**Project Portfolio**

**Air Liquide**

Paris, France

**Work streams “XXX”, “YYY”, etc. in the strategic value chain**

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**Table of Content**

[**Project Outline**](#_87nmyq1hv849) **6**

[Company Presentation](#_8k8t7n3a02q9) 6

[Objectives of Air Liquide in the project in all technical fields it’s involved](#_5j03m6duy0xr) 8

[Global vision of the project](#_r3p6am8g8e6d) 8

[Objectives of Air Liquide](#_9uvyv5i7mwko) 10

[Main technological areas of developments](#_8r21gnd6jdyk) 11

[R&D Projects Before the project](#_wlx1dyp1vslq) 13

[Technology and Challenges – R&D&I Activities within the project in all technical fields it’s involved](#_wlij9tq50e1j) 18

[State of the art](#_4tyqiy6i6t5p) 18

[Technical locks that prevent improvements in the field](#_h3zu8vrc1wbi) 23

[Objectives and technical challenges in the project](#_lfrb9zyh75te) 29

[First Industrial Deployment (FID)](#_n6c4qqk17rll) 43

[Purpose of the FID phase](#_5senkh5d0qla) 43

[Technical challenges in the FID phase](#_nc0swme00bph) 47

[Transition from the FID phase to the mass production / commercialisation phase](#_90d8czly0ewy) 48

[Revenues in the FID phase](#_5cxc6zfrm49q) 48

[Contribution to the hydrogen strategic value chain](#_gevd8yxet3ru) 49

[Project’s position in the hydrogen strategic value chain](#_kaqbkce4pxde) 49

[Industrial value chain in France](#_h6s19ma6m8ka) 49

[Industrial value chain in Europe](#_vwk42mtusc9y) 50

[Intellectual Property Rights](#_lf893wqeuvia) 51

[IP management principles](#_wmauo0s3xpu0) 51

[IP protections principles](#_omft7z5ns7g2) 51

[IP exploitation principles](#_4fmne0cdnx53) 52

[Work Plan](#_ow4gveny53uk) 53

[Investments](#_mpkt5nlgz1im) 54

[Tools and Equipment](#_ib76omtt9zak) 54

[Construction of Buildings/Laboratory](#_f9qfdfgsfgbw) 55

[**Budget**](#_mpyyxi8p1pji) **56**

[Eligible Costs](#_jivjr5o5fx95) 56

[State Aid](#_canqhf4mfx69) 56

[**Spill-over Effects**](#_nu616pqpcnif) **57**

[Spill-over by non-protected results diffusion](#_hw4495wy8oep) 57

[Spill-over by IP protected results diffusion](#_4ici35o64wgm) 57

[Spill-over in the FID phases](#_pjl432r9qqpu) 58

[**Other positive effect on the market**](#_laqtstnoz76) **60**

[Impact of the Project on Employment and New Investments in Europe](#_yb9cjmn5m451) 60

[Environmental protection and reduction in energy dependence](#_epgccplshxin) 60

[Market Failures: Coordination problems](#_e7gdurv9ize6) 61

[Coordination failures between companies and research organizations.](#_w2ilzmg66zam) 61

[Coordination failures between European research organizations themselves](#_cex7co7e1ji8) 62

[Coordination failures between SMEs and industry leaders](#_g1s1yf909lyp) 62

[Coordination failures between European clusters](#_y978j19o5k4n) 63

[Coordination failures of very large-scale R&D project](#_iel7bpku9m94) 63

[Coordination failures associated to contractual incompleteness](#_b929ib2zzkti) 64

[Market Failure: Imperfect and asymmetric information](#_evshx9k6u9gw) 65

[Risks affecting the project](#_vicy64k2ixkv) 65

[Technological risk](#_b2ktebho9vz5) 65

[Economic risk](#_b2ktebho9vz5) 65

[Partnership risk](#_b2ktebho9vz5) 66

[Risk associated with major R&D programs](#_b2ktebho9vz5) 66

[Regulatory risk](#_b2ktebho9vz5) 66

[Strategic and financial risk](#_b2ktebho9vz5) 66

[Difficulty to recruit highly qualified personnel](#_6q0t0o4bhsgx) 67

[Strategic independence of supply](#_4p158o7yksqs) 67

[**Adequacy of the state aid instrument**](#_3qhadyu21z4x) **68**

[**Appropriateness among alternative policy instruments**](#_i0yz45xem0sg) **68**

[The regulation](#_b2ktebho9vz5) 68

[A better funding of public research](#_b2ktebho9vz5) 68

[The research tax credit](#_b2ktebho9vz5) 68

[The innovation tax credit](#_b2ktebho9vz5) 69

[**Appropriateness among different State aid instruments**](#_d431xz37t6ur) **69**

[**Incentive effect**](#_w4d7qz4goplw) **70**

[Absence of similar projects](#_b15ym9780g7v) 70

[Start date of the project](#_sswcsbys8ps) 70

[Counterfactual scenario](#_ne856x1w6oie) 71

[Increase in R&D and FID efforts](#_kezbmlebnd3j) 71

[**Elaboration on Terms of the Funding Gap Questionnaire**](#_2j2y9j3o822t) **72**

[Main hypothesis of the business plan](#_1hthpt60kfwx) 72

[Necessity of state aid](#_ylbgelb6j9vs) 73

[Proportionality of state aid](#_hdejbffezymw) 73

[Firm’s hurdle rate](#_c19qsssbo1pk) 73

[Project’s funding gap](#_izrhtburf1hc) 73

[State aid intensity](#_3n613ko7e76w) 74

[State aid cumulation](#_2g0s0gzfmve0) 74

[Open selection proceeding](#_lwimcae95h4b) 74

[**Limitation of distortion of competition and trade**](#_ci45ypr4ezq0) **74**

[Market affected by the state aid](#_mjjcf94bfj65) 74

[Definition of the relevant market(s)](#_xqhkdalf22mh) 74

[Current Industry Sector](#_9p0xwabbqtsq) 76

[Market Situation / Share today and after IPCEI](#_hj0pnc5kpv61) 76

[No strengthening or creation of market power](#_jaopsqpjdes4) 76

[Limiting distortion of dynamic incentives](#_d2mdi7keylb0) 77

[No maintaining of an inefficient market structure](#_j8af3pc2hth5) 77

[No effect on location activities](#_widbb84zn35k) 77

[**Annex to the Portfolio**](#_ip25fmb3ke8c) **78**

# Project Outline

## Company Presentation

A world leader in gases, technologies and services for Industry and Health, Air Liquide is present in 80 countries with 67000 employees and serves more than 3.7 million customers and patients. Oxygen, nitrogen and hydrogen are essential small molecules for life, matter and energy. They embody Air Liquide’s scientific territory and have been at the core of the company’s activities since its creation in 1902.

Air Liquide’s ambition is to be a leader in its industry, deliver long term performance and contribute to sustainability. The company’s customer-centric transformation strategy aims at profitable, regular and responsible growth over the long term. It relies on operational excellence, selective investments, open innovation and a network organization implemented by the Group worldwide. Through the commitment and inventiveness of its people, Air Liquide leverages energy and environment transition, changes in healthcare and digitization, and delivers greater value to all its stakeholders.

Air Liquide’s revenue amounted to 22 billion euros in 2019 and its solutions that protect life and the environment represented more than 40% of sales. Air Liquide is listed on the Euronext Paris stock exchange (compartment A) and belongs to the CAC 40, EURO STOXX 50 and FTSE4Good indexes.

**Air Liquide in the hydrogen business**

Air Liquide has expertise in the entire hydrogen value chain from production, storage to distribution and has strong expertise in the development of all industrial applications.

For more than 20 years, the Group has developed applications related to hydrogen energy in various sectors, such as mobility, with dedicated teams (technologies, applications, markets, advocacy…).

* In 2017 and 2018, Air Liquide sold 14 billion cubic meters of hydrogen to the refinery and petrochemicals sectors for a total of €2 billion.
* Air Liquide has supported the successive evolutions of Ariane launch vehicles 1 to 5, and was involved from the beginning of the Ariane European program thanks to its cutting-edge gas expertise and position as a global leader in space cryogenics. In this program, Air Liquide is in charge of all cryogenic fluid management, from the design of the system to operation of the plant producing, liquefying, distributing He, N2, H2, H2 on board the tanks rocket which are designed and built by Air Liquide.
* Air Liquide has already designed and installed more than 120 hydrogen stations worldwide, including almost 58 operated by the Group. The stations are located in Europe (France, Denmark, Netherlands, Germany and Belgium), Asia (Japan), North America (United States and Canada), and the Middle East (United Arab Emirates).
* In 2018, Air Liquide invested over 150 million US dollars to build a liquid hydrogen plant in the western United States, with construction starting in february 2020. The plant will have a capacity of nearly 30 tons of liquid hydrogen per day — an amount that can fuel 42,000 Fuel Cell Electric Vehicles (FCEVs). Through this investment, Air Liquide will enable the large-scale deployment of hydrogen mobility on the west coast, providing a reliable supply solution to fuel the 40,000 FCEVs expected to be deployed in the state of California by 2022. The plant will also support other fuel cell vehicle and transportation markets in the region, such as material handling and forklifts and heavy duty trucks. Groundbreaking ceremony is scheduled for May 8, 2020.
* Air Liquide invested in the world’s largest membrane-based electrolyzer in Becancour, Quebec, to develop carbon-free hydrogen production. Air Liquide will install a 20 MW electrolyzer and associated liquefier that increases by 50% the current capacity of its hydrogen facility in Becancour. Utilizing Hydrogenics technology, the proton-exchange membrane (PEM), the electrolyzer will be the world’s largest and will help ensure North America’s supply of low-carbon hydrogen for industry and mobility use. The new production unit will save nearly 27,000 tonnes of CO2 emissions per year - approximately the equivalent of 10,000 sedan cars per year.

In parallel, Air Liquide developed the Blue Hydrogen initiative that aims to gradually lower the carbon content of its hydrogen production dedicated to energy applications. More precisely, Air Liquide is committed to achieving at least 50% of the carbon-free hydrogen necessary for these applications by 2020, by combining:

* the use of low-carbon energies, water electrolysis and reforming of biomethane;
* capture, storage and valorization technologies for the CO2 emitted during the production of hydrogen from natural gas.

Hydrogen, even when produced from natural gas, is a virtuous energy: over an equal distance traveled, the use of Fuel Cell Electric Vehicles decreases greenhouse gas emissions by 20% compared with combustion vehicles and does not emit any particulate matter.  
Moreover, following the commitment which was confirmed in September 2018 by the Hydrogen Council (co-chaired by Air Liquide), 100% of hydrogen for mobility applications will be carbon-free by 2030.

Today's challenge in the use of hydrogen for mobility is to have an effective, cost competitive and safe green hydrogen supply chain from production to refuelling.

Hydrogen is an ultra-light gas that occupies a substantial volume under standard conditions of pressure, i.e., atmospheric pressure. In order to store and transport hydrogen efficiently, this volume must be significantly reduced.

For this reason, its density must be increased using one of the following techniques:

* High-pressure storage in the gaseous form - - the more widespread method
* Very low temperature storage in the liquid form - reserved for certain special applications such as space
* Hydride-based storage in the solid form - not mature

Today, liquid hydrogen can be stored in tanks at -253°C up to 13 bars but the leakage of hydrogen is high as the tanks absorb heat which vaporize the liquid. In addition the current technology of liquefactor does not allow intermittent input. Besides these issues, hydrogen in its liquid form has extensive potential as it allows to store high quantities in a restrictive space. The high quantities stored can answer the needs of the massive market in 2030 and the specific usages requiring liquid hydrogen onboard of the vehicle for autonomy purposes. This is why it is key to develop innovative hydrogen liquefaction plants based on new and more efficient technologies, and the supply chain of liquid hydrogen to answer the two main challenges: the leaks of liquid hydrogen in today’s technology and the intermittency of renewable energy.

The aim of Air Liquide in this project is to develop and scale up a comprehensive set of innovative technologies all across the liquid hydrogen supply chain and further propose an integrated offer which cope with both these technical challenges.

Today, only three companies worldwide master the complete LH2 supply chain for industrial applications : Air Products (US), Praxair-LINDE (US/DE) and Air Liquide (FR).

Those companies are not only operators of the supply chain, but own all the technology bricks along the supply chain. 50 years of LH2 supply chain operations have demonstrated that this technology ownership is key in order to properly understand the issues at stake, reduce the boil off ratios and maximize efficiency of the chain.

**e2 additional recommendations:**

* Don’t use too many words like “number one”, “leader”, “best in the market”, etc.
* Identify existing markets
* Explain R&D strategy
* Don’t use “we” but explicitly mention the company’s name in the whole document
* Identify customer base and their activities

## Objectives of Air Liquide in the project in all technical fields it’s involved

The aim of Air Liquide in this project is to develop and scale up a comprehensive set of innovative technologies all across the liquid hydrogen supply chain in order to cope with two key technical challenges: leaks of liquid hydrogen in today’s technology and the intermittency of renewable energy that will be used as an input for producing hydrogen.

### Global vision of the project

In France, according to the French study "[Let's develop hydrogen for the French economy](http://www.afhypac.org/documents/actualites/pdf/Afhypac_Etude%20H2%20Fce_VDEF.pdf)" (in french) conducted by Air Liquide and 12 other partners with the help of McKinsey, by 2050 hydrogen could account for 20% of France’s energy demand, power 18% of vehicles and cut carbon emissions by 55 million metric tons—almost a third of the reduction required under the reference scenario. In parallel, the “Mobilité Hydrogène France” consortium[[1]](#footnote-1) developed a strategy to rollout simultaneously captive fleets of operators committed to hydrogen and shared refueling stations. The scenario is for 100 stations and 1000 vehicles in 2022 and then 600 stations and 800 000 vehicles in 2030.

In Europe, according to the “Hydrogen scaling up” study conducted by the Hydrogen Council, by 2050, hydrogen could represent a quarter of the EU’s total energy demand (2 250 TWh). This amount would fuel about 42 million large cars, 1.7 million trucks, approximately a quarter million buses and more than 5 500 trains. The massification of the market associated with heavy duty users' requirement to use liquid hydrogen onboard (for sake of autonomy) require the upfront development and deployment of liquid hydrogen infrastructure.

In this context, Air Liquide has the ambition to be a major player in the supply of carbon-free hydrogen particularly for industry and the mobility market. Strong from its unique technological and industrial expertise in the liquid hydrogen field, Air Liquide intends to deploy the value chain of LH2 (liquid hydrogen) from liquefaction to usages with the objective to introduce innovations in every building block, integrate them in a demo plant, scale it up and develop a **Zero Boil Off integrated LH2 supply chain coupled with renewable energy sources** for mobility markets such as :

* M1 : Light duty refueling stations (Gaseous on board storage)
  + S1.1: Light duty FCEV[[2]](#footnote-2) 350 bar & 700 bar on board storage with less than 10kg embarked H2, such as personal vehicles, taxis, small utility vehicles, ...
* M2 : Heavy Duty refuelling stations (Gaseous or Liquid on board storage)
  + S2.1 : Bus & Trucks, 35 MPa & 70 MPa <100kg
  + S2.2 : Bus & Trucks LH2, <100kg
  + S2.3: Train, 35 Mpa >100kg
  + S2.4: Train, LH2 > 100kg
* M3 : Maritime applications (Liquid on board storage)
  + S3.1 : Ferries
  + S3.2 : Long haul
  + S3.3 : Auxiliary power units
* M4 : Aeronautical applications
  + S4.1 : ground support equipments (Gaseous on board storage)
  + S4.2 : Airplane fueling (liquid on board storage)

Liquid hydrogen can be a cost-effective, efficient and reliable zero emission fuel as, compared to gaseous on board storage, it allows to :

* At constant storage weight, **increase the autonomy** by a factor of 3 to 5, depending on the stored H2 quantity
* **Store high quantities of hydrogen on site** : Moreover these liquid storages can be installed underground, which could **increase the level of safety** of the station and **reduce its footprint**.
* **Improve the transport of hydrogen efficiency** by transporting more than four times more hydrogen in liquid form than gaseous form (300 bar). Thus reducing costs as soon as the product demand is higher than 500 kg per day (and distance from the source is higher than 150-200 km).
* **Reduce the overall emissions** linked to the supply chain which are in any case better than gaseous supply chains as soon as the electricity is renewable (as transport is four times more efficient). In case the electrical source has the same carbon content than the current EU mix, emissions will be globally better as soon as the distance from the source is higher than 600km and daily consumption higher than 500 kg per day. The purpose of the project will be to focus on Renewable energy sources.

Today the liquid hydrogen market is limited to niche applications (mostly space activities). The purpose of the project is to develop a comprehensive set of innovative technologies all across the liquid hydrogen supply chain and scale up this supply chain to serve a mass market in 2030 (Hydrogen Energy). This would consist in deploying an industrial scale liquid hydrogen supply chain consistent with the massive volumes required by the hydrogen energy market in 2030, from decarbonized hydrogen produced by intermittent and / or renewable energy sources. Moreover, Liquid hydrogen can be a cost-effective and reliable zero emission fuel when produced in large scale volumes.

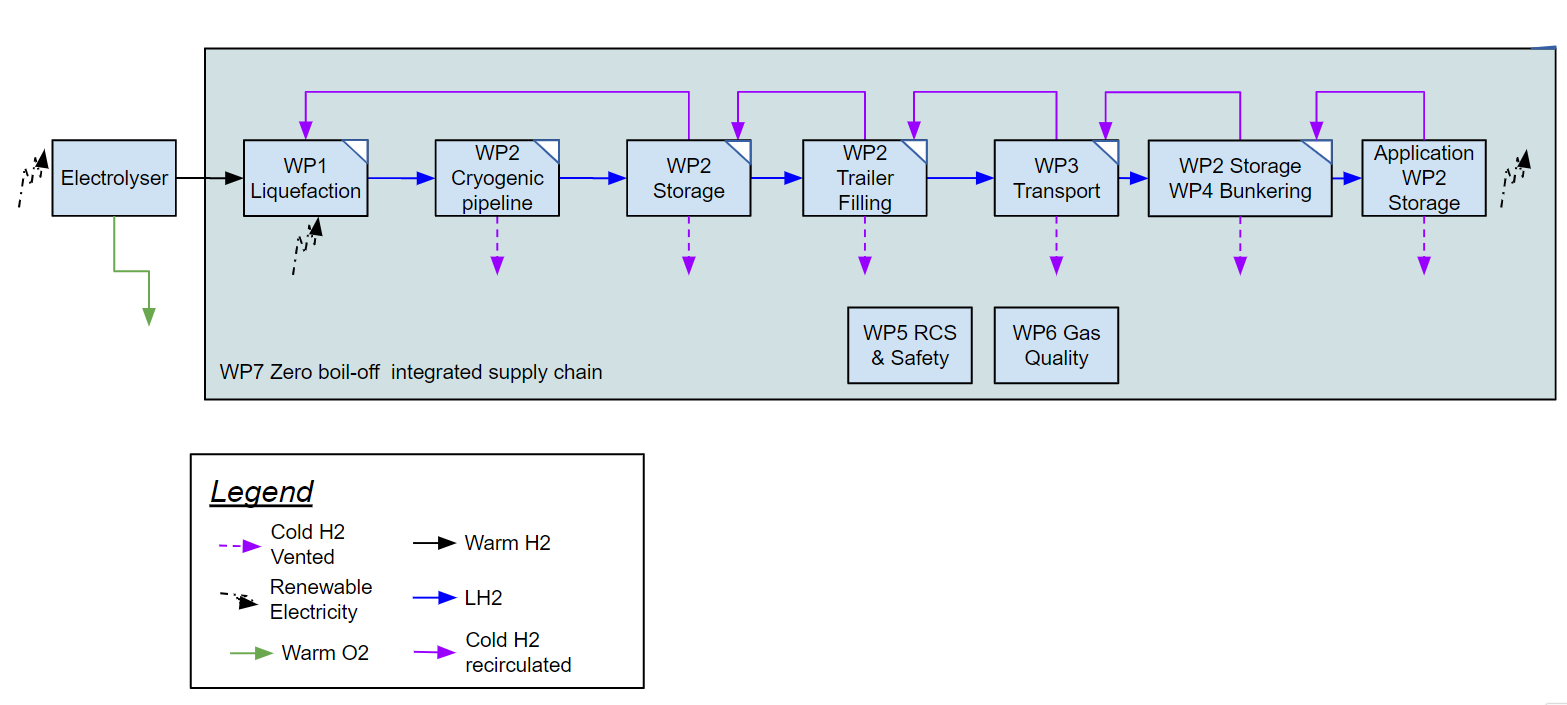
**The project will aim at developing innovative renewable hydrogen liquefaction plants based on new technology, scale up the production of trailers from the current situation** (where only a few trailers are produced every 2 to 5 years) **and upgrade the fleet to around 50 trailers per year, and develop a range of refuelling / bunkering stations. The focus will be also put on improving the current supply chain efficiency, particularly reducing the product losses by evaporation all along the chain.**

The envisaged applications are mostly related to clean transport : light and heavy duty vehicles, trains, ships and aeronautics (planes and ground support equipment). A significant part of the project will aim at filling the gaps and misfits in current regulations, Codes and standards in order to facilitate and democratize the access to liquid hydrogen for transportation. Significant R&D development tasks in each technology brick development work package on safety will support this effort.

To this end, the project will include R&D activities in order to develop each of the technological bricks of the chain.

The project will be organized in work packages (WP), each one (WP 1 to WP 4) describing the R&D and FID activities related to a technology brick. Three transverse WP will address Regulation, codes and standards issues (WP 5), gas quality assurance issues (WP 6), and the integration of all techno brick development deliverables in a pilot (WP7, Task 7.1) and First Industrial Deployment project (FID) (WP 7, Task 7.2).

All the bricks developed will be integrated and tested thoroughly in a first pilot for a time period of 2 years. The chain created will then be upscaled in a FID phase to be ready for mass production of LH2 to serve the emerging market in 2025.

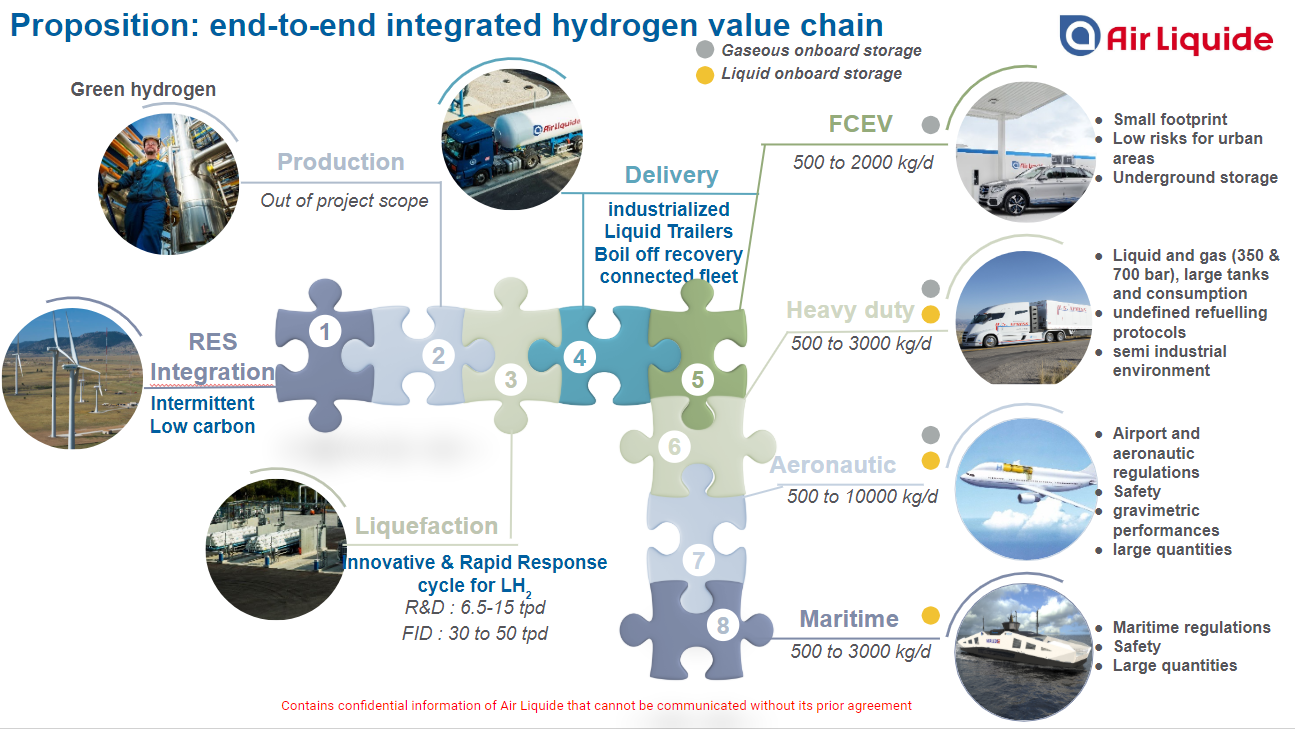


[*Figure 1: LH2 value chain*](https://docs.google.com/presentation/d/1qWCnedvLxidP6hjpGXAvNiWUT_1pJkfknAYV-rikeL0/edit#slide=id.g8171a3ca9d_1_56)

As shown on the figure hereinabove, all bricks are interdependent. Therefore, any disturbance in a block can eventually propagate upstream and downstream; bricks must be designed in such a way to limit these interferences and keep control of the entire process and performances. This is why it is absolutely mandatory to test the entire supply chain system to make sure the integration is correct and the disturbances are properly filtered. This project includes a test at a prototype level, and in a First Industrial Deployment, at full scale.

### Objectives of Air Liquide

The aim of Air Liquide is to engage the necessary technology developments, leading a group of key French and European suppliers to structure the liquid hydrogen sector in France and develop an innovative zero boil-off integrated supply chain dedicated to the mobility market in France and in Europe.



[*Figure 2 : Value proposition*](https://docs.google.com/presentation/d/1qWCnedvLxidP6hjpGXAvNiWUT_1pJkfknAYV-rikeL0/edit#slide=id.g55871b1002_1_0)

Indeed, the centralized production combined to an optimized distribution chain and operation within a suitable regulatory framework will allow Air Liquide to develop a hydrogen offer at a competitive cost for the following applications, for which liquid hydrogen is particularly beneficial:

* H2 refuelling station : hydrogen distribution at 350 / 700 bar in the vehicles. The potential customers are fuel retailers
* Hydrogen bunkering stations (filling on board LH2 tanks). The main added values of liquid hydrogen in this application are the compactness of a liquid tank, the refuelling time, the safety of the low pressure - double wall onboard storage, the cost of the molecule, the optimization of the energy cost of compression, the energy optimization of the station. The main customers are fleet operators.
* Rail freight transport: hydrogen distribution in liquid form. The main added value of the liquid is the optimization of the volume density of energy storage, the safety of the storage, the refuelling time and the capacity to increase the daily H2 distribution quantity compared to gas. **Alstom has expressed interest in this project, consistent with their own development projects**. Generally, the main customers would be rail freight operators.
* Long-haul goods transport: hydrogen distribution at 700 bars or in liquid form in the vehicles. The main added value of the liquid is the optimization of the volume density of energy storage and the capacity to increase the daily H2 distribution quantity compared to gas. Iveco and Daimler are potential partners here. The main customers are fleet operators.

While focusing on mobility applications, the revitalization of the liquid hydrogen market will also allow the following transitions to be made in the industrial sector :

* Electronic Industry: switch from volumes currently delivered in gas trucks and needing additional purification on site, to liquid delivery, without need for purification anymore. Main added value of the liquid: high purity and less trucks on the road (reduction by a factor 4 compared to 300 bar trailers and 10 compared to 200 bar trailers).
* Provision of a back-up in the event of a disruption of the main supply to industries with on-site hydrogen production capacity (for instance, metal treatment or oil refining, sweeteners manufacturing...).
* A potential transfer of industrial volumes from gas or on site supply to liquid thanks to the cost reduction achieved by the project.

The project aims to develop technologies and experiment a complete renewable liquid hydrogen supply chain for Hydrogen mobility application at the scale of an industrial basin while approaching zero hydrogen losses, and still reducing the total cost of ownership of the molecule.

This potential mainly involves a minimum critical size, the use of renewable electricity all almost the distribution chain, a significant cost reduction and a management of losses by evaporation of the liquid tending towards "Zero Losses"[[3]](#footnote-3) throughout the supply chain, i.e. from the liquefier to the station.

**Today the ambition of Air Liquide is to lead this flagship project to implement this strategy and prepare the French and European strategic industrial value chain to the coming liquid hydrogen market.**

### Main technological areas of developments

The research and development work on each technology brick will be needed in order to meet the project goals, to be ultimately tested altogether in the pilot scale project deployment :

* Safety is and will remain the first priority in the technology development work packages. Safety of processes and safety of people will be addressed in a quantitative way for each brick being developed with a severity versus frequency rating of feared events in order to bring the technology to an acceptable level of risk. All events rated as unacceptable will be mitigated either in frequency or in gravity by specific and qualified means (know how). This kind of evaluation, developed at Air Liquide since the 2000’s is considered now as good practice and will serve as a basis for discussion in the elaboration of the Regulation Codes and Standard (RCS) framework with the authorities. All safety related work done in the project will be published and free of intellectual property rights.
* Hydrogen liquefaction cycles : efficient, scalable and capable of handling intermittent hydrogen feed and intermittent electricity supply and yet being cost effective.
* Innovative liquid hydrogen storages, transfert lines and trailer filling systems where cold energy is transferred and stored as subcooled hydrogen, allowing to recondense cold vapors recirculated from the supply chain.
* Serial production of cryogenic trailers, transport containers, with automatic multi layer isolation winding, fast vacuum jacket evacuation, robotised pressure vessel and valve cabinet welding and mounting, compatible with recirculation of boil off back to the liquefier. These technologies will also be adapted to large on board liquid hydrogen fuel tanks in trains and ships.
* Refuelling systems based on liquid hydrogen delivery solutions. Either refuelling stations in the case of final gaseous delivery (at 350 or 700 bar) or bunkering stations, if the on board storage is in liquid form. These equipment will require the development of flow meters, hoses, clean break couplings, low boil off circulating and high pressure pumps, as well as procedures to be user friendly and be safely operated without personal protective equipment and yet being integrated at customer sites or close to them. Those installations should also handle liquid and gas invoices to the final customers. Hence accurate liquid and gas metering shall be developed and approved according to the european and national weight and measures laws.
* Validate new national and European suppliers of subsystems (technology) by integrating them in the development phase of Air Liquide’s technology bricks (through joint development agreements, development contracts or more classical procurement processes) and define conditions for which they could be qualified for First Industrial Deployment.
* A digital approach will be developed at all the techno bricks levels and shall be integrated at system level during the deployment of the pilot plant and ultimately the FID. This will include remote monitoring and operating capabilities, equipment tracing, logistical optimisation tools (dispatch and fleet sizing tools), customer data collection (RGPD compliant), product quality tracing, preventive maintenance tools…
* A transverse Regulation Codes and Standard (RCS) gap analysis and development project will have the final objective to support and facilitate the deployment of technologies and projects. This effort will be done both at European and national levels. All the procedures, interfaces, protocoles defined in this work package will be published and free of intellectual property rights.
* A transverse gas quality assurance work package will, all along the supply chain, allow to monitor and guarantee an adequate level of quality of the gas to be supplied to the applications. Safety will also be addressed in this work package as impurities in liquid hydrogen (solid oxygen) can lead to catastrophic events or interruption of supply (e.g. solid nitrogen clogging the piping).

The First Industrial Deployment (FID) phase will have the following objectives :

* Test the industrialization of the different techno bricks in a fully integrated, at scale, project. The performance of the different bricks should not be affected by this industrialization process.
* Scale up the systems deployed in the pilot scale project to reach full industrial efficiency and eventually meet the 2030 expected market demand.
* Reduce the costs of equipment by industrialization efforts of the different technology bricks, with a focus on trailers, containers, on board storage and refuelling equipment.
* Eventually propose a product at a cost compatible with market expectation. To meet this objective, a list of representative KPI (Key Performance Indicators) will be identified and the system will be tuned up until the different KPI are met.
* Test the capacity of suppliers to accompany the scale up in size of the techno bricks from the first pilot and validate their industrial approach to meet FID costs and performance targets.

The project will be divided into 7 Work Packages. Each WP1 to WP4 is focused on one of the different bricks of the chain described above (see Figure 1) and includes R&D as well as First Industrial Deployment activities for this brick. WP5 is a transverse work package on the development of an adapted regulatory framework, WP6 is a transverse work package dealing with gas quality assurance and safety all along the supply chain, and finally WP 7 corresponds to R&D and First Industrial Deployment of the entire value chain through demonstration and industrial deployment projects.

e2 additional recommendations:

* important de se remettre dans les éléments de language IPCEI : air Liquide doit lancer une activité de R&D et FID pour déployer une chaine industrielle dansle domaine de l’hydrogène liquide
* quelles applications visées?
* idée des WP et des briques technologiques
* réaliser un pilote puis une mise à l’échelle pour une première FID
* List the objectives of the project, from technical, industrial and commercial points of view
* Put weight on innovative aspects (R&D + FID)
* Or put weight on environmental / energy / transports aspects
* Briefly clarify the market intended to be served by the company after the IPCEI in terms of products, potential customers, applications, geographical coverage
* Briefly mention the key potential suppliers impacted by the project
* Briefly describe the impact of the project in terms of CO2 reduction
* Use a table to summarize the information at the end of the section
* Renforcer le volet technique du projet
* vision globale du projet, lister les objectifs du projet (petit parfum)
* Le dossier final fera 80 pages, 35 pour la partie 1, le plus important est le 1.4 et 1.5 (challenges techniques pour la phase de FID == > les questions de la commission porteront sur ces chapitres)
* 1.2 est le format stratégique et de présentation haut niveau du projet 3-5 pages.

## R&D Projects Before the project

Description of the R&D-parts which were necessary for the IPCEI project and that were carried out before start of the project (background).

R&D teams are focusing on 3 dimensions:

1- Science - producing molecules with high added value

2- Technologies - enriching Air Liquide's in-house portfolio for greater diversity

3- Understanding of usages - meeting the societal challenges of Air Liquide's clients and patients

Air Liquide and external studies ([Path-to-Hydrogen-Competitiveness study - Hydrogen Council](https://hydrogencouncil.com/wp-content/uploads/2020/01/Path-to-Hydrogen-Competitiveness_Full-Study-1.pdf)) have determined that the optimum solution for delivering H2 to customers needing several tons per day is a centralized production and the delivery under the liquid form (LH2).

For that purpose, Air Liquide R&D has put in place a multi-year program to support the Air Liquide affiliates developing and putting on the market LH2 related technologies, leveraging the know-how that has been acquired by the Air Liquide Group, since the launch of the European Space Program in the 70’s, that Air Liquide contributed to create.

The key component of the LH2 supply chain is the Zero Boil Off integrated LH2 supply chain with development of the following key domains :

* **Liquefaction**:

Air Liquide developed the liquefaction technologies, the implementation of low temperature equipment in vacuum evacuated with multi layered insulation cold boxes built in Air Liquide workshops.

3 processes are mastered by Air Liquide to liquefy hydrogen at the best total cost of ownership :

* Helium cycle, using helium as a working fluid, relying on simple, low cost, non ATEX helium compressors and turbines. Air Liquide installed this kind of system in China for third party customers, and is operating this technology in Calvert City liquefier (third party technology), started in 2016.
* Hydrogen Claude cycle, where the process fluid is also the working fluid. This technology requires large H2 cycle compressors and turbines, and is adapted for large hydrogen liquefiers. Our plants in France, Canada, French Guyana and Las Vegas are operating on this principle.
* Reverse closed Brayton cycle, where the working fluid is Helium and the work developed in the turbine is recovered in the Helium compressor. This cycle has been developed by Air Liquide since 2007.

Liquid hydrogen is at a temperature of 20K (-253°C). Although the liquid is stored and transported in containers / trailers which are properly isolated (double wall, multilayer insulation and vacuumed jacket), heat losses will occur nevertheless and will induce hydrogen evaporation or heat up in the tanks resulting either in hydrogen loss or tank pressure increase.

Similar losses may occur during transfer of hydrogen from a tank to another. Air Liquide has acquired specific knowledge and developed an expertise in the management and the recovery of those losses and their reliquefaction: from trailer filing management (called multi step trailer filling, patent pending) to subcooling the produced hydrogen, reliquefaction cycles, high performance containers / trailers with liquid nitrogen shields and new filling procedures. The goal is now to achieve zero boil off supply chain.

* **Storage**

Most cryogenic storages consist of double wall cylindrical storages which are workshop manufactured and shipped by road or sea to the sites. CRYOLOR, a fully owned Air Liquide subsidiary located in Ennery, France, specializes in these types of storages.

Their know-how includes multi layer insulation for high thermal performances or for small size or transportable storages, as well as perlite insulation under vacuum for large static storages.

Air Liquide expertise and know-how in this type of storage goes from the development up to the operation, maintenance and safety. Such storages are installed in Waziers, France (4\*250m3), Kourou, French Guyana (2\*300m3), Calvert city, …

For even larger required storage capacities, or when the site is not easily accessible, Air Liquide has the expertise to install spherical storages which are prefabricated in a workshop, assembled, welded and tested on site.

Air Liquide has also expertise in loading Hydrogen in LH2 trailers or on-board storages (example of ferries powered by liquid hydrogen) thanks to bunkering equipment, also called loading bays. Hydrogen is transferred by pressure difference or by circulating pumps. It has developed procedures which minimize the amount of product losses by evaporation in the pipes and flash by pressure drop. Measuring the quantity of LH2 transferred is also particularly complex, and is mastered by Air Liquide, either by using specially designed mass flowmeters or by weighing the final recipient. Air Liquide experts have worked thoroughly in the field of automatisation of these equipment as safety studies demonstrate that most accidents occur during transfilling operations.

* **Transport**

Mobile cryogenic tanks are reservoirs intended for the transport of large quantities of cryogenic fluids; they differ from on-board/embedded tanks in that they carry more matter and that such carried fluid is not used for the propulsion of the transport. Mobile tanks may typically be installed on trailers, trains and ships. Air Liquide owns the technology and know-how allowing for the control of the thermodynamic conditions of the stored fluids, typically through recondensation and subcooling.

Long-distance transport of dangerous goods and especially of cryogenic fluids is one of the core expertise of the Air Liquide Group (ALOS subsidiary), enabling it to associate and match the needs and requirements of its customers with international regulations and standards. Therefore Air Liquide masters the logistics chain of cryogenic fluids (e.g. LN2, LOX, LAr, LHe, LH2 and other gases for medical, industrial and electronics) from the production plant down to the delivery at customers’ facilities.

In the last few years, there has been a growing demand for liquid helium and liquid hydrogen. This brought Air Liquide to be managing a fleet of several hundred LHe ISO containers and some ten LH2 trailers. No fatal accident has been recorded so far, proving the high reliability and robustness of transport equipment designed and run by Air Liquide, as well as the professional quality of its highly trained personnel.

Below are the most recent projects in which Air Liquide has participated, and which focused in particular on mobile cryogenic tanks for the long-distance transport of cryogenic fluids:

- LHe ISO CNT (2018); 40 feet ISO container for liquid Helium, with design features transferable to LH2

- 2, 3.5 and 4 tons LH2 trailers manufactured by Cryolor, a fully owned Air Liquide subsidiary

* **Hydrogen refueling stations** 
  + *Gaseous refueling stations*

Air liquide has developed its technology and know-how in hydrogen refuelling station developpement since the late 1990’s. The first commercial product was a 350 bar refuelling station which was commissioned in Luxembourg in 2003, with a capacity of 120kg/day at 350 bar. 700 bar fast fill stations were first demonstrated during the 2005 challenge bibendum in Paris and in the US (40kg/day).

As demonstrated by the numerous published articles, patents and applications, Air Liquide expertise covers a wide number of areas, both in terms of process development but also hardware (heat exchangers, high pressure buffers, fast fill procedures and dispenser, …)

As of today, 700 bar fast fill stations up to a capacity of 1000 kg/day, fed by high pressure gas of liquid hydrogen are commercially available.

Specific solutions and the related know-how were also developed by Air Liquide for applications in aeronautical or maritime domains, requiring refuelling stations to fill on board liquid hydrogen tanks. Such stations were first deployed for Renault in 1998 in the frame of a project called FEVER.

* + *LH2 Station and LH2 pump development:*

In 2019, Air Liquide made progress on the precise knowledge of LH2 pump technologies and started to set up LH2 test platforms which will be operational next year (2020). The main lines of work were:

* Analysis of existing cryogenic pump solutions: feedback on cryogenic pumps for air gases and LNG (pump plan, operation, maintenance, costs…) in the Air Liquide group as well as on cryogenic station solutions.
* Tests of a LH2 HP pump prototype, performed by an external service provider.
* Implementation of a single-stage cryogenic pump simulation tool, taking into account the dynamic (piston, valves ...) and thermodynamic (heat exchanges, equation of state of real gases) effects.
* Design of a new pump architecture, based on a detailed analysis of the literature, of the tank / pump coupling, and of the first results obtained with the prototype pump with several invention disclosures and patents associated.
* Development of test facilities in order to study solutions for improving existing technologies: subscale test bench for LH2 HP pump seals, at pressures up to 900 bar in LH2 or LN2 baths and with a “fatigue” mode and full scale test bench for the study of multiple technologies on the LH2 chain: filling of LH2 tanks, HP LH2 pumps, BP LH2 pumps, HP filling, on-board tanks.
* Study of the LH2 underground tanks solution for future stations, in order to set up an action plan.
* Development of a generic tool for boil-off calculation, performance improvement and consolidation of supply chain loss calculations.

At the end of this year of work, Air Liquide have made progress in defining and developing an efficient refueling station adapted to LH2 logistics. More particularly this year Air Liquide has increased its knowledge concerning LH2 pumps, LH2 tanks and the supply chain:

* The flow rate of the existing LH2 pump tested strongly depends on the pressure.
* The presence of steam in the compression chamber could explain the low flow rate of the LH2 pump.
* The boil-off rate is very high and goes from 30% at 2000 psi to 150% at 12000 psi.
* The losses at the joints have a significant impact because the Joule-Thomson expansion through the joints generates a lot of heat.
* The sub-cooling of the storage makes it possible to obtain a better flow rate at the outlet of the LH2 pump.
* Thermal inputs when the trailer is pressurized (atmospheric vaporizer) before delivery to the station generally cause the majority of the boil-off generated during distribution.
* In order to be able to deliver low pressure stations that require hydrogen with high density, it is preferable to place them first in the distribution circuit.
* 2 experimental test benches are underway to allow better characterization and improvement of the performance of LH2 systems
* “Direct” burial tanks are arguably the best option for enabling safe and compact implementation of the technology
* **Safety and RCS (Regulations, Codes and Standards)**

Air liquide has been working on hydrogen safety for more than 50 years, more especially for the cryogenic tanks designed and developed for the launch of Ariane 1 in 1979. This experience is recognized in the industry worldwide.

Also, Air Liquide contributes actively to the following cooperative projects dedicated to LH2:

* FCH-JU [PRESHLY](https://preslhy.eu/) (2018-2021): Prenormative Research for Safe Use of Liquid Hydrogen.

*AL contribution:* identify knowledge and RCS gaps, provide recommend and guidelines based on experiments and modelling on specific LH2 behavior

*Partners:* Karlsruhe Institute of Technology, Health & Safety Laboratory, HYSAFE, INERIS, NCSRD, Pro-Science GmbH, University of Ulster, Warwick University

* Norway based [SH2iFT](https://www.sintef.no/projectweb/sh2ift/) (2018-2021): Safe Hydrogen Fuel Handling and Use for Efficient Implementation.

*AL contribution:* Identify knowledge and RCS gaps, Provide recommend and guidelines based on exp. and modelling on H2G and LH2 maritime

*Partners:* SINTEF SMC, SINTEF SER, NTNU, TØI RISE FR, CMR, ARIANE Group, SHELL, TOTAL, NASTA, EQUINOR, AL, GRT gaz

* Horizon 2020 [HEAVEN](https://heaven-fch-project.eu/index.php/en/home/) (2019-2022): High Power Density Fuel Cell System for Aerial Passenger Vehicle fueled by Liquid Hydrogen.

*AL contribution:* airborne LH2 tank realization and safety analysis at aircraft level.

*Partners:* Fundacion Ayesa, Air Liquide Advanced Technologies, Elringkinger Ag, DLR, H2fly Gmbh, Pipistrel Vertical Solutions

* FCH-JU [HyRESPONDER](https://cordis.europa.eu/project/id/875089) (2020-2022): Train the Trainer - A programme in hydrogen safety for first responders.

*Project anterior contribution:* The foundations to training of responders have been already laid by the HyResponse project (funded by FCH-JU 2013 - 2016) which has established the first European Hydrogen Safety Training Platform (EHSTP) to train first responders

*Partners:* Ulster University, ENSOSP (Ecole Nationale Supérieure des Officiers de Sapeurs Pompiers - France), CTIF (International Association of Fire and Rescue Services - Slovenia)

The main goal being to evaluate, based on a scientific methodology, the appropriate safety distances and mitigation measures associated with LH2 operations.

Air Liquide will keep contributing both in Europe and worldwide to R&D projects with partners about LH2 Safety and RCS in the coming years: for mobility applications such as trucks, trains, planes, ferries; and on the infrastructure side on the safety and RCS regarding LH2 trailers and their operations, stations, transport ships and liquefiers.

All safety and RCS related work done in the past have been published and are free of intellectual property rights.

* **Others**
* *CFD modelling tools*

Air liquide has a long track record in the use of CFD modeling tools, that are used for safety studies and process optimization.

In order to go beyond the limitations of the one of the most advanced and recognized codes, FLACS, Air Liquide joined end of 2019 the CERFACS[[4]](#footnote-4) (Centre Européen de Recherche et Formation Avancée en Calcul Scientifique), to work together with TOTAL and GRTGaz on the development of a High Fidelity (HiFi) CFD code for numerical simulation of explosion phenomenon. This code named AVBP is based on the large scale approach (Large Eddy Simulation) of turbulence modeling in order to run numerical experiments of turbulent flame deflagration and detonation.

* *Controls and Operation*

Owning and operating its production plants and delivery assets, Air Liquide has developed particular know how in the following fields :

* Automatization and remote operations : most of the plants are now fully automatic, with unmanned operation and remotely controlled from an OCC (Operation Control Center) which can stop, start, change the plant load (according to customer demand, on site product inventory or energy prices). The OCC are working in close coordination with the local on call operation teams in order to fix potential problems before they become critical.
* Recovering data from sites and using this data in IA / machine learning algorithms to detect premature wear of equipment and execute preventive maintenance, forecast product demand, trigger deliveries, etc…
* Installing hardwares on delivery trucks in order to improve the dispatch tools used for customer delivery, for instance by GPS monitoring of trailer fleets, dynamic traffic management techniques to optimize “milk run deliveries”, … the hardware can also consists in monitoring devices to detect loss of driver alertness, bad driving habits, Safety issues (for example connected TPMS Tire Pressure Measurement system), …

e2 additional recommendations:

* Explique
* Indicate in which projects (name, dates, partners, objective, funding) the company was involved before the IPCEI in the same scientific and technological fields as well as its role / contribution / main results
* Use a table to summarize the information at the end of the section
* intégrer le BIP dans la section 1.3
* condition d'éligibilité IPCEI :
  + Démontrer que la R&D va au delà de l’état de l’art mondial (new product and service with high innovation or fondamental new production process, très fort contenu de R&D)
  + new version of existing product ne sont pas éligibles pour l’IPCEI)
* Expliquer quels sont tous les projets R&D qui constituent le background du projet IPCEI et les résultats obtenu

## Technology and Challenges – R&D&I Activities within the project in all technical fields it’s involved

For each WP describe the state of art, the technical locks, the objective and the technical challenge to solve the technical locks.

### State of the art

e2 additional recommendations:

* For each WP, describe what is the current state of the art as well as the relevant technical KPIs (not costs-related, technical description, rendement...)
* Use a table to summarize the information at the end of the section
* **WP 1 : Hydrogen liquefaction**

All three major industrial gas players are present with their own technology : Linde/Praxair, Air Products and Air Liquide.

For a long time reserved to military usages, Chinese ecosystem is now actively looking for techno providers and is developing some projects.

New large players are entering the market with potential own technology development (e.g. KHI, Kogas). They are mainly looking at large plants (1000 tpd scale) for clean energy export application as a strategic topic supported by both Korean and Japanese governments.

Some suppliers of small helium liquefaction plants for the scientific market are starting H2 liquefaction activities (for instance Cryo Technologies in the US)

Hydrogen liquefaction at an industrial scale (up to 10 tons per day, tpd) is well proven although only 3 plants are installed in Europe. Most of the plants, up to 30 tpd in total, are operated in North America where distance between the customers and the source, as well as large space programs, promoted a lot of this technology.

The state of the art technologies used in most of the significant size liquefiers for industrial purposes operate with a Claude cycle with Hydrogen as a working fluid. This technology requires large high pressure hydrogen piston compressors, which have limited reliability, with process gas expanders not allowing fast process responses to change in feed flow rate, therefore not compatible with intermittent renewable energy direct coupling.

* **WP 2 : Liquid hydrogen storage**

Once produced intermittently, Hydrogen must be stored in order to smooth the plant output and fit the steady customer demand. The storage capacity is a function of the plant failure modes and meantime to repair the demand versus production scenarios and the availability of renewable electricity sources.

Storage of liquid hydrogen is typically done at low pressure in double wall vacuum jacket stainless steel pressure vessels, and are typically operated at a pressure below 1 barg to keep the product as cold as possible.

Liquefier storages are currently either built on site (spheres) or fabricated in workshops (cylinders). There is no clear optimum between the two options, as the operator choice will be function of required stored quantities (spheres for large quantities >1000m3), cost of labor (to the detriment of a sphere in high labor cost countries), cost of shipping and site access (to the advantage of cylindrical storage if site is easily accessible and shipping is cheap).

On site spheres are isolated by perlite under vacuum, with boil off rates lower than 1 % per day, whereas cylinders have multi layer insulation under vacuum with boil off rate lower than 0.3% per day.

About 5 days of production are stored on site, which in most of the case requires the storage to be site erected (spheres) or divided in multiple sub storages (cylindrical).

Typical storage on site capacities are ranging from 250 m3 cylindrical (Air Liquide France) to 4000m3 spherical (NASA Cap Canaveral, currently in construction). As of today, no european based supplier is capable of designing and building cylindrical storages larger than 90 m3, as the subcontractors knowledgeable in large double wall cylinders have closed.

Spherical storage suppliers are currently US or Japan based.

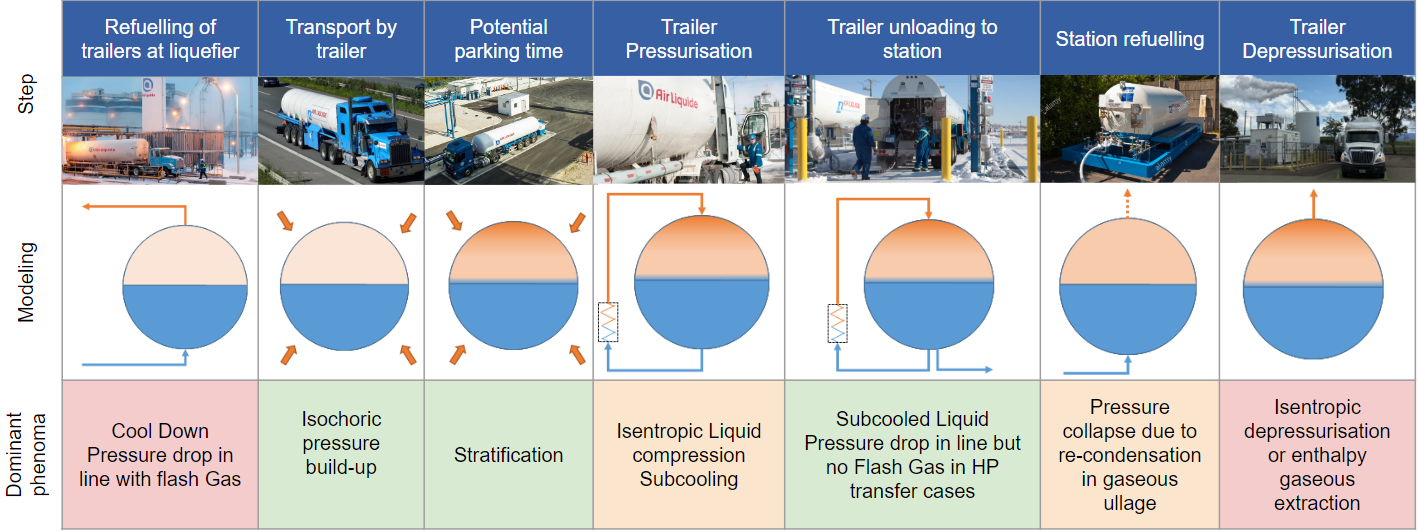
Some major players (for instance CMIC, world leaders in container manufacturing) have currently research and development programs about LH2 storage and transportation.

The current storages operate with saturated liquid hydrogen. The storage only acts as a product buffer, and not as a cold energy storage.

On site storages at customer sites are filled by trailers with industrial type interfaces and minimum automation. They are installed above ground either vertically or horizontally. Storages to be integrated with cryogenic pumps have special piping arrangements.

* **WP 3 : Liquid hydrogen road transport**

Liquid hydrogen is transported from the production site to the customer installation by trailers or ISO containers when multimodal transportation is required.

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*Figue3 : LH2 transport chronological sequence analysis*

As shown in the figure hereinabove, different thermodynamic transformations are associated with trailer filling, transport and delivery, these steps are not easy to simulate and are significantly different than with other cryogenic gas systems (where for instance the liquid is transferred by pumps).

Hence, trailers and containers are also significantly different from other cryogenic gases systems.

Moreover, as liquid hydrogen is flammable, all vents must be collected to a safe location. In order to avoid as much as possible frozen air and air condensation resulting in possible oxygen enrichment, all cryogenic piping must be vacuum jacketed. This results in costly and complex valve cabinets representing a large part of the trailer CAPEX.

Product transfer from usual cryogenic gases (liquid oxygen, Nitrogen and Argon) are typically handled with pumps. Due to the low liquid hydrogen temperature and density, product transfers in LH2 are done by pressure difference. This requires to build the pressure in the trailer with warm hydrogen to handle the transfers which has two consequences : higher trailer design pressure and need to bring energy to the fluid to be transfered (i.e. heating it up).

This is detrimental to the trailer CAPEX (high design pressure) and product quality (higher saturated pressure).

The transfer panel is manual, connexion systems require handling of heavy double wall hose and non user friendly screwed or bolted connectors to transfer product to the customer system, with time consuming inerting and Hydrogen conditioning.

There is currently in Europe only one manufacturer having experience with european LH2 trailers design and manufacturing (CRYOLOR, Air Liquide Group subsidiary), and two suppliers capable of supplying ISO containers. Production volumes are a few trailers once every 5 years (mostly for renewing the existing fleet).

The production capacity of such equipment must be increased dramatically to meet the foreseeable future demand of liquid hydrogen transport, and the manufacturing process has to be adapted to drop the cost.

* **WP 4 : Liquid hydrogen refuelling stations**

Today on the market, there are few refuelling stations fueled by liquid hydrogen (LH2 HRS):

* Around 100 LH2 HRS, to fuel 35 MPa forklifts in operation in the US (most of them designed by Air Product, and operated by PlugPower)
* 8 LH2 HRS to fuel 70 MPa cars in operation in Germany (designed by Linde, and operated by H2M Germany consortium), 2 LH2 HRS in construction in Germany
* 1 LH2 HRS to fuel 70 MPa cars in operation in California (designed by Linde and operated by First Element Fuel), and 50 new LH2 HRS under planning by FEF in California.
* Few LH2 HRS in California to fuel 35 MPa buses in California (designed by Linde and Air Product)
* Few LH2 HRS in Japan to fuel 70 MPa cars and buses (designed and operated by Iwatani).

Most of those stations show a low level of reliability (<< 1000h mean time between failure for the pumps) and a high average level of boil-off.

However, contrary to most of the market actors, Linde demonstrates performant HRS systems, with low boil-off (less than 5kg/day vented H2), thanks to significant investment to develop a well performing LH2 pump and LH2 HRS.

Moreover, the current regulation, codes and standard framework is either very stringent regarding liquid hydrogen (in France for example), or not existing (in China for example).

These facts tend to disqualify quickly the liquid hydrogen based refuelling station despite all the advantages brought by the supply chain and the characteristics of the molecule.

* **WP 5 : Regulations, Codes and Standards, including Safety**

In France, there is no specific regulation on liquid hydrogen refuelling stations. The closer regulation is ‘Rubrique 1416’ : “*Stockage ou Emploi de l’hydrogène, Stations-service : installations, ouvertes ou non au public, où l'hydrogène gazeux est transféré dans les réservoirs de véhicules, la quantité journalière d'hydrogène distribuée étant supérieure ou égale à 2 kg/ jour*“ with the general prescription decree : “*arrêté du 22/10/2018 relatif aux prescriptions générales applicables aux installations classées pour la protection de l'environnement soumises à déclaration sous la rubrique n° 1416”*.

The scope specifically refers to gaseous hydrogen distribution, potentially with a liquid source, but liquid hydrogen distribution is out of scope.

This regulation refers to gaseous and liquid Hydrogen regulation under “rubrique 4715” where the measures related to liquid hydrogen storage are not compatible with the operation of a refuelling station (separation distance of 20 m from the property line whatever the LH2 quantity) as they were drafted more than 20 years ago (12/02/1998).

As of today, Air Liquide can reasonably conclude that, without a considerable effort, a liquid hydrogen refuelling station cannot be installed in France. It is the same case in most of European countries with the notable exception of Germany where demonstration projects can be authorized under an exemption regime.

Applicable European directive related to liquid hydrogen supply chain is mostly related to the industrial facilities storing hydrogen, with the SEVESO 3 directive[[5]](#footnote-5) defining different thresholds[[6]](#footnote-6) quantities of storage of dangerous goods which is translated to national regulation.

In France those thresholds are defined in rubrique 4715, with an authorization process to be followed from 1 ton of stored hydrogen, an authorization with SEVESO 3 low threshold between 5 and 50t and a SEVESO 3 high threshold authorization above 50t stored LH2.

* **WP 6 : Gas quality assurance**

As FCEV are very sensitive to some impurities in H2 which impact stack performances and in some cases can irreversibly damage it, car manufacturers , gas suppliers and public authorities have defined legal requirements with respect to H2 quality specifications and quality assurance standards for H2 suppliers. The current solution (quality assurance = sampling and laboratory analysis) is an essential step in the commissioning of stations.

In the frame of the French regulations, a decree dated 08 December 2017 specifies that the operator of an HRS has to verify the compliance of Hydrogen in accordance with a quality specification (EN 17124).

To carry out this control, the operator has to make the full analysis for the commissioning and regular control based on the risk assessment study related to the HRS according to EN 17124. This control can be subcontracted to external laboratories for the sampling and the following analysis.

The EN 17124 standard gives the list of impurities to control such as N2, Ar, O2, CH4, CO, CO2, H2O, NH3, sulphur components, other hydrocarbons, CH2O, HCOOH, He, and halogenated compounds. All these impurities have a well defined threshold. Some of these impurities may be removed from raw hydrogen or raw syngas in the different purification steps producing fuel cell grade H2. The EN standard also gives a protocol, based on quality risk assessment, to define the quality assurance plan to follow taking into account the production source and the supply chain.

All of these requirements are defined for H2 gaseous supply to FCEV. They have to be adapted and enlarged to match with liquid H2 supply.Indeed, it is critical to take into account the impurities which may liquefy or solidify in liquid H2 and then, could seriously impact the process with explosion risk, process clogging and thermodynamic effects.

* **WP 7 : Zero boil-off integrated supply chain**

There has been no pilot scale demonstration of a full liquid H2 supply chain in the past. In France, the only comparable project was the Horizon Hydrogen Energy project led by Air Liquide and cofinanced by BPI from 2008 to 2015 which consisted in developing a 700 bar supply chain for the stationary fuel cell market. This supply chain was finally not established as the market of stationary fuel cells for telecom sites did not develop as expected and the H2 storage development program was not successful.

In Europe, the total installed liquefaction capacity is 20 tons per day (tpd). This number has been stable for the past 20 years.

The current state of the art is for instance the European Air Liquide liquefier, installed in Waziers (Nord, Hauts de France) in 1986 with a rated capacity of 10 tpd. Gaseous hydrogen coming from the northern european network is liquefied and stored in 4\*250m3 liquid hydrogen storages. The plant operates in production batches to fill the storages, and then stopped, depending on the market demand. A fleet of 12 trailers (last one was built in 2008) and containers (last one was built in 1996) distributes the product to a customer portfolio, mostly in France. Due to the type of operations, boil-off gases are not recovered inducing a net loss of about 14% of the total produced volume.

Liquid hydrogen technologies started to raise interest again in 2018 with a new market focus to H2 Energy applications.

In 2018, Air Liquide launched a 30tpd liquefaction project for the US west coast H2 mobility market based on commercially available - state of the art liquefaction and distribution technologies, developed in the 80’s for the European, Canadian and space launcher markets. Those technologies are not adapted for low boil off supply chain nor for coupling with intermittent renewable energy sources.

In December 2019, Air Liquide and its consortium (Equinor, BKK, Wilhelmsen, Norsea group) was awarded a 3.2 M € subsidy by ENOVA to develop an entire LH2 supply chain in Norway This project is dedicated to the Norwegian LH2 maritime sector with use of the molecule as liquid in boats and production partly coming from a refinery off gas and from an electrolyzer coupled with non intermittent (hydro) renewable energy. This project does not include any terrestrial or aeronautic applications of liquid hydrogen and no exploration of the potential use of the molecule in the merchant hydrogen market is foreseen.

* **Summary of state of the art KPI**

Current technology bricks performances can be summarized with the Key Performance Indicators (KPI) which are summarized here below :

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **KPI Id** | **WP** | **Description** | **Value** | **Unit** |
| KP1-A | Liquefier | Specific Energy | 14.5 | kWh/kg delivered |
| KP1-B | Liquefier | Ramp-up / down | 0 | %/ min |
| KP2-A | Storage | Trailer filling time | 8 | hours |
| KP2-B | Storage | boil off rate | 0.3 | % of full capacity/day |
| KP3-A | Trailers | lead time (order to delivery) | 14 | months |
| KP3-B | Trailers | Cost of H2 transport (400km, 1tpd) | 1.2 | €/kg |
| KP4-A | LH2 Bunkering | time to deliver 3 tons | 4 | hours |
| KP4-B | GH2 refuelling | Boil-off (H2 vented at the HRS when HRS is loaded at 80%) | 20% | of delivered H2 a the FCEV |
| KP5-A | RCS / Safety | Average authorization process duration for a filling station (M1 to M4) | 6 | months |
| KP5-B | RCS / Safety | Authorization process duration for a liquefier (M1 to M4) | 24 | Months |
| KP6-A | Gas Quality  assurance | Analytical capability in Liquid H2 for the control of impurities | 20 | % of all the impurities critical for the safety of the supply chain |
| KP6-B | Gas Quality  assurance | Cost of H2 quality control | 0,6 | €/kg |
| KP7-A | Supply chain | Renewable Energy usage | 0 | (kWh renewable / kWh total) per year |
| KP7-B | Supply chain | boil-off rate | 14 | % of liquefied gas |
| KP7-C | Supply chain | LH2 supply chain TCO  *(30tpd, 400 km from source, 1000kg/d)* | 5.5 | €/kg |

### Technical locks that prevent improvements in the field

Liquid hydrogen distribution in Europe is currently very limited while the USA, where large distances between the sources and the customers, and the NASA activities supported LH2 liquefaction plants for the space program from the early 60’s to the late 90’s, have historically preferred this mode of distribution.

There are four main limiting factors, including two which are related to technology, to the liquid hydrogen market today:

* **Technical difficulties linked to the molecule**

The physical properties of liquid hydrogen require specific solutions that have not been implemented by industry until now due to a lack of market volume. The consequence is that the current products such as liquid pumps, cryogenic connectors, flow meters, emergency couplings, connecting arms,... available on the market are not really suitable for liquid hydrogen, they cause significant H2 losses and have low reliability.

The table here below summarizes the main difference between LH2 and liquid methane, water and the consequences on material design :

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Water** | **LCH4** | **LH2** | **Consequences on LH2 system design** |
| Boiling Temperature @1.013 bar abs (°C) | 100 | -162 | -253 | * Long distance pipes are a challenge. LH2 temperature is below air liquefaction temperature ⇒ **LH2 lines / tanks need to be vacuumed insulated**. * **Risk of oxygen enrichment** at the LH2 / air interface * Loss of product by evaporation during liquid transfert (as transfert lines need to be cooled down) |
| Gas to liquid density ratio | 0.0006 | 0.004 | 0.02 | * Gaseous H2 bubbles in liquid hydrogen to not behave like boiling water. **H2 bubbles have a low buoyancy and are easily entrained by the liquid**. * For the same heat input in a pipe, the volumic gaseous fraction is more important ⇒ **higher risk of gaseous plugs in piping** |
| Latent heat of vaporization ratio between 1 and 6 bar a |  | 1.26 | 0.78 | * LH2 at high pressure is easier to vaporize than at low pressure (opposite for LCH4) **⇒ privilege transport at low pressure** |
| Density ratio between 1 and 6 bar a |  | 0.90 | 0.82 | * LH2 at high pressure is less dense than at high pressure   **⇒ privilege transport at low pressure.**  **⇒ privilege volumetric pumping from low pressure** |
| Hydrostatic height for 1 bar overpressure (m) | 10 | 24 | 140 | * LH2 pumps will cavitate ⇒ **privilege liquid transfert by pressure difference** or **design very specific pumps** |
| Critical pressure (bar a) | 220 | 46 | 13 | * Above 13 bar, no more liquid phase ⇒ **stay below 13 bar** |

On top of those technical difficulties, liquid hydrogen systems will also need to handle gaseous hydrogen which has the following characteristics compared to methane

|  |  |  |  |
| --- | --- | --- | --- |
|  | **CH4** | **H2** | **Consequences on gaseous H2 system design** |
| Density compared to air | 1/10 | 1/14 | * Hydrogen will diffuse much faster than CH4 in air, resulting in different explosive mixture sizes. |
| Diffusion in air (relative) | 1 | 14 |
| Flammability limit in air | 4-17 | 4-76 | * Flammability range is more important for H2 than CH4 |
| Ignition Energy (µJ) | 290 | 20 | * Ignition energy for both gases are below the perceptible levels (1 to 10mJ) |
| Kinematic Viscosity (relative to air) | 1/1.6 | 1/2 | * hydrogen is lighter and less viscous with CH4, hence it will have a tendency to leak easily |
| Material compatibility | No issue | Embrittlement | * H2 fragilizes steels under stress. Therefore correct choice of materials is essential |
| Autoignition temperature (°C) | 537 | 571 | * Autoignition temperatures are similar. Hot surfaces will need to be avoided. |
| Flame temperature (°C) | 1961 | 2130 | * Flame temperatures are similar but H2 flame is much less radiative than CH4 |
| Flame color | orange blue | invisible | * The H2 flame is invisible (however in most of the cases, impurities and water in the flame makes it slightly visible) |
| Smell | when odorized | no smell | * H2 cannot be odorized as mercaptans used for odorization are sulfur based which would poison fuel cells. |

* **Outdated technologies to liquefy Hydrogen**

The only hydrogen liquefaction plant in France is more than 35 years old. The 10 tons per day liquefier is connected to the Northern Europe Hydrogen pipeline. It is switched on and off (0 or 100% load) to fill the on site liquid hydrogen storages (1000 m3, 70 tons capacity). Once the storages are full, the liquefier is stopped. This mode of operation is dictated by the lack of market, the lack of flexibility of the thermodynamic cycle (Claude Hydrogen cycle), the hydrogen expanders and cycle compressors. Thus, even with very large investments, this plant could not be coupled with intermittent renewable energy sources. Moreover this type of operation makes the recovery and condensation of boil off gases impossible when the trailer filling operations are done, as the liquefier section is not operating. Loss of reliability related to temperature cycle linked with frequent stop and start on the machines are also noticed.

These technologies are now outdated, incompatible with coupling to renewable energies, liquefaction yields are low and maintenance costs high. Moreover, this technology uses ammonia as a refrigerant in the first cooling step. It requires onsite ammonia storages which are actually the sizing element in safety studies, more specifically safety distances. Ammonia storage would be very problematic in terms of required safety distances in future plants which will need to be ten-times larger in capacity.

* **Less market perspectives**

The weak growth of the hydrogen market, as well as a good existing gas supply chain network answering industrial needs, have not allowed the standardization of a liquid hydrogen supply chain, limiting its applications to niche markets such as space or electronics industry.

* **Unsuitable regulatory framework**

In France, the safety studies which were used as a basis of the regulations were developed 35 years ago. Since then, the methods of risk assessment and impacts calculations have evolved a lot. This regulatory gap generates long lead time to obtain operating permits and higher costs.

In Europe, only the SEVESO directive regulates the installation of large hydrogen liquefiers.

These four interdependent points have historically limited the liquid hydrogen deployment. To ramp-up the liquid hydrogen sector, the following technological developments and political support are required: .

* **Reassessing safety studies and applicable regulations** with the regulatory authorities via a flagship experimental deployment project, carrying innovations,
* **Implementing larger, more efficient factories** that could be integrated with intermittent and / or renewable energy, enabling ambitious total cost of ownership targets to be reached,
* **Integrating technological bricks designed for liquid hydrogen**, making it possible to reduce evaporative losses to the absolute minimum, with high availability rates.

The project therefore proposes to implement this strategy by developing, experimenting and industrialising a liquid hydrogen supply chain dedicated to the specific zero emission mobility needs.

Technical difficulties more specific to each techno brick are summarized here below :

* **WP1 : Liquefaction**

If the production of decarbonized hydrogen is considered, the production will follow the availability profile of renewable energy, and consequently, could be intermittent. By construction, currently available liquefier technologies cannot handle large changes in hydrogen feed flow which would require real time cold duty adjustment.

Current European plants are not optimized to recover boil off gas and loading bays to deal with it. Those plants produce saturated hydrogen, which makes impossible the boil off recondensation by direct exchange of cold gas with subcooled liquid in the storage. Loading bays are not able to take boil off from trailers and send them to the process.

Some plants, with limited operational flexibility, are operated in batch modes, when the plant is not running, boil off from storage is vented to the atmosphere and not recovered.

Therefore, new liquefaction technologies will need to be developed and scaled up to produce efficiently decarbonized liquid hydrogen.

As of today, even if some plants are connected to electrolysers, both systems are never integrated to valorize the oxygen stream produced by the electrolyser in the liquefier.

* **WP 2 : Liquid hydrogen storage**

Storages are never used to store cold energy by subcooling the incoming liquid, as boil off recovery is not critical in industrial applications.

Due to the limited market, they have never been industrialized, and are built on a case by case basis (to the conttrary of Air gases storages which are managed on inventory).

Technological locks for LH2 storage at customer site

* Valves heat losses: integrating the valves within the vacuum jacket should reduce the losses but should not affect the vacuum level while requiring maintenance access
* Piping heat losses: minimizing as much as possible the distance between the storage and the control cabinet
* Supporting heat losses: new support design, as current designs are complex and not well suited for the application.
* Insulation: new material as well as new methods to instal this insulative material and better vacuum capability will be needed to improve the insulation efficiency in order to reach the cost targets, not possible with current designs

Technological locks for underground storage

* Regulations. Design and installation rules for underground storage tanks of flammable cryogenic liquids must be defined at European level.
* Vessel reaction to soil loading like oxidation must be taken in account (direct buried)
* Heat transfer on a buried storage will be different than on a traditional storage only in contact with air and might impact the insulation needs
* Need to lift up LH2 to the vaporizer installed on the ground while cryogenic pump have limited LH2 suction capability (NPSH)
* Detection of any underground leakage of the buried storage tank must be detected
* Excavation procedure definition
* Potential interaction with soil (seismic risk, …) and risk mitigation.
* In case of a tank installed in a vault : mitigation measures in case of H2 leakage.

Technological locks for storage on board of a train

* Regulations. Currently the RID gives design rules for transport of dangerous goods by road but does not cover the cryogenic tanks and its installations on board of a train nor the fuel cell, the connections and the heat exchangers. This topic will be addressed on the regulation work-package
* Fuel cell supply. Liquid storage will require a vaporizer. Footprint and installation constraints of an onboard system will lead to make this vaporizer more compact than usual and compatible with a confined environment. Heat exchange efficiency will then need to be strongly improved. will be fed from the tank either by the liquid or by the gas piping.
* Onboard tank filling. Need to develop fast and efficient filling tools. This is mainly addressed in the filling station package but here, onboard storage will have to be equipped with quick cryogenic connectors H2 compatible.
* Shocks and vibration will induce pressure fluctuations in the storage which can be detrimental to the fuel cell operation

Technological locks for storage on board of a ship

* Regulations and safety; to our knowledge there isn’t any national (or european) standard for installing liquid H2 storage on-board of any type of boat. Existing standards are covering LNG and are not adapted to LH2
* Totally different working environment ; design of onboard storage for ships would have to take into account the saltiness of the sea air, the boat instability related to the swell and the sea storms, the limited possible safety distances
* Infrastructure for FC fuelling in marine operations; a fortiori on a long distance boat storage and FC will obviously be segregated and machinery environment temperature could be pretty hot unlike open-air conditions faced on land based applications.
* On-board tank refilling; distance between the land-based H2 storage on the harbour and the tank on board of the ship is nothing comparable to what is done today in any H2 refuelling application.
* Shocks, vibration and waves will induce pressure fluctuations in the storage which can be detrimental to the fuel cell operation
* **WP 3 : Liquid hydrogen road transport**

Liquid hydrogen road transport trailers are currently customized to industrial needs. For Hydrogen energy uses, additional requirements apply to the trailers, such as :

* Capacity to deliver liquid at different saturated pressure levels, this is currently not possible on LH2 trailer fleet for industrial customers without venting large amounts of gas
* Capacity to deliver liquid in semi urban areas, with increased level of safety, where large trucks cannot manoeuver easily, this requires to develop delivery procedures and equipments (automatic connectors, automatic valves sequencing) which are not present on the current LH2 trailer fleet for industrial customers.
* Reduce as much as possible delivery times, hence develop new delivery procedures (automatic, high flow, …) which requires new types of gas cabinets on the trailers and innovative product transfer modes (transfer pumps for instance)
* Capacity to recover boil off and recirculate them to the liquefier. As of today, the current fleet does not allow this.
* **WP 4 : Liquid hydrogen refuelling stations**

Current refuelling station technology running on liquid hydrogen as a feed stream are not properly integrated with the upstream supply chain, inducing high level of losses; moreover, due to lack of market LH2 pumps currently on the market are designed for “standard” cryogenic liquid such as liquid nitrogen and have very poor performances and reliability when they are in hydrogen service.

Liquid transfer to on board LH2 tanks (so called LH2 bunkering) is not a common operation as of today and is only managed in industrial plants. Current good practices require the operators to wear personal protective equipment, and to follow strict inerting procedures, using screwed connectors and handling heavy hoses. These practices clearly cannot be used in the frame of a hydrogen bunkering station as the operators will not be LH2 trained specialists and need to have user friendly equipements. Liquid hydrogen connectors, breakaway and specific procedures need to be developed to reach this objective in a safe manner.

It is interesting to note that a very similar lock was existing in the early 2000’s when the first demonstration projects for gaseous filling at 350 bar were developed. The lack of experience in handling gaseous H2 in non industrial areas and the absence of adapted coupling (actually derived from CNG, but with material compatibility and service pressure issues) on top of the absence of industrial experience above 200 bar were making the first deployments very difficult, with safety attention to be taken during the refuelling unacceptable for the general public. This situation has now evolved with gaseous hydrogen to a point where a 700 bar cold filling in 3 minutes is possible to handle without personal protective equipment in an urban area (example of corner street HRS in California) at an acceptable level of risk.

Current customer invoicing is done by weighting the LH2 trailer in and out the customer installation. This will not be possible for Hydrogen energy customers ( a weighing station cannot be integrated at each refuelling station), and will be required to develop specific billing mass flow meters[[7]](#footnote-7) compatible with the LH2 environment.

* **WP 5 : Regulations, Codes and Standards, including Safety**

In France, there is no specific regulation on liquid hydrogen refuelling stations. The situation is somehow locked as the authorities will review a regulation draft based on an actual demonstration project which needs to be implemented with technology adapted to the H2 Energy market, hence in the frame of this project. If we would develop the regulation with the current technology, the requirements would not be adapted to the technologies that we need to develop to meet the H2 Energy market.

* **WP 6: Gas quality assurance**

In Europe, the operators of HRS have to verify the compliance of hydrogen quality in accordance with the specification given in the EN 17124 standard. To respect this engagement, they have to manage a quality control program including a full analysis check at the commissioning time. A verification of quality compliance must also be done after major maintenance. The current solution to analyse these impurities is to sample hydrogen at the nozzle of the HRS and to send this sample to a validated laboratory. This laboratory could have a variable response time leading to a loss of time during the commissioning of the station (quality control).

By the few number of available validated laboratories, the analysis cost and the response time are significant. The analysis of all the impurities specified in EN 17124, can be achieved in the hydrogen gas phase. In the case of liquid H2 there is a lack of analytical tools to control all of these impurities accurately. Moreover there are currently no low cost sensors available on the market for real time control of key impurities in hydrogen before and after liquefaction.

All along the liquid hydrogen supply chain, from upstream the liquefier to the customer installation, proper gas quality control protocols need to be developed to guarantee the safety of hydrogen infrastructure, operators and customers.

* **WP 7 : zero boil-off integrated supply chain**

WP 7 integrates all the techno bricks developed in the project. As they are all process wise integrated together, they need to be tested thoroughly as a whole in this WP at a first pilot scale and later at an industrial scale. The obstacles mentioned above also apply to WP 7.

More specifically, the setup of a supply chain for LH2 requires that there is a critical mass of LH2 to be deployed for H2 Energy applications, which cannot be the case as of today without strong incentives from the member states. This project would need to be deployed based on an existing regulatory framework which is as of today not adapted to H2 Energy. The purpose of this project is to unlock this situation by setting up a regulatory task force in WP 5 while developing the supply chain in WP 7. This parallel approach has already shown to work in the context of Hydrogen refuelling station in warehouses with DGPR[[8]](#footnote-8) and AFHyPAC[[9]](#footnote-9).

* **Summary of Key technical obstacles**

|  |  |  |
| --- | --- | --- |
| **WP** | **Description of technical obstacle** | **Type of improvement prevented** |
| ALL | outdated technologies | * Integration to intermittent renewable energies * Optimization of efficiency * Optimization of boil off |
| 1 | Not possible to use intermittent renewable energies with current liquefaction technologies | * Production of decarbonized LH2 from intermittent renewable energies |
| ALL | no technologies dedicated to LH2 specificities | * Optimization of efficiency * Optimization of boil off * Optimization of MTBF[[10]](#footnote-10) |
| 2 | limited industrialization level | * High costs * Important lead times |
| 2 | Absence of RCS framework | * Technical feasibility and approval of the system endangered |
| 3 | Not possible to deliver in non industrial areas (Hydrogen Refuelling Stations) with current trailers | * Use by non LH2 trained people in non industrial areas |
| 3 | Capacity to maintain the product quality with current trailer designs | * Use in high efficiency liquid hydrogen pumps |
| 3 | Capacity to recover boil off in order to maximize efficiency | * Optimization of efficiency |
| 4 | Current technologies are not efficient enough. too much product losses | * Optimization of efficiency |
| 4 | Procedure bunkering of LH2 in an on board storage is not adapted to non industrial environments (Hydrogen refuelling station) | * Use by non LH2 trained people in non industrial areas |
| 4 | LH2 mass metering devices do not exist | * invoice the customer |
| 5 | No regulation adapted and authority having jurisdiction requires a demonstration project to validate a draft regulation. | * Fast authorisation process and multiplication of projects |
| 6 | lack of low cost analytical tools for quality control of impurities in liquid H2 | * Development of analytical methods to reduce the cost of quality assurance |
| 7 | Minimizing the boil off in a supply chain requires all the techno locks described above to be resolved. | * Optimization of efficiency * Optimization of boil off |

e2 additional recommendations:

* For each WP, specify what technical obstacles the sector encounters that prevent further improvements in the field (current limits of the state of the art) quelles sont les verrous dans les WP actuels
* Use a table to summarize the information at the end of the section
* pas un objectif majeur pour le 20 Mars

### Objectives and technical challenges in the project

e2 additional recommendations:

* For each WP, describe in sufficient detail the objectives / innovations that the company aims at in the IPCEI with the associated technical KPIs (the “what?”)
* For each WP, prove that these objectives / innovations have never been met on the market so far (new to the world)
* For each WP, describe in sufficient detail what activities will be carried out to reach the objectives (the “how?”); they have to bring about fundamental novelty in the light of the state of the art
* Note: Please be very specific in this section, sentences of the form: “(performance indicator) will see a (%) rise/drop by (date)”
* les KPI doivent être comparés à ceux de l’état de l’art du 1.4.1
* Use a table to summarize the information at the end of the section, for example:

**WP 1.1 - Liquefaction R&D activities**

* Description and objectives

The objective of this WP is to develop, demonstrate and scale-up an efficient hydrogen liquefaction unit compatible with the requirements of coupling to renewable intermittent energies, including a recovery system for the liquid hydrogen evaporated in the supply chain.

The hydrogen liquefaction process is referenced with units in operation for many years. However, until now, the use of liquid hydrogen has been very limited, this explains small and limited units in operation today.

In order to meet the anticipated market needs for liquid Hydrogen in the coming decade (see chapter 7), the development of larger liquefaction units is necessary: selection of most cost effective process depending on plant size, scale up of key technologies such as rotating, ensure critical components supply chain scale up. In addition the efficiency of the whole value chain must be improved by improving liquefaction efficiency and recondensation of the gas returning from the vaporization of liquid hydrogen during the consecutive filling operations in the hydrogen stations. The recondensation of these molecules in the liquefier allows to limit losses in the chain and therefore the initial production of hydrogen (molecule recycled and no longer lost). The challenge lies in the fact that these returns of molecules (frequency, quantity, duration) are irregular and impact the liquefaction unit as they are generated by the downstream distribution logistics chain. Moreover, some impurities can be present in this returned gas.

The additional challenge to take into account is the intermittency of the hydrogen production by electrolysis using intermittent renewable electricity sources. The unit shall therefore adapt its load according to this unstable feed flow.

This work package will also focus on the development of cryo-coolers to be integrated with LH2 storages in hubs to make “zero loss storages'” with boil off condensation to lower from approx 5 to 0 % the amount of hydrogen lost during a transfer in an intermediate storage (This mode of operating LH2 supply chain is currently not done due to this high amount of losses). Technical studies will be carried out in order to determine the cold power to supply and the optimal technical solutions in terms of cost and ways to be directly integrated on storages.

The boil-off gas generation is classically due to :

* Natural heat inleaks on storage and transfer lines
* Trailers from liquefiers to feed the hub: heat inleaks during road travel and pressure build-up device (liquid inside trailer is vaporized and injected on top of the trailer).
* Trailers fed by the hub (in order to deliver customers) : heat inleaks during road travel, trailer depressurization directly in the hub and flash losses during trailer filling at the hub

National suppliers of magnetic bearings and high speed motors will be integrated into the development and industrialization process (S2M, Vernon), as well as suppliers of plate heat exchangers (Fives Cryogenie, Epinal).

* Novelty to the world
  + coupling to intermittent renewable energies
  + thermodynamic cycle
  + zero boil off
* How to achieve the objectives

After selection of main processes, a real industrial size (TRL7) system should be tested and validated in a test center. Once the system is qualified, the unit will be relocated on an industrial site for the prototype supply chain project and operated as such.

Not every innovation/concept will be tested in the unit described above. Extra prototypes and test benches (either internal or with Partners) are required.

* Main Innovations to be tested and validated
  + New process of liquefaction
  + Machine arrangement
  + Machine technology (centrifugal compression, liquid turbine)
  + Alternative ortho-para catalyst
  + Optimised purification : adsorbent selection and process cycle
  + Alternative Cold Box insulation
  + Advanced Control system for a full optimized unit
  + Packaged solution for a full CAPEX and layout optimization
* **WP1.1 : R&D Activities (up to TRL6 included)**
  + Development of an Air Liquide proprietary Ortho-Para Catalyst, in cooperation with the University of Strasbourg and taking advantage of the [Axel’One](https://axel-one.com/en/consortia/axelone-analysis/) Industrial Analysis Plateau;
  + Cold Purification of Hydrogen: investment of an R&D Cryogenic Breakthrough Test Bench for kinetics measurements on innovative adsorbents at 77K;
  + Reactive Catalytic Exchanger Design Tool Development with experimental validation;
  + Development of an Air Liquide in-house catalytic Brazed Aluminum Heat Exchange (BAHX), including design and modeling up to an R&D pilot, thus reaching TRL6;
  + Development of an Air Liquide LH2 Turbo-Brayton, adapted from the commercial Liquid methane Turbo-Brayton, including advanced modeling;  
    The objective of this project is to build an R&D pilot, thus reaching TRL6.
  + Develop further innovative ways to liquefy and take benefit from LH2 subcooling (liquid turbine);
  + Develop loading bays and process schemes / arrangements able to recover boil off from trailers
  + Being able to upscale the different technological bricks to be able to meet the foreseeable market demand up to 100tpd plants.

**WP 2.1 - Strategic storage - R&D activities**

* Description and objectives

The objective of this WP is to develop, demonstrate and scale-up innovative storage systems of liquid hydrogen for the following applications :

1. **Strategic storage** of product and cold energy at the liquefier site (between 70 and 200 t) to constitute a strategic stock in the event of a supply disruption, coupled with the recondensation system developed in WP 1.
2. **Customer installation storages**, above or underground (between 1000 and 4000 kg) in link with WP 4
3. **On board storages** for trains and ships (between 500 and 4000 kg), linked with customer specifications and properly integrated with bunkering equipments developed in WP 4

European based manufacturing plants and suppliers shall also be developed (new plant or refurbishment) for each of the products

**1- Strategic storages**

Gas liquefaction facilities have on-site storages to manage unplanned outages, or to cut-off the facility from the electricity network in the event of a temporary increase in the cost of energy. This is a classic use of storage in order to manage the available product inventory as needed. It is proposed here to add a cooling energy storage function to the storage by sub-cooling the liquid. Thus it will be possible not only to store liquid hydrogen but also the cold energy to limit losses by evaporation. The current liquefier technologies do not allow this experimentation, this must be coupled with the experimentation of new liquefaction cycles developed in WP1.

In this work package, the opportunity of installing liquid hydrogen strategic storages in the supply chain with the goal to recondense boil off and reduce the LH2 saturated pressure will be studied. These storages would be used as logistical hubs. A primary logistical loop consisting in large semi trailers would fill a hub intermediate storage from the liquefaction plant, and more compact and automatized trailers would deliver the liquid hydrogen to the final users. This scheme has the advantage of delivering liquid hydrogen to applications in urban areas with compact trailers and cooling down the liquid hydrogen in an intermediate storage just before delivery. This kind of storage could also be considered as strategic storages in case of rupture of supply. However, the cost of this solution would significantly increase the final molecule cost. Therefore, the opportunity of installing logistical hubs should be carefully considered depending on the applications to be targeted.

The hubs will not create boil off gases as the liquid will be cooled down by a cryogenic cooler to be developed in WP1 while it is stored.

The storage could be developed by European companies (ex CRYOSPAIN) in case of spherical storage, and in collaboration between Air Liquide and Chaudronnerie de l’Est (Langres) in case of large cylindrical storages.

**2- Customer installation storages**

* Description and objectives for **Liquid hydrogen storage at customer sites**

Existing LH2 storage installations consist of a tank made of an inner tank, in contact with liquid H2, insulated and nested inside an outer tank built in order to reach an extreme vacuum inside the interstice between the 2 tanks and an aside skid mounted control cabinet leaned against the tank. Current heat losses through the piping and valves material as well as through the tank construction (insulation efficiency and inner tank supporting inside the outer tank) drives so call boil-off rate of about 1% daily losses of hydrogen. Improvement of this boil-off rate will lead to direct material saving

* Objectives

The main objective is to reduce the hydrogen losses due to pressure rise inside the tank and the related degassing phenomenon. As a side win, this will minimize installation safety distances. To achieve this objective, the insulation of the tank must be improved. This improvement will call for new insulation material and for thermal bridges heat losses reduction. Such reduction is mainly due for inner tank supports, valves and connection piping. Ideally valves and accessories could be integrated inside the vacuum jacket but this integration must not affect the insulation capability of the tank although an inspection hatch will be required for maintenance purpose. The operations of these valves will have to be done remotely (i.e. with a dedicated automatic control unit).

* How to achieve the objectives

A prototype cryogenic vessel will be designed and built using such latest developments and then operated and monitored over a 12 months test period to validate the efficiency of these developments on different operating conditions. Once confident with the results, a bigger prototype will then be manufactured and evaluated on the LH2 supply chain of an HRS as part of this project. After a given period of utilization, industrialization should be able to be launched.

* Main Innovations to be implemented

o new insulation

o cryogenic valves integrated inside the tank (in vacuum jacket)

o automatic filling

* Description and objectives **for Underground Liquid hydrogen storage**

Hydrogen Refueling stations (HRS) suffer from rather large footprints because of their intrinsically bulky hydrogen equipment, especially when compared to conventional fuels. For example, a stationary LH2 tank takes about 4 times more space than a Diesel tank for the same equivalent usable energy… to be compared with the ratio of 20 for compressed storage at 30 bar and room temperature. The only way to overcome this drawback is to install those LH2 tanks underground, as it is done today for conventional refueling stations.

Underground storages could be foreseen either buried directly or installed in an underground cavity. One can quickly choose to go for the buried solution since its cost will be much cheaper while this move is not trivial as it might have other significant drawbacks (integration with a pump).

* Objectives

The objective of this WP is to develop a set of solutions for storing liquid hydrogen in horizontal or vertical underground static vessel (direct buried of in a vault, depending on safety analysis) located in a filling station in a city in order to keep comparable footprint than traditional fuel filling station and to minimize the safety distances of usual ground based storages.

To reach this target the design must be compliant with buried installations even in a seismic area, that means all supporting including the one between the inner and the outer vessel of the tank must be reworked as well as the diverses coupling point and that means also special coating or surface treatment to reduce oxidation phenomena and chemical reactions with the soil will be required.

Immersed circulation pumps are foreseen in order to ensure the LH2 transfer to the ground based vaporizer; this pump immersed in a cryogenic liquid has to be developed and its installation inside a tank will call for a manhole with all the related tightness and insulation concerns links to LH2 storage.

Special attention will be given to define the means to operate underground tanks in safe conditions

* How to achieve the objectives

Regulation should be addressed with operators, cities and standardization organizations within the regulation work-package

A prototype cryogenic vessel at reduced scale will be operated and monitored in an underground environment for a 12 months test period. A thermo-mechanical model will then be developed to extrapolate the experimental results and to serve as an engineering tool for designing a bigger prototype. Such a bigger prototype will then be manufactured and evaluated on the LH2 supply chain of an HRS as part of this project. After a given period of utilization, industrialization should be able to be launched.

* Main Innovations to be implemented
  + Circulation pump immersed in cryogenic flammable liquid
  + Manhole compatible with extreme tightness
  + Highly insulated manhole
  + Thermal model for underground structure
  + Remote automated valve box

**3- On board storages**

* Description and objectives **for Liquid hydrogen storage On board of a Train**
* Objectives

The main objective of this package is to develop a set of solutions for storing onboard liquid hydrogen to feed a fuel cell to make electricity to power the electric motors which have replaced the train ICE .

Going further in the details, optimizing the losses of the tank storing liquid hydrogen will be a priority because it will allow the greatest possible autonomy. This optimization requires the development of very specific on-board tanks that comply with specific regulations not yet defined. To fill the tank safely, quick coupling connectors compatible with liquid hydrogen and equipped with a anti-tow-away system must be developed as well as means to inert the tank filling line as well as the connection hose for safety purposes.

A gas handling unit will be developed to manage the safety of operations, and the H2 delivery to the fuel cell.

* How to achieve the objectives

Different means to achieve the main objective will be developed and tested separately. Once qualified, these sub-parts will be integrated in the onboard hydrogen storage and supply system design. A first series of prototypes will then be manufactured and tested on an OEM system (yet to be identified). If needed reworks will be done to tune the functionalities of these new onboard LH2 tanks. When the solution will be validated by the OEM, industrialization will start in the FID phase.

* Main Innovations to be implemented
  + Definition of integration principles
  + Segregation of the interfaces and the tank
  + On-board LH2 volume maximization related to the volumetric footprint available
  + Automatic filling
  + Automatic H2 supply to the fuel cell (with Gas Handling Unit)
  + Fast and safe cryogenic coupling
* Description and objectives **for Liquid hydrogen storage On board of a Ship**
* Objectives

In terms of logistic and on-board storage of H2, we can split the float in 2 categories: the one covering long distances like the huge container ships and the one covering inland and short distances like ferries and self propelled barges. Indeed long distance will need large amounts of H2 stored on-board as there are not any fueling stations in open sea and here liquid H2 has strong advantages against compressed H2 thanks to its volumetric capacity (volume occupied for a given H2 quantity reach a ratio of 9 compared to 350b). But today such Hydrogen storage is a key technological barrier to the development and widespread use of fuel cell power technologies in marine transportation.

The main objective of this WP is to develop a set of suitable and profitable solutions for storing liquid hydrogen onboard diverse vessels to feed a fuel cell making electricity to power the electric motors which would replace ICE . These fuel cells + LH2 storage could be installed either inside the ship hold or on the deck.

Going further in the details, as for the train application, optimizing the losses of the tank storing liquid hydrogen will be a priority because it will allow the greatest possible autonomy. This optimization requires the development of very specific on-board tanks that comply with both IMDG and shipowner regulation as well as the typical marine implantation constraints like corrosive environment or supporting frame rocked by the waves.

On-board storage refilling infrastructures as well as FC fuelling infrastructures adapted to several scenarii of vessel sizes and storage typical on-board installations will be developed and optimized, having in mind how safety is critical on a vessel.

* How to achieve the objectives

The 2 options (on the deck or inside the hold) will be deployed in parallel so the development. Each sub-parts will be developed and tested independently until their evaluation matches the target. Preliminary tests will be performed on a prototype integrating the different elements developed under liquid nitrogen for a 1st validation and optionally iterative reworks will be done. This prototype will then be tested in a workshop built specifically to reproduce the conditions of a tank in the hold in cooperation with an OEM ant in liquid hydrogen this time. Once qualification tests are passed successfully, a first of a kind industrial size system will be designed, manufactured with its ancillary gas handling station and integrated onboard of a boat as well as all the required Hydrogen safety devices.

* Main Innovations to be implemented
  + New insulation concept
  + Design of vacuum isolated liquid transfer lines.
  + Integration of the main valves in the vacuum lines or in the vacuum inter-wall
  + Segregation of the interfaces and the tank
  + Automatic filling
  + Automatic H2 supply to the fuel cell (with Gas Handling Unit)
  + Fast and safe cryogenic coupling
* Novelty to the world
  + Zero boil off storage with integrated recondensation
  + Safe underground storage integrated with pump
  + on board LH2 storages for maritime and rail applications with optimized user experience

**WP 3.1 - Transport - R&D activities**

* Description and objectives

The objective of this work package is to move away from the 50 years old solutions to transport LH2 and to develop adapted and cost effective solutions for transport of liquid, compatible with the zero boil off goal and specificities of the delivery of liquid hydrogen in H2E applications. More specifically, the quantified objective is to go from 14% losses on the total supply chain to less than 2% which is considered to be a realistic absolute minimum (as some H2 still needs to be used to purge and cool down the transfert lines).

A large part of these efforts shall be focussed on industrializing the production of trailers and containers, from a few units every 5 years to dozens every year to follow the expected rise of the demand.

The transport of liquid hydrogen is well controlled to date and the main accidents are road accidents, for which the transported hydrogen was not the cause and where it has not worsened the consequences (apart from the usual precautions linked to the search for leaks during first aid intervention).

However, optimizing losses during the filling and emptying phases of transport trailers has never been a priority. This optimization is closely linked to the upstream and downstream equipment and requires the development of specific transport trailers. In addition, product delivery for hydrogen mobility applications usually take place in non-industrial environments and must be automated, which is currently not the case.

* Novelty to the world
  + Dedicated H2 Energy Trailers and containers
* How to achieve the objectives

Different means to reach the targeted objective will be developed and tested separately. Once qualified, these sub-parts will be integrated in the container or trailer design. A first series of prototypes will then be manufactured and evaluated on the LH2 supply chain as part of this project. If needed reworks will be done to tune the functionalities of these new containers.

After this development step, industrialization will start.

* Main Innovations to be implemented
  + Maximized the ratio transported volume/container footprint
  + Fully automatic valve box
  + Fast and safe cryogenic coupling
  + Cryogenic flow meter for billing
  + Ability to perform multiple filling at different loading conditions

As part of this work package, a supply chain optimization will be done, involving :

* + filling systems for truck, objective to recover gas evaporated during the transport of liquid and recondense it in the liquefier
  + Standard trucks, adapted to the needs of the H2 Energy market
  + Adaptation of the Air liquide fleet sizing software to the specificities of the LH2 supply chain for H2 Energy applications
  + Dispatch optimization tools with telemetry data integration from connected truck and site demand, with features specific to hydrogen energy : dynamic traffic control for delivery forecast in urban area, control of boil off, control of liquid hydrogen quality (saturated pressure)
  + Process optimization: integrated Boil-Off Management Process Tool including new innovations like subcooling, transfer pump, boil-off pump, etc.;
  + Critical hardware equipment development, adapted to the use in liquid hydrogen, such as billing flow meters, clean break coupling, emergency release couplings, hoses.
  + Technical study of a LH2 to LH2 station to perform refueling of onboard liquid hydrogen tanks for mobility applications such as long-haul trucks, ferries and planes.

**WP 4.1 - Stations / Usages - R&D activities**

* Description and objectives

The objectives of this work package is to develop specific refuelling stations for each identified market, and get customer satisfaction on the fueling experience and fueling business model.

In all cases, the implementations are closely linked to the regulatory environment, they must be developed on a case-by-case basis. The project therefore proposes to develop a range of stations supplied by liquid hydrogen that can be installed in most environments, making it possible to deliver hydrogen in liquid form, or in gaseous form at 350 and 700 bar. High pressure pumps, quick couplings and emergency liquid couplings, as well as heat exchangers and liquid saturators will be developed in this work package. Specific liquid hydrogen storages (above or underground) will need to be developed.

Each of the segments will require dedicated products, with strong synergies between the technology bricks. The regulation, Codes and standards approach (to be developed in WP 7) will be extremely different between a station to be implemented at a corner street (S1.1) and in an airport (S4.2).

In M1 market, gaseous and liquid dispensing will be developed. M2 and M4 will be mixed usages. M3 will be purely liquid dispensing.

* **Light duty refueling stations (Gaseous on board storage) (M1)**
* **Heavy Duty Road - Buses & Trucks - (M2)**

* **Heavy Duty Rail - Train (M2)**: to expand the autonomy of Fuel Cell trains (passengers or freight), while not impacting the size of the train car and/or not drastically reducing the payload of the train, liquid hydrogen will be the solution for the zero emission trains in many geographies and applications. Specific developments and pilot will be required to validate the technology and the operating framework, such as to identify and solve the technology challenges for having LH2 onboard a train, the refueling sequences from an operating and safety point of view, and validate the autonomy benefits in terms of cost-value compared to a gaseous hydrogen solution. **Alstom already expressed its interest to collaborate with Air Liquide on this program**. This WP will be synchronized with work done in WP2 - on board LH2 storage.
* **Maritime Applications (M3) :** . The development and use of LH2 can play a role in shipping decarbonization, aligning with the International Maritime Organisation (IMO) ambition to achieve 50% emission reduction for maritime transport by 2050 compared to 2008 baseline. The commercial-scale LH2 development includes the bulk international transportation on ships as well as offering LH2 as fuel to marine customers. It is essential to have credible, low-cost concepts and solutions to ensure such opportunities are economically viable.

**

*Figure 3 : Advantages of LH2 in maritime applications. Source BKK*

* **Civil aeronautics (M4)** : In parallel to the development of H2 powered aircraft, the conditions for deploying a suitable hydrogen infrastructure in airports must be studied. First H2-powered aircraft will be available for demonstration between 2025-2030. This implies to study and validate the issue addressed by this project earlier and making H2 available for other types of users. Then, in order to prepare the aeronautical sector to the introduction of hydrogen in an aircraft (main power for propulsion, APU units or galley) and ground support vehicles running on Hydrogen, it is expected in a first step to deploy typical fuel cell electric vehicles refuelling stations in the vicinity of the airport in order to adapt the current regulation codes and standards applying to an airport environment (both inside the airport and in the surrounding zone). Also, the operating framework to supply and to use liquid hydrogen in the vicinity of the airport, to fit with its daily activity while not preventing the expansion of the airport activities in the long term (i.e. regulation constraints) will be developed and adapted for the full scale. Concretely, installing an inventory of liquid hydrogen next to the airport will allow to start solving some of the relevant permitting issues while serving customers both inside and outside the airport.  
  Main target of the first phase will be fleet vehicles such as taxis, shuttle buses and delivery trucks. Then, ground support equipment operating on the airport area, and refuelled outside will be developed. Once these two steps will be validated and the regulation codes and standards framework will be ready, the refueling of airplanes operating with on-board liquid hydrogen tanks will be addressed. In this market, the main interest of liquid hydrogen is its volumetric and gravimetric storage efficiency. The main actor identified as of today in France / Europe are Airbus for passenger aircraft (short haul and subsequently longer haul airplanes). **Air Liquide initiated early discussions with Airbus and plans to set-up development works, together with VINCI Airports, fitting with the above objectives. Section of this work package could be developed at the Lyon airport.**  
  Other smaller aircraft manufacturers such as DAHER (former SOCATA), Pilatus, Beechcraft for single or twin engine aircraft carrying up to 19 passengers would also be interested in the outcome of this project. Note that these smaller aircrafts are using turbo propulsors that could directly burn liquid Hydrogen instead of converting hydrogen into electricity via a fuel cell.
* Novelty to the world
  + Full range of hydrogen refuelling and bunkering stations with optimized user experience
* How to achieve the objectives

To achieve the objectives, it is necessary to perform those activities:

* + Market understanding and definition of appropriate functional requirements for each market
  + System engineering
  + Component qualification and testing
  + System testing
  + Improve the system with operational return of experience
* Main Innovations to be implemented
  + LH2 piston reciprocating pumps at 450 bar and 900 bar, at low flow (45kg/h) and high flow (600kg/h)
  + LH2 transfer pump to transfer LH2 at high speed with low boil-off
  + HRS fueling processes to fuel light duty FCEV (700 bar 1kg/min) to Heavy Duty (700bar, 100kg/min)
  + Low boil-off and automatic off-loading process between LH2 trailer and LH2 HRS
  + Fueling protocols
  + Fueling hardware development (nozzle, hose, breakaway)
  + Low boil-off LH2 tank
  + Underground tank
  + Reliable valves
  + Reliable dispensers
* Activities:

LH2 Refueling Station:

* + Advanced LH2 Pump design and prototype development with European partners;
  + Process Modelling of all station equipments and specifically a refined model for the pump and the liquid hydrogen tank, taking into account the architecture and the hardware components, e.g. seals, check valves, drive, pipings;
  + Underground LH2 storage to reduce hydrogen refuelling station footprint
  + Underground LH2 Storage Surroundings Thermal Analysis to evaluate the insulation and mitigation measures needed to avoid the soil freezing around the storage.
  + Development of two subscale test benches to perform specific tests on both HP LH2 pump seals and check-valves, in order to improve the design and materials of the two most critical components of the LH2 HP pump.
  + CcH2 / LH2 Composite Hydrogen Tank Development with specialty chemicals and advanced materials partner Arkema and composite tank manufacturer Covess.
  + FCH-JU OBLHyT project submitted to AWP 2020 to develop onboard liquid hydrogen tanks for trucks. Air Liquide being the main actor of a consortium gathering key industrial players such as Engie, Shell, SAG, Daimler, Volvo Trucks, etc.
  + Development of a LH2 test pad in Air Liquide's Grenoble facility to perform full-scale experimental tests of LH2 high-pressure (up to 1000 bars) pumps, LH2 flowmeters, LH2 transfer pumps and LH2 tanks.
  + First-Of-Its-Kind LH2 Station Development in the US to refuel light-duty 700 bar hydrogen vehicles.

**WP 5.1 - Regulation, Codes and Standards, including Safety - R&D activities**

* Description and objectives

The objective of this WP is complete a RCS gap analysis and develop a dedicated regulatory framework for the use of liquid hydrogen and the associated supply chain together with the competent national and European authorities:

* In France: Ministère de l'écologie et du développement durable, Direction Générale de la Prévention des Risques.
* In Europe thru prenormative research projects and discussions with the commission in case opportunities for new directives are detected.

During previous deployments of hydrogen solution for mobility (for example H2 refueling station for forklift), the development of adapted regulations was carried out by Air Liquide in close collaboration with the regulatory authorities (DGPR) as part of a real deployment project serving as a model. It is proposed in this project to keep the same approach. The pre normative and security research must be carried out beforehand in order to propose installation rules which will be discussed and integrated into standard or adapted nomenclatures or orders.

The RCS (*Regulations, Codes and Standards*) approach will have to closely support both the different bricks of the supply chain (vertical approach) but also the different market segment envigased (horizontal approach).

RCS work will be done in close collaboration with INERIS *(Institut national de l'environnement industriel et des risques*) and AFHYPAC (*French Association of Hydrogen and Fuel Cells*), with possible participation of external testing laboratories and representatives from the industry (insurance companies, third party experts, fire brigade…).

This Work package will also handle Safety related activities of the project,

* Novelty to the world
  + Set of adapted regulations for hydrogen liquefaction and refuelling stations
  + Hazardous scenarios calculation and consequences mitigations tools for liquid hydrogen used in Hydrogen energy environments.
* How to achieve the objectives

For each country where a gap in regulation is identified for a specific techno brick, a draft regulation will be proposed and discussed with the authorities having jurisdiction in a working group managed by a professional association (AFHYPAC in France, or EIGA at European level). The FID project will serve as a pilot project for the implementation of the regulation.

**WP 6.1 - Gas quality Assurance - R&D Activities**

* Description and objectives

The objective of this WP is to develop a quality assurance protocol, low cost measurement methods and ultra purification techniques to monitor and guarantee the gas purity at the customer interface. When considering liquid hydrogen, quality of the gas also includes monitoring the impurities which may liquify or solidify in liquid H2. These impurities could ,in the best case, clog the heat exchanger, in the worst case, create an explosion risk (solid oxygen accumulation) but also guaranteeing a liquid thermodynamic state (saturated pressure, subcooling level) at the customer interface.

First a technical document detailing the impurities that may exist in LH2 would need to be developed. To quantify the risk of impurities for LH2 transfill, relevant analytical data from high purity hydrogen transfill from liquid hydrogen tanks will be used (in Waziers, France for instance) Hydrogen quality for Fuel cell applications is critical to guarantee over time the fuel cell performances.

Hydrogen quality insurance must be defined at different level of the supply chain, and must be addressed adequately :

* Beforehand the liquefaction step, it is important to remove all traces of impurities to avoid their solidification at liquid hydrogen temperature. First consequence would be to clog heat exchangers or damage turbines, in the worst case it would be an explosion in the case of accumulation of solid oxygen (less than 0.5g of solid oxygen in a liquid hydrogen pipe is enough to break it). low cost and reliable analytical methods shall be developed for the key impurities to control in order to have a real time monitoring of the incoming gas quality.
* After hydrogen liquefaction, all impurities in liquid hydrogen at 20K are supposed to be solid, accumulate in storages, and are not present in the distributed liquid. This supposition has never been verified, as some impurities at low levels of a few ppb or tens of ppb could very well be dissolved in the liquid hydrogen. Very little literature exists on the subject, and studies should be done to verify experimentally the solubility level of impurities in liquid hydrogen.
* In the storage, accumulation of solid impurities can create a hazardous scenario, either by physical clogging of piping (like level or pressure measurement) or by risk of explosion in case of comburant (most likely solid oxygen) accumulation, and further ignition linked with particle displacement or shock. Procedures shall be developed to monitor the accumulation of such particles, safely and economically purge them from the storage when the critical quantity has been reached.
* During the delivery process, air and humidity can ingress in the liquid hydrogen. Moreover, liquid hydrogen heats up and therefore its saturated pressure increases. This increase can be detrimental to the operation of the customer installations such as pumps and storages (as the density and latent heat of vaporization are a decreasing function of saturated pressure). Therefore, most of the customers include in their product specification requirements not only impurities but also saturated pressure. This temperature and pressure requirement is not at all considered in current operations of the industrial liquid hydrogen supply chain and might have dramatic consequences on the cost of the molecule if it needs to be further cooled down during the delivery process.

It is therefore necessary to develop all along the liquid hydrogen supply chain, from upstream the liquefier to the customer installation proper gas quality control and assurance to make sure liquid hydrogen is on specs and safety is insured. This work will be performed in close collaboration with partners to be identified.

* Novelty to the world

Gas quality assurance procedures and analytical instrumentation compatible with H2 mobility specifications and constraints, particularly costs and safety associated to the risk of solid impurities accumulating in LH2 systems

* How to achieve the objectives
* State of art detailing the impurities that may exist in LH2
* Experimental tests showing the solubility level of impurities in liquid hydrogen
* Development of quality assurance protocol, low cost measurement methods and ultra purification techniques to monitor and guarantee the gas purity at the customer interface
* Main Innovations to be implemented
* Identification of potential impurities to be found in H2 according to the production process before liquefaction
* Development of low cost solutions including low cost sensors for real time control of key impurities before liquefaction
* Study of impurities in LH2 after liquefaction
* Study of epuration processes in case of issues with impurities
* Study of potential contamination among the supply chain including the storage

**WP 7.1 - zero boil-off integrated supply chain - R&D Activities**

* Description and objectives

The objective of this WP is to demonstrate the effectiveness of an integrated zero boil-off liquid hydrogen supply chain by assembling all the technological bricks developed in the work packages 1 to 6 to create a first low scale pilot project (R&D, TRL6)

In this work package, a transversal operation control system able to manage the full production chain and allow visibility for molecule availability, predictive maintenance and remote operations /monitoring capabilities will be developed and validated.

Each of the techno bricks described above are intimately linked as the product losses along the supply chain should be recirculated to the liquefier to avoid losses.

It is proposed to implement a pilot industrial project of a significant size to reach competitive prices (6 to 15 tpd) in order to validate at a reasonable level the full supply chain in predetermined pilot applications. This plant capacity, still being significant, only represents the daily consumption of 20 to 40 ships, 300 to 600 buses, or 50 to 100 trains.

The objective of this pilot scale project will be to validate the technical feasibility of the zero boil off supply chain in a representative environment at a critical size.

The project will also validate the feasibility of a renewable liquid hydrogen production and distribution to end users as required by the market.

* How to achieve the objectives

setup from a single source of renewable hydrogen, a liquid hydrogen supply chain, relying on technology bricks developed in WP1 to WP4,and methodologies, standards developed in WP5 and PW6.

This will require to develop a critical size early customer portfolio, secure a renewable gaseous hydrogen source, a land to install the liquefier preferably next to the source, engage solution development process and engineering studies, start discussion with authorities to approve the system, design, manufacture and install the liquefaction plant with its utilities. Meanwhile, operation team will need to be hired, trained operation procedures will be determined, and remote operation principles will be developed.

customer installations will be developed and installed on the same operating mode. A fleet of LH2 trailers will be ordered, manufactured and operation will be prepared by setting up the logistical optimization tools to manage dispatching. Transport companies will be selected to operate on a daily basis the trailer fleet.

* Main Innovations to be implemented

renewable LH2 supply chain dedicated to Energy market implementing all the innovative techno bricks developed in the different project work packages..

## First Industrial Deployment (FID)

*For each WP describe the FID investment and linked Opex insisting on the description of beginning of FID (after R&D phases) and the end of FID (before mass production).*

*Cf. FID definition in Guidelines.*

### Purpose of the FID phase

**WP 1.2 - Liquefaction - FID activities**

* Objectives

1. Demonstrate the industrial model developed at the R&D phase
2. Upscale the technology developed during R&D phase
3. Complete at industrial scale unit the Engineering Design phase and solve all technology and manufacturing details
4. Industrialize specific equipments in order to reach FID targeted costs
5. Test the market for full scale equipment supply
6. Check the operability at full plant scale (start up, stop, ramp up, ergonomy…)
7. Confirm the CAPEX / OPEX hypothesis developed during the Pilot phase
8. Reassure the market about the concept industrial feasibility and open new market for the mass deployment
9. Test the applicability of the regulatory framework (safety distance, permitting procedures, acceptance from authorities & neighbours…).

* How to achieve the objectives

1. Develop a business case (identification of Clients, site, Utilities provider)
2. Confirm the business plan and associated economics and funding (including subsidies mechanism).
3. Define the execution strategy, e.g. partner with engineering company for the design integration and general contractor for the construction
4. Develop a Front End Engineering Design to confirm :
   1. the plant design,
   2. technical solutions for different innovative technologies scale up,
   3. capital investment cost of the First Of It Kind unit
5. Partner with component manufacturers to industrialize subsystems (motors, turbines, compressors, heat exchangers ...) including development of design tools, performance test bench, specific manufacturing tools
6. Confirm the long term product design, execution strategy and associated performances and costs
7. Perform site performances and long term run tests including specific monitoring, advanced control loops, specific testing protocols that could affect plant normal production plan.

Above successful pilot innovations which KPI performances are achieved and which are relevant to fulfil the FID project business plan will be scaled up and industrialised for first of its kind at scale project. In particular, we expect to implement :

* + New process of liquefaction
  + New Machine technology (centrifugal compression, liquid turbine)
  + Alternative ortho-para catalyst
  + Optimised purification : adsorbent selection and process cycle
  + Alternative Cold Box insulation
  + Advanced Control system to cope with renewable power supply

**WP 2.2 - Strategic storage - FID activities**

* Objectives
* How to achieve the objectives
* Main Innovations to be implemented

**WP3.2 : Transport - FID activities**

* Objectives

The main objective is to be able to move from a few units every 5 years of known containers to dozens every year of several new models as per the development results in order to reduce the boil-off to follow the expected rise of the demand. To improve the lead time as well as the throughput of the manufacturing lines we will need not only to invest in new production means but also to perform an efficient industrialization.

* How to achieve the objectives

Special attention must be given to

* Faster welding processes implementation; from submerged arc welding to automatic TIG welding for example.
* Faster insulation processes implementation; this will require at least 2 specific tooling developments. One for the right placing of the insulating fabric to get the targeted insulation density and one to speed-up the time to get the required vacuum between the inner and the outer shells.
* Faster accessories mounting implementation; this will require several specific tooling developments to install the frame on the ISO container or to instal the powertrain on the trailers.
* Separated automated valves box manufacturing capability; development of mounting jigs.
* Main Innovations to be implemented

**WP4.2 : Stations / Usages - FID activities**

* For each of the market identified, **engineering** of the appropriate **HRS solutions**, taking into account specific market constraints:
  + Fueling requirement (quantity to fuel, fueling time, time between 2 fuelings, Total Cost of Ownership...)
  + Availability & redundancy requirements
  + User interface requirements (trailer <->HRS and HRS<->FCEV)
  + Footprint & Height constraints
  + Fueling metering, boil-off management …
* Development of **engineering models** (process models, risk analysis, failure analysis..)
* **Supplier Qualification** and **component** **testings**, including **co-development** and **procurement contracts** with suppliers, normative and specific endurance testing under hydrogen or liquid hydrogen, in European labs or in Air Liquide testing facility in Air Liquide Advanced Technologies - Sassenage
* Selection and qualification of an i**ntegration partner** in Europe, for LHRS solution integration.
* **Vehicle simulation test bench** development and build
* **Tests** of the **full LHRS** system in Air Liquide Advanced Technologies Sassenage test zone.
* **Technical watch** of the operations and maintenance
* **Product improvement**
* Objectives
* How to achieve the objectives
* Main Innovations to be implemented

**WP 6.2 - Gas quality assurance - FID Activities**

* Objectives:
  + Ensure the level of impurities before liquefaction to avoid risk due to solidification or dissolution of impurities in liquid hydrogen
  + Ensure for each supply chain, the hydrogen quality at the point of use (nozzle for HRS) according to the requirements of CEN 17124.
* How to achieve the objectives
* Installation of analytical methods to control critical impurities before liquefaction
* Make a quality risk assessment study for each supply chain based on the requirements of CEN 17124 and the risk of impurities solidification
* Control the impurities among the supply chain from the production to the point of use (nozzle)
* if impurities are found above the the threshold values given in CEN 17124, identify the source to solve the contamination issue
* establish the assurance control plan according to the sourcing and supply chain of the LH2 including the list of impurities for each part of the supply chain, the frequency of analysis, the type of analysis (off line or on line)
* Define metrological guidelines for the sensors and analysers to ensure the quality according to the sourcing and supply chain of LH2
* Main Innovations to be implemented
* new sampling systems and sampling protocol adapted to the liquid H2 supply chain which will maintain the integrity of the sample f
* New sensors or low cost analysers for on-line measurement of the critical impurities.

**WP 7 - Zero boil-off integrated supply chain - FID activities**

* Objectives

The final objective of the project is to develop a cost competitive renewable LH2 supply chain, adapted to the market objectives of 2030 at a regional scale. Both market volumes and cost objectives will require to scale up the pilot scale industrial project developed in WP7.1 to a plant size of about 30tpd.

This work package will be about scaling up, reducing the costs but also standardizing the product offer while reaching the FID KPI defined later in this application.

* How to achieve the objectives

A full scale renewable liquid hydrogen supply chain from liquefaction to usages will be set up with a pool of end users justifying the final product size. The supply chain will be operated by a dedicated H2 Energy team.

* Main Innovations to be implemented

All the innovative techno bricks developed in WP1 to WP5, Safety, RCS developed in WP6 will be integrated in WP7 in order to operate the full supply chain

* **KPI to measure the objectives - End of FID phase**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **KPI Id** | **WP** | **Description** | **Value** | **Unit** |
| KP1-A | Liquefier | Specific Energy (compared to state of the art) | -40% |  |
| KP1-B | Liquefier | Ramp-up / down | 10 | %/ min |
| KP2-A | Storage | Trailer filling time | 3 | hours |
| KP2-B | Storage | boil off | 0.3 | % of full capacity/da |
| KP3-A | Trailers | lead time | 8 | months |
| KP3-B | Trailers | Cost of H2 transport (400km, 1tpd) | 1 | €/kg |
| KP4-A | LH2 Bunkering | time to deliver 3 tons | 1 | hours |
| KP4-B | GH2 refuelling | Boil-off (H2 vented at the HRS when HRS is loaded at 80%) | 1% | of delivered H2 a the FCEV |
| KP5-A | RCS / Safety | Average authorization process duration for a filling station (M1 to M4) | 2 | months |
| KP5-B | RCS Safety | Authorization process duration for a liquefier (M1 to M4) | 9 | Months |
| KP6-A | Gas Quality  assurance | Analytical capability in Liquid H2 for the control of impurities | 100 | % of all the impurities critical for the safety of the supply chain |
| KP6-B | Gas Quality  assurance | Cost of H2 quality control | 0,2 | €/kg |
| KP7-A | Supply chain | Renewable Energy usage | 80 % | (kWh renewable / kWh total) per year |
| KP7-B | Supply chain | boil-off | 2 | % of liquefied gas |
| KP7-C | Supply chain | LH2 supply chain TCO  *(30tpd, 400 km from source, 1000kg/d)* | 4 | €/kg |

e2 additional recommendations:

* According to the footnote (1) to the annex of the IPCEI Communication, “First industrial deployment refers to the upscaling of pilot facilities, or to the first-in-kind equipment and facilities which cover the steps subsequent to the pilot line including the testing phase” (our emphasis); please make your choice in one of the two possibilities
* Explain in detail what the objectives of the FID phase are (the “what?”), provide the start date and the end date
* Explain in detail what activities will be carried out to reach these objectives (the “how?”)

### Technical challenges in the FID phase

e2 additional recommendations:

* According to letter (g) in the annex of the IPCEI Communication, “the industrial deployment [must] follow on from an R&D&I activity and itself contain a very important R&D&I component which constitutes an integral and necessary element for the successful implementation of the project”; prove that the FID phase has a strong R&D content, i.e. explain and quantify as far as possible the RDI efforts needed to overcome the technical challenges expected during the FID (without a strong R&D content, the FID costs will not be eligible to public funding)
* Use a table to summarize the information at the end of the section, for example:
* inclure des boucles de rétroactions pour ramener l'installation à un niveau de perf industrielle
* ensemble des challenges à surmonter

|  |  |  |  |
| --- | --- | --- | --- |
|  | What? | KPI | How? |
| WP1-A | Coupling to Renewable Energy | KP1-B | Develop a thermodynamic cycle which is capable to handle intermittent power and hydrogen supply |
| WP1-B | Reduce the cost of liquefaction | KP1-A | industrialize technologies and develop large scale liquefaction |
| WP2-A | Reduce the storage boil off | KP2-B | Subcool LH2, optimize isolation, develop subcooling units |
| WP2-B | Integrate storages in non industrial area - above or underground |  | develop standard LH2 storage designs, under or above ground |
| WP2-C | integrate LH2 storages on board trains for propulsion |  | work with train OEM, develop applicable RCS framework and safety concepts |
| WP2-C | integrate LH2 storages on board ships for propulsion |  | work with shipyard / shipowners, develop applicable RCS framework and safety concepts |
| WP3-A | develop LH2 trailers for H2 Energy market |  | Specific trailer development with OEM based on H2 Energy functional specification |
| WP3-B | industrialize LH2 trailers | KP3-B | USe Air gases return on experience to industrialize LH2 trailers |
| WP4-A | develop specific train bunkering stations |  | develop connectors, breakaway, LH2 circulating pumps, hoses, mass flowmeters, overall system compatible with the segment functional requirements. |
| WP4-B | develop specific ship bunkering stations |  |
| WP4-C | develop specific heavy duty vehicles bunkering stations |  |
| WP4-D | develop specific heavy duty and light duty vehicles refuelling stations |  |
| WP5-A | develop specific RCS framework for H2 liquefaction plants |  | Work with professional associations and authorities on draft regulation in the frame of the WP7.1 solution development and project execution. Validate the regulation framework during the execution of WP7.2 |
| WP5-B | Develop specific RCS framework for hydrogen refuelling and bunkering stations |  |
| WP5-C | Develop safety assessment tools for LH2 (simulation of feared event, consequences, and effects of mitigation measures) |  | Establish partnerships with academics to understand and simulate the physics, elaborate analytical models reproducing simulations and validate the models with third parties experts. |
| WP6-A | Develop specific gas quality assurance methodology, with associated analytical methods |  | develop analytical methods, risk based product quality assurance |
| WP7-A | Integrate all developed techno brick in a LH2 supply chain to provide renewable liquid hydrogen | KP7-A | DEvelop a customer portfolio and a business case to justify the investment of the R&D pilot synchronized with work packages deliverables |
| WP7-B | Develop a LH2 supply chain with less than 3% boil off rate | KP7-B | Proper integration of techo bricks work packages deliverables |

### Transition from the FID phase to the mass production / commercialisation phase

It is proposed to use the set of KPI listed in chapter 1.5.2 (noted KP1-A to KP7-B) to validate the transition from FID phase to the mass production commercialisation phase.

e2 additional recommendations:

* va permettre de valider l’ensemble des coûts éligibles : définir les KPI pour vérifier qu’elle fonctionne de manière efficace (le financement s’arrête)
* Define which KPIs will be used and the associated values to decide that the FID phase is over and the Mass production / commercialisation starts
* Note: The transition from FID to mass production must be based on technical criteria not market one.

### Revenues in the FID phase

e2 additional recommendations:

* If the company decides to have revenues during the FID phase, provide detailed, convincing explanations why the company consider that the amount of sales during the FID phase should not be viewed as normal sales / commercial activities; explain the nature of these sales during the FID phase: what kind of products will be sold, to whom and for what purposes?
* Note: typically, samples and testing or feedback sales can be reconciled with the concept of FID under the IPCEI Communication; however, important volumes and revenues of sales typically correspond to commercial activities under the IPCEI Communication; the sales shall not be larger than 20% of steady state commercial sales
* Eviter de dire que ce sont des revenus commerciaux standard. (batterie : transferer des échantillons)
* regle

## Contribution to the hydrogen strategic value chain

### Project’s position in the hydrogen strategic value chain

Air Liquide’s project has the unique ambition to be integrated across all streams of the liquid hydrogen logistic chain. Thanks to its industrial and technological unique expertise in liquid hydrogen, Air Liquide will lead the suppliers ecosystem through this breakthrough development and rise the overall competitiveness of the value chain.

The project will however limit its scope to the liquefier and all downstream equipment, and will source decarbonated hydrogen from the market (can be from the deliverable of other R&D and subsidized on going projects). This supply will be with the same contractual clauses than any gas supply agreement. The supply will likely to be local as it is not envisaged to build a dedicated pipeline for this equipement.

### Industrial value chain in France

The project will rely on French industrial existing players but also will help some new players to enter the market as it emerges, with the following companies already identified :

* WP1 Liquefaction

Magnetic bearings : S2M (Vernon)

Heat exchangers : Fives CRYO (Epinal)

O/P catalyst : CETIM (Strasbourg) - tbc for large scale production

Design tool : PROSIM (Toulouse)

Valves : Flowserve (Thiers plant)

RSBD (VENDIN-LE-VIEIL)

ONEX (Parthenay)

CEFA (Soultz-sous-Forêts)

CMI (CROUY)

ABB (plant)

KSB

* WP2 : Storage

Chaudronnerie de l’Est CDE (Langres)

CRYOLOR (Ennery)

* WP3 : Transport

CRYOLOR (Ennery)

Running gear : MAGYAR

valves : BOM

* WP4 : Stations / Usages

Hydrogen refuelling station development will require outsourced equipements, and assembly lines. Amongst the potential subcontractors are Fives Cryo (LH2 Pumps and exchangers, Golbey), RAVANAT (Assembly, Saint Jean de Moirans), Kelvion (Heat Exchanger, Nantes), TSM (Assembly, Champ sur drac), Turbolub (Assembly, Commentry), Sertronic (Assembly, Torcy), SisNovam (Assembly, Valenton), Cryotec (assembly, Saint-Gély-du-Fesc), Cryopal (assembly, LH2 tanks, Bussy St Georges), Staubli (Connectors, Faverge), Supervision systems (Schneider, Grenoble), Heating & Chilling systems (Eurodiffroid, Montreuil), Identification & Paiement system (Fillndrive, Paris), LH2 pipes (ITP-Interpipe, Louveciennes).

* WP5 : RCS, Safety

Tests : INERIS

Third party expert : Bureau Veritas

* WP6 : Gas Quality

Validated Laboratory for H2 quality control according to EN 17124 in France : CEMIAG,

Analytical equipments suppliers in France: APIX (µGC, Grenoble), AP2E (optical analyser , Aix-en provence)

SIS NOVAM

SERTRONICS

* WP 7 : zero boil-off integrated supply chain

e2 additional recommendations:

* Describe the French partners
* Explain the complementarities / synergies with French partners and their projects

### Industrial value chain in Europe

The project will rely on European industrial existing players but also will help some new players to appear as the market emerges, with the following already identified :

* WP 1 Liquefaction

Compressors : BC Howden, NEA (Neuman & Esser), Burckhardt, MAN Energy Solutions

SIMIC

ASTRA Refrigeranti

SIEMENS

* WP 2 : Storage

CRYOSPAIN (Madrid)

CHART FEROX ( Czech Republic)

SIMIC

* WP 3 : Transport

trailer manufacturer: GOFA (CHART group)

Axes : JOST MERCEDES, SAF

valves : SELFA , LESER, BOM , HEROSE

* WP 4 : Stations / Usages

Pumps: KRYTEM

Coupling : Walther Praecizion, WEH, MANTEK

Hoses: Nexans

Tests LH2 : ET München

Valves; Weka Ag, Schwanner...

* WP 5 : RCS, Safety

DNV, HSL, TUV, Lloyds

* WP 6 Gas Quality Assurance

Reference gas mixtures for calibration : National Metrological Institutes : NPL, VSL, LNE, RISE, etc……

Gas analyser suppliers : Cascade (UK), Vaisala (Finland), Kaiser (Germany), Antelia (Belgium)

* WP 7 : zero boil-off integrated supply chain

e2 additional recommendations:

* Describe the European partners
* Explain the complementarities / synergies with European partners and their projects

### Intellectual Property Rights

#### IP management principles

Air Liquide will be the owner of all the IP and will implement protection via French Patent applications and extensions to foreign countries, in particular through the PCT process. Air Liquide recognises that a strong intellectual property position is vital, not only to create value but also to maintain a competitive edge in the marketplace in future. The company will be proactive in protecting IP that arises from the project. Thus, any IP that is generated from this project will be actively protected by filing patent applications in a timely manner. Air Liquide respects the IP rights of third parties and is not aware of any existing third-party IP that may affect project delivery or exploitation. The IP strategy is integrated with the scientific progress and commercial opportunities of the company and is reviewed regularly.

#### IP protections principles

Throughout the project, Air Liquide will continuously contribute to the identification of project results that may qualify for IP protection. In order to avoid problems related to IP and maximise the impact of the project, special attention will be paid to the section dedicated to IP. Intellectual property rights owned by a specific partner before the signature of the contract (background IP, including but not limited to patents, know-hows, copyrights)) shall be made available on transfer conditions to the partner requiring it, for the execution of the tasks within the scope of the project, and to the extent defined in the consortium agreement. The use of such background IP will be defined in the consortium agreement and strictly limited to achieving the project goals and restricted to the duration of the project.

Foreground IP (i.e. intellectual property generated during the project) shall be owned by the partner or partners who developed it. Each partner will be responsible for taking the appropriate steps for securing intellectual property of the knowledge or results created during the project (e.g. filing of patent applications). Each partner will be obliged to fully inform the exploitation manager and the project coordinator of the filing of patent applications of knowledge or results created in the field of the project within two weeks of the date of filing.

The aim of Air Liquide is to maximise the exploitation of the project findings. In case of joint ownership, a co-ownership agreement shall define the exclusive and non-exclusive domains of exploitation and the conditions upon which each owner shall be authorised to use such result ; the general principle shall be that the exploitation by one of the owners should be authorised if all the co-owners agree and such exploitation is in line with all signed agreements. Project results shall be made available free of charge to partners of the consortium requiring them for the execution of their tasks within the scope of the project, and to the extent defined in the consortium agreement. Results owned by one or more of the partners shall be licensed to other partners of the consortium on favourable conditions to the extent necessary to enable these partners to exploit their own results commercially.

#### IP exploitation principles

The receiving partner or partners will be requested to sign appropriate confidentiality agreements with the providing partner. A description of the background IP rights of each partner will be included as an annex to the consortium agreement. All partners shall be entitled to license their background IP to third parties to the extent necessary to exploit their own results. After the termination of the project or for purposes outside of the scope of the project, licensing of background IP to third parties will be done on commercial terms and conditions whereas licensing of background IP to partners of the consortium will be done on fair and reasonable terms and conditions.

## Work Plan

***POUR TOUT LE MONDE les données financières sont à rentrer dans le gsheet https://docs.google.com/spreadsheets/d/17aWWzPW-HqD5HKRUQYzkfeicUI-adCy\_MsTPeMex-MU/edit#gid=144905754***

Please describe your work plan in respect to the described work in the Technical Fields (TF) annex.

In the project the work will be carried out by several entities of Air Liquide:

* E&C:
* ALAT
* Cryolor
* R&D
* ALFI

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **AL entity** | **Type of activities** | **WP** | **WP Title** | **Total PM** |
|  | R&D | WP1 | Liquefaction | **472** |
| ALAT | R&D | WP1 | In house machines, optimized liquefaction process and BO management schemes | 74 |
| R&D | R&D | WP1 | O/P conversion, cold adsorption, in house catalytic HX | 182 |
| E&C | R&D | WP1 | In house catalytic HX, optimized liquefaction process and BO management schemes, low MW centrifugal compression | 77 |
| E&C | R&D | WP1 | In house catalytic HX, alternative insulation | 108 |
| ALAT | R&D | WP1 | Demo in-house machines (liquid turbine, bigger TC) | 23 |
| E&C | R&D | WP1 | Demo in-house machines (liquid turbine, bigger TC) | 8 |
| ALAT | R&D | WP1 | demo TBL1400 | 0 |
|  | R&D and FID | WP2 | Stockage | **82** |
| ALAT | R&D | WP2 |  | 20 |
| R&D | R&D | WP2 |  | 18 |
| E&C | R&D | WP2 |  | 17 |
| E&C | R&D | WP2 | Alternative insulation | 27 |
| Cryolor | R&D | WP2 |  |  |
| Cryolor | FID | WP2 |  |  |
|  | R&D and FID | WP3 | Transport | **1413** |
| Cryolor | R&D | WP3 | Liquid trailers development | 451 |
| ALAT | R&D | WP3 | Liquid distribution Boil-off | 643 |
| R&D | R&D | WP3 | Liquid distribution Boil-off | 319 |
| Cryolor | FID | WP3 |  | 0 |
|  | R&D and FID | WP4 | Refueling stations |  |
| ALAT | R&D | WP4 |  | 783 |
|  | FID | WP4 |  | 0 |
|  | R&D | WP5 | Regulation |  |
|  | R&D |  |  | 0 |
|  | R&D |  |  | 0 |
|  | R&D | WP6 | Purity |  |
|  | R&D |  |  |  |
|  | R&D |  |  | 0 |
|  | R&D and FID | WP7 | Pilot scale validation & Large scale light house project |  |
| E&C | R&D | WP7 | Factory build up (Pilot) | 0 |
| ALFI | R&D | WP7 | Test and Operation of the unit (pilot) | 0 |
| E&C | FID | WP7 | Factory build up (Large scale) | 0 |
| ALFI | FID | WP7 | Test and Operation of the unit (large scale) | 0 |

Table 1: Work Packages (WP) vs. Person Months (PM)

e2 additional recommendations:

* Please remember that FID “must allow for the development of a new product or service with high research and innovation content and/or the deployment of a fundamentally innovative production process”; FID costs will be eligible only if FID activities have a strong R&D content
* Ajouter diagramme de gantt

## Investments

***POUR TOUT LE MONDE les données financières sont à rentrer dans le gsheet https://docs.google.com/spreadsheets/d/17aWWzPW-HqD5HKRUQYzkfeicUI-adCy\_MsTPeMex-MU/edit#gid=144905754***

### Tools and Equipment

Please cluster your investment by technology classification. Please provide also a brief and simple description of 1 or 2 sentences to the table (what is the purpose of the investment?).

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Technology  Classification | No. of Tools | Examples of Tools | Investment Cost [EUR] | Year\* | TF no. | WP no. |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  | Total |  |  |  |  |

\*Investment year

Table 2: Overview of investment in tools and equipment

e2 additional recommendations:

* The costs of plug & play equipment (i.e. not modified by R&D activities) are not eligible because they are considered as part of mass production equipment (no R&D content)
* Only the depreciation corresponding to the use of the instruments / equipment for the IPCEI activities will be considered eligible cost (R&D or FID)

### Construction of Buildings/Laboratory

Please provide a brief and simple description of 1 or 2 sentences to the table (what kind of building? for what purpose?). Please cluster your investment so that the table does not exceed 1 page.

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Technology Classification | No. of Tools | Examples of Tools | Investment Cost [EUR] | Year\* | TF no. | WP no. |
|  |  |  |  |  |  |  |
|  |  |  |  |  |  |  |
|  |  | Total |  |  |  |  |

\*Investment year

Table 3: Overview of investment in buildings or laboratories

e2 additional recommendations:

* Please explain whether the building would be used only for the IPCEI activities or also for other activities / activities carried out after the period covered by the IPCEI
* Only the depreciation corresponding to the use of the building for the IPCEI activities will be considered eligible cost (R&D or FID)

# Budget

## Eligible Costs

Eligible costs only cover costs made for the purpose and the time span of the project:

• The following costs should be listed in a disaggregate manner:

• Costs for each of the R&D activities

• Costs for each of the FID activities

• And, within the FID costs, the costs of R&D carried out in the FID phase should be mentioned; this could give an idea of the overall importance of the R&D

• The cut-off date of the R&D and FID phases should be provided explicitly by each company (The template Excel contains vertical lines, showing these cut-offs, these should be adapted per company)

• Eligible costs cover costs up to the end of the FID phase (even if the FID phase goes beyond the national granting period for some companies)

• The end result of this step should be one figure: the total amount of eligible costs at the end of the IPCEI, including the FID phase

Note: all costs mentioned in the Excel sheet are considered by the Member States as eligible costs under the IPCEI Communication.

## State Aid

Indicate the State aid requirement in nominal terms and discounted terms, as well as the anticipated yearly instalments.

# Spill-over Effects

Different dissemination activities, ranging from awareness to exploitation, are proposed by Air Liquide to ensure the translation of development and outputs into new findings and market opportunities for third parties (research organisations, companies, Member States, industrial sectors). The Objective is to reach the fullest range of potential users and uses among research, social, investment and policy makers. Air Liquide will develop a specific Work Package in the project’s global Work Plan for planning dissemination actions . These actions will be targeted towards companies and research organisations that are not direct participants in the IPCEI on Hydrogen, towards Member States that are not supporting the IPCEI on Hydrogen and towards industrial sectors that are not represented in the IPCEI on Hydrogen.

## Spill-over by non-protected results diffusion

Air Liquide commits to undertake the following dissemination actions of non-IP protected results from the IPCEI on Hydrogen:

Share results with the scientific & technological community through conferences/workshops

* Share results with the scientific & technological community through publications
* Share results with the scientific & technological community through the participation in large European research projects (e.g. Horizon Europe)
* Share Results with the scientific & technological community through R&D collaborations with universities and public research organisations
* Share results with the scientific & technological community through actions in industry associations
* Promote/fund the completion of doctoral work in the field
* Promote/fund the completion of post doctoral work in the field
* Set up/ Participate in courses & training
* Set up/Participate in apprenticeship programs

## Spill-over by IP protected results diffusion

The IPCEI on Hydrogen is about the development of a complete European supply chain for low CO2 hydrogen supply and applications. Each IPCEI partner will develop technological building blocks to develop this European supply chain. Some of them will be IP protected typically through filing of patents. Air Liquide is committed to developing Intellectual Property (IP) such as patents. IP creation will range from process technology, general architecture, software, and hardware development.

Regarding the exploitation of IP-protected results, only a low number of exclusive IP licenses deriving from the IPCEI on Hydrogen results are expected. Indeed, the patents that will be licensed will be related mainly to generic technological building blocks; therefore, they will not be blocking for the final products or processes because alternative processes and solutions could be implemented. This will actually serve to create further innovation in Europe as wider industry takes the building blocks present and then develop their own products and processes.

In the exceptional case of a request for an exclusive license for commercial exploitation of results from the IPCEI on Hydrogen, the domain and the duration of the exclusivity will be limited. In addition, in case of non-exploitation of the technologies for the application purposes provided for in the license within a reasonable contractual period (in the light of the tests to be carried out), the exclusivity will fall automatically in order not to block the diffusion of new technologies in the involved domain.

Moreover, dissemination policies will be implemented in order to promote and stimulate new approaches regarding the licensing of generic IP building blocks (avoiding any blocking issues for final product), with a view to serve other application fields through different value chains in order to get wider societal impacts. The IP will be generated with the intent to be as open as possible in order to facilitate the best possible uptake of new technologies from the IPCEI on Hydrogen.

Air Liquide expects to file patents on results from the IPCEI on Hydrogen, regarding the technological building blocks addressed by the work packages # 1, 2, 3, 4, 6, 7.

Air Liquide’s IP strategy will also allow for the cross-industrial use of its IP protected results from the IPCEI on Hydrogen. More specifically, Air Liquide commits to grant FRAND licenses on its IP-protected results to:

* research organizations, start-ups that are NOT direct participants in the IPCEI.
* towards industrial sectors other than those covered by the hydrogen supply chain

## Spill-over in the FID phases

Within the project timeframe, FID activities in the IPCEI on Hydrogen will lead to significant spill-over effects in downstream and upstream markets, among IPCEI partners but most importantly also beyond them. In general words, downstream and upstream markets parties will benefit in many ways from the FID phase. The IPCEI on Hydrogen will enable them to develop new equipment / instruments, new methodologies, new product applications and designs and to acquire specific skills as well as knowhow, which again can be used in cooperation with third parties (inside and outside the IPCEI).

A key asset of the IPCEI on Hydrogen is to embed many players from all along the hydrogen strategic value chain, either as direct or indirect participants. Additional cooperation programs will bring even more players inside and outside the Member States which fund the IPCEI. This is a strategic advantage that will make easier access to them inside the European Union. Air Liquide's strong implantation in most European Member States will attract many actors such as research labs, SMEs, start-ups… in the context of innovation proposals around provision of sustainable energy solutions.

In the IPCEI on Hydrogen, Air Liquide will provide access to hydrogen handling, transportation and distribution solutions by creating new technologies issues from the FID phase to partners, large companies, SMEs and PROs. This will be very helpful for SMEs and PROs (e.g. as listed in the Chapeau document as direct or indirect partner in all Work streams) which want to develop products and services throughout the value chain of liquid hydrogen. These partners will benefit from early access to the latest engineering methods and the most innovative testing equipment. This will empower them to use liquid hydrogen solutions in a wider geographic area.

Downstream market players (basically, related to mobility and industrial applications of hydrogen) tend to be the main contributors initiating new requirements for hydrogen supply chains: new designs, new technologies, new testing equipment, new products. Once the need is known by a potential customer, through market studies or direct market request, a feasibility study is launched. Eventually, a decision is made in order to start R&D&I work. But during the R&D&I phase, the new methods / technologies / testing equipment are not reliable enough. The downstream market is usually not interested to test such innovations at this stage.

Conversely, when entering the FID phase, the innovative methods / technologies / testing equipment have demonstrated their intrinsic value: functionality, reliability and a minimum level of repeatability. At this point, some engineering methods / technologies / testing equipment can be translated to downstream markets. Sampling with demonstrators, while sharing the risks between the potential end user and the technology provider, can start and continuously involve R&D&I phase in downstream markets: mock-up conception, measurement and testing campaign, additional specification request, data gathering and processing, several generations of prototyping, reliability at application level, are some examples of typical R&D&I activities of downstream market partners.

The FID activities from the provider of liquid hydrogen and the R&D&I from the downstream markets will both progress at the same time. This is because the FID activities will be a decisive phase to assess the new technologies and make the downstream markets use them. A successful final stage is when downstream markets initiate their own FID while using the technologies developed by the provider of liquid hydrogen.

The FID phase will also generate spill-over effects to other industrial partners such as equipment / instruments manufacturers present all over Europe. Indeed, in order to support the FID phase, some technological progress will be needed from these industries. Air Liquide will lead the way in creating liquefaction solutions for hydrogen as well as developing surrounding infrastructure. Therefore, the equipment / instruments manufacturers will benefit from their own “feedback R&D'' improving their own equipment, materials, methodologies and processes. This spill-over will be reinforced since the scope of IPCEI on Hydrogen is very large.

Thus, the benefits of the FID phase are clearly not limited to the company itself but will also spill-over to the project’s partners and further expand to many EU high-tech industries, businesses and research organisations. IPCEI on Hydrogen will create positive spill-over effects on multiple levels of the value chain.

More specifically, Air Liquide will commit to communicate through conferences, publications, and engage in academic collaborations and specific partnership with key components suppliers (start-ups, SME…). The FID will be also the opportunity to make educational visits to the liquefaction plant for the scientific and academic community, and to the operators of such similar plants to cross fertilize good practices across the cryogenic gases industries.

In order to inform the European technological and scientific community about this new opportunity, the company commits to communicate through press releases, media tools and during workshops about the inauguration of the new manufacturing facility, as well as to actively approach several European SMEs and PROs from non-IPCEI Member States each year to check whether they could be interested in deploying usages of liquid hydrogen.

# Other positive effect on the market

## Impact of the Project on Employment and New Investments in Europe

Estimation of the quantitative and qualitative impact of your project on direct and indirect employment and training in European economy and society new investments in Europe.

e2 additional recommendations:

* Detail the magnitude of employment that is envisioned
* Include a time-line of employment (how is employment associated with each step in the process?)
* What is the nature of employment? (Industry/qualifications of potential jobs)? Explain and estimate the project's contribution to creating new jobs in the green economy.
* Will Air Liquide be training this extra workforce?
* Discuss also what kind of indirect impact on employment there could be (employment that results from the project but not directly attributable to Air Liquide)
* Are there any downstream projects that could result in additional employment in the future? (Air Liquide or another firm)

The LH2 project represents the creation of hundreds of jobs between the components suppliers involved in the various technologies across the LH2 value chain, and the operation activities of this chain once mature and deployed (liquefaction plants, logistics). The employment intensity will follow the rate of the technology deployment.

As most of the technology components will be French or European, this LH2 value chain development will directly benefit the European ecosystem.

The R&D and prototype phases will mostly secure current employment and help develop specific competencies and industrial know-how about hydrogen compression, safety related to hydrogen and cryogenic fluids handling, cryogenic storages. This development phase will be the opportunity to engage several academic laboratories to support the technology developments. The specific prototype phase may generate direct and indirect 20 jobs (mostly in France).

The First Industrial Deployment will speed-up the momentum on the supplier's side, will call for efficient industrial processes and for scale-up plans. Besides, the operation of the FID is expected to generate 60 direct and indirect employment. At this stage of the project, the choice of the location of the FID is still not finalised, thus the share of French and European jobs created by the FID phase is unknown.

Air Liquide will disseminate and share its know-how related to safety of hydrogen and specifically to liquid hydrogen, to regulatory bodies involved in the normative evolution, to suppliers and users which will not be direct Air Liquide employees. Air Liquide will participate in safety and hazards reviews to support the different final users that will convert their processes to LH2 (maritime, aeronautic, railway, trucks and other terrestrial mobility).

Once the value chain will be fully operative and mass dissemination initiated (horizon 2030), the above employment benefits shall be increased tenfold to properly address the market demand, in Europe and worldwide.

## Environmental protection and reduction in energy dependence

Description of the project influence on environment protection and on the reduction of energy dependence.

e2 additional recommendations:

* How much savings of CO2 emissions per year does the project represent?
* Detail the above by including potential reduction in CO2 due to reduction in imports.
* Explain and estimate the projects contribution to reducing European industry’s pollution (air, water and soil); is there a significant reduction of pollution linked to the equipment that is to be deployed?
* What is the difference in energy-efficiency between current industrial mainstream and this project?
* How will the project change the % of energy in the region that is due to renewables?
* Explain and estimate the project’s contribution to more circular products.

## Market Failures: Coordination problems

### Coordination failures between companies and research organizations.

The very large number of public and private initiatives to define a mainstream trend to develop the next generation Hydrogen creates important coordination problems. Academia and businesses differ greatly in many aspects. The goal of scientists’ activities is the growth of knowledge, while for companies the principal motivation is profits. Each one tends to underestimate or even discard the objective that the other pursues. Reward modes are also orthogonal: an important scientific discovery will contribute to the reputation of the team that makes it, while a significant innovation will enrich the company that develops it. Finally, scientific results acquire their value when they are shared through scientific publications, while businesses’ R&D&I results get their value if they are patented. The reconciliation of the two approaches is possible but often causes misunderstandings and conflicts.

The goals of research organizations and companies are often disconnected. The main reason is due to the time horizon under consideration. While research organizations are often concerned with plausible long-term trajectories, companies are oriented towards projects that can have clear value added in the short term. This causes a large disconnect between the kind of research that is done by research institutions and the kind of research that firms need in order to act. In simpler terms, research organizations are often concerned about possible paths the economy could take, whilst companies are concerned more about which paths are more “effective” in terms of direct economic benefits.

The difficulties that companies and research organizations face when trying to work together are well documented. In particular, these relations are known to be much more complicated in Europe than in the United States. A lack of investment by public and private actors inhibits knowledge transfer by directly limiting the transfer capacity between public research organizations and companies, leading to limited communication and increases in coordination failures. This lower investment could be attributable to a stricter dichotomy in Europe between public and private financing.

In the case of the European Hydrogen strategic value chain, this lack of coordination between research organizations and companies in most Member States is a major systemic failure. Its outcome is a deficit of growth and competitiveness as compared to other parts of the world, particularly Japan and the United States. This is reflected in the loss of momentum of European players in research and innovation capacity, particularly visible in the low impact of their patents worldwide.

In addition, partnerships between research organizations and companies tend to be set up only at a local dimension. They prefer to collaborate when they know each other well and are close, which leads to neglecting other partnership opportunities that could be more productive from the scientific and technological points of view. The lack of cross-frontier public funding leads some public research organizations to focus solely on local companies for partnerships. This means that there could be potential synergies that could be exploited at the more European level in the form of cooperative projects if far-reaching connections were facilitated.

The IPCEI on Hydrogen will promote an intense cooperation between academic partners and industrial partners from numerous different Member States. Market forces alone cannot lead to such cooperation. This major European R&D&I and industrial partnership will significantly intensify scientific and technological exchanges between European players from academia and from players across the industrial value chain. As part of the IPCEI on Hydrogen, the research agendas of academic laboratories and companies will be better aligned, and exchanges will transcend the borders established by local tropisms. Thus, the ambition of R&D&I activities can be of a higher level. The IPCEI on Hydrogen initiative will foster new trans-border collaborations between EU companies. Without the IPCEI on Hydrogen, such collaboration would very likely not have happened.

### Coordination failures between European research organizations themselves

Most European research organizations suffer from sub-critical size to engage in advanced research in next generation hydrogen. Such research activities require heavy resources in manufacturing equipment and characterization. No European public research laboratories own the full set of equipment including a complete production line to carry out their research activities.

The sub-critical size of European research organizations, particularly compared to the United States, combined with a lack of coordination between them, leads to dispersion and redundancy. Important efforts are made on some research topics without exchange of information, leading to a deteriorated scientific productivity, while other topics are neglected. The setting up of in-depth discussions within each technological field of next generation Hydrogen can enable knowledge production to be more efficient.

The IPCEI on Hydrogen will mobilize and bring together many European research laboratories, thus making it possible to overcome the lack of coordination that characterizes them. As part of the project, the redundancies will be removed, synergies and exchanges will be developed to pursue common R&D&I objectives in the field of advanced materials for Hydrogen and next generation Hydrogen, considered to be strategic for Europe.

### Coordination failures between SMEs and industry leaders

The IPCEI on Hydrogen will provide SMEs with access to R&D&I activities and innovative infrastructure that they would not have accessed in the absence of the project. Without State aid, Air Liquide would work with some of these SMEs in a standard "client-supplier" logic, rather than associate them as partners and allow them to anticipate technological breakthroughs. Thus, most of these SMEs simply would not have the ability to work on these highly challenging technological areas.

The State aid encourages many European SMEs to collaborate and invest in R&D&I, by pooling and sharing risks. The project will enable the actors to collectively achieve the critical size that is needed to carry out advanced hydrogen R&D&I activities. European SMEs in the hydrogen sector will coordinate R&D&I activities with much higher levels of ambition and risk.

### Coordination failures between European clusters

The European hydrogen industrial value chain is limited in size and scope because of the market’s infancy and lack of business / technological opportunities. It is insufficiently coordinated to foster complementarities, synergies, and learning curves that are key in order to compete globally. The weakness of cross-frontier public funding for large projects leads each cluster’s actors to carry out their R&D&I activities in a regional logic, e.g. at a level of a city that wants to purchase a dozen hydrogen buses with the associated hydrogen infrastructure. The weakness of cooperation between European clusters leads to redundancies, neglecting synergies and significant complementarities, and finally to significant losses in terms of scientific and technological productivity.

The scientific and technological objectives of the IPCEI on Hydrogen constitute a major scientific, technological and organizational challenge, particularly for the development of new technology platforms, pilot lines and large scale roll-out projects. All players across the European industrial value chain must engage in closely coordinated R&D&I, FID activities and environmental / energy / transports projects to achieve this development, reducing redundancies, developing synergies and complementarities.

### Coordination failures of very large-scale R&D project

The great scope, scale and the high scientific and technological complexity level of the IPCEI on Hydrogen require joint work amongst a very large number of actors, most of them industrial companies and some being public research organizations and university laboratories.

The intensity of collaboration inside IPCEI on Hydrogen is very important, program partners will work in a very strong interdisciplinary sense, which could not be mobilized without the State aid. The results obtained by each partner will impact the other partners' actions. The collaboration must be coordinated in a very close and dynamic way, in order to get the best results from trials and error experiences of R&D&I, FID activities and environmental / energy / transport projects, as well as to reorient all work packages as a result of the progress of each partner, so that the R&D&I, FID and EET program can achieve its objectives. Round trips will be necessary between the different partners to coordinate their work, in order to remove the technological barriers that will be identified. This is a huge task.

State aid to partners of the IPCEI on Hydrogen deeply strengthens the coordination of the consortium. The disbursement of the public funding will be spread over the lifetime of the project, thus necessitating a very close monitoring by public authorities through progress reports, milestones, etc. All partners know that they must progress together towards the achievement of IPCEI on Hydrogen objectives to get the public funding. Thus, the State aid gives each partner very strong dynamic incentives to overcome the difficulties of such a large-scale and long-lasting project. It makes possible to set up a very large European R&D partnership which constitutes an efficient and responsive mode of organisation, able to catalyse synergies between partners and ensure gathering and coordination of the broad spectrum of necessary sector skills for the realization of such an ambitious project. Major European players in the hydrogen field will all work together for the first time in a collaborative approach around a major unifying R&D&I and industrial program, kick-starting the European hydrogen market, as well as lowering the technical and economic barriers.

### Coordination failures associated to contractual incompleteness

The State aid will also limit the coordination difficulties related to the contractual incompleteness of major collaborative R&D&I programs. It is well known that R&D&I contracts are incomplete, that is, they cannot anticipate or take into account all possible situations and all future contingencies. Indeed, R&D&I programs are characterized by high uncertainty: not all results can be determined in advance ("serendipity"), unanticipated scientific and technological hurdles can arise, with a potentially strong impact on the program's calendar or costs, successes or failures can come from where they were not expected, etc.

Contractual incompleteness may encourage opportunistic partners' behaviours, reducing their commitment to the collaborative R&D&I project. In such context, cooperation is rendered very unstable by the alternative opportunities that are offered to the partners. The occurrence of an unforeseen event in the contract can lead to a chain of reactions from the partners, putting at risk the primary purpose of the partnership. Naturally, this risk is all the more important as the number of partners grows and the research is of a high level of complexity, which is very clearly the case for the project IPCEI on Hydrogen.

A very large collaborative R&D&I project like IPCEI on Hydrogen is characterized by a high uncertainty, which means the occurrence of unpredictable events during the project. A partner could invoke the occurrence of an unforeseen contingency in the contract to defend opportunistically his interests. The collaboration contract cannot therefore prevent these behaviours. Sanctions or penalties cannot solve this problem: a sanction can only apply over a behaviour considered as deviant by reference to foreseeable configurations provided for in the contract.

Second, the interests of the partners may diverge over the content of the program, or its objectives, or even its costs, as it progresses. This is common in a very large collaborative R&D&I program like IPCEI on Hydrogen, since project developments are very likely to deviate from the initial plan. Therefore, each of the partners would tend to influence the program in such a way as to favour its interests to the detriment of the common interest of the consortium, while it would be hardly possible to invoke the contract to prevent it (in particular, through penalties provided for in the contract). This may for example involve renegotiating the allocation of costs between the partners, to the detriment of the effectiveness of the project.

Third, it is very difficult, if not impossible, to anticipate and define in an exhaustive way the totality of the results of a very large R&D&I program. Thus, one of the partners might be tempted to appropriate some unanticipated results of the program by claiming that they would result from R&D&I activity outside the program. Here again, applying fines could not address anything, because of the intrinsic uncertainty of the very large collaborative R&D&I programs and the resulting contractual incompleteness.

The examples above, where a partner might be interested in adopting opportunistic behaviour, are not exhaustive. However, they provide an overview of the wide range of opportunities for partners in a very large collaborative R&D&I program like the IPCEI on Hydrogen to derive a profit from the program at the expense of the common interest of the partners. Thus, although collaborative R&D&I contracts are essential for framing partnership relations, they may reveal a limited effectiveness in managing the divergences of interests that do not fail to appear, especially in the context of a program as expensive, long and complex as the IPCEI on Hydrogen. Since it is very difficult to anticipate all situations in which a partner might have an interest in opportunistic behaviour, or even to prove this type of behaviour, it is impossible to provide for an appropriate system of sanctions.

State aid makes it possible to reduce a priori the opportunistic behaviour that may result from contractual incompleteness, and thus facilitates the coordination of IPCEI on Hydrogen partners. Indeed, for each partner, the risk related to the implementation of the program will be shared with the public authorities, limiting its potential financial losses in case of failure. This sharing of risks reduces each partner's incentives to use opportunistically contractual incompleteness to his advantage.

## Market Failure: Imperfect and asymmetric information

### Risks affecting the project

#### Technological risk

The European Commission generally recognizes that a greater technicality of a R&D project goes along with a greater probability of failure. R&D and innovation are highly complex and challenging in the hydrogen sector, and therefore they inherently carry a very high level of risk.

In the specific context of the IPCEI on Hydrogen, Air Liquide will undertake RDI activities in order to explore scientific and technological paths which require a high level of integration of the different techno bricks in order to operate at the specified level of performances. A failure in the development of a techno brick will involve a failure in the project. As multiple techno bricks need to be simultaneously developed, the overall risk of failure is multiplied accordingly.

Safety is and will remain the priority in Hydrogen energy, however, zero risk level does not exist.

Required acceptable safety levels of operation or design are determined thanks to gravity / frequency risk acceptance matrices. These commonly accepted practices mean that an event with a high gravity (death of several people) is supposed to happen with an extremely low probability making it still acceptable. However, with the expected massive deployment of H2 Energy solutions, it is statistically almost sure that an event with a high gravity will once occur.

Inherent technology risks linked to Liquid hydrogen technologies are quite well known as the product has been used for more than 50 years in the industry. However, with hydrogen energy, a new safety mindset has to rise as the product will not be used in industrial setup but in a more “consumer” type world, where the societal acceptance of the risk is different. This societal risk is not per say a technology risk, but is largely induced by the introduction of new technologies on the market.

#### Economic risk

Different learning curves for different competing technologies for hydrogen production will develop as a consequence of market expansion in the coming decade. In this respect, there is a risk that not only Air Liquide products will be introduced too late on the market but also that the cost of competing technologies decreases quicker than the cost of Air Liquide solutions, entailing a significant economic risk is attached to the innovative application of liquid hydrogen technologies. For instance, if technology increases volume transportation efficiency more than weight transportation efficiency, then transporting liquid becomes less interesting.

Different usages of liquid hydrogen will emerge successively at a rhythm difficult to predict. There is therefore a risk to invest in a liquid hydrogen supply chain well oversized for the market demand, with assets underutilized for a significant amount of time, generating fixed costs difficult to handle.

#### Partnership risk

The risk of partnership of a very large R&D and industrial program such as the IPCEI on Hydrogen results from the difficulties to organize the coordination and the synergies between such a large number of actors and centers of competences that are culturally very different, as well as to maintain the cohesion of the partnership in the long run.

The R&D and industrial partnership set up in the IPCEI on Hydrogen involves a very large number of partners coming from various sectors, they also have different sizes and institutional origins. Indeed, the IPCEI on Hydrogen requires academic research laboratories and companies to work together on common scientific and technological objectives. Given the strong interdependence between their activities, it will be very difficult to coordinate their numerous contributions to the project. It is clearly the case regarding the contributions of the numerous public research laboratories, which will work in parallel on multiple tasks of scientific modelling and development of basic technological building blocks.

#### Risk associated with major R&D programs

Major R&D and industrial programs such as IPCEI on Hydrogen, which extend over several years and aim at many technological breakthroughs across complementary steps in the value chain, are generally exposed to numerous and significant risks that are not all identified and even less quantified. For example, it is common for nominal objectives not to be achieved; also there may be defects at the interfaces, delays in the availability of the results of a subsystem, failures of partners during the program, technical and functional problems, etc. This is why significant uncertainty often weighs on the fulfillment of the initial schedule, as well as on the forecasted estimation of R&D and industrial expenditures. The two risks are associated to the extent that each year of delay generally induces significant additional costs.

#### Regulatory risk

WP5 -Regulation codes and standards, including Safety work package specifically tackles this risk, as there is no current regulatory framework adapted for the deployment of LH2 solutions for H2 Energy applications.

The installation of large Hydrogen liquefier falls under the SEVESO 3 directive[[11]](#footnote-11), high threshold for the targeted quantities. These installations are extremely difficult to be approved by authorities having jurisdiction, requiring extensive safety studies, public enquiries, etc.... There is a significant risk that the authorization process duration (for instance in case of legal claims from the neighbourhood during the public inquiry) jeopardizes the market development in case of rapid growth of the product demand.

#### Strategic and financial risk

There is a strategic and financial risk in relation to the signal sent by Air Liquide to the financial markets with a large R&D&I and FID program like IPCEI on Hydrogen. Indeed, the financial markets favour a perspective of short-term profitability rather than a longer-term industrial vision. Therefore, for a company like Air Liquide, financial analysts favour criteria such as the optimization of the gross margin and the operating margin. They would even favour a rebalancing of the cost structure in order to limit exposure to the euro / dollar exchange rate. Likewise, the risk for Europe of not being able to ensure its strategic independence in these advanced technologies is not considered in their analysis.

All these elements plead in favour of a reduction in Air Liquide’s R&D&I and FID spending, which goes precisely the opposite way of a project such as IPCEI on Hydrogen. Therefore, when committing itself to a project as large as IPCEI on Hydrogen, Air Liquide faces the risk of a deterioration in its appreciation on the financial markets.

### Difficulty to recruit highly qualified personnel

At the global level, the hydrogen sector suffers from an important difficulty for the recruitment of highly qualified profiles, a problem that hinders the development and commercialization of innovative technologies. This shortage is a result of highly qualified personnel being risk averse with regards to their professional trajectory and overlooking the risks of moving to an industrial sector as immature as hydrogen with no tangible results on their actions short term..

They prefer less risky / more visible and short term rewarding professional options, typically space industry for people specialized in cryogenics.

Moreover, the relatively low visibility of Hydrogen energy in the renewable energies global picture has not driven universities or professional institutes to develop skills trainings as they might have done in other sectors such as solar energy or batteries for instance. It is even more the case for the specific case of cryogenic hydrogen which has been historically considered as a niche industrial sector.

One of the main objectives of the public support for the IPCEI on Hydrogen is precisely to give more visibility and public awareness about the hydrogen industry, and to enhance the attractiveness of the European hydrogen clusters regarding the highly qualified labor market. It will also support the evolution of academia to train and supply to the market these highly qualified profiles. For that purpose, thanks to public funding, the IPCEI on Hydrogen will implement the following features at a very large European level: a strengthening of partnerships, a better circulation of ideas and people and a better mutual understanding between public research organisations and companies.

### Strategic independence of supply

Europe is strongly reliant on imports of energy, including crude oil and refined petroleum products.

Hydrogen produced by renewable energies will not be dependent upon import of primary energy.

Air Liquide activities in the IPCEI on Hydrogen target liquid hydrogen to be mainly used in mobility applications as a substitute to gasoline, diesel, jet fuel, heavy fuel, ... In case of success and diffusion of this technology Europe-wide, it will result in less dependence on European imports of crude oil and refined petroleum products.

## Adequacy of the state aid instrument

### Appropriateness among alternative policy instruments

There is no other less distortive policy instrument than State aid which would make it possible to achieve the same result for the IPCEI on Hydrogen.

#### The regulation

Regulation is a standard and widely used public policy instrument. The use of regulation to implement the IPCEI on Hydrogen has little practical consistency. In theory only, Member States could impose on companies in the industry to develop the innovations proposed in the IPCEI on Hydrogen, based on full technical specifications. However, because of the numerous technological uncertainties weighing on the technological building blocks and integrated systems to be developed, such regulation does not seem to be realistic. For example, it is very likely that due to deficient information from the State regarding the evolution of the hydrogen market, regarding the technological state of the art, regarding the strategies of the different actors, etc., the choice to impose the development of such an innovation rather than another would be inefficient.

It is much more efficient to trust the strategies and technological choices of companies to decide on their R&D and industrial projects. This is the option retained in the IPCEI on Hydrogen.

#### A better funding of public research

The IPCEI on Hydrogen aims at removing technological barriers and demonstrating the technical and economic viability of many industrial innovations in the field of hydrogen. The project must therefore have a strong technological and industrial component, on top of its scientific dimension. To this end, R&D activities must be carried out simultaneously in public research organisations (which will contribute, with their advanced knowledge, to the development of scientific models) and in companies, which have the essential role to ensure the development of new technologies and their industrial and commercial deployment. For this specific purpose, the environmental / energy / transports projects that are funded in the IPCEI on Hydrogen play a major role as they enable early and large-scale implementation and roll-out of the innovative technologies. A very important gap (in terms of time, cost, and risk) separates the concepts studied in PROs from the demonstration of the technico-economic viability of an innovation, carried out in companies.

A better funding of public research would not achieve the same effect as the State aid from France for the IPCEI on Hydrogen, meaning the structuration of a sustainable ecosystem of research, innovation and roll-out around a very large R&D and industrial partnership between many public and private actors from numerous EU Member States.

#### The research tax credit

In order to succeed, the project IPCEI on Hydrogen must implement a strong collaborative logic between multiple public and private European actors.

A general tax measure in favor of R&D, such as the research tax credit (Crédit Impôt Recherche in French) implemented since 2008 by the French government, may lead French companies to boost their individual R&D efforts. However, it is not oriented towards the deployment of the European collaborative logic of the IPCEI that is a necessary condition for its success.

Moreover, there are strong complementarities in the IPCEI on Hydrogen between R&D / FID activities on the one hand, and environmental / energy / transport projects on the other hand. The former develop and supply innovative hydrogen technologies while the latter enable early and large-scale implementation and roll-out of these innovative technologies. EET projects are not eligible to the research tax credit, which thus cannot be a suitable policy instrument to promote a comprehensive package of activities for both the supply and demand of innovative hydrogen technologies.

#### The innovation tax credit

The innovation tax credit is a French tax measure reserved for SMEs to stimulate their innovation activities, such as building a prototype or a pilot installation of a new product. In concrete terms, a SME having incurred innovation expenses of up to € 400,000 will be able to receive a 20 % reduction in the cost of the expenses incurred in favor of the innovation.

The IPCEI on Hydrogen is dependent on the complementary contributions of a very large number of partners: large companies, SMEs and public research organizations, in France but also in several other Member States. All contributors that are not SMEs nor French cannot benefit from the innovation tax credit. Conversely, the IPCEI on Hydrogen cannot start based only on the contributions of French SMEs that would be supported by the innovation tax credit. Therefore, this fiscal measure is not an appropriate policy instrument to promote the large R&D and industrial collaboration envisioned in the IPCEI on Hydrogen.

Moreover, some key partners, including Air Liquide, will have expenditures far above the 400,000 euros ceiling of the innovation tax credit. This is another reason why this fiscal measure does not constitute an appropriate policy instrument to promote the activities carried out in the IPCEI on Hydrogen.

### Appropriateness among different State aid instruments

In the context of the IPCEI on Hydrogen, the main market and systemic failures come from spillovers, coordination problems and Europe’s strategic dependence. To address these failures, a grant is the most appropriate State aid instrument.

The market failure or other important systemic failure which the State aids aim to address are neither a problem of access to finance nor a problem of risk sharing. As such, a public soft loan, a State guarantee or a repayable advance are not taken into account.

The grant is intended to compensate for the low profitability of the project for Air Liquide without State aid, induced notably by the very high level of spillovers (see Chapter 3). Air Liquide understands that committing to disseminate the results of the project is a requirement for its activities to be eligible for State aid funding in the IPCEI framework. This being said, it remains that such spillovers result in a lack of incentives to invest in the project and this is partly contributing to the negative NPV for the project. It is well known in economic theory that such positive externality has to be corrected by granting a so-called Pigouvian subsidy to the economic agent who is at the origin of the externality. This refers here to Air Liquide who will carry out R&D and FID activities that will largely benefit third parties as a result of the company’s commitments to disseminate the project’s results.

The simulation of a repayable advance in the business plan can only have a marginal impact on the project’s profitability: public money is received in the first hand but reimbursed including interests in the nominal scenario of success. Only a direct grant has the potential to have the profitability reach the company’s hurdle rate by filling the funding gap.

The grant also addresses the coordination problems (see Section 4.3), being a cement of the coordination of the partnership. The grant will encourage partners to commit to the project although it is exposed to a high degree of uncertainty and to returns that will materialize only in the long term. Indeed, the payment of the grant, spread over the four years of the project and closely monitored by French public authorities (progress reports, key milestones, decision-making milestones), offers dynamic incentives for the partners (including Air Liquide) to overcome the difficulties of coordinating the very large research partnership, and to progress together towards the achievement of the project objectives.

The payment of the grant also limits the potential financial losses of the partners in case of project failure, which reduces their incentives to opportunistically use contractual incompleteness to their advantage. Repayable advances have a major drawback in this respect: they provide an additional incentive to opportunistically use contractual incompleteness, since putting the project in a situation of failure from the contractual point of view makes it possible to avoid repayment of the advance (while the project could be a success from the technical and commercial point of view). The grant to Air Liquide is therefore the appropriate aid instrument to address the coordination problems in IPCEI on Hydrogen.

The IPCEI on Hydrogen is designed to bring together public and private sectors to undertake a very large-scale project that provides large benefits to the Union and its citizens. It is very clear that the huge coordination challenge rooted in the IPCEI on Hydrogen could not be addressed by providing a public soft loan, a State guarantee or a repayable advance to the IPCEI’s partners. Only a direct grant can adequately address such market or systemic failure.

However, the grant provided by France to Air Liquide could be backed upon a claw-back mechanism that shall be targeted on the FID activities and related costs / State aid (they are closest to the market). The principles of this claw back mechanism will be considered and developed in the Chapeau text of the IPCEI on Hydrogen.

# Incentive effect

## Absence of similar projects

According to Air Liquide and the French Authorities’ best knowledge and according to public information, no similar project exists today in Europe.

## Start date of the project

Air Liquide has submitted a demand for public funding to the French public authorities on (to be defined). The project will likely start in 2020, in any case not before June 30th which is the deadline of the French call for expression of interest regarding the IPCEI on Hydrogen. Thus, the incentive effect of the aid cannot be presumed to be null.

## Counterfactual scenario

Air Liquide did not consider an alternative project nor a clearly defined sufficiently predictable alternative project in its internal decision-making process (point 29. of IPCEI Communication). Thus, there is no counterfactual scenario.

However, Air Liquide understands there needs to be a baseline in order to assess the increase in R&D and FID efforts associated with the State aid from France. Therefore, the company’s “business as usual” activities are described below.

Without the IPCEI on Hydrogen and the associated public support, Air Liquide would continue to seize business opportunities in the production, handling, storage and transport of liquid hydrogen on the emerging European hydrogen market. The company would continue to use the same liquid hydrogen supply chain technologies it’s been using for years and which represent the worldwide state of the art (see section 1.4.1 above).

Regarding R&D specifically, Air Liquide would continue to promote small publicly funded projects focusing on specific technological building blocks (see section 1.3 above). The company would not have the capacity (human and financial) nor the opportunity to carry out on its own a large integrated R&D project that would target the development of a comprehensive set of innovative technologies for the production, handling, storage and transportation of liquid hydrogen. No FID activities would take place. Air Liquide is commercialising a few liquid hydrogen projects based on technologies it’s been mastering for years, not to say for decades for specific technological building blocks. The car fueling project the company launched in California at the end of 2018 is a typical example.[[12]](#footnote-12)

## Increase in R&D and FID efforts

The State Aid from France will allow Air Liquide to conduct more R&D targeting the development of a comprehensive set of innovative technologies for the production, handling, storage and transportation of liquid hydrogen. The FID phase in the IPCEI will allow Air Liquide to first industrialise these innovations, overcome the technical challenges to start mass production and commercialise these innovative technologies, products and services. From a technical point of view, liquefaction of hydrogen is a very interesting option to reduce the cost of long-distance deliveries of hydrogen.

In the IPCEI Hydrogen scenario supported by a public funding in France, the main positive effects of the project would be:

1. The essentially improved level of innovation

Air liquide plans to develop a comprehensive set of innovative technologies all across a full liquid hydrogen logistics chain by targeting increased efficiency for each technology brick, as well as transversally, e.g. for minimising boil-off losses.

2. The integrated approach all across the value chain

Air Liquide proposes to develop innovative technologies all across the liquid hydrogen logistic chain:

* Liquefaction
* Storage
* Transportation
* Bunkering
* Delivery

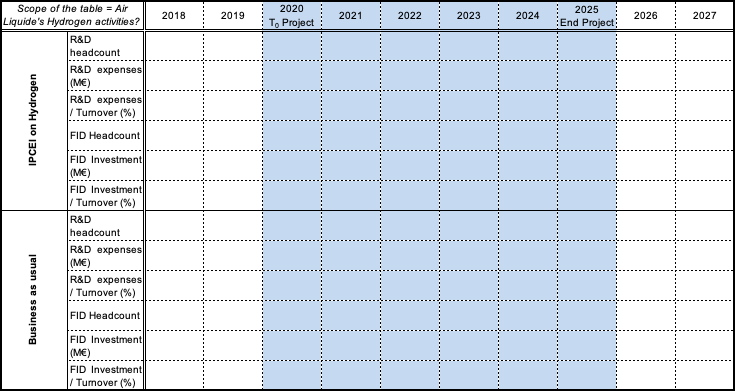
All these technology bricks are complementary and each of them is necessary in order to be able to supply liquid hydrogen for mobility applications on a competitive basis.

3. The scaling-up from a demo plant to a first industrial deployment

The IPCEI will allow Air Liquid to integrate all important R&D results into a demo plant. Only though this milestone can R&D be done at the interfaces between all technology bricks in order to make an additional step forward in terms of overall performance of the logistic chain.

In a next step, the IPCEI will allow Air Liquid to scale-up the demo into first industrial deployments. They will focus on the manufacturing of liquid hydrogen trailers, fueling stations as well as on the integrated supply chain.

Globally speaking, over the period 2020-2025, the French State aid for Air Liquide would allow a strong increase in R&D and FID efforts, as indicated in the table below:



# Elaboration on Terms of the Funding Gap Questionnaire

## Main hypothesis of the business plan

Annex B describes precisely the different assumptions made in the Business Plan and demonstrates that Air Liquide’s assumptions are reasonable. Due to technological evolution toward Hydrogen solutions, Air Liquide expect next generation liquefaction to be more efficient and make the installed technology obsolete by XXXX, as such it will placeAir LIquide’s business case in the period XXXX-XXXX.

The terminal value was assessed using the net book value of the assets at XXXX.

*Revenues*

o **Volume:** Volumes start in YYYY with XXX MW of sales of Air Liquide products. Progressive production ramp-up increases sales from XXX tons in YYYY to XXX MW per year in YYYY. Sales assumed to remain stable from YYYY to YYYY. Considering that the next generation hydrogen solutions will start mass production in YY years from now, new standards for manufacturing and fueling stations will progressively replace the current paradigm. Therefore Air Liquide has assumed a XXXX MW per year decline of sales volumes from YYYY to YYYY. Therefore, volumes are limited to XXXX MW in YYYY and null in YYYY.

o **Selling price**: The expected selling price of electricity is assumed to be XXXX in YYYY. This price is based on historic trends as well as potential carbon tax. According to research by the consulting firm, Name Air Liquide expect the price to increase/decrease by x% a year from YYYY to YYYY.

o **Additional revenues from the sale of by-products**: On top of the above-mentioned sale plan (YYYY to YYYY), Air Liquide has assumed, in YYYY during the FID phase, revenues of XXX k€. These revenues come from the sale of service stations which are expected to bring in XXXX of revenue, which will amount to XXXX at selling price XXXX.

**e2 additional recommendations:**

o Please include a table here, Columns will have years, row 1 will have sales Volumes, row 2 will have sales price, and row 3 will have Sales/Revenue.

*Variable costs*

Variable costs are estimated on current raw materials costs and central scenario for recipients and production costs taking into account the existing experience of processes and future complexity of the products.

*Terminal value*

The funding gap questionnaire has been set in accordance with the expected duration of stations and electrolysis to be employed. So, terminal value is only limited to trade working capital recovery.

*Inflation*

All revenues and costs are not inflated and expressed on 2019 basis, idem WACC is without inflation impact.

*WACC*

The WACC has been calculated post-tax to be consistent with the funding gap (also calculated post tax). On Date YYYY, Air Liqudie has publicly disclosed its calculation of the WACC on, a competitor of Air Liquide. The competitor WACC has been calculated at XXXX%, therefore very close to Air Liquide’s own WACC calculation (XXXX%).

## Necessity of state aid

According to point 28 of the IPCEI Communication, the aid must not subsidize the costs of a project that an undertaking would anyhow incur and must not compensate for the normal business risk of an economic activity.

In order to assess the activities grouped under the IPCEI on Hydrogen, Air Liquide built a business model considering the incremental efforts and the incremental returns.

Air Liquide’s Internal Rate of Return for the IPCEI on Hydrogen is equal to XXXX % without State aid, in a nominal scenario based on conservative and reasonable assumptions. It is almost XX points below the company’s WACC (xxxx %). Thus, it is clear that the State aid does not subsidize the costs of a project that Air Liquide would anyhow have carried out.

## Proportionality of state aid

## Firm’s hurdle rate

According to point 30 of the IPCEI Communication, in the absence of an alternative project, the Commission will verify that the aid amount does not exceed the minimum necessary for the aided project to be sufficiently profitable, for example by making possible to achieve an IRR corresponding to the firm’s hurdle rate.

Air Liquide’s Internal Rate of Return for the project IPCEI taking into account a XXXX k€ State aid from France would be XXXX %. Thus, the State aid required would provide the necessary incentive to enable Air Liquide to launch these highly ambitious and long-term R&D and FID activities, by raising the IRR just at the level of the WACC. The State aid does not confer extra profits for the company, it is proportionate.

## Project’s funding gap

According to point 31 of the IPCEI Communication, the maximum aid level will be determined with regard to the identified funding gap in relation to the eligible costs. The funding gap refers to the difference between the positive and negative cash flows over the lifetime of the investment, discounted to their current value on the basis of an appropriate discount factor reflecting the rate of return necessary for the beneficiary to carry out the project notably in view of the risks involved.

Air Liquide’s funding gap, calculated as the discounted difference between the positive and negative cash flows over the lifetime of the IPCEI on Hydrogen, amounts to -XXXX k€ (with a discount rate of XXXX % equal to the company’s WACC).

The State aid granted to Air Liquide, in the form of a direct grant amounting to XXXX k€ nominal, has a post-tax Net Present Value of XXXX k€. Thus, it is exactly equal to the funding gap; the State aid is proportionate.

## State aid intensity

The eligible costs to carry out the proposed activities are calculated only to the level necessary for achieving the project objectives. They consist of personnel costs (technicians, engineers and other supports mandatory for the project completion), materials costs and equipment costs the details of which are provided in section 1.8. For equipment, only the part of the cost prorated with the usage in the IPCEI on Hydrogen is considered.

The total amount of eligible R&D and FID costs is XXXX k€.

Thus, the required State aid is limited to XXX % of the eligible costs, which is far below the threshold of 100 % set by the Community guidelines for IPCEI.

## State aid cumulation

In the light of the beneficiary's declarations and to the knowledge of the French authorities, Air Liquide does not receive any State aid other than that indicated in point 2.2 of this notification to finance its share of work under the IPCEI on Hydrogen.

This State aid may come from the State budget or local authorities as well as from the structural funds.

## Open selection proceeding

The selection of Air Liquide as a partner for the IPCEI on Hydrogen and as a beneficiary of public support in France was done in the context of an open call for expression on interest launched on 21st January 2020, based on objective criteria which are neither discretionary nor discriminatory. Twenty-nine companies applied, among which Air Liquide was selected. This contributes to reinforcing the proportionate nature of the State aid.

# Limitation of distortion of competition and trade

## Market affected by the state aid

## Definition of the relevant market(s)

**-Market potential**

**Globally**, according to the “Hydrogen, scaling up” study conducted by the Hydrogen Council, **by 2050,** the market should be worth US$2.5 trillion and involve over 30 million skilled jobs with an output of 400 million private cars, 15 to 20 million trucks and around 5 million buses ([Hydrogen Council /McKinsey nov 2017](http://hydrogencouncil.com/wp-content/uploads/2017/11/Hydrogen-scaling-up-Hydrogen-Council.pdf)).

**By 2030** :

* 1 in 12 cars sold in California, Germany, Japan and South Korea could be powered by hydrogen
* 250 to 300 TWh of surplus solar or wind energy to be converted into hydrogen
* over 50 million households to be connected to a network combining gas and hydrogen
* H2 to replace 10 to 15 million metric tons of chemical raw materials currently used by industry.

To achieve these goals by 2030, an investment of US$280 billion or US$20-$25 billion per year would be required. These figures should be viewed against the US$1.7 trillion spent on energy globally each year. Any such investment would have to be made in close collaboration with governments as part of an approved public policy.

**By 2050:**

* More than 400 million cars, 15 to 20 million trucks and around 5 million buses
* more than 10 000 commercial regional aircraft could be powered by liquid Hydrogen with an annual consumption of 5 millions tons of Hydrogen (equivalent to 25 millions fuel cell vehicles)
* a fifth of total energy consumed, in which case hydrogen could account for 18% of final energy demand
* hydrogen could generate more than US$2.5 trillion per year in revenues and create 30 million jobs
* hydrogen could help reduce carbon emissions by 20% (under the 2 °C scenario), and 40% of transportation sector emissions
* the potential recovery of 500 TWh of renewable electricity otherwise “lost,” i.e., the equivalent of 10 million metric tons of hydrogen.

**France by 2050 :**

* **In France**, according to the French study "[Let's develop hydrogen for the French economy](http://www.afhypac.org/documents/actualites/pdf/Afhypac_Etude%20H2%20Fce_VDEF.pdf)" (in french) conducted by Air Liquide and 12 other partners with the help of McKinsey, **by 2050** hydrogen could account for 20% of France’s energy demand, power 18% of vehicles and cut carbon emissions by 55 million metric tons—almost a third of the reduction required under the reference scenario. The hydrogen industry is expected to generate 40 billion euro of annual revenue and create more than 150,000 jobs by that point.

In parallel, a [French study](http://www.afhypac.org/documentation/mobilite-h2-france/H2_Mobilite_France_Presentation_AVERE_04-2016.pdf), funded by the “Mobilité Hydrogène France” Consortium and the European Union as part of the Hydrogen Infrastructure for Transport (HIT) project, was conducted in 2014. Further to initiatives developed in other European countries, including Germany, Great Britain, Denmark, Netherlands and Sweden, on the basis of shared economic data, synchronized vehicle and hydrogen fueling station rollout scenarios were developed focusing on costs and the environmental, economic and social benefits of a transition to hydrogen-based electric mobility.

The “Mobilité Hydrogène France” consortium has around 30 public and private partners brought together in AFHYPAC, the French association for hydrogen and fuel cells. Since 2015, it has been rolling out its 2030 hydrogen mobility plan. **The Mobilité Hydrogène France plan** is based on the simultaneous rollout of captive fleets of operators committed to hydrogen (delivery companies, service providers, taxis, municipal services, etc.) and shared fueling stations for which the capacity is based on users’ needs. **The scenario is for 100 stations and 1,000 vehicles in 2022, and then 600 stations and 800,000 vehicles in 2030.** This plan kicked off in 2015 with various initiatives, such as the rollout of the **Hype** hydrogen taxi fleet in Paris (currently around 75 vehicles).

## Hydrogen liquefaction production

Air Liquide envisions to deliver

**Potential market for liquid H2 application**

**Liquid hydrogen** is a very interesting alternative for certain applications. It’s a technology that Air Liquide has been applying efficiently and safely for many years, operating liquefaction plants and the associated logistics chain. For example, in the United States, most of the sites of the 20,000 or so forklifts using hydrogen are supplied with liquid hydrogen.

Liquid H2 is also the only way to totally decarbonize commercial aircraft since batteries and high pressure gaseous H2 are respectively about ten and four times heavier. Notice 1 kg of H2 used in a fuel cell delivers about the same energy on the propeller as 4 kg of kerosene or is equivalent to 3 kg of kerosene when directly burned inside the turbofan.

The overcost and additional CO2 emissions linked with the liquefaction of hydrogen is paid off by saving in logistics and application for driving distance higher than 400 km between the source and the application for industrial applications, and from 200 km for hydrogen energy applications, where the compactness of the storage and the saving in compression costs brings an additional value for the liquid.

In some of the business cases which are currently studied, liquid hydrogen is the only way to go

Air Liquide currently has about 50% of liquid hydrogen production capacity and has 1/3 market share of liquid hydrogen sales(capacity is not currently fully utilized). With Praxair and Linde each having 25% market share. Air Liquide currently sells around 5 tonnes of liquid hydrogen a day for 8 euros a kilo, giving it a revenue of 14.4 million attributable to liquid hydrogen, which if we assume the Hydrogen market is about 2 billion dollars, so Air Liquide’s market share represents less than 1% of the hydrogen market.

* However Air Liquide is “Les liquéfacteurs seront commercialisés sur un mode ingénierie avec des briques technologiques standards, avec quelques unités (pas d’industrialisation)

”

The big players that will compete with Air Liquide are Shell, Engie, Ariane, Vattenfall (energy provides), they all have plans to enter the hydrogen market and some plans specifically for liquid hydrogen market. Shell and Linde specifically have a project for development of a 50t/j liquefaction systel. Engie and Shell are partners for Air Liquide for on storage of liquid hydrogen.

Although Air Liquide currently has

## Hydrogen distribution in liquid form

Though Air Liquide is one of the largest producers of liquid hydrogen stations, Air Liquide currently has no liquid hydrogen stations in operation.

Liquid hydrogen distribution is only advantageous in large volumes, specifically for more than 500kg of supply by day.

The conditions for entry in the liquid hydrogen market are generally subject to quite asymmetric regulatory environment. For example, whilst in Germany, the regulatory method is of the form “If it isn’t prohibited, it is allowed”, the French regulatory environment requires Air Liquide to ask for authorization to expand its facilities. As a result of this asymmetry Linde is the number one provider of hydrogen stations with liquid hydrogen.

The main customers are rail freight operators and fleet operators (long-haul).

## Hydrogen refuelling stations

Definition: Hydrogen refuelling stations

Liquid hydrogen is useful to reduce to the cost of transportation, but the ultimate source may still require gas hydrogen. As such Air Liquide will develop some standard hydrogen refuelling stations. The current market situation of Air Liquide is that it operates a very low proportion of such stations.

The market for HRS is unlikely to have strong barriers to entry. The typical capital requirement to enter the market is around ten million euros, or less than 2 % of the opex. Moreover, the fact that many companies, including start-ups like McPhy, have plans to enter the growing HRS market shows that entry is relatively easy.

According to the Hydrogen council report, France and Scandinavia have about 150 stations each; Germany is on track to have 400 stations by 2023, the rest of Europe on track to have 820 stations between them, the main operators of these stations being local companies. Outside of the European project, the UK is on track to have 1150 stations by 2030, and the Norther United states expected to have 350 stations by 2027. As a continent, the Asian markets is the largest, with China and Japan on track to have over 1900 stations by 2030, and South Korea will have 310 stations by 2022.

The major market players for the provision of Hydrogen refuelling stations in Europe are Air Liquide, ITM Linde. Air Products.

## Liquid hydrogen Production trailers

Air Liquide is a leader in the production of trailers, being responsible for 100% of sales. Scale of production of trailers from a few every 2-5 years to 50 a year. The main customers from trailers are electronics, food production and metallurgy.

## Bunkering stations trailers

Bunkering stations are useful when the final use of the hydrogen is in liquid form and usually confined so that it impossible to refuel on the go. So in general bunkering is for much larger applications, (Large boats, planes, and future trucks )

### Current Industry Sector

The main method of current hydrogen production is steam methane reforming (SMR). It accounts for 95% of hydrogen production. Its principle input is Natural Gas and Coal, as such, it would be considered as “grey” energy. It is [estimated](https://www.iea.org/reports/the-future-of-hydrogen) that hydrogen usage is 6% of natural gas use and 2% of coal use and is thus responsible for 830 million tonnes of CO2 emissions.

### Market Situation / Share today and after IPCEI

Today the liquid hydrogen market is limited to niche applications (mostly space activities).

Only a few trailers are produced every 2 to 5 years

Air Liquide current market share is XXXX and practically non-existent. Air Liquide is a major player in numerous countries, What and what volume and market share currently? Is there a projection on future market share?

After the IPCEI, Air Liquide intends to build capacity of X tonnes (build capacity of how many tonnes?). If this capacity is fully utilized, Air Liquide expects to have XXXX% market share of the NNNN hydrogen market.

Moreover, according to reports the size of the hydrogen energy market will be of 40MW a year and still set to increase in large quantities, entailing that there will be ample room for growth in the future.

For all the above-mentioned reasons, the French State aid to Air Liquide for the IPCEI on Hydrogen is highly unlikely to deter the company’s competitors’ investments in R&D and FID to develop competing technologies.

## No strengthening or creation of market power

On the selling side of Hydrogen, Air Liquide will have strong European competitors such as NNNN which will not benefit from Air Liquide competition, indeed there is unlikely to be much effect on market power since Air Liquide envisages only XX% market share. Indeed, a stronger presence for Air Liquide is likely to reduce the market power of existing larger firms.

Newcomers such as Oil & Gas Companies (SHELL) or large conglomerates (KHI, Kawasaki Heavy Industries) are also investigating the technology and investing into prototype supply chain at reduce scale with a clear vision of upscaling (see the LH2 to Japan import project from KHI)

On the buyer’s side, Air Liquide will have the solutions to large energy industrial and commercial energy suppliers such as Engie, EDF and Vattenfall. This will mean that there will not be much scope for the supply side to increase its market power.

Air Liquide actual and future market position, the presence of very strong established competitors, the anticipated growth of the market and the strong buying power of its future customers make it reasonable to assume that the State aid from France to the company will not create nor strengthen any market power. As a new entrant, Air Liquide will rather positively affect the competition at a European level by weakening the market concentration and providing an alternative to the currently Asian-dependant European Hydrogen manufacturers.

## Limiting distortion of dynamic incentives

Being a potential new entrant in the hydrogen market, Air Liquide will have to face strong competition from well-established European/Asian/American competitors.

The State aid required by Air Liquide for the IPCEI on Hydrogen amounts to XX M€ per year on average (four year XXXX-XXXX), that is approximately XX M$ per year. It is small compared to the size of the market (for example, less than XX % of the XXXX sales of the top players who are YYY reported in Table 1 above). Moreover, it will be dedicated to R&D funding for ZZ% approximately and to FID for only 1-ZZ%, which makes it less likely to distort dynamic incentives.

Moreover, according to Hydrogen Europe, the anticipated growth rate is set to be around 5% with the Hydrogen market doubling by 2030 and increasing by eight times by 2050. As a result of this forecasted market growth, there will remain ample opportunities to develop profitable business for Air Liquide’s competitors on the Hydrogen market.

For all the above-mentioned reasons, the French State aid to Air Liquide for the IPCEI on Hydrogen is highly unlikely to deter the company’s competitors’ investments in R&D and FID to develop competing technologies.

## No maintaining of an inefficient market structure

The State aid that is granted to Air Liquide in France for the development and first industrial deployment of innovations in the field of Hydrogen will not adversely impact a market that is not suffering from overcapacity and is not declining. Indeed, the European hydrogen sector is still in its infancy and should experience an important growth in the coming decade, nurtured by strong innovations and competition. Moreover, the installed capacity in Europe is marginal, while the number of new entrants is expected to rise significantly. These features are typical of dynamic and efficient markets.

## No effect on location activities

Air Liquide’s current industrial activities are located in the country; it is also the case for its R&D and FID activities in the IPCEI on Hydrogen that the location of the project (NNNN) does not depend on the source of public funding. The company did not consider locating its activities related to the IPCEI on Hydrogen outside France, and it did not demand any public funding to another Member State for the same project.

Thus, there is no risk of a subsidy race between Member States that may arise in particular with respect to the choice of Air Liquide’s location for the IPCEI on Hydrogen.

# Annex to the Portfolio

1. *Funding Gap Questionnaire*
2. *(If necessary) Internal Company Documents substantiating the counterfactual scenario*

1. The “Mobilité Hydrogène France” consortium has around 30 public and private partners brought together in AFHYPAC, the French association for hydrogen and fuel cells. [↑](#footnote-ref-1)
2. Fuel Cell Electric Vehicle [↑](#footnote-ref-2)
3. For clarification, “Zero losses” refer to a supply chain with less than 3% losses, 2% expected. [↑](#footnote-ref-3)
4. <https://www.cerfacs.fr/avbp7x/index.php> [↑](#footnote-ref-4)
5. Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC Text with EEA relevance [↑](#footnote-ref-5)
6. The thresholds are defined as a ponderated sum of the different dangerous goods quantities stored on site. The example taken considers that only LH2 is stored. In a H2 liquefier, this might be untrue as NH3 can be used as a refrigerant. [↑](#footnote-ref-6)
7. Current LH2 flow meters are turbine flow meters, and cannot measure a mass flow (because of diphasic flow) [↑](#footnote-ref-7)
8. Direction Générale de la Prévention des Risques [↑](#footnote-ref-8)
9. Association Française de l’Hydrogène et des Piles A Combustible [↑](#footnote-ref-9)
10. Mean Time Between Failures [↑](#footnote-ref-10)
11. *Directive 2012/18/EU of the European Parliament and of the Council of 4 July 2012 on the control of major-accident hazards involving dangerous substances, amending and subsequently repealing Council Directive 96/82/EC Text with EEA relevance* [↑](#footnote-ref-11)
12. See e.g. <https://energies.airliquide.com/air-liquide-build-first-world-scale-liquid-hydrogen-production-plant-dedicated-supply-hydrogen> [↑](#footnote-ref-12)