previously been commented, FHa facilites are prepared for both producing and storing H_2. In terms of H_2 production, FHa has different water electrolysis technologies.

Water electrolysis is a electrochemical process whereby water molecule is split into oxyen and hydrogen, thanks to the application of electrical energy. Moreover, if this energy used for the process comes from a renewable source, such for example a PV field or a wind farm, the H_2 produced will be “green hydrogen”, which means that is 100% renewable H_2.

There are four different electrolysis technologies, depending mainly on the type of electrolyte material used for the split of the water molecule: 1) Alkaline Water Electrolysis (AWE); 2) Proton Exchange Membrane (PEM); 3) Anion Exchange Membrane (AEM); and 4) Solid Oxide Electrolysis (SOE).

At FHa facilities, there are three electrolysers of the first three technologies (PEM, AWE and AEM), which are breifly detailed here below.

4.3.1 Alkaline Water Electrolyser (AWE)

For AWE technology, electroldes are inmersed in an alkaline solution, usually potassium hydroxide (KOH) or sodium hydroxide (NaOH), which supports the transport of ions, and thus, the electrolysis process. This technology is commonly used in large-scale hydrogen production plants, because it is the more mature and cheaper electrolysis system. On the other hand, the purity of the H_2 at the output of the system is not as high as other water electrolysis technologies, and also the corrosion is a huge challenge of this electrolysers.

At FHa facilities there is an AWE electrolyser, supplied by the French company McPhy Energy. Namely, it is a 50kW electrolyser, with a maximum H_2 flow rate production capacity of 8Nm^3/h at 8 barg, which means a maximum **H_2 daily production of 17 kilograms**. **Error! Reference source not found.** shows an image of this AWE electrolysers at FHa facilities.

Figure 8: AWE electrolyser installed at FHa facilities

4.3.2 Proton Exchange Membrane (PEM)

In contrast to AWE technology, PEM electrolysers work in an acid environment. Those electrolysers do not contain liquid electrolytes, but a solid and acid proton conducting membrane. Thanks to that, corrosion compared to AWE technology is significantly decreased, and also the H_2 purity is improved and it can achieve higher efficiencies. However, main constraint for the development of PEM technology is the high manufacturing cost, mainly regarding the membrane.

The existing PEM electrolyser at FHa is a 5kW electrolyser, manufactured by the Spanish firm H2Greem, which is capable to produce 1Nm^3/h of H_2 at a maximum output pressure of 6 barg. Thus, with this equipment, it can be reached a **H_2 daily production of 2 kilograms**. This PEM electrolyser is shown in 9.

Figure 9: PEM electrolyser at FHa facilities

4.3.3 Anion Exchange Membrane (AEM)

Anion Exchange Membrane (AEM) electrolysis is the newest electrolysis technology. It combines the less harsh conditions of alkaline technology with the simplicity and high efficiency PEM electrolysers. In these systems, anode and cathode are separated by an anion exchange membrane. Still under development, the maturity of this technology is low, but it shows a high potential.

At FHa facilities, there are four 2,5kW AEM electrolysers, supplied by Italian company Enapter. Each of these modules produces 0,5Nm^3/h of H_2 at a maximum output pressure of 35 barg. Thus, the four modules combined can produce up to **4 kilograms of H_2 per day**. **Error! Reference source not found.** shows the four Enapter modules instaled FHa building.

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Figure 10: AEM electrolysers installed at FHa facilities

Summarizing, with the three different water electrolysis systems previously described in this chapter, a **daily production of 23 kilograms of H_2** can be achieved at FHa facilities. But it is also important to highlight that this daily production should cover not only the H_2 demand for the upscaling of the Spotlight pilot plant, but also for the rest of the H_2 consumptions regarding different projects FHa is or will be involved, and for refilling Fuel Cell Electric Vehicles with both HRS. Most of the H_2 produced at FHa facilities is used at the HRS, and it can be estimated a weekly need of 12 kilograms of H_2. By taking into account that part of the H_2 must be used in other applications, an estimation of about 10 kilograms per week could be available for the pilot plant.

4.4 H_2 STORAGE SYSTEM

The H_2 produced with the electrolysers is stored at both HRS installations

The HRS350 is composed by a low-pressure storage tank, with a total volume of 4Nm^3. The maximum of this tank is 35 bars, which allows to store up to 12 kilograms of H_2. Then, a double-stage membrane compressor increases the pressure of the H_2 up to 350 bars, and this H_2 is stored in a high-pressure storage rack. This rack is composed by 9 bottles, with a capacity of 50 litres each one, which leads to a total storage capacity of 23 kilograms. Thus, in this first HRS the total amount of H_2 stored is 35 kilograms.

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The second HRS (HRS700) will be prepared for refilling FCEV at 700 bars. The low-pressure storage tank is the same one as the one explained for the HRS350, because both installations share the low-pressure system. Then a diaphragm compressor increases the H2 pressure, and it is stored in two different high-pressure system: 1) the first one is a 1.166 litres-rack, with a maximum H2 capacity of 37 kilograms at 500 bars; and 2) the second rack stores H2 up to 900 bars in a total volume of 550 litres, which entails a total capacity of 26 kilograms of H2.

Thus, in both HRS installations, the total capacity of storing H2 at FHa facilities is up to **98 kilograms**.

4.5 OUTPUT MANAGEMENT

For the final use of the gases produced within the system (CH_4 with Sabatier reaction, CO with reverse water gas shift process), a dedicated review of the State of Art of potential end users should be accomplished, mainly to better understand requirements of those future benefitiaries and also to obtain an estimation of the amount of those gases they would be interested in, because at the moment of preparing this report there is any perspective to be used at FHa facilities in any current or coming project.

Depending on these requirements, a dedicated gas storage system for both CH_4 and CO would be sized, and also the logistic of the shipment to those end users.

4.6 POTENTIAL MODIFICATIONS

As it has previously commented, the selected location for the upscaling of the pilot plant will be the plot located next to the FHa main building. There are two spaces available at this plot, two sils 9x9 meters size. One of those screeds would be chosen for installing all the components of the pilot plant (reactor, the Balance of Plant, the LFR and the LED systems and the control system).

In terms of electrical power, there is a 50kW socket available at this plot and it is equipped with all the security systems and electrical protections for this maximum power, so any modification is identified at this point.

The only modifications foreseen would be to install a roof aiming at protecting the pilot plant and the dedicated area for installing the control system of the plant.

5 BIOGENIC CO_2 SOURCES: ANALYSIS AND OPTIONS

Biogenic CO_2, the carbon dioxide resulting from the decomposition, digestion, or combustion of biomass or biomass-derived products, plays a crucial role in the sustainable carbon cycle. Unlike fossil CO_2, which adds to the atmospheric carbon burden, biogenic CO_2 is part of the natural short carbon cycle, being absorbed by biomass through photosynthesis and then released back into the atmosphere or soil. This cyclical nature ensures that there is no net increase in atmospheric CO_2, making it a climate-friendly alternative.

Primary resources for biogenic CO_2 come from various biomass-related processes, including solid, liquid, and gaseous biomass fuel combustion, bioethanol fermentation, wine and beer production, and the biogas upgrading process. During these processes, biogenic CO_2 is generated and can be captured for use in various applications, contributing to the reduction of greenhouse gas emissions.

5.1 Storage Solutions for Biogenic CO_2

Biogenic CO2 can be captured and stored using various advanced methods, contributing significantly to reducing atmospheric CO_2 levels:

- Bio-CCS (Biogenic Carbon Capture and Storage): Bio-CCS involves capturing biogenic CO_2 and storing it permanently in geological formations such as depleted gas fields or deep saline aquifers. This method ensures that the captured CO_2 is removed from the atmospheric cycle, effectively achieving negative emissions and providing a substantial environmental benefit[1][2].

- Bio-CCUS (Biogenic Carbon Capture, Utilisation, and Storage): Bio-CCUS combines the capture and long-term storage of biogenic CO_2 with its use in manufacturing new materials. This includes the production of construction materials or plastics, which store CO_2 over long periods. By integrating CO_2 into new products, Bio-CCUS not only sequesters CO_2 but also creates valuable materials, supporting a circular carbon economy.[3]

5.2 Providers of Biogenic CO_2

Several facilities across Europe are leading the way in producing and utilizing biogenic CO_2, showcasing the potential and versatility of this resource:

- Metha Treil (France): Located in Loire-Atlantique, this facility uses livestock effluents, cover crops, corn silages, and vegetable by-products as feedstock. It produces 1,500 tons of biogenic CO_2 annually, which is used in local greenhouses to enhance plant growth [2].

- Revis Bioenergy (Germany): Situated in Cloppenburg, this plant processes manure to produce 103 tons of biogenic CO_2 per year. This facility is notable for its circular

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[1] https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane
[2] https://www.europeanbiogas.eu/wp-content/uploads/2022/10/Biogenic-CO2-from-the-biogas-industry_Sept2022-1.pdf#:~:text=URL%3A%20https%3A%2F%2Fwww.europeanbiogas.eu%2Fwp
[3] https://gasforclimate2050.eu/biomethane/

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industrial approach, integrating biomethane, biogenic CO_2, and organic fertilizer production[2].

- Agricultural Cooperativa Speranza (Italy): Based in Candiolo, this cooperative utilizes agricultural by-products and animal wastes to generate 4,000 tons of biogenic CO_2 annually. The CO_2 is sold to local industrial gas companies and mineral water bottling companies, replacing CO_2 that would otherwise be extracted from underground wells[2].

- Greenville Energy Ltd (Northern Ireland): Operating since 2012, Greenville Energy processes crop residues, food waste, and livestock effluent, producing 5 tons of biogenic CO_2 daily. The CO_2 is converted into dry ice for industrial use, with plans to expand its bio-LNG production for road vehicle fuel[2].

- Renevo (Norway): This project in Stord, Eldøyane, utilizes salmon fish residues and livestock manure, producing an estimated 11 tons of biogenic CO_2 per day. The liquefied CO_2 is intended for commercial uses such as dry ice production[2].

- Korskro Biogas Plant (Denmark): Located in Korskro, this facility processes manure to produce 16,250 tons of biogenic CO_2 annually, used in the food industry. It highlights the scalability and industrial relevance of biogenic CO_2 in commercial applications[2].

6 LOCAL PERMITS AND SAFETY REQUIREMENTS

6.1 PROCESSING OF PERMITS

Methane production under current legislation is classified as an industrial activity, specifically as a chemical industry to produce industrial gases. Therefore, the production of both small and large quantities of methane requires the same permits and legal requirements defined for the chemical industry. These procedures are enforceable in all Autonomous Communities (CCAA). The type of processing required is defined below.

6.2 LAND USE QUALIFICATION FOR INDUSTRIAL USE

The methane production unit is considered a chemical installation regardless of technology, power, or storage capacity. Therefore, any location for this purpose requires a compatibility report for land use for industrial purposes according to the PGOU (General Urban Planning Plan) or equivalent municipal document.

6.3 ENVIRONMENTAL PERMITS

Methane production, without categorization based on production method, quantity, or use, is subject to Integrated Environmental Authorisation with Environmental Impact Assessment. As mentioned earlier, these permits are defined for large-scale chemical industries and are managed by the competent environmental authority in each CCAA.

Procedure	Competent Authority	Time	Link
Integrated Environmental Authorisation with Environmental Impact	Instituto Aragonés de Gestión Ambiental (INAGA)	8-10 months	Link

In the case of the SPOTLIGHT project, since it is for research purposes, it is exempt from processing the environmental permit, but it is advisable to inform the administration of the activity to be carried out.

6.4 PROCEDURES RELATED TO INDUSTRIAL SAFETY REGULATIONS

Depending on the project's details, the system may be subject to different procedures related to industrial safety regulations as detailed below. All these procedures are directed to the Provincial Industry Service.

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- **High and Low Voltage Regulation**: Depending on the system's voltage below 1000V, a communication procedure must be followed (Low Voltage Regulation).
- **Pressure Equipment**: A communication procedure must be completed due to the commissioning of pressure equipment.
- **Fire Protection**: A communication procedure must be processed.
- **Storage of Chemical Products**: The APQ Regulation does not apply to installations integrated into the process units or to products and activities for which specific industrial safety regulations exist. Thus, Article 2 of said regulation defines the process unit as the set of production elements and installations, including the equipment and containers necessary for process continuity. If the storage is not process-related, it will be necessary to process the commissioning of the installations according to the APQ Regulation once the storage works are completed and before commissioning. Additionally, chemical product storage is associated with an environmental procedure detailed in the following table.

Procedure	Competent Authority	Time	Link
Low Voltage Installations	Servicio Provincial de Industria, Gobierno de Aragón	Commissioning communication	Link
Pressure Equipment	Servicio Provincial de Industria, Gobierno de Aragón	Commissioning communication	Link
Execution and Commissioning in Fire Protection	Servicio Provincial de Industria, Gobierno de Aragón	Commissioning communication	Link
Storage of Chemical Products	Servicio Provincial de Industria, Gobierno de Aragón	Commissioning communication	Link

6.5 SAFETY REQUIREMENTS

Applicable Regulation	Detail
ATEX:	
● Directive 1999/92/EC transposed by Royal Decree 681/2003 - Protection of the health and safety of workers exposed to the risks arising from explosive atmospheres in the workplace.	Prevention of explosions and protection against them, explosion risk assessment, obligations of the various parties, zone classification, and explosion protection documentation.
● Directive 2014/34/EU transposed by Royal Decree 144/2016 - Essential health and safety requirements for equipment and	Ensures that marketed products meet the requirements providing a high level of protection for the health and safety of people, especially workers, and property.

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protective systems intended for use in potentially explosive atmospheres.	
Storage of Chemical Products	
● Royal Decree 656/2017 - Regulation on the Storage	Warehouses will be classified according to the quantities of products of each class identified in the ITC, and within each warehouse category, aspects such as fire-fighting equipment or safety distances between storage areas and other exposure agents like public roads, inhabited buildings, or classified activities of fire or explosion risk will be defined. This Supplementary Technical Instruction will not apply to containers in use and containers in reserve essential for uninterrupted service continuity, only Article 9 on usage will apply.
● Regulation (EC) No. 1272/2008 transposed by Royal Decree 363/1995 - Regulation on the classification, packaging, and labelling of dangerous substances.	Related to the classification, packaging, and labelling of dangerous substances.
Electrical Risk	
● Royal Decree 614/2001 - Minimum provisions for the protection of the health and safety of workers against electrical risk.	This Royal Decree applies to electrical installations in workplaces and to the techniques and procedures for working on or near them.
● Royal Decree 842/2002 - Low Voltage Electrotechnical Regulation (REBT).	This Royal Decree must be considered when mounting, commissioning, operating, and maintaining the system.
● Directive 2014/30/EU transposed by Royal Decree 186/2016 - Regulates the electromagnetic compatibility of electrical and electronic equipment.	This regulation applies to any radio or telecommunications equipment that has the fuel cell system as a control or safety system.
Equipment and Work Machines	
● Council Directive 89/655/EEC transposed by Royal Decree 1215/1997 - Establishes minimum safety and health requirements for the use of work equipment by workers.	Establishes minimum safety and health requirements for the use of work equipment by workers.
● Directive 2006/42/EC transposed by Royal Decree 1644/2008 - Establishes standards for the marketing and commissioning of machines.	Since the project is for research purposes, this regulation does not apply as detailed in point “h” of Article 1 “Machines specifically designed and manufactured for research purposes for temporary use in laboratories”.
Self-Protection	
● Royal Decree 393/2007 - Basic Self-Protection Standard for centres, establishments, and dependencies dedicated to activities that may give rise to emergency situations.	This Royal Decree must be considered if the conditions specified in its ANNEX I are met.

Fire Protection	
● Royal Decree 2267/2004 of December 3rd approving the Safety Regulation against Fire in Industrial Establishments.	This Royal Decree must be considered before the installation and commissioning of the entire system.
● Royal Decree 513/2017 - Approves the Regulation of fire protection installations.	Establishes and defines the conditions that fire protection devices, equipment, and systems must meet, as well as their installation and maintenance.
Pressure Equipment	
● Directive 2010/35/EU transposed by Royal Decree 1388/2011 - Transportable pressure equipment.	This regulation must be considered for pressure vessels used for gas storage.
● Royal Decree 809/2021 - Regulation on pressure equipment and its supplementary technical instructions.	Applies to the installation, periodic inspections, repair, and modification of pressure equipment subjected to a maximum allowable pressure greater than 0.5 bar.
● Royal Decree 709/2015 - Essential safety requirements for the marketing of pressure equipment.	Applies to the system's gas storage equipment and accessories and the pressure equipment.
Occupational Risk Prevention (PRL)	
● Council Directive 89/391/EEC transposed into Law 31/1995 - Occupational Risk Prevention Act.	Law on Occupational Risk Prevention.
● Royal Decree 39/1997 - Regulation of Prevention Services.	Complements the Occupational Risk Prevention Act.
● Royal Decree 286/2006 - Protection of the health and safety of workers against risks related to exposure to noise.	Implement the necessary measures to ensure the protection of the health and safety of workers exposed to hazards arising from the installation, commissioning, operation, and maintenance of the entire system.

7 HAZOP STUDY AT FHA FACILITIES

In order to discuss the further analysis and HAZOP study of the process at the pilot plant in Cologne, a dedicated session was held on 23 May 2024 to include hydrogen production at the FHA facility where the scale-up and feasibility study is being conducted.

The methodology followed was the same as the one carried out during the initial HAZOP of the project, explained in deliverable *D6.3. HSE Engineering report*.

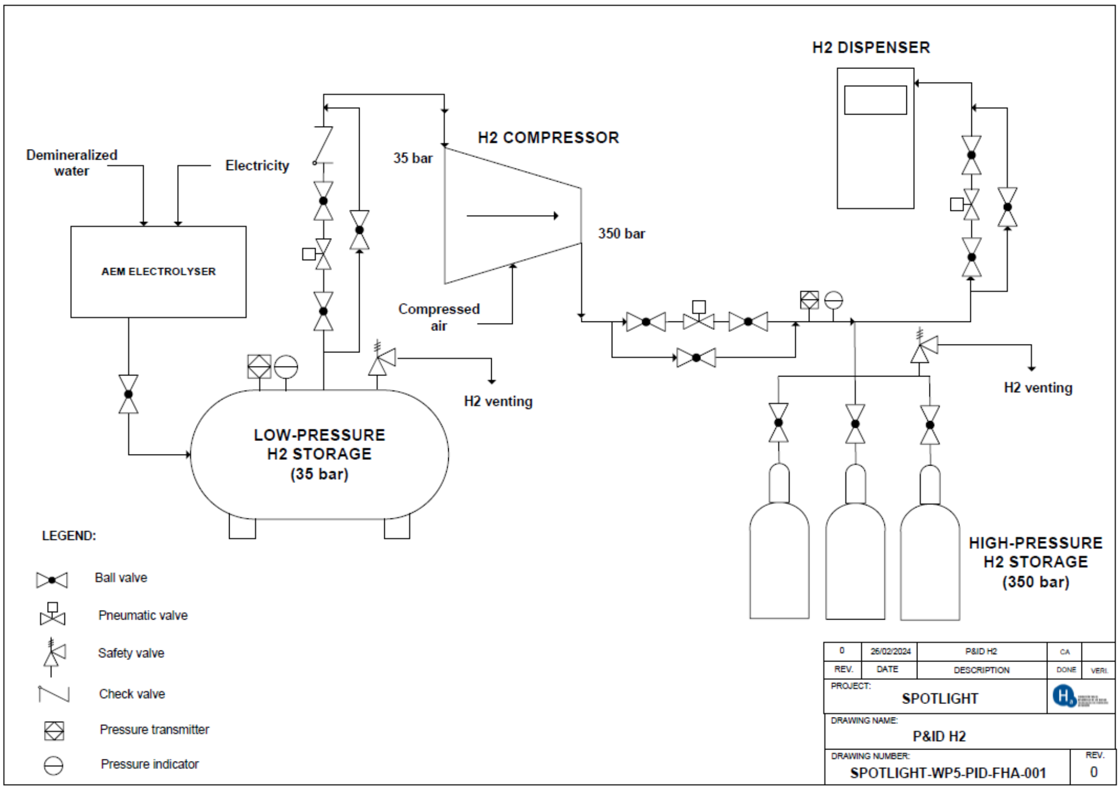

Figure 11. P&ID of hydrogen production at FHA facilities

And the following is the summary of the session to analyse the safety risks in hydrogen production at FHA:

Session: (1) 23/05/2024
Node: (1) FHa H_2 production process
Drawings: SPOTLIGHT-WP5-PID-FHA-001_Rev.0 - P&ID H_2

Parameter: Pressure

GW	Deviation	Cause	Consequence	Safeguards
More	Higher Pressure	External fire	Damage of the low pressure H_2 storage with consequent loss of containment and possible fire/explosion events	Safety valve on the low pressure H_2 storage sized @ 38 bar
			Damage of the line to the high pressure H_2 storage and H_2 dispenser and relevant equipment with consequent loss of containment and possible fire/explosion events	Safety valve on the high pressure H_2 storage inlet
		Malfunctioning of the H_2 compressor	Damage of the line downstream the compressor up to the pneumatic valve	Internal safety systems of the compressor stopping the equipment itself
		Pneumatic valve downstream the low pressure H_2 storage blocked in closed position	No significant consequences identified (the system stops in stand-by configuration without any issue for the whole system itself)	
		Pneumatic valve downstream the H_2 compressor blocked in closed position	No significant consequences identified (the compressor stops due to the out of mode pressure conditions)	
		Pneumatic valve upstream the H_2 dispenser blocked in closed position; in this operating mode the safety valve downstream the H_2 compressor is closed as well	No significant consequences identified (no possible damages on the interested lines due to the H_2 dispenser stopping working)	
		Operator error leaving closed a manual valve downstream the low pressure H_2 storage after maintenance operations	No significant consequences identified (the system stops in stand-by configuration without any issue for the whole system itself)	
		Operator error leaving closed a manual valve downstream the H_2 compressor	No significant consequences identified (the compressor stops due to the out of mode pressure conditions)	
		Operator error leaving closed a manual valve upstream the H_2 dispenser; in this operating mode the safety valve downstream the H_2 compressor is closed as well	No significant consequences identified (no possible damages on the interested lines due to the H_2 dispenser stopping working)	
		Operator error leaving closed a manual valve on a high pressure H_2 cylinder after a maintenance/replacement operation	No significant consequences identified (the compressor stops due to the out of mode pressure conditions)	

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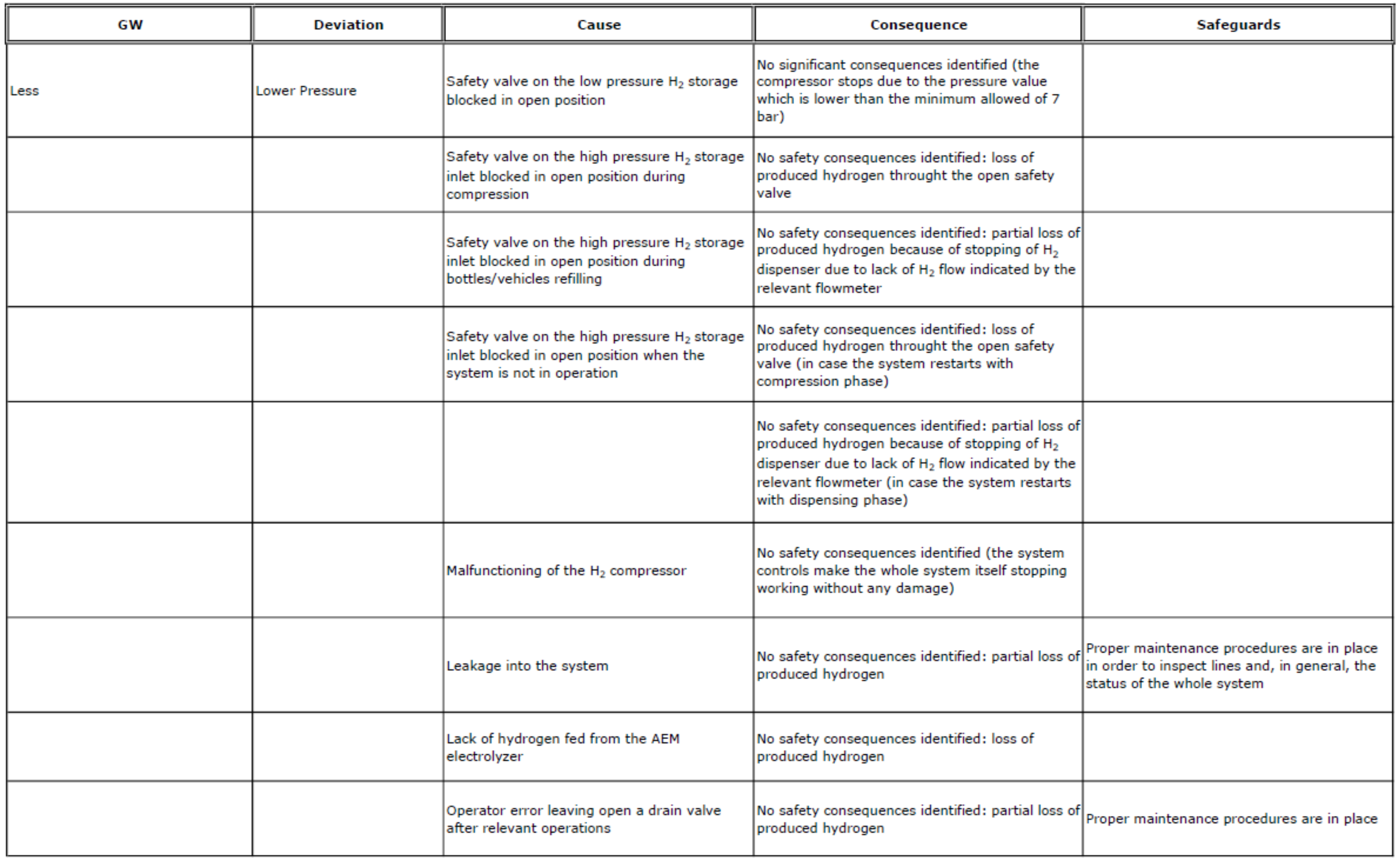

GW	Deviation	Cause	Consequence	Safeguards
Less	Lower Pressure	Safety valve on the low pressure H_2 storage blocked in open position	No significant consequences identified (the compressor stops due to the pressure value which is lower than the minimum allowed of 7 bar)	
		Safety valve on the high pressure H_2 storage inlet blocked in open position during compression	No safety consequences identified: loss of produced hydrogen throught the open safety valve	
		Safety valve on the high pressure H_2 storage inlet blocked in open position during bottles/vehicles refilling	No safety consequences identified: partial loss of produced hydrogen because of stopping of H_2 dispenser due to lack of H_2 flow indicated by the relevant flowmeter	
		Safety valve on the high pressure H_2 storage inlet blocked in open position when the system is not in operation	No safety consequences identified: loss of produced hydrogen throught the open safety valve (in case the system restarts with compression phase)	
			No safety consequences identified: partial loss of produced hydrogen because of stopping of H_2 dispenser due to lack of H_2 flow indicated by the relevant flowmeter (in case the system restarts with dispensing phase)	
		Malfunctioning of the H_2 compressor	No safety consequences identified (the system controls make the whole system itself stopping working without any damage)	
		Leakage into the system	No safety consequences identified: partial loss of produced hydrogen	Proper maintenance procedures are in place in order to inspect lines and, in general, the status of the whole system
		Lack of hydrogen fed from the AEM electrolyzer	No safety consequences identified: loss of produced hydrogen	
		Operator error leaving open a drain valve after relevant operations	No safety consequences identified: partial loss of produced hydrogen	Proper maintenance procedures are in place

Figure 12. H2 production HAZOP analysis

8 CONCLUSIONS

This report includes the main conditions to be considered in order to evaluate a potential scale-up of the process developed in the pilot plant of the project at the FHA facilities, so that the advantages of on-site production of green hydrogen can be maximized.

Different aspects that could determine the feasibility of scaling up the SPOTLIGHT process at the FHA facilities have been evaluated:

- the availability of space to scale up the process in the FHA building environment.
- Photovoltaic energy production.
- The hydrogen production capacity at FHA and the different existing systems.
- The hydrogen storage available at FHa.
- the services and ancillary systems of the process and potential modifications.
- the need for new permits or the extension of existing permits.
- risks and associated prevention measures.

Having analysed the above aspects, a 10:1 scaling of the process would be feasible in terms of space requirements in the slabs with gas and electricity services provided on the plot adjacent to the FHa building. The hydrogen demand of the process in this case would be only 0.5 kg/day for the Sabatier process and 0.3 kg/day for the rWGS process. Both demands can be met by on-site production of green hydrogen and local storage, without compromising other planned hydrogen applications.

There is insufficient data available to evaluate the possibility and installation requirements of the solar concentrator of the pilot plant, a pre-existing element of the project, although there is the possibility of rearranging the photovoltaic arrays of the self-consumption installation on the annexed plot.

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