SAFETY COST OF A LARGE SCALE HYDROGEN SYSTEM FOR PHOTOVOLTAIC ENERGY REGULATION

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ABSTRACT

Hydrogen can be used as a buffer for storing intermittent electricity produced by solar plants and/or wind farms. The MYRTE project in Corsica, France, aims to operate and test a large scale hydrogen facility for regulating the electricity produced by a 560 kWp photovoltaic plant.

Due to the large quantity of hydrogen and oxygen produced and stored (respectively 333 Kg and 2654 Kg), this installation faces safety issues and safety regulations constraints that can lead to extra costs. These extra costs may concern detectors, monitoring, barrier equipments, that have to be taken into account for evaluating the total cost of the system.

Relying on the MYRTE example that is a R&D platform, the present work consists in listing the whole environmental and safety regulations to be applied in France on both Hydrogen and Oxygen production and storage. A methodology for evaluating safety extra costs is currently being developed. This methodology takes into account various hydrogen storage technologies (gaseous and solid state).

The result of this work will be used to extrapolate the future safety costs for the next large scale hydrogen systems for further PV or wind energy storage applications.

1.0 CONTEXT AND OBJECTIVES OF THE PROJECT

Renewable energies are an important part of research and development in European programs. Despite the fact that renewable energies are free in the environment (sun, wind, sea …), they need to be transformed in exploitable energy like electricity. Due to climatic intermittence, renewable energies need to be stored when production is higher than human needs, and restituted when production becomes insufficient. Hydrogen appears to be a good energy vector to store these renewable energies.

The insular context has the particularity to need autonomy from the continental electrical grid, and some insular lands have a great potential to exploit renewable energy sources. In this way, a demonstration project called MYRTE (Renewable hYdrogen Mission for Electrical grid inTegration), located in Corsica, has been established to test a hybrid solar-hydrogen technology in a real scale for developing an optimal strategy of operation between a photovoltaic field and a high power hydrogen chain.

This 21 M€ project federates public and private actors: the **University of Corsica** (project leader and site manager), the **French Atomic and Alternative Energies Commission** (**CEA**, institutional partner), and **Hélion Hydrogen Power** (industrial). The University of Corsica is interested in the means of renewable energy storage, and has developed the opportunity to federate multiple actors in the field. It develops research and development activities in the field of renewable energy and energy storage. The French Atomic and Alternative Energies Commission develops a great knowledge both on hydrogen storage and photovoltaic systems. Hélion Hydrogen Power is a designer and a manufacturer of electrolysis and fuel cell systems.

MYRTE project is part of the energy plan adopted by the Territorial Collectivity of Corsica (which aims to achieve 34% of renewable energies by 2020) and in the cluster Corsica-PACA called “CAP ENERGIES”. The MYRTE platform is part of an overall project of the solar energy storage platform in Vignola location, developed by the University of Corsica. The platform is south exposed and located on the Sanguinaires road, close to Ajaccio, in Corsica, France (GPS location: lat +41° 54' 45.83", long +8° 39' 13.78", alt 85m). The 3670 m² photovoltaic panels installed will produce 560 kWp, thanks to an average sunshine of 4,4 kWh/m² per day. As shown in the Figure 1, a part of this energy will be converted in gaseous hydrogen and in gaseous oxygen by a 35 bar electrolyzer, and then will be stored in 35 bar pressured vessels. Hydrogen could be later stored in hydrides, under a solid form. To optimize performance and save energy, heat from the electrolyzer and fuel cell is stored through phase-change materials. Water is also recovered at the fuel cell outlet to be reused in the electrolyzer.

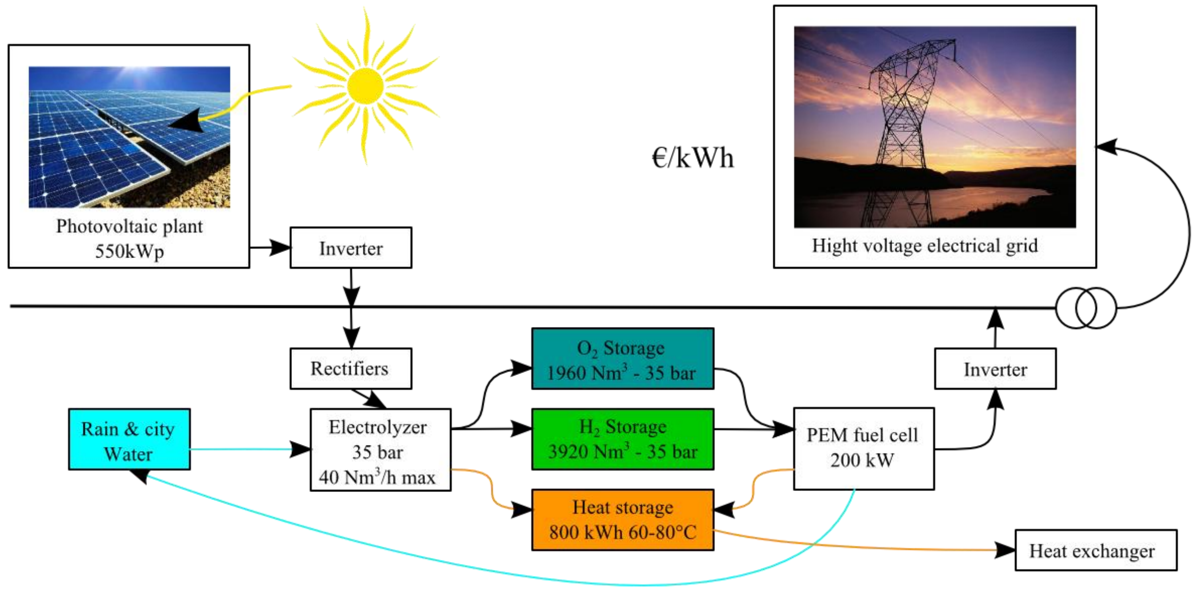

Figure 1. Simplified representation of the hydrogen chain

Figure 2 presents a three dimensional view of the MYRTE platform facility. Electrolyzer, fuel cell and electrical system are located in the experimental building, widely ventilated to prevent explosive atmospheres. Hydrogen and oxygen are stored outside, in a pit specially dug to ensure platform’s safety. An emergency access is also provided for firemen in case of fire.

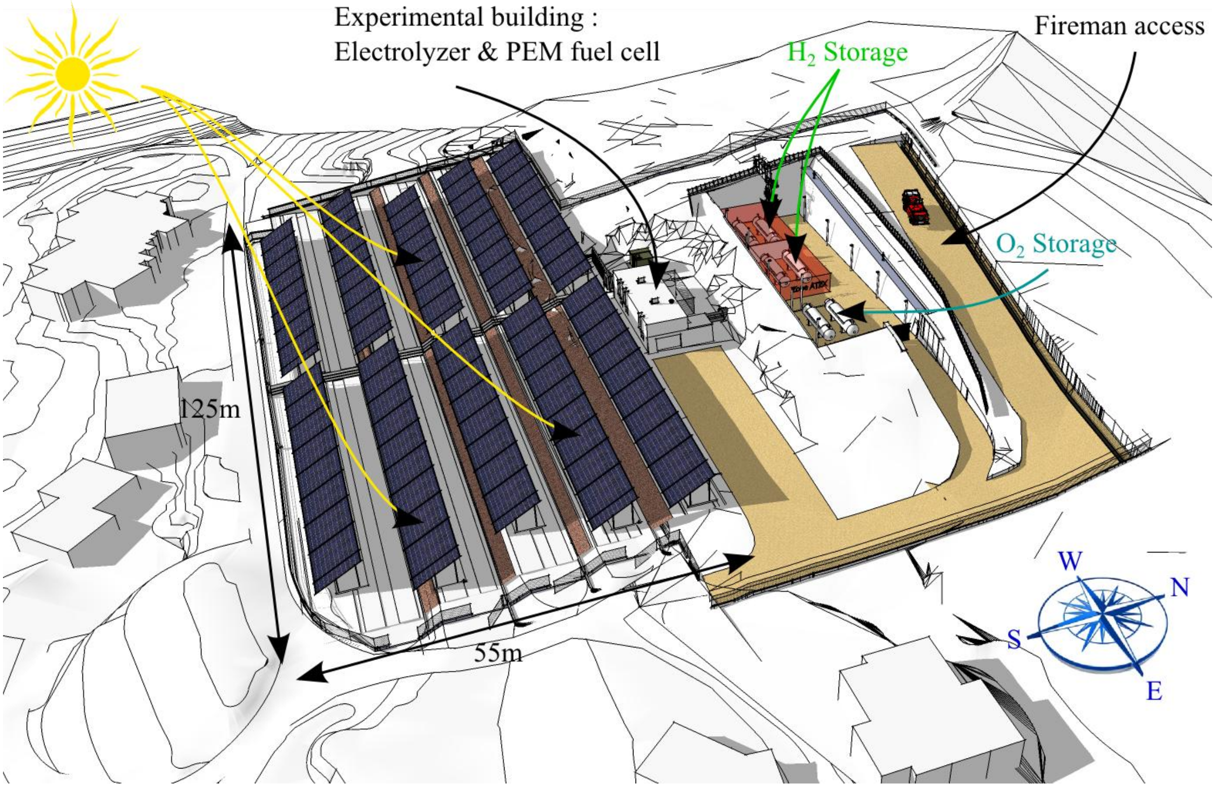

Figure 2. Three dimensional view of the MYRTE facility

The 200 kW PEM fuel cell chosen work with both hydrogen and oxygen. Both hydrogen and oxygen will be stored in high quantity (respectively 3920 Nm^3 be 333 Kg at 15°C and 1960 Nm^3 be 2654 Kg at 15°C) on the platform, which reinforces the caution used in security.

The project’s objective is to establish a feedback on the possibilities offered and on fuel cell systems behavior, in a hybrid solar-hydrogen system. One of these objectives is to evaluate the security cost of coupling hydrogen and oxygen storage.

Initially, determinating the security impact on the costs involves identifying the risks associated with implementation of hydrogen and oxygen. A literature research was done on standards and regulations: it covers all types of risks identified. The review covers production, storage (gaseous or in metal hydrides) and hydrogen use.

In a second step, a methodology is developed to assess the costs associated to the risks management of hydrogen and oxygen (safety cases, French Classified Installations for the Environment statement, choice of equipment to detect leaks, explosive atmospheres equipment, impact on the commissioning, operation and maintenance of the platform ...).

In a third step, the cost components are collected from CEA and Corsica University researchers and from Hélion Hydrogen Power. After collecting data, an allocation of costs will be obtained by category, but this step is an ongoing work.

The final step is to study the evolution of safety costs depending on the platform size, to anticipate the costs related to hydrogen safety for future projects.

2.0 FEEDBACK ON THE SYSTEM INSTALLATION REPORTING

French regulations on the hydrogen and oxygen production, use and storage applied under the Classified Installations for the Protection of Environment (ICPE), which definition and nomenclature are given by the Book V of the French Environmental Code. A Classified Installation for the Environment Protection is a fixed facility whose operation presents a potential risk to the environment. The nomenclature determines whether a facility is subject to this regulation. It gives a list of substances and activities subject to thresholds : products quantity, facility power... Thresholds specified in the classification define the regulatory context : declaration or authorization.

Facilities subject to declaration do not present serious dangers neither disadvantages, but they must meet general requirements. The operator must specify the nature of activities envisaged, the quantity of the substance produced and/or stored, the exact title or heading in the nomenclature to which the activity or substance belongs, the treatment method of wastewater, all kinds of fumes and waste. Moreover, he has to indicate the provisions taken in case of disaster.

Facilities subject to authorization have a danger or a nuisance potentially serious to the environment. The authorization request includes a risk assessment, an impact study, and a health and safety notice. The appraisal process is longer than the declaration procedure and includes a public inquiry. The operator is responsible to meet the prefectural technical requirements and works to ensure its employees and vicinity safety. Before commissioning, the classified installation must perform a more or less complex procedure according to its threshold of classification. The ICPE may be controlled by classified installations inspectors. Regulatory violations may induce criminal, civil or administrative sanctions (power of prefect’s special police).

Compared to the activities cited by the ICPE nomenclature [1], the MYRTE platform facilities are affected by three headings described in the Table 1.

Table 1. ICPE headings adapted to MYRTE platform facilities [1]

Heading	Activities	Threshold of classification
1220	Use or storage of Oxygen	≥ 2 T Declaration ≥ 200 T Authorization ≥ 2000 T Authorization with servitude
1415	Production of Hydrogen	< 50 T Authorization ≥ 50 T Authorization with servitude
1416	Use or storage of Hydrogen	≥ 100 Kg Declaration ≥ 1 T Authorization ≥ 50 T Authorization with servitude

From the design of the project, the administration was informed and involved in meetings. Discussions took place between the partners and the administration to consider a way for responding to regulation. According to MYRTE platform context, the Table 2 presents the ICPE applicable regulations. Given this Table 2, MYRTE was subject to a derogation on hydrogen production by local authorities, thanks to :

1. the non-commercialization of hydrogen produced,
2. the experimental nature of the platform covered by the IPPC (Integrated Pollution Prevention and Control) directive [11].

The quantity of Hydrogen produced is determined by the amount present in the electrolyzer, excluding piping and storage.

Table 2. Nature and quantity involved in MYRTE platform facilities applied to ICPE regulations

Name of the section	N° of the section	Quantity of substance involved	Regime
Use or storage of Oxygen	1220	2654 Kg	Declaration
Use or storage of Hydrogen	1416	333 Kg	Declaration
Production of Hydrogen	1415	0,179 Kg	Exemption of authorization

The experimental nature of the hydrogen production was the decisive factor that allowed the project not to be in the authorization case. An exemption scheme was used. Hence, the proposed file is a declaration file that covers both emissions (air, noise, water, waste ...) and provisions taken in case of emergencies. These provisions will impact on the cost of hydrogen and oxygen storing and relate to different points.

The installation and accessibility rules take into account the units of hydrogen and oxygen storage to be installed outdoors at a minimum distance of 8 m from each other to avoid cumulative effect, but also at a minimum distance of 8 m from properties and buildings located nearly these units. The experimental building and storage areas will be accessible, at least on one facade to allow the intervention of fire departments and rescue as well as their gears (see fireman access on Figure 2). Finally, the experimental building will include opening for the passage of equipped rescuers.

The Hydrogen building will house facilities for hydrogen and oxygen production. As a result, it will present the following minimum specifications:

- Local command isolated (materials M0),
- Interior firewall doors of 2 hours level and self-closing equipped,
- Fire, hydrogen and oxygen detection with slaving on gas production equipments and room ventilation,
- Gas-compatible storage units,
- Storage (or the experimental site) surrounded by a 2 m high metal fence.

On the other hand, being a 350 m^3 closed room, evacuation devices will be installed down the wall and on the ceiling to facilitate evacuation (cladding and ventilation) in case of gas leakage, smoke or combustion gases. Evacuation devices will renew the air in the room in 4 min maximum: permanent extraction rate will be 5000 m^3/h. In case of gas detection (hydrogen $>1\%_{vol}$ or oxygen $>23\%_{vol}$), a command control will perform various security actions like stopping all subsystem alimentation (gas and heat storages, electrolyzer, and fuel cell), intensifying the extraction rate up to 10000 m^3/h, and signaling the gas risks outside the building. Moreover, orders for manual opening will be placed near the access.

The means to fight against the fire include the site clearing nearby storage places which reduces the risk of fire and air pollution. In case of fire nearly the installation, protection needs steps to be taken. In that way, a traffic lane is provided around experimental building and storage tanks. Security materials are also provided close to facility:

- A 50 Kg wheeled powder extinguisher in the experimental building and storage area,
- Several 9 Kg powder extinguishers,
- A 40 mm fire hose equipped with a nozzle capable of being instantly servicing, located near storage facilities and experimental building.

Locked fences will be implemented to define the security perimeter. On the other hand, the site will be enhanced by a video surveillance system and remote monitoring facilities.

Facility operations will be supervised by a person designated by the operator. This will bring knowledge on the facility functioning and on dangers and disadvantages of the stored and used products.

3.0 COST ESTIMATION METHODOLOGY APPLIED TO HYDROGEN AND OXYGEN SYSTEMS

3.1 Kinds of risks related to hydrogen and oxygen implementation

The implementation and use of hydrogen or oxygen presents a number of risks that must be identified before mastering them. Hydrogen is a flammable gas while oxygen is an oxidizing gas. Table 3 synthesizes the risks related to hydrogen and oxygen.

Table 3. Risks associated to hydrogen and oxygen implementation

Hydrogen H_2 [2]	**Oxygen O_2 [3]**
- <u>Fire</u>: extremely flammable ($4\text{-}75\%_{vol}$ in the air, ambient pressure and temperature) - <u>Inhalation</u>: can cause asphyxia in high concentrations - <u>Specific risk</u>: exposure to fire may cause containers to rupture / explode. Low flammable energy, from 0.02 mJ - <u>Incompatible materials</u>: can form explosive mixture with air. May react violently with oxidizing agents - <u>Leak</u>: molecule small size leaks easily - <u>Embrittlement</u>: degradation of mechanical properties of metals, can lead to component failure	- <u>Fire</u>: may cause or intensify fire - <u>Inhalation</u>: continuous inhalation of concentrations higher than 75% may cause nausea, dizziness, breathing difficulties and convulsions - <u>Specific risk</u>: exposure to fire may cause containers to rupture / explode. Sustains combustion - <u>Incompatible materials</u>: may react violently with combustible materials. May react violently with reducing agents. Violently oxidizes organic material
- <u>Leak</u>: creates flammable clouds - <u>Pressure</u>: enlarges flammable clouds	

If hydrogen is known to be a high reactive gas and needs precautions for using it, its combination with oxygen needs enhanced precautions. Oxygen is an oxidizing gas, naturally present in the air ($21\%_{vol}$). If oxygen leaks from a tank or from a connection, oxygen concentration rises up in the air and can cause accidental fires. Figure 3 shows the fire triangle. It represents the 3 necessary conditions for a fire to start. Depending on mixture and confinement conditions, a deflagration or a detonation can occur.

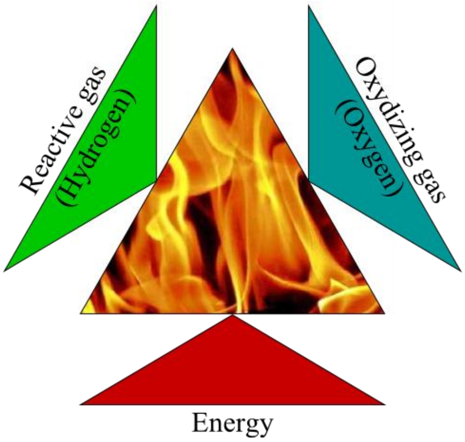

Figure 3. Fire triangle applied to hydrogen and oxygen case

At ambient pressure and temperature, hydrogen natural flammability zone is 4-75%$_{\text{vol}}$ in the air. This flammability zone will become larger if the atmosphere is enriched in oxygen. For example, the flammability zone of hydrogen mixed in oxygen is about 4,1-94%$_{\text{vol}}$ [6], which is not significant in terms of flammable volume but the flammable mass is expanded. The ignition energy of the hydrogen-air mixture should also be lower in an oxygen enriched atmosphere: hydrogen can also react faster and more violently (detonation zone become 15-90%$_{\text{vol}}$ instead of 18,3-59%$_{\text{vol}}$ [6]).

Both risk of ignition and rate of combustion increase with higher concentrations of the oxidizing gas. Higher pressure usually results in a lower ignition temperature and increased combustion rate. If oxygen pressure gets high while an adiabatic compression, temperature will rise and the risk of ignition will get easier as the value of energy that must be added to start a fire will decrease. With sufficient pressure and ignition energy, nearly all substances can burn in pure oxygen, including substances which are not usually regarded as flammable, like some metals.

Combined with oxygen, hydrogen risks become more significant. Materials needed to master hydrogen and oxygen risks should then respond to both hydrogen and oxygen regulations and normalizations.

3.2 Normative and Regulatory context for hydrogen and oxygen implementation

Both hydrogen and oxygen gases are odorless and colorless: they are not detectable by human sensitive. Thus special detectors have to be used to detect any leakage and prevent a flammable cloud formation. Normative and regulatory context applies all along the hydrogen and oxygen chain: production, storage, and use. The types of risks that may be encountered along the chain are shown in Figure 4.

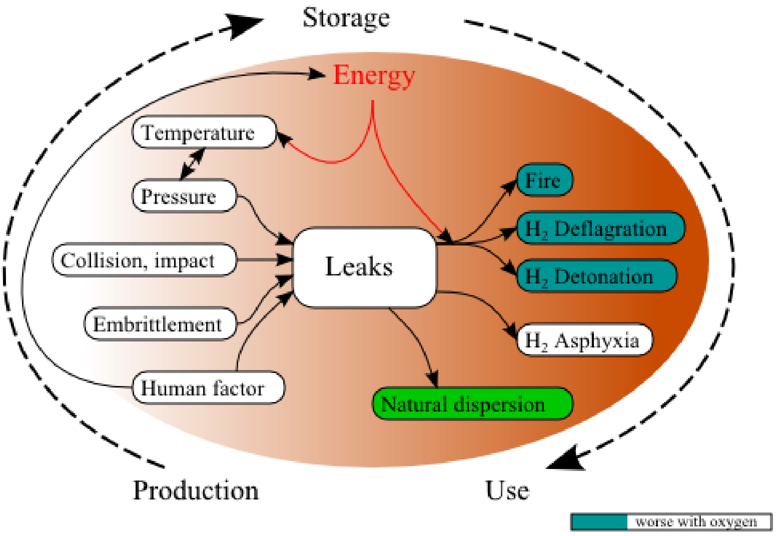

Figure 4. Types of risks related to the production, storage and use of hydrogen, and their consequences

Risks related to production, storage and use of gaseous hydrogen are mainly due to hydrogen leaks (depending on the flow rate and oxygen content, such leaks could lead to the occurrence of flammable gaseous mixtures), embrittlement of metals in contact with hydrogen, as well as the risk of using pressurized gas. The Figure 4 shows that these types of risks have to be taken into account for each sub-system of the whole hydrogen system implemented in MYRTE project (electrolyzer, gas storage, and use in PEM fuel cell).

Actual French and European regulations [4-5] require implementing security measures all along the project phases: conception, installation, exploitation and maintenance of the platform. Some of these security measures are listed in the Table 4.

Table 4. Security methods of French & European regulatory documents

Conception / installation	**Exploitation / maintenance**
- Declaration or authorization of H_2 and O_2 storage, depending on the quantity stored - Regulatory material with "CE" marking to work with pressurized gas, explosive atmosphere, fire risk, low tension, or electromagnetic field - Intelligent arrangement of the different units of production, storage and use - Respect of safety distances - Adequate room ventilation - Installation of gas detectors coupled with automatic and manual stop of gas circulation and electrical alimentations - Preparation of fireman access - Deposition of a work and/or a fire permit	- Access control - Regular cleaning (ventilation, water drainage…) - Labeling of dangerous substances - Monitoring the amount of gas stored - Verification of electrical systems - Verification of individual protections - Verification of facilities for combating fire - Safety formations

Due to hydrogen properties like its low flammable energy, standardization documents help to develop security systems. There are many standardization documents [6-7-8-9] depending on the country they have been published. The MYRTE project gives the opportunity to analyze the whole regulatory and standardization documents and their recommendations regarding security solutions. Based on this analysis a cost evaluation can be conducted.

3.3 Proposal of a methodology for assessing the costs related to security hydrogen and oxygen safety

The project provides the opportunity to develop and implement a specific methodology for evaluating the costs induced by hydrogen and oxygen safety. Such methodology is currently being developed and has to be applicable for other future hydrogen projects.

In order to evaluate the induced safety costs, it is proposed to rely on the "life cycle" steps of the hydrogen project (Figure 5): plant and equipment design, plant and equipment construction, equipment installation, plant commissioning, plant use and maintenance, plant decommissioning.

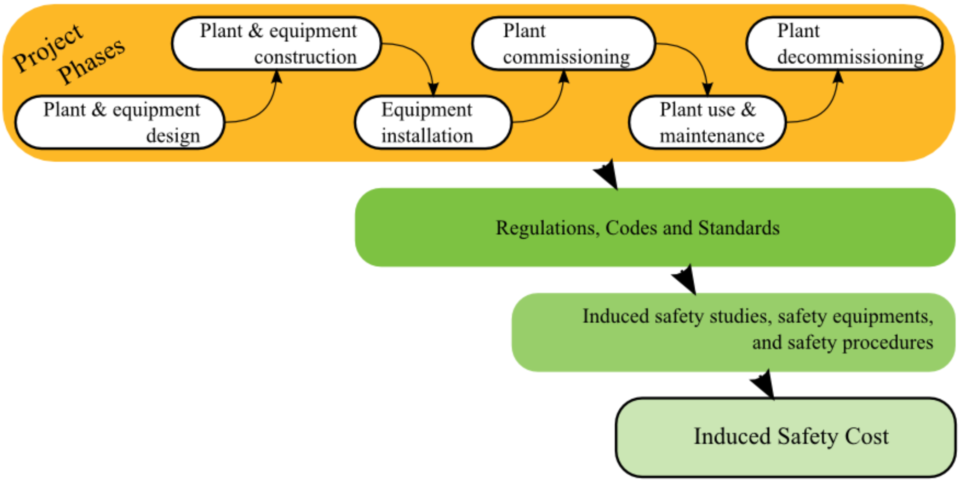

Figure 5. Overall approach for the evaluation of induced safety costs over the whole MYRTE project.

The first step of the methodology consists in specifying the characteristics of the assessed hydrogen system, in terms of hydrogen and oxygen production (maximal working pressure, maximal flow rate), storage (capacity, maximal working pressure, maximal flow rate), and use (pressure, flow rate).

Relying on this first analysis, the second step of the methodology consists in identifying all the regulations, codes and standards related to safety aspects and that are applicable to the studied system, all along the project lifetime (design, statement of safety records, construction, installation, commissioning, use, maintenance and decommissioning).

The objective of the third step of the methodology is to identify all the consequences and recommendations related to the implementation of this regulatory and normative framework. This step comprises the time spent for the safety studies (such as French “ICPE” regulation described in § 3.0), the inventory of the safety equipment to be implemented for each platform sub-system (hydrogen and oxygen detectors, ventilation, safety valves, etc.), the consequences in terms of civil engineering (e.g. safety distances between oxygen and hydrogen storage systems, additional walls for separating the containers, etc.) and finally the consequences regarding the commissioning, use, maintenance and decommissioning phases. For example, in this last category, the use of inert gas can be taken into account each time that maintenance is required, as well as non destructive control protocols that have to be planned regularly.

The final step of the approach consists in collecting the raw cost data related to each one of the consequences previously identified. The data collection can be made by a crossed analysis between the main phases of the project and the hydrogen sub-systems involved in the plant. Then the costs related to hydrogen and oxygen safety can be highlighted for each step of the project and for each sub-system of the hydrogen chain (electrolyzer, storage, PEM fuel cell).

Figure 6 represents the first approach of the methodology’s practical implementation for evaluating the specific cost of hydrogen and oxygen safety. Consequences and recommendations related to the implementation of the regulatory and normative framework can be divided in three safety measures :

1. prevention : to reduce the probability that an event occurs,
2. detection ; to detect the occurrence possibility of an event to anticipate the hazard and thereby to prevent or reduce it,
3. mitigation : to mitigate the impact of an event.

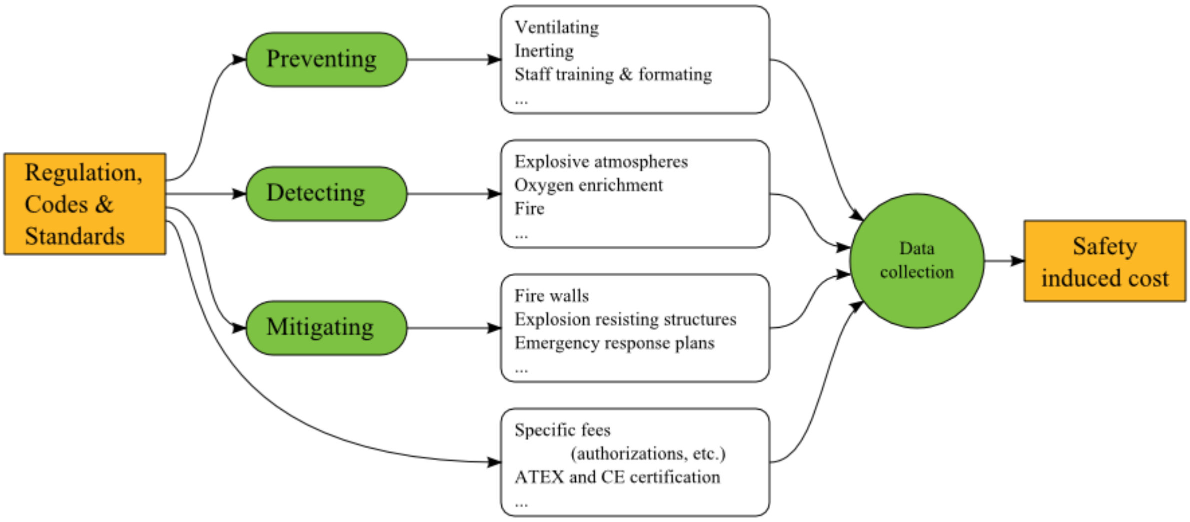

Figure 6. Practical implementation of the methodology for evaluating induced safety costs.

Another hydrogen and oxygen safety cost is linked to specific fees of material certification or to local regulations on quantities stored. For example, French ICPE [10] states a fee for any authorization on hydrogen production, and an annual fee depending on the quantities of hydrogen and oxygen produced and stored. The aim of this cost evaluating methodology is to apply not only to the MYRTE project, but also to other similar projects of coupling renewable energy with a hydrogen chain, with different capacities.

3.0 CONCLUSION

The objective of MYRTE project is to demonstrate the ability of hydrogen technologies to be used for smoothing the intermittent photovoltaic energy production. The project involves a 560 kWp photovoltaic plant, a 40 Nm^3/h PEM electrolyzer producing reactive gases at 35 bar, hydrogen and oxygen storage systems (3920 Nm^3 and 1960 Nm^3 respectively, stored at 35 bar max), and a 200 kW PEM fuel cell. Oxygen storage is one characteristic of this project. It has been chosen to store the oxygen coming from the electrolyzer, so that the fuel cell system could be fed directly with pure oxygen, which leads to higher efficiency than H_2/air systems.

The study presented in this paper focuses on the safety aspect of the demonstration project. The practical challenges faced by the plant developers have been described, especially regarding the plant construction authorization process and corresponding induced delays. Complementary to this return of experience in regulatory authorization procedures, the project provides the opportunity to develop and implement a specific methodology for evaluating the costs induced by hydrogen and oxygen safety. The induced safety costs are evaluated taking into account the whole “life cycle” steps of the hydrogen project, that is to say plant and equipment design, plant and equipment construction, equipment installation, plant commissioning, plant use and maintenance, plant decommissioning. It is planned to compare the safety constraints depending on the type of hydrogen storage technology (compressed gas, hydrides), storage pressure and amount of gas to be stored.

This work is on-going and the implementation of the cost evaluation method on this real case study will lead to first quantitative results in the next months. Based on these results, it is planned to extrapolate the future safety costs for the next large scale hydrogen systems for further PV or wind energy storage applications. The methodology for the safety cost estimation will lead to a relevant checklist, which will be available to further projects of coupling a renewable electricity production to a hydrogen chain.

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