Interreg North-West Europe H2SHIPS

System-Based Solutions for H2-Fuelled Water Transport in North-West Europe

Deliverable: Study on the suitability of hydrogen as a fuel for the waterborne transport of household waste

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AMO Consulting engineers, contracting authority support
ATEX EXplosive ATmospheres

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BV	Bureau Veritas, vessel control and classification body
CCNR	Central Commission for the Navigation of the Rhine
DRCPE	Explosion prevention document
DREAL	Regional Directorate of Environment, Planning and Housing
DRIEA	Regional and Interdepartmental Directorate of Equipment and Planning
ES-TRIN	Européen Standard- Technical Recommandation Inland Navigation
EVP	Twenty-foot Equivalent Unit (TEU)
FC	Fuel Cell (= pile à combustible)
ICPE	Environmentally Classified Installations
LIE	Lower Explosive Limit (LEL)
LES	Upper Explosive Limit (UEL)
OMR	Residual household waste
PAC	Fuel cell
PLU	Local Urban Plan
PPR	Risk Prevention Plan
RVBR	Inspection regulations for Rhine vessels
TCO	Total Cost of Ownership (= coût total de possession)
VNF	Voies Navigables de France (Navigable Waterways of France)
WP	Work Package

1 Summary

As part of the H2Ships project, the objective of this mission, included in the ***WPT2 - Defining requirement for uptake of H2 propulsion in water transport in NEW***, was to study the modalities of development of a water transport hydrogen motorization within the framework of a pilot project. The pilot project selected by SYCTOM is the water transport of waste from the transformation sorting center of Romainville / Bobigny, located on the Ourcq canal. In this context, containerized household waste will be transferred by river to three outlets on the Seine.

The objective of this mission was to define for the H2 motorization:

- The technical characteristics of the motorization to be used
- The regulatory framework to which H2 navigation is subject
- The identification of the related needs that guarantee the feasibility of the project (in terms of refueling in particular)

The definition of the H2 engine is based on the logistical assumptions detailed in previous studies. It should be noted that the water transport equipment needs identified for the SYCTOM project are as follows:

- 1 to 2 canal pusher boats dedicated to navigation on the Ourcq Canal
- 1 pusher boat dedicated to navigation on the Seine
- 5 to 8 barges

Requirements are in fact likely to change depending on the stage of advancement of the Romainville-Bobigny project.

The pushers will be powered by hydrogen, stored in gaseous form at a pressure of 350 bar.

The estimated needs for H2 consumption are based on the establishment of a fuel station on the Seine at the exit of the Saint-Denis lock (in the direct vicinity of the Ourcq canal). This hypothesis will have to be confirmed by the dedicated WP (research specific to refueling treated within the framework of WPI2).

The waterway transport cost calculated for this study varies from € 13.8/ton to € 9.5/ton depending on the volumes transported and therefore appears reasonably competitive if we take into account the interest of the attached decarbonization, compared to a transport cost of € 11/ton for a conventional diesel engine that uses very carbonaceous fossil fuel.

Subsequent feasibility and constructability studies for barges and pushers should confirm this preliminary estimate.

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2 Introduction

As part of its participation in the H2Ships project, SYCTOM wishes to study the deployment of a pilot hydrogen motorization project integrated into the transformation project of its Romainville-Bobigny sorting center. This project consists of requalifying the Romainville-Bobigny waste treatment center and, in this context, of organizing the transfer by river of part of the treated waste to the other SYCTOM outlets located in the Paris region and close to the Seine (Saint-Ouen, Issy-les-Moulineaux and Ivry-sur-Seine).

The river logistics scheme has already been the subject of previous research.

In accordance with the specifications "Additional research on river motorization for the transport of household waste in containers", the objective of this mission is therefore to assess the feasibility and the conditions for implementing a propulsion system for a pusher river boat using a cell system of fuel and hydrogen, for barges of household waste containers transported as part of the Romainville-Bobigny project.

To do this, three aspects will be addressed in this research:

- Phase 1: determining the technical characteristics of the motorization to be used.
- Phase 2: the induced impacts on the river route and the adaptations to be planned.
- Phase 3: related regulatory and financial analysis.

3 Research hypotheses

3.1 Transferred products

3.1.1 Product typology

The products transferred by river as part of this mission are raw OMR packaged in ampliroll containers whose external dimensions are similar to those of ISO 20 ’containers.

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Figure 1 – 20' ISO ampliroll compaction container for the transfer of residual household waste (OMR)

Deployment of the Romainville-Bobigny project is planned in two development phases:

- **Phase 1 : Simple case** with only 1 outlet served (Issy-les-Moulineaux) and 120,600T gross OMR transferred each year
- **Phase 2 : Multiple case** with 3 outlets served and 290,000T gross OMR transferred each year

3.1.2 Transferred volumes

3.1.2.1 Phase 1 – Simple case

The volumes transferred in the simple case, when the new Romainville / Bobigny treatment centre is started, are as follows:

Table 1 – Summary of the transferred volumes in the simple case

	OMR Issy-les-Moulineaux	Unit
Tonnage	120 600	Tons
Load per container	12.92	Tons
Annual traffic (ampliroll)	9 338	TEU
Barge capacity	24	TEU
Number of annual stopovers	390	Barges
Number of weekly stopovers	7.5	Barges
Number of daily stopovers	1.5	Barges
Total time of the barge at the quayside (Romainville)	3.2	h
Total time of the barge at the quayside (outlet)	4.8	h

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A maximum of 8 barges will be transferred each week in the simple case of Romainville-Bobigny to Issy-les-Moulineaux (i.e. a maximum of 2 barges per day).

3.1.2.2 Phase 2 – Multiple case

If the transfer of waste put in place to Issy-les-Moulineaux is conclusive, SYCTOM plans to eventually develop the transfer by river on a larger scale. In this case, the Issy-les-Moulineaux wharf alone will not be able to take all the transferred waste and the additional outlets at Saint-Ouen and Ivry-sur-Seine will be adapted to receive waste by river. The volumes transferred to each outlet will then be as follows:

Table 2 – Summary of the transferred volumes in the multiple case

	OMR Issy	OMR St-Ouen	OMR Ivry	TOTAL	Unit
Tonnage	150 000	70 000	70 000	**290 000**	Tons
Load per container	12.92				Tons
Annual traffic (ampliroll)	11 614	5 420	5 420	**22 455**	TEU
Barge capacity	24				TEU
Number of annual stopovers	484	226	226	**936**	Barges
Number of weekly stopovers	9.3	4.4	4.4	**18**	Barges
Number of daily stopsovers	1.9	0.9	0.9	**4**	Barges
Total time of the barge at the quayside (Romainville)	3.2				h
Total time of the barge at the quayside (outlet)	4.8	4.4	3.8		h

A maximum of 18 barges per week will be transferred by SYCTOM.

In fact, a maximum of 4 barges per day will be sent from Romainville / Bobigny to the outlets according to the following breakdown:

- 2 barges bound for Issy-les-Moulineaux
- 1 barge bound for Saint-Ouen
- 1 barge bound for Ivry-sur-Seine

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3.2 River route hypotheses

3.2.1 River scale

The choice of the scale and the location of the site require the river traffic of barges on the Ourcq Canal at "large scale" only. As the only possible entry into the canal is through the Saint-Denis canal, self-propelled barges must pass the Romainville site and go up to the Pavillons-sous-Bois turning basin where they can perform their U-turn manoeuvres to come back to the site and dock.

To overcome this constraint, SYCTOM has chosen to use barge + pusher boat convoys. Pusher boats can manoeuvre the barge upstream or downstream, this allows greater manoeuvring flexibility but induces additional constraints in terms of the length of the wharf, which must allow the pusher boats to manoeuvre on two sides of each barge, i.e. a sufficiently safe space to manoeuvre a pusher boat between two barges alongside.

Figure 2 – Example of a pushed convoy

In view of the navigation constraints on the Ourcq canal, the use of 24 TEU barges operated by pusher boats was selected by SYCTOM. This solution is more flexible than using self-propelled motors given the size of the canal.

3.2.2 Outlets

The waste will be placed in containers and transhipped onto barges on the Romainville / Bobigny river platform. The barges will then take the Ourcq canal and then the Seine to the 3 SYCTOM outlets:

- Saint-Ouen

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- Issy-les-Moulineaux
- Ivry-sur-Seine

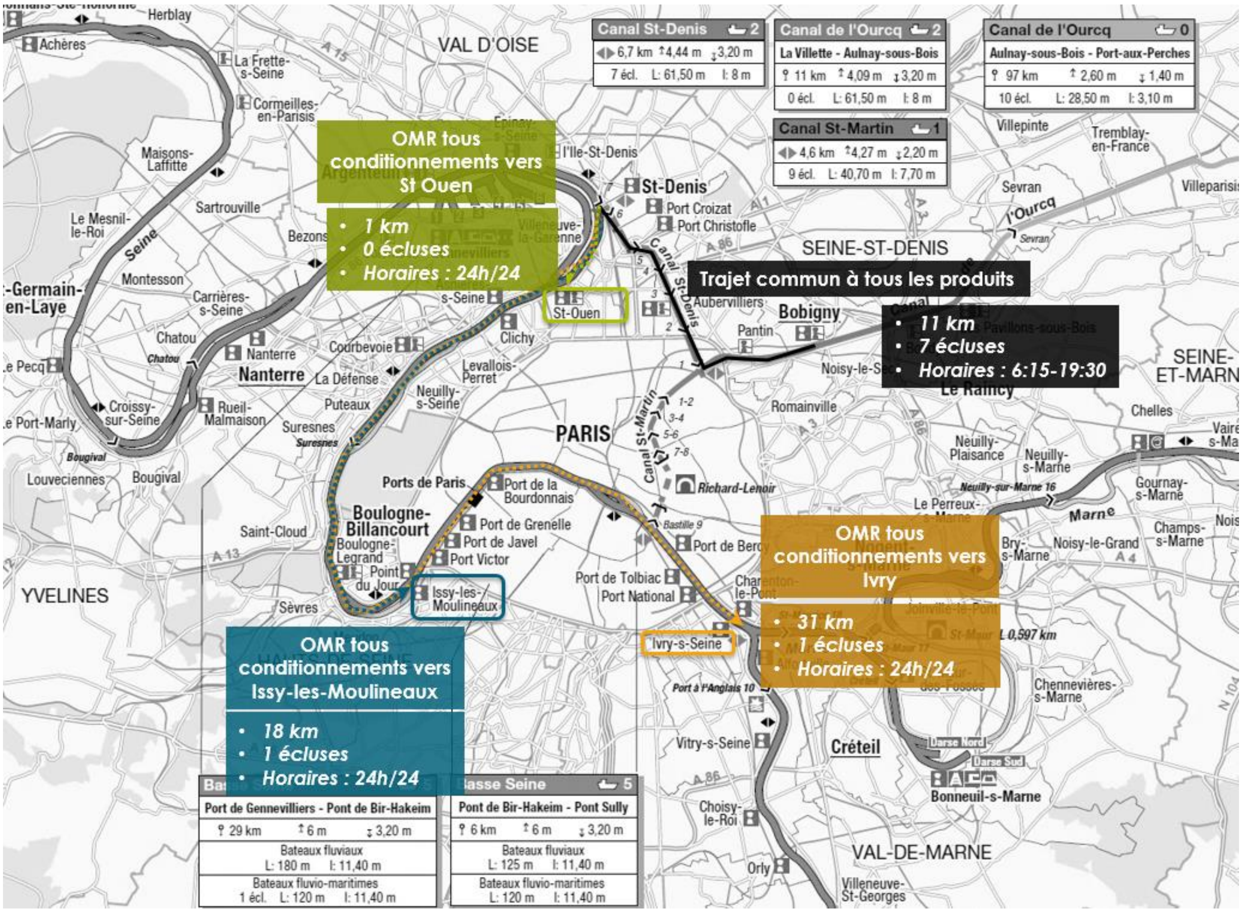

Figure 3 - River routes taken by barges in the Paris basin (© VNF)

3.2.3 Port platforms

The existing docks will have to be adapted to allow the loading / unloading of barges. These adaptations have been considered in the context of previous studies and are not the subject of this report.

These port platforms will be operated from Monday to Friday, i.e. 5 days a week.

3.2.4 Business hours of facilities

If traffic on the Seine is authorized 24 hours a day, time constraints must be taken into account for the opening of the various facilities on the river route:

Table 6 – Time constraints to be taken into account on the river journey

	Opening	Closing
Romainville-Bobigny wharf	6h	20h
Ourcq canal locks	6h15	19h30
Saint-Ouen wharf	5h	22h
Issy-les-Moulineaux wharf	6h	20h
Ivry-sur-Seine wharf	6h	20h

These constraints will have to be integrated into the logistics plan of the barges.

3.2.5 Features of the river route

3.2.5.1 The waterway

The barges and pusher boats will use two different types of waterways:

- A portion of the journey will be carried out on the Ourcq canal (large gauge part)
- A portion of the journey will be made on the Seine

The characteristics specific to each waterway are summarized in the table below:

Table seven – Features of waterways used by barges

	Ourcq Canal	Seine
Manager	Canaux de Paris	VNF
Maximum authorized speed on the waterway	6 km/h	20 km/h
Locks opening hours	6h15 – 19h30	24h
River gauge	Max width : 8 m Max length : 61,5 m Air draft : 4,09 m Draft : 2,60 m	Max width : 12 m Max length : 160,5 m Air draft : 6 m Draft : 4,10 m

The maximum and minimum speeds of loaded boats on the Seine are regulated by:

- Inter-prefectoral decree n° 2014238-0013 on inland navigation on the river network of the city of Paris.
- Police regulations / Inland navigation police.

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The speeds considered for river journeys are as follows:

Table 8 – Selected regulatory speed and speed limit

	Maximum authorized speed on waterway (km/h)	Speed limit for loaded boat (km/h)	Speed limit for light boat (km/h)
Ourcq canal	6 km/h	5 km/h	6 km/h
Seine	20 km/h	8.5 km/h	12 km/h

In the rest of the research, we consider that:

- Barges returning from outlets loaded with empty containers will operate at the light boat speed limit
- Barges loaded with full containers coming from travel at the speed limit for loaded vessel
- The passage time of a lock is estimated at 30 min per lock.

3.2.5.2 Organization of the river journey

As the characteristics of the Ourcq canal and the Seine are significantly different for navigation, the logistics scheme selected consists of using two different pusher boats depending on the used waterways:

- **The pusher boat « Ourcq »** will take charge of the barges from the Romainville / Bobigny river platform until after the Saint-Denis lock
- **The pusher boat « Seine »** will take charge of the barges from the Saint-Denis lock to the outlet.

This scheme will also make it possible to constitute pushed convoys on the Seine in the evolving case and thus to pool the journeys.

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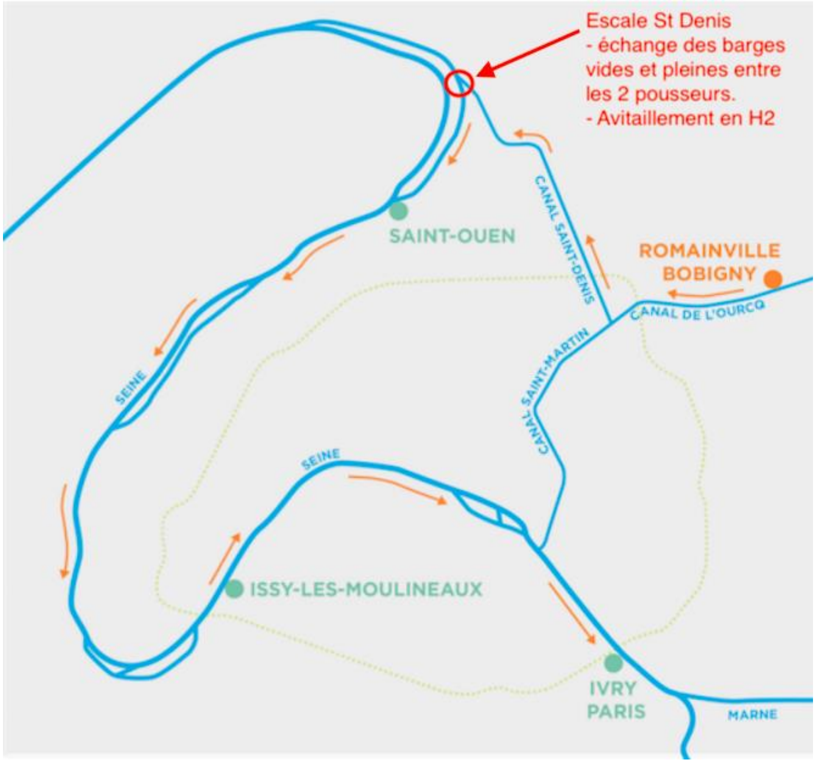

Figure 9 – Map of the river route

A convoy grouping / ungrouping area should be provided at the exit of the Saint-Denis lock so that the Ourcq pusher uncouples the barge, which will then be taken over by the Seine pusher.

The implemented logistics plan on the project aims to limit as much as possible the journeys made empty, that is to say the pusher boat alone without barge.

Consequently, during each stop at a river platform, the pusher boat will exchange his full or empty barge for another full or empty barge to bring it back in the opposite direction.

In view of the characteristics of the locks of the Ourcq canal, the Ourcq pusher boat will only handle one barge. On the Seine, convoys pushed to a maximum of 2 barges could be provided to pool flows.

3.2.6 Rotation time

The absolute barge rotation times (without taking into account any waiting times linked to the time constraints of the equipment) have been studied beforehand and lead to the following cycle hypotheses:

- **Romainville / Saint-Ouen / Romainville : 17h59**
- **Romainville / Issy-les-Moulineaux / Romainville : 22h08**
- **Romainville / Ivry-sur-Seine / Romainville : 23h18**

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3.3River logistics diagram

3.3.1 Simple case - River logistics diagram

For the simple case, only the Issy-les-Moulineaux outlet will be served. In this context, the pusher boat will always support a maximum of one barge.

- The Ourcq pusher will take charge of the Romainville / Bobigny barge until it leaves the Saint-Denis lock.
- At the exit of the lock, the barge will be taken over by the Seine pusher boat that will take it to Issy-les-Moulineaux.
- The Seine pusher will then take charge of an empty container barge waiting at Issy-les-Moulineaux to reroute it to the Ourcq canal
- The empty barge will be deposited by the Seine pusher boat upstream of the Saint-Denis lock.
- The canal pusher boat will then take charge of it to reroute it to Romainville / Bobigny.

To estimate the rotation time of a barge, in view of the time constraints for the opening of the various equipment, a simulation of the rotation time was carried out (see Annex 1). The average rotation time of the barge is 37h45min taking into account the waiting times; or a little more than 1.5 days between departure and return to the Bobigny wharf.

A maximum of 2 barges per day can be loaded at the port of Romainville / Bobigny, this means that 3 to 4 barges must be provided for river operations in the simple case.

In terms of navigation time, the 2 daily barge transfers define the following needs for the pusher boat :

- A rotation of the pusher boat on the Ourcq corresponds to 9h45min (round trip). An occupation period of **19h30min** per day should be planned over one day for this pusher boat.
- A rotation of the pusher boat on the Seine corresponds to 5h05min of navigation. To ensure the two daily transfers, the occupation of the Seine pusher in navigation is **10h10min**

This logistics scheme assumes that the two pushers always take charge of a barge (whether for the outward journey or the return journey).

The pusher boat trips will have to be coordinated so that no trip is made empty (the pusher boat deposits a full barge in Saint-Denis and leaves with an empty barge).

The logistics plan put in place should therefore provide for a barge to always be on standby at the exit of the Saint-Denis lock so that the two pushers do not have a load break.

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Following this analysis, it is necessary to provide for the simple case:

- **An Ourcq pusher boat dedicated to navigation on the canal**
- **A Seine pusher boat dedicated to navigation on the Seine**
- **5 barges (3 barges in operation + 1 standby barge + 1 emergency barge)**

3.3.2 Multiple case - River logistics diagram

For the multiple case, all the outlets will be served. A maximum of 4 barges / day will be loaded at Romainville / Bobigny according to the following distribution:

- 2 barges to Issy-les-Moulineaux
- 1 barge to Saint-Ouen
- 1 barge to Ivry-sur-Seine

The Saint-Ouen outlet being located in direct proximity to the Saint-Denis lock (30 min of navigation); it is not coherent to provide for the recovery of the barge bound for this outlet by the Seine pusher boat. The barge bound for Saint-Ouen will therefore be exclusively managed by the Ourcq pusher boat.

To pool barge transfers, the barge bound for Ivry-sur-Seine will be grouped with a barge bound for Issy-les-Moulineaux. The Seine pusher boat will drop off a barge at Issy-les Moulineaux then continue its journey to Ivry-sur-Seine where it will drop off the barge loaded with full containers and take charge of the waiting barge loaded with empty containers. On the way back, it will stop again at Issy-les-Moulineaux to group its convoy with the barge loaded with empty containers waiting at Issy and will reroute the two barges to the Saint-Denis lock.

Finally, a transfer on the Seine will be a single barge with a barge bound for Issy-les-Moulineaux taken over by the Seine pusher boat.

In the multiple case, it is therefore necessary to provide 2 rotations of the Seine pusher boat:

- A rotation with a grouped convoy of 2 barges to Issy-les-Moulineaux then Ivry-sur-Seine
- A rotation with a convoy of a single barge to Issy-les-Moulineaux

As for the simple case, a simulation of the rotation time of the barges towards each of the outlets was carried out (details available in Annex 2); the average rotation times retained for the barges taking into account the waiting times are as follows:

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- Saint-Ouen : 31h 08min
- Issy-les-Moulineaux : 37h 34min
- Ivry-sur-Seine : 40h 48min

A maximum of 4 barges per day will be loaded / unloaded at Romainville / Bobigny and each must supply the outlets. This logistical organization is complex and it requires careful organization to keep waiting times as low as possible.

In terms of navigation time (excluding manoeuvring time and waiting time), the 4 daily barge transfers define the following needs for pusher boats:

- **Ourcq:** 4 rotations / day are carried out on the Ourcq canal, which corresponds in total to **39 hours of navigation**.
- **Seine :** 2 rotations / day are carried out on the Seine :
  - For rotation 1 (Issy-les-Moulineaux then Ivry-sur-Seine), the total navigation time on the Seine is **8h45min.**
  - For rotation 2 (Issy-les-Moulineaux only), the total navigation time on the Seine is **5h05min.**
  - In total, the navigation time of the Seine pusher boat in this configuration is therefore approximately **14 hours/day.**

We will therefore retain the following needs in the multiple case:

- **2 Ourcq pusher boats will be necessary to complete all the transfers**
- **1 Seine pusher boat will be sufficient to perform the two rotations on the Seine**
- **3 additional barges should be planned (in addition to the 5 barges initially planned)**

3.4 Definition of pusher boats

3.4.1 Main features

The analysis of the flow data leads to the following conclusions:

- The journey times and the different navigation conditions between the canal and the Seine require at least 2 pusher boats to correctly operate phase 1.
  - 1 "Ourcq" pusher boat dedicated to canal navigation, convoy of a single barge of 500 tons
  - 1 "Seine" pusher dedicated to navigation on the Seine, convoy of one to two barges (500 to 1000 tons)

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- The push barges are of suitable dimensions 50x7m (160 tons light, maximum carrying 500 tons, average load 420 tons)
- The barges are ballasted for the return of empty containers to respect the air draft (TA) of the canal at 4.09m

3.4.2 Differences between the pusher boat operating on the canals and the one on the Seine.

Pusher boats are therefore still operating for the "Outbound" trip, with barges loaded between:

- 380 and 500 tons on the canals, speed 6 km/h
- 380 and 1000 tons on the Seine, speed 12km/h

The pushers still operate for the "Return" trip with barges loaded with empty containers, respecting the authorized speeds on the canals and on the Seine (6 and 12 km/h).

Navigating the canals requires little energy: there are no currents and climatic variations have little influence (mainly wind conditions). The pusher boat therefore needs instantaneous power to perform certain manoeuvres but consumes little energy for its navigation.

Navigating the Seine requires more energy: there are variations in the direction of the current depending on the direction of navigation (up or down). The intensity of the current can also vary from weak to strong until the flood conditions are added to the wind conditions. In this case, the pusher needs instantaneous power to perform the manoeuvres but also to navigate in all circumstances, so it consumes more energy while sailing than a pusher operating on the canals does.

The two pushers will therefore be of appreciably different design and sizing. Their main characteristics are detailed in §5.1.

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4 Inventory of H2 forms

4.1 Inventory of H2 forms

Like electricity, hydrogen is primarily an energy carrier and not an energy as such, although a few sources of natural hydrogen production have been observed. It is therefore produced from an energy source. Currently, for economic reasons, 95% of it comes from the transformation of fossil fuels (mainly from natural gas).

As with electricity, as part of the energy transition and to achieve carbon neutrality in 2050, research into carbon-free energy production, from renewable energy in particular, is in progress. In this context, the production of hydrogen by electrolysis of water is being studied. Currently used mainly in chemicals or refining, hydrogen could find other applications such as decarbonizing certain industrial sectors, ensuring the storage of electricity or supplying the transport sector.

The existing forms of hydrogen are:

- The main resources used to produce dihydrogen H2 are **water and hydrocarbons** (coal, oil or gas).
- Hydrogen is also found in hydrocarbons, which are made from the **combination of carbon atoms and hydrogen**. This is the case, for example, with methane, the main constituent of natural gas, whose formula is CH4, one of the simplest combinations for hydrocarbons.
- Hydrogen also exists **naturally**. The first natural sources of hydrogen were discovered at the bottom of the sea in the 1970s, and other sources have more recently been identified on land. The exploitation of natural hydrogen at the bottom of the sea, in very deep waters and very far from the coast, is not economical. More recently, more readily available hydrogen fumes on land have been detected. However, the exploitation of these forms of hydrogen is not planned now: knowledge on the origin of the formation of this hydrogen and research on production techniques must still progress to that this source becomes profitable.

At present, there are 3 production techniques, which consist in extracting hydrogen from the primary resource, namely:

- The most widely used technique is the **reforming of natural gas with water vapour**. This involves reacting methane with water to make a mixture containing hydrogen and CO2. The CO2 emitted by this process can optionally be captured, and stored, to produce carbon-free hydrogen. Instead of natural gas, the use of bio methane (methane

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from the fermentation of biomass) is also a solution for producing carbon-free hydrogen;

- **Gasification** makes it possible to produce, by combustion, a mixture of CO and H2 from coal (a solution that emits a lot of CO2) or biomass;
- Hydrogen can also be produced from water and electricity; it is the **electrolysis of water**. The electrolyser separates a molecule of water into hydrogen and oxygen. This route is still not very widespread because it is much more expensive (2 to 3 times more expensive than reforming natural gas) and reserved for specific uses, such as electronics, which require a high level of purity.

Today, 95% of hydrogen is produced from hydrocarbons (petroleum, natural gas and coal), the cheapest solution. However, this process emits CO2.

To produce carbon-free hydrogen, two options are available to manufacturers:

- Either **capture the CO2 emitted during production** by transformation of fossil fuels, then transport it to store it geologically,
- Either produce it via the **electrolysis of water**, the electrolysis being carried out from carbon-free electricity supplied by wind or solar energy. However, the challenge remains the cost of this mode of production, which is much more expensive to date than that of reforming.

Hydrogen could meet three essential challenges of the energy transition:

- **Decarbonize the industrial sector**, which consumes a lot of energy. In this case, hydrogen would have two uses: on the one hand, to supply carbon-free energy to the industrial units concerned; on the other hand, contribute to the decarbonisation of the industrial processes concerned by replacing the fossil fuels currently used; this is the case, for example, with the manufacture of steel which results from the reduction of iron ores; this reduction carried out today via coal could tomorrow be done using carbon-free hydrogen.

- **Address the variability in the production of certain renewable energies** with the possibility of storing hydrogen. Hydrogen is produced by electrolysis of water, electricity being supplied by wind or photovoltaic production, and then stored according to different possible storage methods (batteries, massive storage in salt cavities) depending on the use that is desired. One advantage of this storage is to be able to then convert this hydrogen into electricity, and thus to optimize the capacity of electricity production to be built and to compensate for the intermittences of production of wind and solar renewable energies, and, finally, to meet the peaks of consumption. This therefore requires being able to produce non-carbon hydrogen.

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This can be obtained either by the conversion of fossil fuels (including in particular the reforming of natural gas) which can be decarbonized by capturing CO2 and then storing it in the subsoil permanently (this is blue hydrogen), or by electrolysis, electricity being produced from renewable energies (this is green hydrogen).
Hydrogen produced by electrolysis can also be carbon-free if the electricity is of nuclear origin. The production of "green hydrogen" is not yet a reality. A transformation of energy systems and of the technical and economic context will be necessary to achieve this.

- Moreover, the objective of the study is **decarbonizing the transport sector**. Electrified transport equipped with a fuel cell (PAC) transforms hydrogen into electricity and water vapour, but this solution is environmental friendly only if hydrogen is produced from carbon-free sources. Furthermore, hydrogen has advantages over batteries, in terms of autonomy, and recharging time.

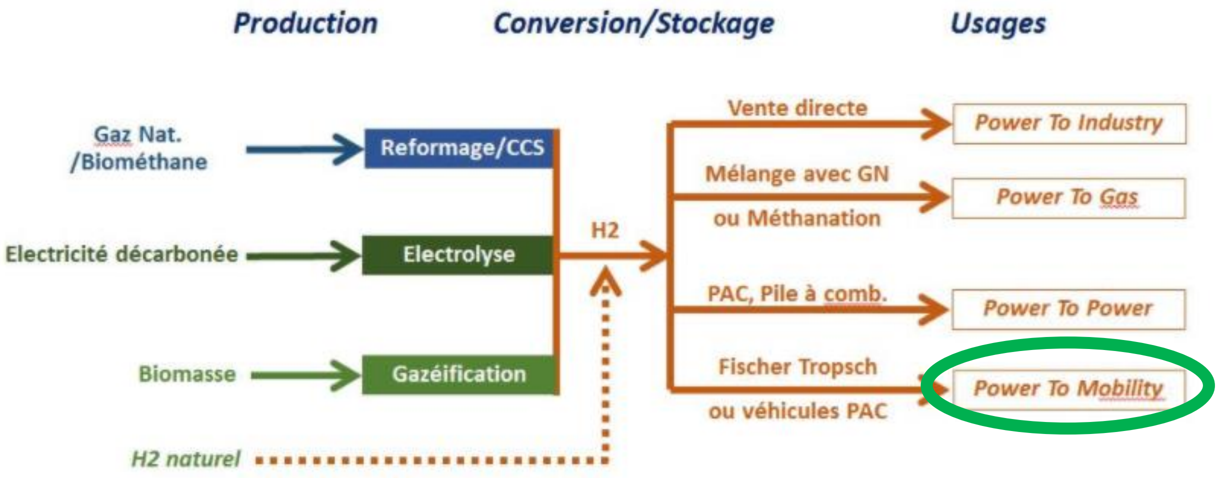

Figure 4 – Production of hydrocarbons from syngas (CO + H2)
(CCS: Carbone Capture & Storage - Fischer Tropsch)

4.2 Recommendation of the H2 form

Hydrogen is considered to be one of the energy carriers of the future. This gas can be used as fuel in various applications while making it possible to meet society's demand in terms of sustainable development. However, this requires several technological obstacles to be overcome.

One of them is the storage of hydrogen gas.

It must offer on the one hand a high degree of safety, and on the other hand ease of use in terms of energy density and kinetics to allow fuel cells to operate under acceptable technical conditions.

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For hydrogen to become a viable solution to the problems posed by energy needs to the environment, storage processes must therefore be safe, economical and adapted to the various possibilities of use: for us river transport.

Today, several storage methods provide interesting potential, but they still require a lot of research before implementation of realistic prototypes and industrial development.

These different modes are described below, addressing the physical (compression, liquefaction) and chemical solutions (adsorption in porous solids and absorption in chemical hydrides.

4.2.1 Storage of pressurized gas

The pressurized hydrogen gas, (usually around 200 to 250 bar) is generally stored in a steel tank. This technique has been proven for many years and is widely used in the industrial world today. However, this technology is strongly penalized by the weight of the bottles.

At room temperature, the volume capacity is of 14 g/dm3 at 200 bar. Considering the hydrogen-induced weakening problems of steel, the walls must be sufficiently thick and strong. Any increase in pressure thus leads to an increase in the mass of the casing, limiting any future development of this technique.

The innovative solution for pressurized storage today comes from wound fibre and resin structures, which allow much higher storage pressures to be achieved, while reducing the mass of the envelope.

Currently, working pressures of 350 bar and 700 bar are commonly proposed and research is moving towards even higher pressures of the order of 900 bar to 1200 bar.

Under these conditions, volume capacities of 40 g/dm3 are obtained, and specific capacities of more than 10% for the complete system can be envisaged.

The advantages and disadvantages of the technology are summarized below:

Table 1 – Advantages and disadvantages of storage in gaseous form

Advantages	Disadvantages
- Controlled technologies - Very fast filling of the tank	- Low volume density: even when compressed to 700 bars, hydrogen only represents 4.9 + 8 MJ.L from an energy point of view. Shape of current tanks

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Advantages	Disadvantages
	unsuitable for application in the area of transport.

4.2.2 Storage in liquid form

Another form of storage can be **in liquid form**. Hydrogen liquefies below 20 K (Kelvin) at atmospheric pressure. Under these conditions, the liquid is 800 times denser than the gas at room temperature, and depending on the type of cryogenic tank used, a mass capacity of around 6.5% is obtained for the complete system.

The gas liquefaction processes consists of complex techniques, which combine cold input and adiabatic expansion.

Although having a good volume capacity of 70 g/dm3, liquid storage poses difficult problems to solve.

First, this process requires cryogenic tanks with very high thermal insulation, which penalizes both the volume and the weight of this storage method, and does not make it possible to prevent the inevitable thermal losses at 20 K. On the other hand, for obvious safety reasons, the tanks are designed with an "open" architecture controlling a possible rise in pressure of the system in the event of vaporization of the gas. This results in significant losses, by evaporation, of part of the hydrogen (boil-off phenomenon) which can reach 1% per day. This phenomenon is also not without consequences for the safety of storage systems used in confined environments. Finally, the energy cost of liquefaction is very important. It essentially depends on the production capacity of the liquefaction plant but can reach 50% of the hydrogen lower heating value (LHV), which makes this storage system not very profitable in terms of energy.

The advantages and disadvantages of the technology are summarized below:

Table 2 – Advantages and disadvantages of storage in liquid form

Advantages	Disadvantages
- Large storage capacity	- Complex process - Significant losses during storage - Expensive process with low yield

4.2.3 Storage in solid form

The last common form of storage is storage in **solid** form.

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Many metals, alloys and intermetallic compounds have the property of storing hydrogen with good properties in terms of safety, energy efficiency, and long-term storage.

However, to be able to respond to applications, they must have high capacity, good reversibility, and high reactivity.

Many compounds are known for their absorption properties and are listed in the literature. Most of them are intermetallic compounds formed by the association of an element having a strong affinity for hydrogen, forming a stable hydride (element A: alkali, alkaline earth, metal transition period, rare earth or actinide), and an element having a low affinity for hydrogen, i.e. forming hydrides only under very high pressure (element B: transition metal middle or end of period).

In addition to the low mass capacity, one of the problems associated with the use of hydrides remains the heat associated with absorption and desorption reactions. This represents about 25% of the lower heating value of the stored hydrogen. To achieve a desorption pressure of one bar of hydrogen; temperatures above 300°C are usually required.

The storage of hydrogen can also be carried out in solids by physisorption at low temperature on materials having large specific surfaces. The adsorption phenomenon brings into play molecular hydrogen without dissociation of the molecule, so that, strictly speaking, hydrides cannot be used.

Different families of materials can be considered for the storage of hydrogen by adsorption at low temperature.

The advantages and disadvantages of the various systems are defined, among other things, by the volume capacities for storing hydrogen under pressure, in liquid form, or absorbed in a metal hydride, and can thus be compared.

It clearly appears that the main advantage of a hydride system lies in its storage volume density. In addition, there is no need for compression or liquefaction, which results in energy losses typically ranging from 10% to 50% of the specific energy of hydrogen, and with a clear advantage in terms of the safety of the hydrogen system.

No energy loss is theoretically associated with storage on hydride because the hydrogen is stored and released at the same pressure, provided that the hysteresis is small, which can be adjusted by substitution. Another substantial advantage is related to the presence of the pressure plate, which allows a large quantity of hydrogen to be stored and recovered in a very restricted pressure range. The value of this pressure can be finely adjusted to a given temperature by suitable substitution, as well as the slope by a homogenization heat treatment. Finally, hydrides benefit from the possibility of shaping better suited to mobile applications than pressurized gas or liquid hydrogen.

On the other hand, hydrides are penalized by their mass.

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The objectives set around 6% by mass seem very difficult to achieve, if only by the thermodynamic contradiction between hydrides with high capacity and low thermal stability.

Another major handicap is related to the management of the heat of transformation, which is equivalent to about 25% of the lower heating value. This desorption heat must be supplied to the system and be able to evacuate it during the filling of the tank.

In view of the kinetic limitation of the chemical reaction, and the limited value of the heat transfer, a hydride stock requires, in principle, a much longer filling time than the two other storage methods mentioned.

Finally, another drawback of hydrides is the variation in their volume during the charge and discharge cycles, which can reach 25%. This poses problems of heat transfer, of limiting the effective storage capacity due to the creation of free volume, and of mechanical stress on the reservoir.

The advantages and disadvantages of the technology are summarized below:

Table 3 – Advantages and disadvantages of storage in solid form

Advantages	Disadvantages
- Large storage capacity - Shaping more suitable for mobile applications than gas or hydrogen	- Large mass - Long filling time - Large volume variation during charge and discharge cycles

4.2.4 Conclusion: choice of storage mode for our study

The possibility of storing hydrogen makes this gas particularly attractive compared to electricity, which is difficult to store. It is still necessary to be able to store it densely and in complete safety.

Three ways to store hydrogen have been presented, each one showing advantages and disadvantages. The choice of system is probably not universal and of course depends on the application.

In our use case, which are pusher boats equipped with an electric / hydrogen propulsion chain, the concepts of mass, size, capacity, safety, maturity and time to start up must be taken into account.

Different choices can also be made depending on the quantity stored and the place of storage on the boat.

In the current state of progress of the project, all of these criteria were considered, and allowed us to determine that a **hydrogen gas storage type solution at a pressure of 350 bar** was the solution meeting the previously mentioned requirements.

The last criterion could be the economic aspect; this point will be addressed later in the report.

5 Technical features of the motorization

5.1 River size

5.1.1 Barge

As part of the Romainville / Bobigny project, the transfer of containerized waste is planned to the SYCTOM outlets, preferably by waterway transport.

The dimensions of the barges are constrained by the Ourcq canal, which has a maximum draft of 4.09m.

The barges having to use the Ourcq canal, their characteristics are the following:

- Type : barge + pusher boat
- Barge : ballastable allowing the transport of 24 TEU maximum

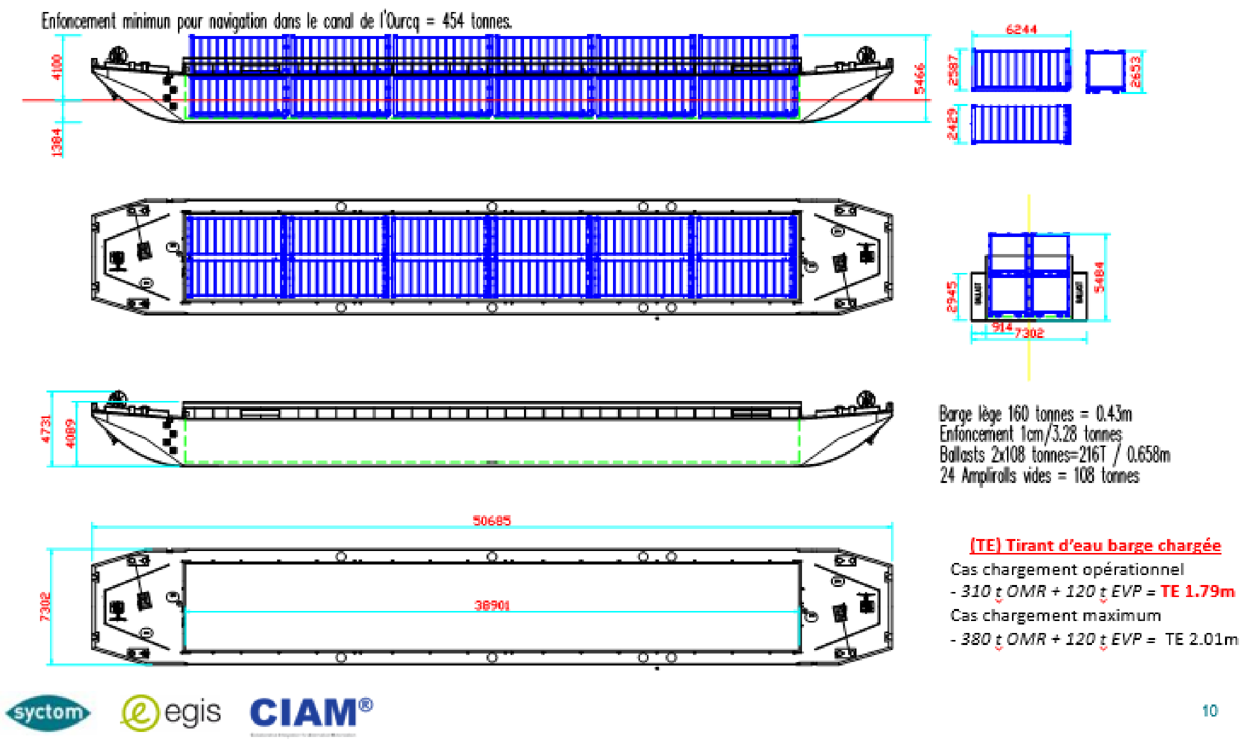

Figure 10 – Plan of the barge

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5.1.2 Saint-Ouen pusher boat

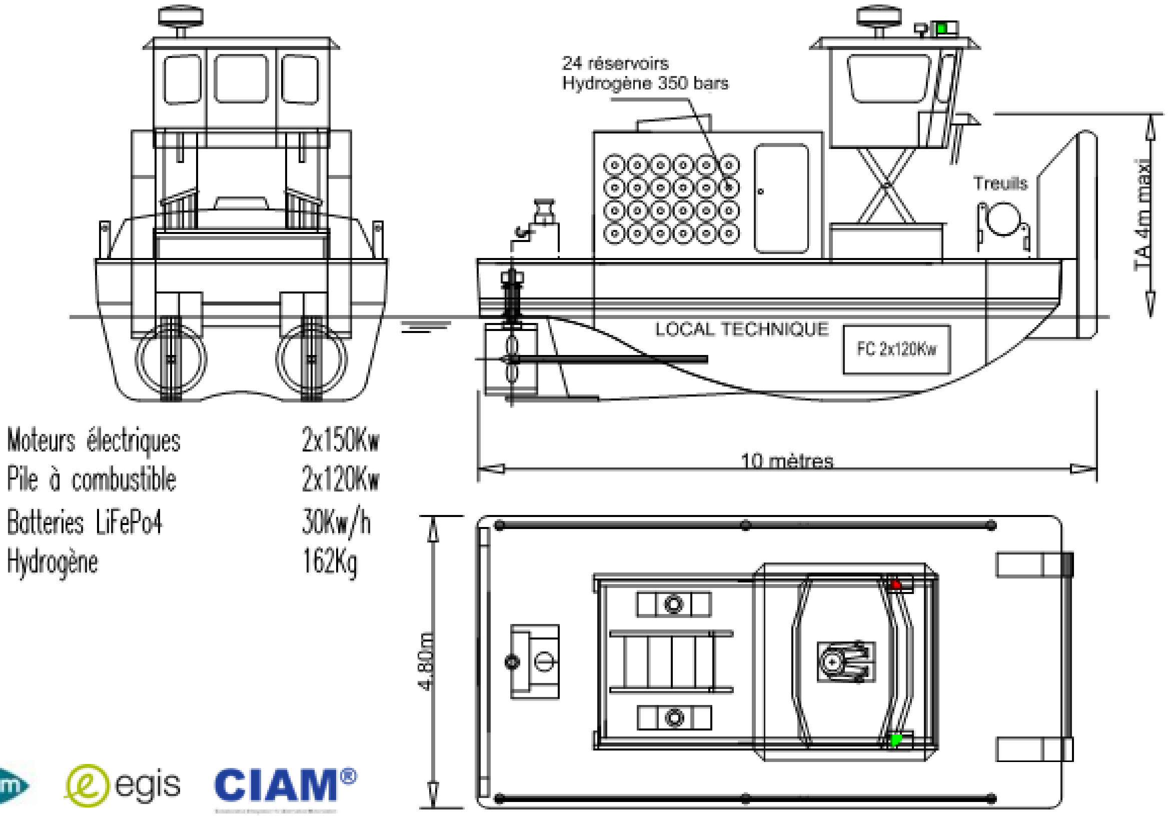

Figure 12: Plan of the canal pusher boat

The characteristics of the pusher boat are as follows:

❑ Fuel cell (P nominal) :	2 x 120 kW
❑ Daily requirement :	133 kg H2
❑ H2 storage :	162 Kg
❑ Storage pressure :	350 bars
❑ Number of tanks :	24
❑ On-board H2 energy :	5400 kWh
❑ Fuel cell efficiency	0.49
❑ Efficiency of the propulsion chain	0.47
❑ LiFePo4 battery capacity	30 kWh
❑ Battery power boost :	60 kW maxi
❑ Hourly H2 consumption :	6.84 kg
❑ Average power in operation :	107 kW
❑ Maximum power in operation :	300 kW

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- ❑ Nominal operating speed : 6 km/h

5.1.3 Seine pusher boat

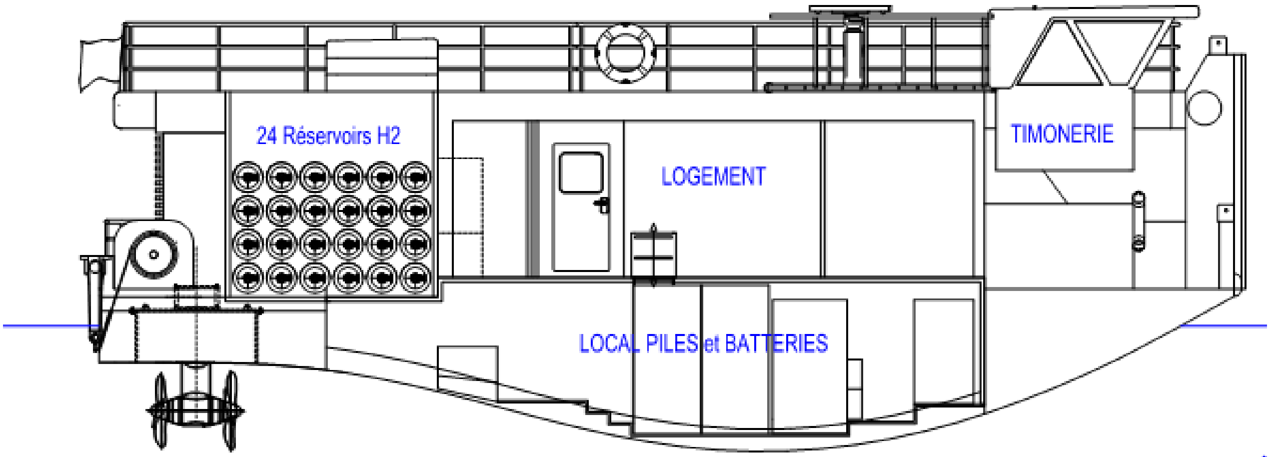

Figure 13: Plan of Seine pusher boat

The characteristics of the pusher boat are as follows:

- ❑ Fuel cell (P nominal) : 2 x 150 kW
- ❑ Daily requirement : 153 kg H2
- ❑ H2 storage : 162 Kg
- ❑ Storage pressure : 350 bars
- ❑ Number of tanks : 24
- ❑ On-board H2 energy : 5400 kWh
- ❑ Fuel cell efficiency 0.49
- ❑ Efficiency of the propulsion chain 0.47
- ❑ LiFePo4 battery capacity 100 kWh
- ❑ Battery power boost : 200 kW maxi
- ❑ Hourly H2 consumption : 11 kg
- ❑ Average power in operation : 180 kW
- ❑ Maximum power in operation : 500 kW
- ❑ Nominal operating speed : 12km/h

5.2 Summary and construction schedule

The construction schedule for the pusher boats is proposed below:

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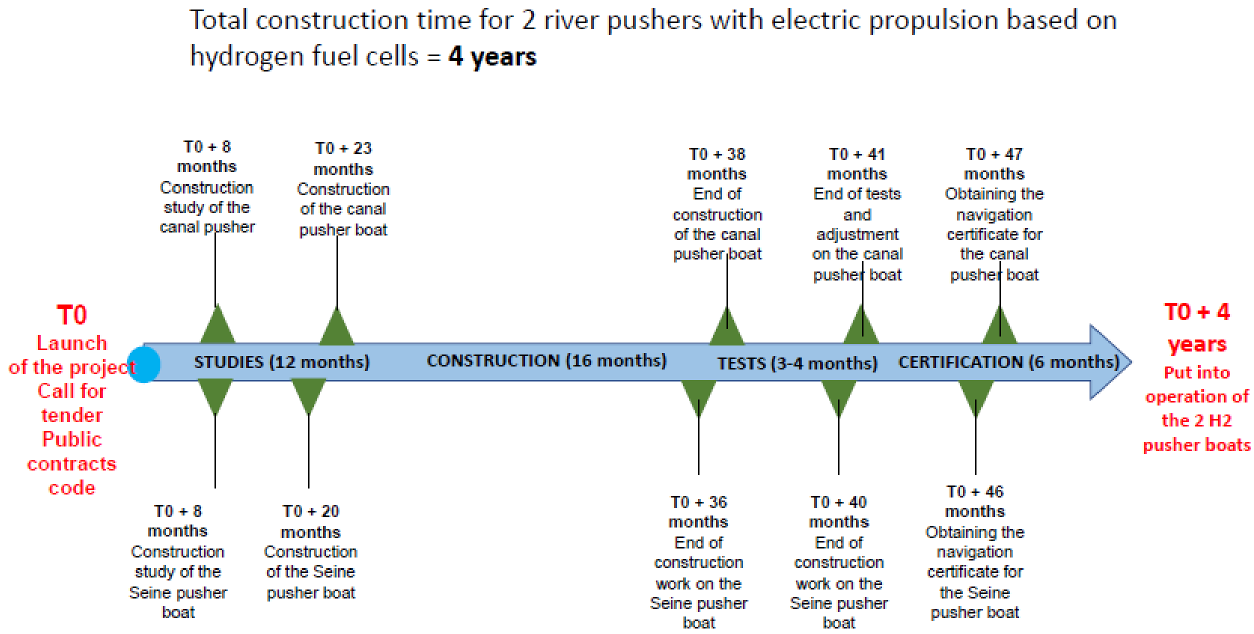

Figure 5 : Construction schedule for river pusher boats

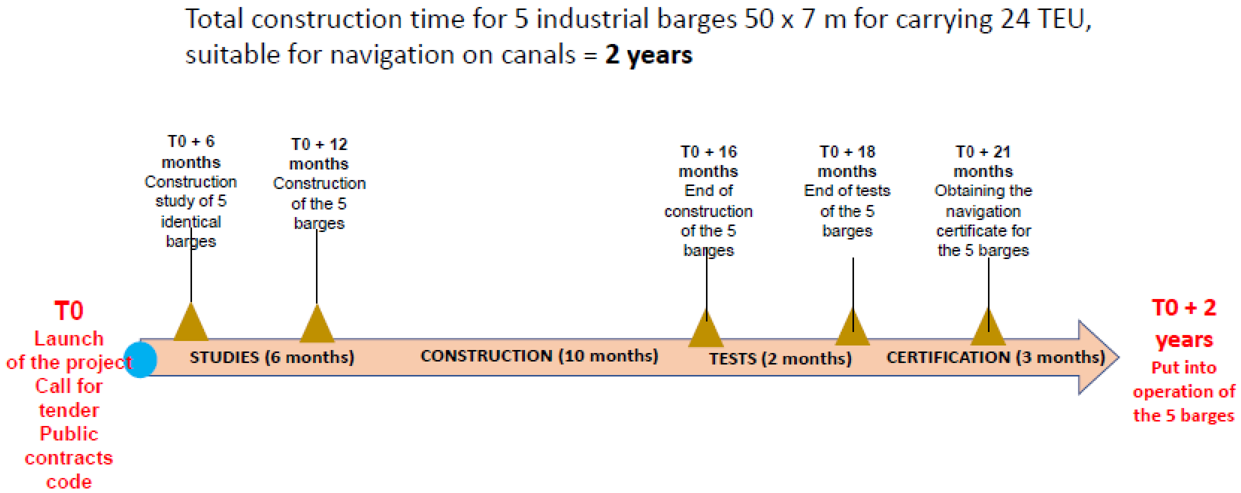

Figure 6 : Construction schedule for barges

The construction of the barges can be carried out in time concealed from that of the pusher boats. This does not increase the total construction time.

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6 Constraints on the river route

6.1 Constraints and risks associated with the H2 motorization

6.1.1 Navigation

6.1.1.1 Typology of constraints

With regard to users ON BOARD

Safety on board, both for crew and for navigation, is based from the design stage on the following fundamental principles:

- Full application of the rules dictated by ES-TRIN and particularly ;
  - Safety distance on the bottom and planks (B/5) for the installation of H2 systems (tanks, batteries, adjoining circuits).
  - Reinforced casings, fenders, mechanical securing of systems to resist shocks and collisions.
  - Monitoring and classification of the boat by a class company such as Bureau Veritas.
- Risk analysis and resulting technical solution (detection, safety valve, procedures, etc.)
- Definition and modelling of ATEX zones: forced ventilation, detection, alarm ...
- Automatic fire protection and extinguishing, NOVEC system.
- Automation control system, safety device.

- **Risk analysis**

During the design phase, a risk analysis carried out with all stakeholders in construction but also in operation is carried out under the responsibility of a reputable entity for this type of exercise. This entity can be BV Solutions used to managing this type of risk on board ships (LNG for example). This analysis identifies all the risks, causes, failures and defines the means or precautions to be implemented to reduce or eliminate the effect.

- **ATEX**

The presence of a flammable and therefore explosive gas on board, such as hydrogen, makes it necessary to define and classify the areas where this gas can disperse or accumulate.

Zone classification is used to determine the level of safety required for equipment installed in explosive gas atmospheres (CEI 60079-10). The objective of classifying an installation in zones is twofold (according to ATEX 1999/92/CE):

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- Specify the categories of used equipment in the indicated areas, provided that they are suitable for gases, vapours or mist and/or dust.
- Zone hazardous locations to avoid sources of ignition and to make the correct selection of electrical and non-electrical equipment. These zones will be established according to the presence of an explosive gas atmosphere.

With regard to OTHER BOATS during the navigation phases

Although if by an adapted design, the majority of the risks related to hydrogen have been integrated during the construction, the fact remains that in the event of collision with another ship and under certain unforeseeable conditions, the sudden and rapid dispersion of hydrogen can result in a strong explosion and/or a major fire on board.

This risk cannot be totally excluded.

A barge using hydrogen as a fuel should be easily identified by other users of the waterway. Specific signage must be established and could be included in the general police regulations (RGP).

6.1.1.2 Constraints and risks associated with the use of hydrogen

Characteristics of explosive mixtures :

- An explosion is the "rapid transformation of a physical system giving rise to a high emission of gas, accompanied by a significant emission of heat."
- This chemical gas explosion is akin to a combustion characterized by its violence and suddenness, which involves chemical reactions and dynamic phenomena, creating a rapid expansion of mixtures in a confined environment, or not.
- Hydrogen mixed with air is liable to explode and ignite under certain conditions.
- An EXplosive Atmosphere (ATEX) is a mixture of hydrogen with air in which, after ignition has occurred, combustion spreads to the entire unburned mixture.
- The limit flammability concentrations constitute the limits of the explosive range of hydrogen **(LEL : 4% - LSE : 75%)**

Self-ignition temperature : The auto-ignition temperature of a gas is the lowest temperature of a hot surface at which, under specific conditions, the ignition of an explosive atmosphere can occur (400° C for H_2).

The flash point:

- For vapours, therefore in the presence of the liquid, which gives rise to them, the flash point is determined. This point is the minimum temperature at which a mixture of vapours and air can be ignited.
- **In our case, using hydrogen gas, this flash point is therefore not applicable** (Definition: vapour emanating from a liquid).

6.1.2 Fuelling

6.1.2.1 Regulatory framework

The fuelling station will be a classified facility, covered by the nomenclature **ICPE 4715: Hydrogen**. As such, the following provisions apply:

- If the **quantity H2 <100 kg**, there is no administrative constraint.
- If - 100 kg < **H2 quantity** < 1000 kg, a declaration of the installation must be provided.
- If - 1000 kg > **H2 quantity,** an installation authorization procedure must be carried out.

- The H2 storage depot, must be at least 8 meters away :
    - Of a building inhabited or occupied by third parties ;
    - A clearance accessible to third parties or a public road ;
    - Of a building constructed of combustible materials, of any deposit of combustible or oxidizing materials, and of any activity classified as risk of fire or explosion.
- This last distance will not be required if the depot is separated from the building, from the depot for combustible or oxidizing materials or from the classified activity by a solid wall without opening, constructed of non-combustible materials and of two-hour fire-rated characteristics, a minimum height of 3 meters and extended from the depot by a canopy constructed of non-combustible materials and flame retardant of one hour rate, with a minimum width of 3 meters in projection on a horizontal plane.
- This wall must be extended on either side and on the side of the depot by return walls without opening, constructed of non-combustible materials and one-hour fire-rated, 3 meters high and 2 meters wide at least.
- The deposit must be protected by a closed enclosure with a minimum height of 2 meters totally or partially with a screen.
- This enclosure must be provided with at least one door, opening outwards and constructed of non-combustible materials. This door must

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be closed outside of the needs of the service and can only be opened from the outside by the attendant in charge using a key.

- If the storage location is included in the perimeter of a fully fenced establishment, access to which is normally monitored, this fence may be removed, but the storage location must be demarcated. If the circulation of vehicles is possible near the depot, this delimitation must be marked on the ground (painting, stakes, etc.).

6.1.2.2 Technical definition of the station

To date, there is no specific standard defining the technical requirement of hydrogen fuelling station for vessels. The requirements applied to our design are therefore the ones applying to vehicles hydrogen fuelling station. The related needs are presented below.

The components of the fuelling station are described below.

- **The distribution station must include :**
  - **A flow regulator**. In normal operation, this adjusts the downstream flow to limit the temperature rise in the boat's tank in accordance with the values specified in the standards applicable to hydrogen vehicles (J2601) ;
  - **A positive safety isolation valve ;**
  - **A safety valve ;**
  - **A hydrogen detector** in the distribution terminal and a system for detecting an abnormal drop or rise in pressure, both causing the defined emergency automatic shutdown.

- **The distribution hose must be fitted with :**
  - **Specific, certified fittings** compatible with the desired distribution pressures, allowing the filling of ships' tanks ;
  - An anti-tear system ;
  - **Devices for securing** in the event of **tearing or bursting of the hose** ;
  - **Protection against abrasion** and wrinkling.
  - By design, when the operator handles the hose during the connection and disconnection phases to the ship, the hose is no longer under pressure.
  - The hose is installed so that it does not touch the ground when connected to the vessel.
  - The hose is changed after any degradation and preventively in accordance with the supplier's recommendations.

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- **The nozzle, or distribution connector :**
  - Is specific to a **given flow and pressure** and can only be connected to vehicle receptacles approved to receive this flow and pressure;
  - Is equipped with a **non-return valve** or equivalent device preventing the entry of air ;
  - Cannot be disconnected from the vessel without prior depressurization and draining of the hose.
    - IV - The filling control interface is compatible with ATEX zoning.
    - V - The hydrogen flow rate in the distribution terminal is limited to the value specified in article 2.1 of the current decree by at least one flow limiting device (calibrated orifice or other device) and a second independent flow limiting device or detection of a break in the hose making the installation safe in accordance with article 2.8.
  - These devices must be protected from unauthorized external manipulation.

6.1.2.3 Specific provisions of the hydrogen fuelling station

The filling control interface must be compatible with ATEX zoning.

The flow of hydrogen in the distribution terminal must be limited to the value specified by at least one flow limiting device (calibrated orifice or other device) and a second independent device for limiting the flow rate or for detecting the rupture of the hose, making the installation safe.

These devices must be protected from unauthorized external manipulation.

A general emergency stop device must be put in place to secure the entire installation in all circumstances and automatically, in particular:

- By securing the hydrogen production equipment ;
- By isolating the main and intermediate hydrogen storage ;
- By stopping the distribution device by closing the isolation valve ;
- By venting the hydrogen contained in the distribution hose ;
- By shutting down the entire electrical circuit, with the exception of the emergency lighting systems that are necessary and not liable to cause an explosion, of the alarm system and the communication system if necessary.

This device must be able to be triggered:

- Manually, being easily spotted and operable
    - From inside the storage area ;
    - Near the distribution terminal ;

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- From an area outside the storage area, outside the targeted danger zones, easily identifiable and easily accessible in all circumstances by the emergency services.
- And automatically by fire detectors

The filling control interface must include the following detectors:

- Fire detectors ;
- Hydrogen detectors ;
- Pressure drop and overpressure detectors ;
- Hose break detector.

In case of triggering of the emergency stop:

- A visual alarm is activated ;
- An audible alarm is activated when the emergency stop device is automatically triggered (by fire detectors, hydrogen detectors and pressure drop and overpressure detectors) ;
- The designated person in charge of monitoring the installation is automatically informed ;
- The installation can only be put back into service after the operator has noted that there is no risk.
- In the case of a self-service installation without personnel on site, a communication device allows immediate alerting and communication with the designated person in charge of monitoring the installation, reachable 24 hours a day. This device is easily located, accessible from the distribution area and outside the targeted danger zones.

The filling of the vessel's tank must be:

- Carried out only by hydrogen pressure balancing, without it being possible to exceed the pressure and the maximum admissible temperature of the vessel's tank ;
- Preceded by a hose tightness test ;
- Carried out only if the results of this check are satisfactory.

Pressure and flow should be measured throughout filling to avoid overpressure in the vessel's tank. A device allows automatic stop of filling in the event of an anomaly within a period of less than 5 seconds.

Table 4 – Features of the fuel station to be created in the simple case (initial phase of deployment)

Features of the hydrogen fuel station – initial phase	Values
Pusher boats length	10 to 15m
Number of pusher boats to fuelled (per day)	2
Minimum time between 2 berths	30 min
Free-board of the pusher boats	<0.90m

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Features of the hydrogen fuel station – initial phase	Values
Storage pressure	350 bars
Tank maximum admissible pressure	500 bars
Number of tanks per pusher boat (cluster assembled)	24
H2 maximum volume per fuelling cycle per pusher boat	153 kg
Operating days/week of the hydrogen fuel station	5
Maximum H2 need for Syctom	306 kg
Average H2 fuel volume distributed per week (average cycle)	800 kg
Maximum H2 fuel volume distributed per week (maximum cycle)	1 430 kg
Yearly H2 volume need for Syctom – initial phase (mini / maxi)	40/72 tonnes
Minimum buffer store of the fuel station	600 kg
Number of fuelling distribution point	Single point portside
Type of distribution	Normalized nozzle (350 bars)
Type of liaison between the pusher boat and the quay	Flexible hose on jib boom
Fuelling cycle duration	43 min / SAEJ2601
Transfer pressure control, temperature/pressure	Yes/Yes by RFID measure – SAE J2799
Through-going connection between the pusher and the fuel station	Yes (CANBUS)
Refrigerated connection	Yes (-40°C)
Equipotential connection	Yes cable + earth clamp

6.2 Synergies with projects under development on the Seine

6.2.1 Hydrogen, the energy carrier

Hydrogen is the energy carrier of tomorrow. Indeed, if it is not present in its simplest form in nature (molecule made up of 2 atoms: H2), it is the most abundant element in the universe representing 75% by mass and 92% in number of atoms. Most importantly, its use in a fuel cell (FC) is clean, generating only energy in the form of electricity, heat and water.

It can be produced in several ways (more or less environmentally friendly), from a wide variety of raw materials, including water. For the record, one kilogram of water contains 116 grams of H2, so it can be produced almost anywhere. Its production by electrolysis from the electricity network is more or less virtuous depending on the electrical origin. In France we agree that the electric kWh generates between 50 and 80 g of CO2 depending on the energy mix used (energy mix = nuclear + hydroelectricity + wind + solar + thermal power plant).

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In the case of wind power alone (green electron), the electric kWh produced generates only 10g of C02, if we integrate everything that constitutes the manufacture, use and recycling of the wind turbine.

The production of hydrogen by electrolysis of water is a very ecological method (decomposition of the water molecule into H2 and O2 by circulating an electric current) provided that the necessary electrical energy is itself produced ecologically. The electrolysis yield is of the order of 55-60% to date. It is believed that over time it will be possible to achieve yields of around 65-70%. The cost of producing hydrogen by electrolysis is therefore almost exclusively linked to the cost of electricity. To date it takes around 1.7kWh of electricity to produce 1kWh H2. This process naturally finds its place in association with renewable energies (solar, wind) as a means of storing electricity in the form of H2. This is the EnR / H2 coupling.

6.2.2 Projects on the Seine axis

Hydrogen, which can be used as clean energy for the motorization of river boats on the Seine axis, has been seriously considered for five years and is the subject of several studies for all types of river boats but also maritime. To address only pushers on the Seine, three more or less advanced projects are underway. These projects are led by CFT, CEMEX and LAFARGE.

At the same time, a few studies have started to try to solve the quayside supply. As part of the European H2Ships project, HAROPA is carrying out a research on the establishment of fuelling areas on the Seine.

Hydrogen appears to be, for the moment, the only clean and on-board energy, which can meet the needs of high powers, but also in terms of autonomy necessary for commercial vessels.

River passenger vessels, Compagnie des Bateaux Mouches (CBM) and Compagnie des Bateaux Parisiens are on the lookout for a potential migration of part of their fleet to the green solution of hydrogen. The only energy suitable for the power and range of their larger boats, the battery being reserved for uses that require less energy. The CBM was the first in the race with a detailed research of their AIREO project presented to the CCNR in Strasbourg in 2015. This project received the strongest encouragement from the national authorities presented to this committee.

More generally, a hydrogen ecosystem is emerging around the Seine axis. The Hype taxi fleet, launched since 2014 with 40 hydrogen fuel cell vehicles, aims to increase the number of its vehicles to 600 taxis by 2021. The Paris city hall

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has also announced that it wants 30,000 taxis, ie almost all of the Parisian fleet to run on hydrogen by 2030.

H2 truck projects for use as concrete mixers or last mile transport are currently the subject of advanced studies at the level of major construction and transport groups, an identical approach for dump trucks for household waste may be relevant.

These uses therefore require the establishment of a hydrogen distribution network with several recharging points distributed on both sides of the Seine.

6.3 Adaptation of river docks to be planned

6.3.1 Waiting areas

The formation of grouped convoys and the use of different pusher boats for the two portions of the river route requires the provision of waiting areas for barge manoeuvres. These waiting areas shall be planned:

- At the exit of the Saint-Denis lock
- Near the Port Victor wharf in Issy-les-Moulineaux

6.3.1.1 Saint-Denis lock

The waiting area at the exit of the Saint-Denis lock should ideally correspond to the supply zone provided for the pusher boats, the exit of the Saint-Denis lock constituting the only common point on the route of the two pusher boats. The identified zones are described in §6.3.2.1

6.3.1.2 Issy-les-Moulineaux

The length of the wharf at the quay of Issy-les-Moulineaux (Port Victor) is very small. The pusher manoeuvres that will allow the two barges to be uncoupled cannot therefore be planned on this quay.

The Point du Jour shared-use quay, located opposite the Port Victor wharf, may be a good option for these manoeuvres.

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Figure 7 : Potential waiting area for barges near the wharf planned for SYCTOM operations

6.3.2 Fuelling

6.3.2.1 On the Seine

As part of the H2Ships project, a WP is dedicated to the study of the implementation of fuelling areas in the Seine basin. This study is led by HAROPA. The objective of this mission not being to replace this study, we approached HAROPA to check the areas available at the exit of the lock and their adequacy with the needs of the project:

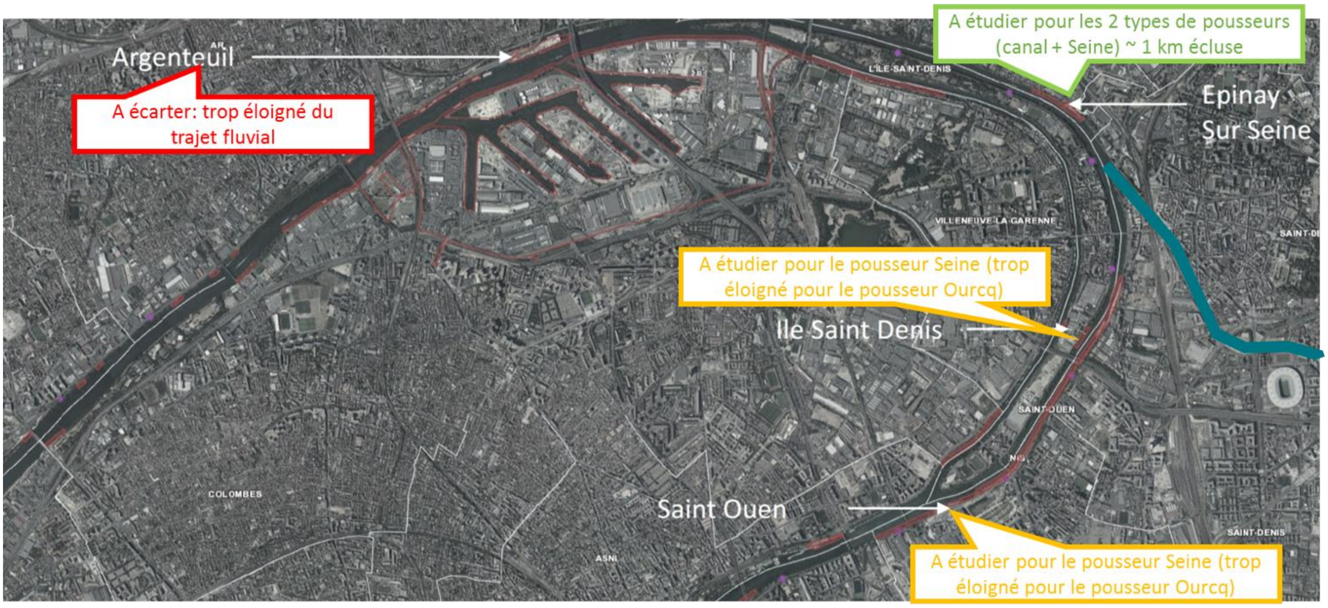

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Figure 14 : Analysis of river wharfs available for H2 fuelling and exchange pushers near the Saint-Denis lock

The analysis of the compatibility of the sites identified with the project is as follows:

- The Argenteuil site was dismissed because it was too far from the river route.
- The Epinay-sur-Seine site, although located slightly downstream from the Saint-Denis lock, is the preferred option since its proximity to the Saint-Denis lock would allow the two pusher boats to be refuelled.
- In the event that this site is not ultimately selected, the Saint-Ouen and Saint-Denis wharfs could be considered for supplying the Seine pusher boat. However, they are too far from the Saint-Denis lock for the Ourcq pusher to refuel on these docks. If these docks are ultimately selected, alternative refuelling should be provided on the Ourcq Canal.

6.3.2.2 On the Ourcq Canal

To anticipate possible difficulties in supplying the Canal pusher at the Saint-Denis lock (if finally another location on the Seine axis is selected by HAROPA), we analysed the feasibility of installing a refuelling station on the Ourcq.

A) <u>Station installed on the Romainville / Bobigny platform</u>

Several factors do **not make it possible** to validate the installation of an H2 station on the river platform:

- **The opening of the towpath to the public** does not allow safety standards to be respected
- The **significant offset between the platform and the quay** requires the presence of 2 operators during refuelling operations (one at the quay side and one at the station)

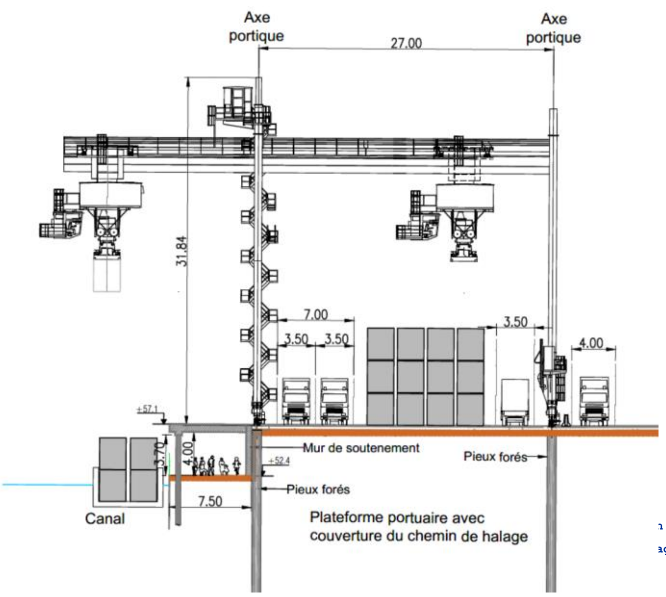

Figure 15: Cross section of Romainville/Bobigny platform

- **The available space** on the port platform is not sufficient to set up an H2 station : the available space is located on the far right of the platform where the berthing of barges is forbidden, which is does not enable the implantation of a H2 fuelling station

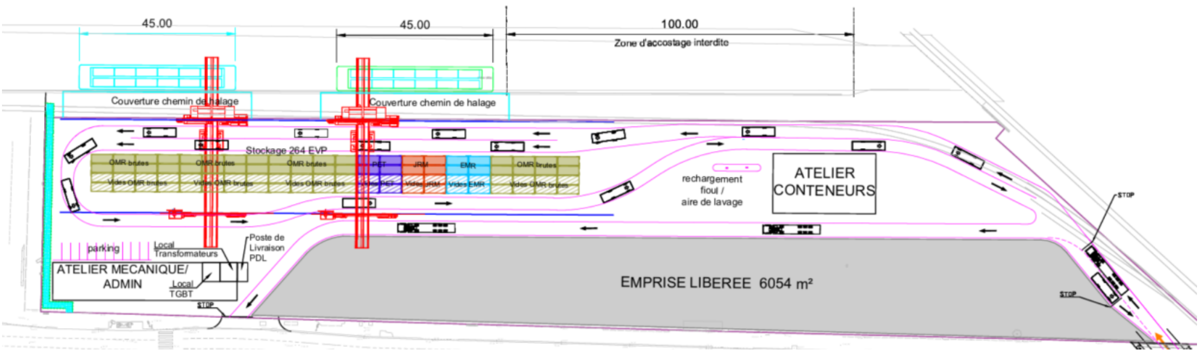

Figure 16 : Plan view Romainville / Bobigny platform

B) <u>Search for suitable locations</u>

We studied the surfaces available near the Romainville/Bobigny platform. Four river berths are identified as potentially suitable for receiving an H2 fuelling station.

- Pavillon-sous-bois
- Bondy (Décathlon)
- Bondy (Conforama)
- Pantin (Paris-plage)

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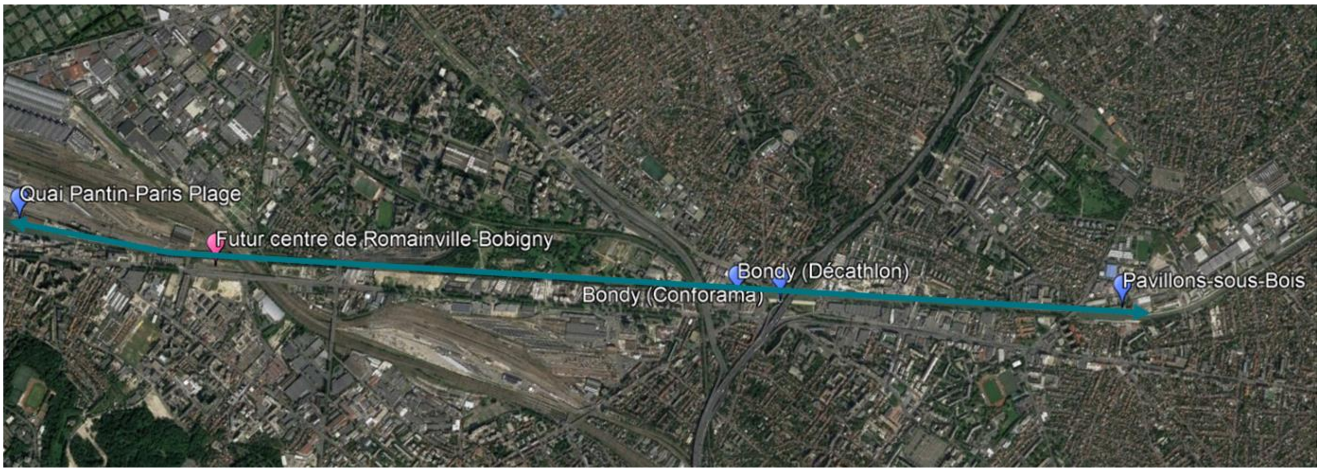

Figure 17 : Potential river wharfs identified on the Ourcq Canal

Table 5 - Characteristics of the river wharfs identities on the Ourcq Canal

	Pavillons-sous-Bois	**Bondy (Décathlon)**	**Bondy (Conforama)**	**Pantin Paris-Plage**
Distance to Romainville platform	5.4 km	2.85 km	2.6 km	1.05 km
Truck accessibility	Easy	Possible but traffic	Possible but traffic	Constrained (dead end)
Public accessibility	Open to the public (temporary closure possible)	Open to the public	Possible site closure	Open (pedestrian + cyclists)

As the Pantin Paris-Plage site is the only one located on the barge's river route, we recommend that this site be studied if H2 fuelling is to be considered on the Ourcq canal.

7 Regulatory analysis for the implementation of H2 motorization.

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7.1 Navigation

7.1.1 Classification

It is not customary to have river pusher boats classified by a classification body such as Bureau Veritas (BV).

As part of an innovative construction, as could be these pusher boats, and as at the time of writing this report, no river (or maritime) regulations correctly and completely describe what should be such a study.

Collaboration with a classification society is mandatory to successfully complete this project, and thus ultimately obtain a certification for navigation, such as Union Certificate.

The BV has published a set of recommendations for the implementation and use of hydrogen on board ships.

The pusher boat must be classified by Bureau Veritas or another equivalent certification entity.

7.1.2 Regulatory process

The main actions of the various stakeholders in the regulatory process are as follows:

- **Subject**: issuance of the navigation permit by the **DRIEA** authority (Regional and Interdepartmental Directorate of Equipment and Planning).
- The **applicable construction rules for river vessels** are as follows:
  - **Compliance Decree of November 25, 2018** relating to the technical safety requirements applicable to goods vessels, passenger vessels and floating devices navigating or stationing on inland waters
  - **RVBR for freight or passenger vessels** falling within these navigation areas and the dimensions set out in Article 1.02 "Scope"
  - **Compliance with the ES-TRIN** (European Standard laying down Technical Requirement for Inland Navigation), **now it is the ES-TRIN which constitutes the technical corpus of the RVBR** (Rhine Boat Inspection Regulations) **as a text of reference article 1.03 of the RVBR, it is therefore legally the RVBR that applies).**

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- As the hydrogen pusher is an innovative project not covered by the previous construction rules, **the consequences of "Alternative Design" on the regulatory framework** are as follows :
  - In the RVBR, there is a non-compliance of machine installations using fuels with a flash point lower than 55°C. However, innovation is still allowed under "Alternative Design". Nevertheless, it requires the competence of an unclaimed classification society usually for conventional river constructions using diesel fuel.
  - In fact, an **approval process from classification societies under the supervision of the authorities and the CCNR (Central Commission for the Navigation of the Rhine)** must be provided for pusher boats.
  - **As a "special vessel", the issuance of the navigation title will be restricted for a defined navigation area which** may be extended (eg: Romainville - Bobigny, Seine downstream or Seine upstream, etc.)
- The **role of the classification society** will be as follows:
  - Construction monitoring, continuous verification of class and RVBR conformity (ES-TRIN) with discussions on CCNR recommendations.
- **The competent DRIEA authorities:** issue at the end of the construction, the union certificate authorizing the use of the pusher boat in navigation.

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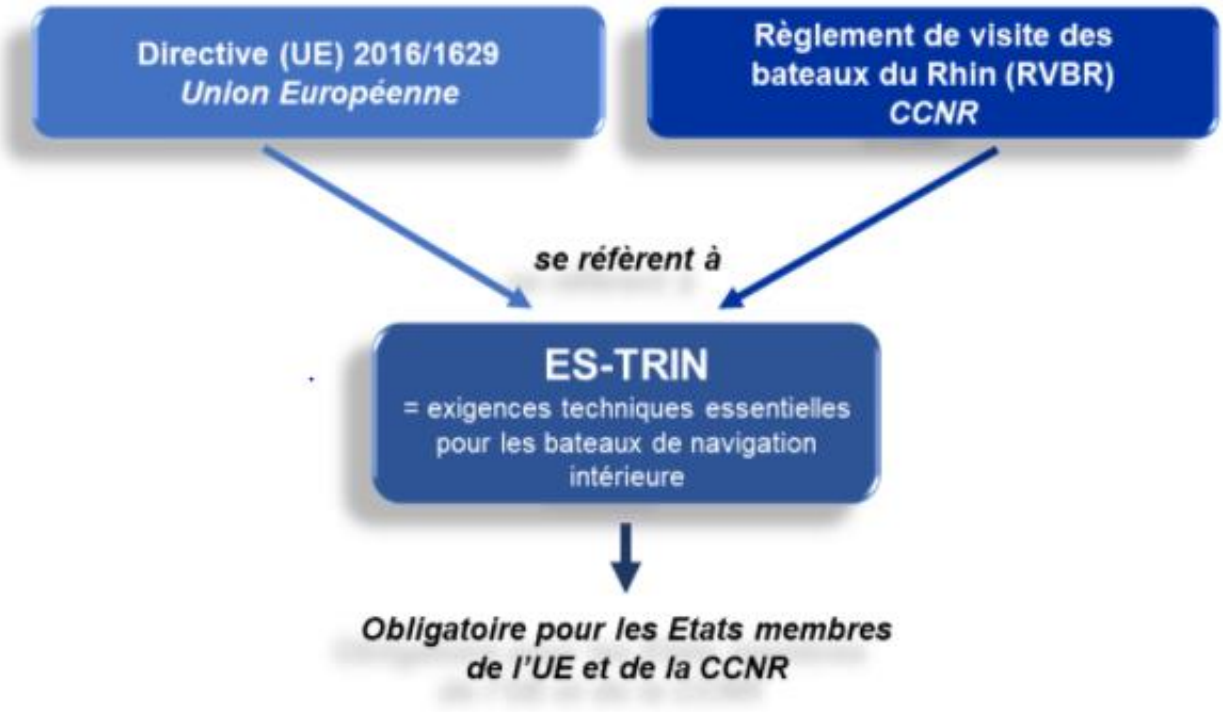

Figure 8 – Summary of applicable regulations for river construction

7.2 Fueling

7.2.1 General requirements for hydrogen stations

To date, there is no specific standard defining the technical requirement of hydrogen fuelling station for vessels. The requirements applied to our design are therefore the ones applying to vehicles hydrogen fuelling station.

Two texts of the same date introduced regulations for hydrogen stations. Decree No. 2018-900 of October 22, 2018 created a section 1416 "Storage or use of hydrogen" in the nomenclature of classified installations (ICPE - described in phase 2).

The decree of October 22, 2018 provides for the regulations applicable since January 1, 2019. The decree targets stations open or not to the public, which produce more than 2 kg of hydrogen per day and where the hydrogen is transferred to the vehicle tanks. The text sets the rules relating to the compliance of hydrogen stations, the operation of installations, safety, and the management of water, waste and noise.

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The decree of October 22, 2018 relates more explicitly to the general requirements applicable to installations classified for environmental protection subject to declaration under section No. 1416 (gaseous hydrogen distribution station) of the nomenclature of classified installations and amending the decree of November 26, 2015 relating to the general requirements applicable to installations using gaseous hydrogen in an installation classified for environmental protection to supply gaseous hydrogen "products" when the quantity of hydrogen present at the establishment falls under the declaration regime for section no.4715 and modifying the decree of August 4, 2014 relating to the general requirements applicable to installations classified for the protection of the environment subject to declaration under section No.4802.

7.2.2 The actual fuelling phase of the boat

NR 529 (Gas Fuelled Ships) sets out the various points of vigilance to be considered on the boat and identifies the documents to be produced relating to these requirements.

NI547 (Risk Based Qualification of New Technology Methodological Guidelines), applies to installations of fuel cell systems in ships using gas as fuel and oxygen from ambient air as oxidant. The gas can be stored in a compressed gas state or liquid state.

And finally, the risk of explosion must also be identified by defining risk zones **(ATEX zoning),** in order to assess the risk, and thus define and formalize appropriate measures.

7.2.2.1 Components of the hydrogen station

A hydrogen charging station is made up of three elements: a hydrogen storage area, a compression and buffer storage area, and a distribution area.

- **Storage area**

At present, in France, hydrogen is produced centrally on less than ten sites. For its distribution to the places of use, the hydrogen is stored at low pressure (200 bars) in bottles or tube trailers and transported by truck. In most cases, the stations are supplied with hydrogen by frames of bottles stored on the site.

For some stations, hydrogen is produced on site by means of an electrolyser, by electrolysis of water.

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- **Compression and buffer storage area**

The various models of hydrogen vehicles available on the market are equipped with hydrogen tanks of 350 or 700 bars. Charging stations must therefore be able to distribute hydrogen at 350 bars and / or 700 bars. The hydrogen delivered at 200 bars is therefore pressurized by a compressor and then stored in bottles called "buffers".

- **Distribution space**

The distribution space is equipped with a hose, a nozzle and a control screen. In some cases, the vehicle will need to be earthed, then the operation is to connect the nozzle to the vehicle. Once the connection has been made, the filling of the tank is managed by the station's computer.

To fill, the operator connects then locks the nozzle of the station on the vehicle tank before starting the filling procedure.

The station's controller manages the filling speed according to the protocols of the SAE J2601 standard. These filling protocols have been defined in order to control the physical phenomena associated with the rapid transfer of pressurized gas (heating of the gas liable to damage the internal liner of the tank).

During filling, the battery is stopped. The filling stops automatically and a signal indicates to the operator that he can unlock the valve. Several storage levels at the station are planned, the pressures of which are increasing:

- A first low pressure storage (a few tens of bar): corresponds to 1 or 2 days of consumption in order to manage any production contingencies and guarantee service
- A second medium pressure storage (typically 420 bars): intermediate pressure. The management of this compression chain must make it possible to guarantee that hydrogen will always be available at the level of the station and that the latter will be able to ensure the recharging of several successive vehicles while respecting the filling times, specified in the station specifications.

7.2.2.2 Logistics optimization on a case-by-case basis

There is no "typical" supply chain for hydrogen.

For each situation, the determination of the chain from the production of hydrogen to its consumption depends on the context and the environment.

The choices will result from a global optimization analysis taking into account logistical, technical and economic parameters.

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An analysis of TCO (Total Cost of Ownership) makes it possible to determine, according to the profitability objectives targeted over a chosen period of time, which model to favour and the financial means to implement (CAPEX, OPEX).

The regulatory aspect is also to be taken into account, since it can influence the implementation times and costs (ICPE4715).

7.3 Typical case recommended for the project: Installation of a hydrogen distribution station (20m2 – 300 kg/d)

7.3.1 Applicable regulations

Several regulations must be taken into account for the installation of a hydrogen distribution station:

- Compliance with local building regulations ;
- The application of safety rules related to the presence of hydrogen on the site ;
- Certification of compliance of station equipment and service provided to vehicles.

7.3.1.1 Local building regulations

The installation of a station requires a building permit and civil engineering arrangements such as:

- A stabilized asphalt area or concrete pads to deploy the station ;
- Access from the road if the land has not been developed beforehand ;
- Possibly a fence or walls when the storage part needs to be isolated from the public.

All these elements require a building permit.

The Local Urban Plan may also impose additional special arrangements.

7.3.1.2 Hydrogen safety rules

Hydrogen charging stations are part of classified installations for environmental protection (ICPE).

As such, they are concerned by several specific sections:

- Section 4715 for the storage ;
- Section 1416 specific to gaseous hydrogen distribution stations.

Compliance with the aforementioned regulations requires:

- Safety distances between the station and the property lines varying according to the quantity stored and / or maximum leakage rates. These distances can be reduced if a wall meeting specific constraints is installed ;
- Safety distances between the station and other energy stored or distributed on site (e.g. gasoline or electricity) ;
- Depending on the stored quantity, making a declaration or obtaining an authorization from the DREAL: in the current state of the regulations, the storage of more than one ton of hydrogen requires an authorization ;
- The implementation of security elements such as :
    - Hydrogen and fire detectors in closed rooms ;
    - A degassing vent (aeration canal) ;
    - At least one access to allow the intervention of the fire and rescue services at any time.

For each project, you should contact the local DREAL for a first general presentation explaining the implementation project, with:

- Site plan ;
- The method of supplying the station and any on-site production capacity by electrolysis, specifying the quantities of water that will be consumed ;
- The quantities stored on site ;
- The types of uses concerned by the distribution site ;
- Possible development prospects for the site.

Based on this presentation, DREAL will indicate whether an ICPE simple declaration or authorization procedure should be initiated.

It should be taken into account that in addition to the specific regulations in force for hydrogen installations, the DREAL will take into account specific local factors, in particular from the point of view of the environmental impact and the various installations and activities already existing, in the proximity perimeter.

The site must include a certain number of security elements (signage, possible access management, cameras) and communication (alarms, operating or emergency stop indicator, etc.). Means of monitoring alarms and maintenance must be put in place.

This list only contains the main recommendations and it is mandatory for the installer and the operator to refer to the decrees in force available on the DREAL website.

Finally, a risk prevention plan (PPR) can lead to the application of other rules (town planning, environment).

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7.4Equipment conformity certification

Equipment manufacturers must demonstrate that they have CE marking in accordance with:

- European Directive PED 2014/68/EU concerning pressure equipment (PED), for fixed equipment.
- European Directive 2010/35/EU relating to the transport of hazardous materials and pressure equipment, for mobile equipment.
- Directive 2006/42/EC on Machinery.

Equipment manufacturers must also give the definition of the ATEX (Explosive Atmosphere) zoning of the station, which will make it possible to construct the document relating to the prevention of explosions (DRCPE), a document to be certified by a control office. Depending on the type of vehicles refuelled, the equipment must meet the following SAEJ filling standards:

- 2601 for light vehicles. This standard distinguishes between 350 bar and 700 bar fillings ;
- 2601/T40 conventionally for 700 bar vehicles: this includes hydrogen cooling to -20 ° C to speed up the filling time ;
- 2601-2 for filling heavy vehicles at 350 bars with a higher flow rate than for light vehicles.

SAEJ standard is usually related to onshore vehicles. In the absence of a specific standard for barges, this standard is applied for inland waterway transport.

7.5 Construction, installation and operation of the station

7.5.1 Establishment study

The detailed establishment study can be carried out upstream of the consultation, potentially with the help of specialist consultancies, or downstream in partnership with the station supplier.

The study aims to define the following elements:

- Mark of the future station and interactions with the environment (distance to property boundaries, interactions with other activities on the site, potential interactions with the passage of vehicles and pedestrians, etc.);

- Possible mark for future equipment (e.g. addition of an electrolyser for on-site hydrogen production, increase in the size of the station to meet the growth in demand, installation of recharging of other energies on the site ...) ;
- Final location on the plot depending on access, neighbourhood, security and regulatory constraints (see ICPE) ;
- Access for suppliers (delivered H2), customers and manoeuvre areas. Note that the local urban plan may impose specific circulation of hydrogen logistics ;
- Security service intervention procedure (SDIS) if necessary ;
- Civil engineering needs :
  - For on-site access and manoeuvres
  - For the station :
    - Concrete slab if separate elements, or simple cones in the case of containerized stations ;
    - Anti-collision safety cones for vehicles ;
    - Possible walls ;
    - Possible wire fence;
    - Canopy.
- Electricity needs (for example high voltage if electrolysis on site or normal voltage if just for lighting and powering the computers), assessment of the possible need for a dedicated substation ;
- Mapping: installation area, location of equipment and characteristics of connections, fire network, ancillary equipment (demineralizer, transformer / rectifier station), ATEX zoning.

7.5.2 Production and installation

This phase includes on-site construction, installation and putting into service of the station. If the client does not have the appropriate technical skills or if he wishes to delegate the monitoring of the construction of the station, it may be relevant to choose consulting engineers (AMO).

The mission of the AMO is to help the client define, manage and operate the project. It has an advisory and / or assistance role, and a proposal, with the decision-maker remaining the owner.

The main stages of the realization include:

- Civil engineering works ;
- Connection work and the establishment of dedicated supply contracts;
- Delivery of the already assembled station (for the smallest) or its assembly on site ;

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- Installation of safety equipment and signage ;
- Putting into service of the station (carried out by the supplier) ;
- Final site visit with the security services (SDIS) ;
- Acceptance of the station with a vehicle-filling indicator.

The station supplier should as far as possible perform the maximum validation tests off-site, that is to say before shipment and installation.

In the same way as for the roles and responsibilities must be clearly defined for the construction phase between the different service providers (civil engineering, station, connections, etc.).

The contracting authority must appoint a project manager in charge of coordinating all the parts and subjects. Any restrictions on access or working days must be taken into account when calculating the completion time.

The station supplier must carefully monitor the progress of the work to verify that the civil engineering, connections and inputs correspond to the needs of its equipment.

The construction of the site and the installation of the station must be planned as much as possible in parallel in order to avoid very long delays between tasks. If the works prevent the smooth running of a pre-existing economic activity on the site, it may be useful to provide for financial compensation to avoid a conflict that could lead to delays.

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8 Financial analysis

8.1 CAPEX

8.1.1 CAPEX simple case - A single outlet

8.1.1.1 Fleet

N°	1. SYCTOM RIVER FLEET ACQUISITION COST ESTIMATE designation	BASIC CASE (Phase 1) Cost Excl. Tax	duration
1	**Detailed construction study**		20 months
	definition of construction of the 10m pusher boat intended to navigate on canals	*175 000 €*	
	construction definition of the 15m pusher boat intended to navigate on the Seine	*225 000 €*	
	definition of common parts (mutualisation design of FC H2 Li mot systems)	*290 000 €*	
	container barge construction definition	*80 000 €*	
	Subtotal Studies	**770 000 €**	
2	**Construction of 10m pusher boat designed to navigate on the canals (N°1)**		18 months
	hull and superstructure	*900 000 €*	
	wheelhouse	*175 000 €*	
	60kWh Boost Lithium battery system and chargers	*49 000 €*	
	electric motor and control command	*180 000 €*	
	various technical equipment and sets	*135 000 €*	
	2x120kW fuel cells and associated systems	*350 000.00 €*	
	fueling, storage of 24 H2 tanks and distribution	*200 000.00 €*	
	homologation of the 10m pusher boat in H2 version	*75 000.00 €*	
	Subtotal 10m pusher boat canals (N°1)	**2 064 000.00 €**	
3	**Construction of the 15m pusher boat intended to navigate on the Seine**		18 months
	hull and superstructure	*1 100 000 €*	
	wheelhouse	*200 000 €*	
	100kWh Boost Lithium battery system and chargers	*95 000 €*	
	electric motor and control command	*230 000 €*	
	various technical equipment and sets	*155 000 €*	
	2x150kW fuel cells and associated systems	*435 000.00 €*	
	fueling, storage of 24 H2 tanks and distribution	*200 000.00 €*	
	homologation of the 15m pusher boat in H2 version	*75 000.00 €*	
	Subtotal 15m pusher boat Seine	**2 490 000.00 €**	
4	**Construction of 5 container barges**		24 months
	hull	*680 000 €*	
	technical equipment (pumps, winches, etc.)	*150 000 €*	
	navigation certificate	*15 000 €*	
	subtotal 1 barge	***845 000 €***	
	Subtotal 5 identical barges manufactured at the same time	**4 225 000.00 €**	
	TOTAL FLEET ACQUISITION Basic case	**9 549 000.00 €**	

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8.1.1.2 Infrastructure

N°	2. COST OF ADAPTATION OF LAND INFRASTRUCTURES designation	SIMPLE CASE Cost Excl. Tax	durée
1	**Detailed study**		20 months
	Studies (AVP-PRO-DCE)	*568 500 €*	
	Environmental impact, feasibility and engineering study	*1 000 000 €*	
	Works supervision (DET/VISA/AOR)	*227 400 €*	
	Subtotal Studies	**1 795 900 €**	
2	**Construction of an H2 fueling station at the exit of the Saint-Denis lock**		18 months
	Authorization for temporary occupation of the river area	*20 000 €*	
	Fueling station	*1 800 000 €*	
	Civil engineering and development works (concrete slab, clorure, fire wall, etc.)	*100 000 €*	
	Subtotal for fueling Seine	**1 920 000.00 €**	
3	**Adaptation of the Port Victor wharf to receive river waste (see specific study)**		10 months
	CAPEX wharf adaptation + equipment	*781 000 €*	
	Subtotal adaptation of wharfs	**781 000.00 €**	
4	**Related investment**		10 months
	Installation of water / electricity terminals 63A to 125 A on each port platform (3 in total)	*15 000 €*	
	Connection to terrestrial drinking water and electricity networks (fixed price)	*75 000 €*	
	Installation of a dolphin (Port Victor)	*50 000 €*	
	Installation of an additional bollard (Port Victor)	*1 500 €*	
	Subtotal Related investments	**141 500.00 €**	
	TOTAL ADAPTATION OF LAND INFRASTRUCTURE	**4 638 400.00 €**	

8.1.2 Option: fuelling dedicated to SYCTOM

N°	OPTION - ADDITIONAL LAND INFRASTRUCTURE designation	BASIC CASE Cost Excl. Tax	durations Days
3	**Construction of an H2 fueling station dedicated to SYCTOM**		18 months
	Authorization for temporary occupation of the river area	*20 000 €*	
	Environmental impact, feasibility and engineering study	*750 000 €*	
	Fueling station	*1 800 000 €*	
	Civil engineering works (slab)	*20 000 €*	
	Subtotal dedicated fueling station	**2 590 000.00 €**	

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8.1.3 CAPEX multiple case - 3 outlets

8.1.3.1 Fleet

N°	1. SYCTOM RIVER FLEET ACQUISITION COST ESTIMATE designation	MULTIPLE CASE (Phase 2) Cost Excl. Tax	duration
1	**Resumption of detailed construction study**		8 months
	resumption of construction plans for the 10m pusher intended to navigate the canals	*80 000 €*	
	resumption of study of common parts (verification of evolution of FC H2 Li mot systems)	*100 000 €*	
	resumption of barge construction file	*30 000 €*	
	Subtotal Studies	**210 000 €**	
2	**Construction of the 10m pusher designed to navigate the canals (N° 2)**		12 months
	hull and superstructure	*900 000 €*	
	wheelhouse	*175 000 €*	
	60kWh Boost Lithium battery system and chargers	*49 000 €*	
	electric motor and control command	*180 000 €*	
	various technical equipment and sets	*135 000 €*	
	2x120kW fuel cells and associated systems	*350 000 €*	
	fueling, storage of 24 H2 tanks and distribution	*200 000 €*	
	homologation of the 10m pusher boat in H2 version	*75 000 €*	
	Subtotal 10m pusher boat canals (N°1)	**2 064 000 €**	
3	**Construction of 3 container barges**		24 months
	hull	*680 000 €*	
	technical equipment (pumps, winches, etc.)	*150 000 €*	
	navigation certificate	*15 000 €*	
	subtotal 1 barge	*845 000 €*	
	Subtotal 3 identical barges manufactured at the same time	**2 535 000 €**	
	TOTAL ACQUISITION OF MULTIPLE OUTLETS CASE	**4 809 000 €**	

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8.1.3.2 Infrastructure

	2. ESTIMATE COST OF ADAPTATION OF LAND INFRASTRUCTURES	MULTIPLE CASE (Phase 2)	
N°	designation	Cost Excl. Tax	duration
1	**Detailed study**		20 months
	Studies (AVP-PRO-DCE)	*961 000 €*	
	Works supervision (DET/VISA/AOR)	*384 400 €*	
	Subtotal Studies	**1 345 400 €**	
2	**Construction of an H2 fueling station at the exit of the Saint-Denis lock**		
	Authorization for temporary occupation of the river area	*NA (included simple case)*	
	Storage	*NA (included simple case)*	
	Buffer storage	*NA (included simple case)*	
	Distribution system	*NA (included simple case)*	
	Station approval?	*NA (included simple case)*	
	Subtotal fueling Seine	**0 €**	
3	**Construction of an H2 refueling station at the Romainville-Bobigny wharf**		
	Storage	*NA (included simple case)*	
	Buffer storage	*NA (included simple case)*	
	Distribution system	*NA (included simple case)*	
	Station approval?	*NA (included simple case)*	
	Subtotal fueling Romainville-Bobigny	**0 €**	
4	**Adaptation of the quayside outlets for the reception of river waste (see specific study)**		18 months
	CAPEX adaptation of the wharf + Saint-Ouen equipment	*2 062 000 €*	
	CAPEX adaptation of the wharf + Ivry-sur-Seine equipment	*2 683 000 €*	
	Subtotal adaptation of wharfs	**4 745 000 €**	
5	**Related investment**		3 months
	Installation of water / electricity terminals 63A to 125 A on each port platform (2)	*10 000 €*	
	Connection to terrestrial drinking water and electricity networks (fixed price)	*50 000 €*	
	Subtotal related investment	**60 000 €**	
	TOTAL ADAPTATION OF LAND INFRASTRUCTURE	**6 150 400 €**	

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8.2OPEX

8.2.1 OPEX PUSHER BOAT METHOD BASIC CASE

ANNUAL TECHNICAL OPERATION COSTS 2 PUSHER BOATS BASIC CASE					
Energy (hydrogen)	Hour of annual use	Hourly consumption kg	Total consumption Kg H2	Price per kg of H2	Annual cost
Seine pusher boat	2 682	10.94	29 341	8 €	234 729 €
Canal pusher N°1	5 148	6.84	35 212	8 €	281 699 €
Subtotal cost of hydrogen energy	7 830		64 553		**516 427 €**
Seine pusher boat maintenance (2682 h/year)	Basis	Cost	Annual frequency	Remarks	Annual cost
fuel cell life	20 000	282 750 €	0.13	provision	37 917 €
tank control	10 years	24 000 €	0.10	provision	2 400 €
routine maintenance	1/month	2 500 €	12.00		30 000 €
revision	1/year	15 000 €	1.00		15 000 €
technical stop and major maintenance	1/7years	200 000 €	0.14	provision	28 571 €
class tracking by BV	0.5/year	5 000 €	0.50		2 500 €
hull and machine insurance and warranty	1/year	35 000 €	1.00		35 000 €
Subtotal Seine pusher maintenance					**113 888 €**
Canal pusher boat maintenance N°1 (5148h/year)	Basis	Cost	Annual frequency	Remarks	Annual cost
fuel cell life	20 000	227 500 €	0.26	provision	58 559 €
tank control	10 year	24 000 €	0.10	provision	2 400 €
routine maintenance	1/month	2 500 €	12.00		30 000 €
revision	1/year	15 000 €	1.00		15 000 €
technical stop and major maintenance	1/7years	200 000 €	0.14	provision	28 571 €
class tracking by BV	0.5/year	5 000 €	0.50		2 500 €
hull and machine insurance and warranty	1/year	35 000 €	1.00		35 000 €
Subtotal canal pusher maintenance					**134 530 €**
Note: the operating costs linked to the fueling station(s) are not included in this OPEX, they are normally taken by the external operator in charge of the station and incorporated in the price per kilogram of hydrogen.					
Total direct annual technical operating cost of the 2 pusher boats					**764 845 €**

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8.2.2 OPEX BASIC CASE

OPEX ANNUAL BASIC CASE (Phase 1)				
	value	duration	annual cost	Observations
amortization 2 pushers + 5 barges	9 549 000 €	25	381 960 €	
H2 fuel	516 427 €	1	516 427 €	
maintenance	248 418 €	1	248 418 €	
Labor, time per 2 crew	43.00 €	12000	516 000 €	6 crews of 2 per week +
total annual cost			1 662 805 €	1.5 extra crew
transported household waste	9300 TEU	120600	**13.79 €**	per ton

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8.2.3 OPEX PUSHER BOAT METHOD MULTIPLE CASE

ANNUAL TECHNICAL OPERATION COSTS 3 MULTIPLE CASE PUSHER BOATS					
Energy (hydrogen)	Hour of annual use	Hourly consumption kg	Total consumption Kg H2	Price per kg of H2	Annual cost
Seine pusher boat	3 755	10.94	41 080	8 €	328 638 €
Canal pusher N°1	5 148	6.84	35 212	8 €	281 699 €
Canal pusher N°2	5 148	6.84	35 212	8 €	281 699 €
Subtotal cost of hydrogen energy	8 903		76 292		**892 035 €**
Seine pusher boat maintenance (3755h/year)	Basis	Cost	Annual frequency	Remarks	Annual cost
fuel cell life	20 000	282 750 €	0.19	provision	53 086 €
tank control	10 ans	24 000 €	0.10	provision	2 400 €
routine maintenance	1/mois	2 500 €	12.00		30 000 €
revision	1/an	15 000 €	1.00		15 000 €
technical stop and major maintenance	1/7ans	200 000 €	0.14	provision	28 571 €
class tracking by BV	0.5/an	5 000 €	0.50		2 500 €
hull and machine insurance and warranty	1/an	35 000 €	1.00		35 000 €
Subtotal Seine pusher maintenance					**129 058 €**
Canal pusher boat maintenance N°1 (5148h/year)	Basis	Cost	Annual frequency	Remarks	Annual cost
fuel cell life	20 000	227 500 €	0.26	provision	58 559 €
tank control	10 ans	24 000 €	0.10	provision	2 400 €
routine maintenance	1/mois	2 500 €	12.00		30 000 €
revision	1/an	15 000 €	1.00		15 000 €
technical stop and major maintenance	1/7ans	200 000 €	0.14	provision	28 571 €
class tracking by BV	0.5/an	5 000 €	0.50		2 500 €
hull and machine insurance and warranty	1/an	35 000 €	1.00		35 000 €
Subtotal canal pusher maintenance					**134 530 €**
Canal pusher boat maintenance N°2 (5148h/year)	Basis	Cost	Annual frequency	Remarks	Annual cost
fuel cell life	20 000	227 500 €	0.26	provision	58 559 €
tank control	10 ans	24 000 €	0.10	provision	2 400 €
routine maintenance	1/mois	2 500 €	12.00		30 000 €
revision	1/an	15 000 €	1.00		15 000 €
technical stop and major maintenance	1/7ans	200 000 €	0.14	provision	28 571 €
class tracking by BV	0.5/an	5 000 €	0.50		2 500 €
hull and machine insurance and warranty	1/an	35 000 €	1.00		35 000 €
Subtotal canal pusher maintenance					**134 530 €**
Note: the operating costs linked to the fueling station(s) are not included in this OPEX, they are normally taken by the external operator in charge of the station and incorporated in the price per kilogram of hydrogen.					
Total direct annual technical operating cost of the 3 pusher boats					**1 290 152 €**

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8.2.4 OPEX MULTIPLE CASE

OPEX ANNUAL MULTIPLE CASE (Phase 2)				
	value	duration	annual cost	Observations
amortization 3 pushers + 8 barges	14 358 000 €	25	574 320 €	
H2 fuel	892 035 €	1	892 035 €	
maintenance	398 118 €	1	398 118 €	
Labor, time per 2 crew	43.00 €	20800	894 400 €	10 crews of 2 per week + 3
total annual cost			2 758 872 €	extra crew
transported household waste	22500 TEU	290000	**9.51 €**	per ton

9 Conclusions and Recommendations

This preliminary study tends to confirm the feasibility of installing a hydrogen motorization for the project for the transfer of residual household waste by river for SYCTOM. In this context, specific pusher boats and barges should be provided for river operations but, given the high occupancy rates of this equipment for SYCTOM transfers, this investment seems consistent.

The river equipment needs assessed to meet SYCTOM's needs are as follows:

- 1 to 2 canal pusher boats for transfers on the Ourcq Canal
- 1 Seine pusher boat for transfers on the Seine
- 5 to 8 ballastable barges

The pushers will be powered by gaseous hydrogen compressed to 350 bar.

The costs of inland waterway transport are evaluated between 14€/ton transferred in the single case and 9.5€/ton transferred in the multiple case. These costs, compared to those of a transfer by diesel motorization of 11€/ton, evaluated within the framework of a previous study, appear reasonable and confirm that, in the near future, the H2 motorization will be competitive compared to an increasingly controlled diesel engine. Indeed, it should be kept in mind that the study was carried out at a time t with an estimate of the cost of hydrogen of 8€/kg of H2 which will undoubtedly be reduced in the years to come while the cost of diesel motorization will increase (resource scarcity, implementation of environmental taxes, etc.).

This first study must nevertheless be developed and updated once the preferred sites for the installation of the fuelling station on the Seine have been identified by the dedicated Work Package. Likewise, the characteristics of the pusher boats may have to change depending on the type of storage and supply chosen. As fuelling and motorization are intrinsically linked, the changes in assumptions compared to this study will require an update.

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A feasibility and constructability study of the pushers will then have to be carried out to go further in the project. At the same time, studies relating to the logistics plan will have to be continued, in consultation with HAROPA, to identify the waiting areas and the planning of the outlets.

10 Annexes

10.1 Annex 1 – Simple case: simulation of the logistics diagram

To estimate the rotation time of a barge, given the time constraints for the opening of the various equipment, a simulation of the rotation time was carried out:

Issy-les-Moulineaux		1/1														
Next day		Monday														
Beginning of loading operation	Hp	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Romainville/Bobigny																
OMR	Barge	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Loaded barge	01:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30	06:30	07:30
Ourcq navigation	04:45	12:15	13:15	14:15	15:15	16:15	17:15	18:15	19:15	07:00	08:00	09:00	10:00	11:00	11:15	12:15
Issy-les-Moulineaux																
Berthing of the barge @ Issy-les-Moulineaux	02:40	14:55	15:55	16:55	17:55	18:55	19:55	06:55	07:55	09:40	10:40	11:40	12:40	13:40	13:55	14:55
Loading/unloading barge operation @ Issy-les-Moulineaux	04:48	19:43	06:43	07:43	08:43	09:43	10:43	11:43	12:43	14:28	15:28	16:28	17:28	18:28	18:43	19:43
Return to Romainville/Bobigny																
Return navigation (Seine)		08:38	08:53	09:53	10:53	11:53	12:53	13:53	14:53	16:38	17:38	18:38	06:23	07:23	07:38	08:38
Ourcq Navigation	04:15	12:53	13:08	14:08	15:08	16:08	17:08	18:08	19:08	06:53	07:53	08:53	10:38	11:38	11:53	12:53
Unloading of empty containers	01:45	14:38	14:53	15:53	16:53	17:53	18:53	19:53	06:53	08:38	09:38	10:38	12:23	13:23	13:38	14:38
Number of days (if > 24h)		24:00	24:00	24:00	24:00	24:00	24:00	24:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00
Total duration of the rotation		32:38	31:53	31:53	31:53	31:53	31:53	31:53	41:53	42:38	42:38	42:38	43:23	43:23	42:38	42:38

Figure 9 : Simulation of a barge rotation of residual household waste towards Issy-les-Moulineaux

The average rotation time of the barge is therefore 37h45min taking into account the waiting times; or a little more than 1.5 days between departure and return to Bobigny berth.

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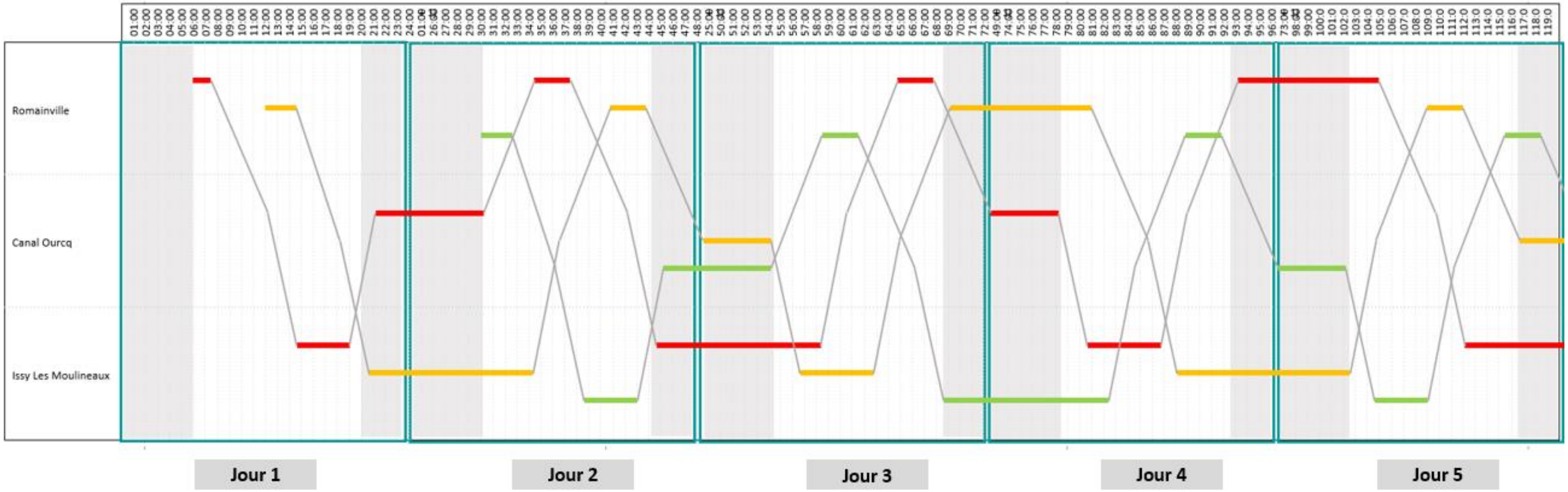
The journey of the barge on the river network integrating the various waiting times related to the loading / unloading of barges and the opening / closing times of equipment is modeled over a week below:



Legend	Stopover color			
	Barge number	Barge 1	Barge 2	Barge 3
	Journey color			

Figure 10 : Simple case: modeling the river transfer of barges over a week at each outlet

Knowing that a maximum of 2 barges per day must be loaded at the port of Romainville / Bobigny, this means that 3 to 4 barges must be provided for river operations in the simple case.

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10.2 Annex 2 – Multiple case: simulation of the logistic scheme

As for the simple case, a simulation of the rotation time of the barges towards each of the outlets was carried out:

St-Ouen		1/1														
Next day		Monday														
Beginning of loading operation	Hp	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Romainville/Bobigny																
OMR	Barge	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Loaded barge	01:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30	07:30	07:30
Ourcq navigation	04:45	12:15	13:15	14:15	15:15	16:15	17:15	18:15	19:15	07:00	08:00	09:00	10:00	11:00	12:15	12:15
St-Ouen																
Berthing of the barge @ St-Ouen	00:45	13:00	14:00	15:00	16:00	17:00	18:00	19:00	06:00	07:45	08:45	09:45	10:45	11:45	13:00	13:00
Loading/unloading barge operation @ St-Ouen	04:24	17:24	18:24	19:24	20:24	21:24	05:24	06:24	10:24	12:09	13:09	14:09	15:09	16:09	17:24	17:24
Return to Romainville/Bobigny																
Return navigation (Seine)	00:35	17:44	18:44	06:29	07:29	08:29	05:44	06:44	10:44	12:29	13:29	14:29	15:29	16:29	17:44	17:44
Ourcq Navigation	04:15	07:59	08:59	10:44	11:44	12:44	09:59	10:59	14:59	16:44	17:44	18:44	19:44	06:44	07:59	07:59
Unloading of empty containers	01:45	09:44	10:44	12:29	13:29	14:29	11:44	12:44	16:44	18:29	19:29	06:29	07:29	08:29	09:44	09:44
Number of days (if > 24h)		24:00	24:00	24:00	24:00	24:00	24:00	24:00	24:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00
Total duration of the rotation		27:44	27:44	28:29	28:29	28:29	24:44	24:44	27:44	52:29	52:29	38:29	38:29	38:29	38:44	37:44

Ivry-sur-Seine		1/1														
Next day		Monday														
Beginning of loading operation	Hp	06:00	07:00	08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00	18:00	19:00	20:00
Romainville/Bobigny																
OMR	Barge	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Loaded barge	01:30	07:30	08:30	09:30	10:30	11:30	12:30	13:30	14:30	15:30	16:30	17:30	18:30	19:30	07:30	07:30
Ourcq navigation	04:45	12:15	13:15	14:15	15:15	16:15	17:15	18:15	19:15	07:00	08:00	09:00	10:00	11:00	12:15	12:15
Ivry-sur-Seine																
Berthing of the barge @ Ivry-sur-Seine	03:45	16:00	17:00	18:00	19:00	06:00	07:00	08:00	09:00	10:45	11:45	12:45	13:45	14:45	16:00	16:00
Loading/unloading barge operation @ Ivry-sur-Seine	03:48	19:48	06:48	07:48	08:48	09:48	10:48	11:48	12:48	14:33	15:33	16:33	17:33	18:33	19:48	19:48
Return to Romainville/Bobigny																
Return navigation (Seine)	03:30	09:48	10:03	11:03	12:03	13:03	14:03	15:03	16:03	17:48	18:48	06:33	07:33	08:33	09:48	09:48
Ourcq Navigation	04:15	14:03	14:18	15:18	16:18	17:18	18:18	19:18	06:18	08:03	09:03	10:48	11:48	12:48	14:03	14:03
Unloading of empty containers	01:45	15:48	16:03	17:03	18:03	19:03	06:03	07:03	08:03	09:48	10:48	12:33	13:33	14:33	15:48	15:48
Number of days (if > 24h)		24:00	24:00	24:00	24:00	24:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00	48:00
Total duration of the rotation		33:48	33:03	33:03	33:03	33:03	43:03	43:03	43:03	43:48	43:48	44:33	44:33	44:33	44:48	43:48

Figure 11 : Simulation of a rotation of residual household waste barge towards Saint-Ouen and Ivry-sur-Seine

The average rotation times retained for the barges taking into account the waiting times are as follows:

- Saint-Ouen : 31h 08min
- Issy-les-Moulineaux : 37h 34min
- Ivry-sur-Seine : 40h 48min

A maximum of 4 barges per day will be loaded/unloaded at Romainville/Bobigny and they must each supply the outlets. This logistical organization is complex and it presupposes a fine organization to limit waiting times as much as possible.

To check the potential interference between the different convoys and the waiting times induced at each wharf, the Consultant carried out a simulation of the river journeys of the barges over one week to each outlet, taking into account the various identified constraints.

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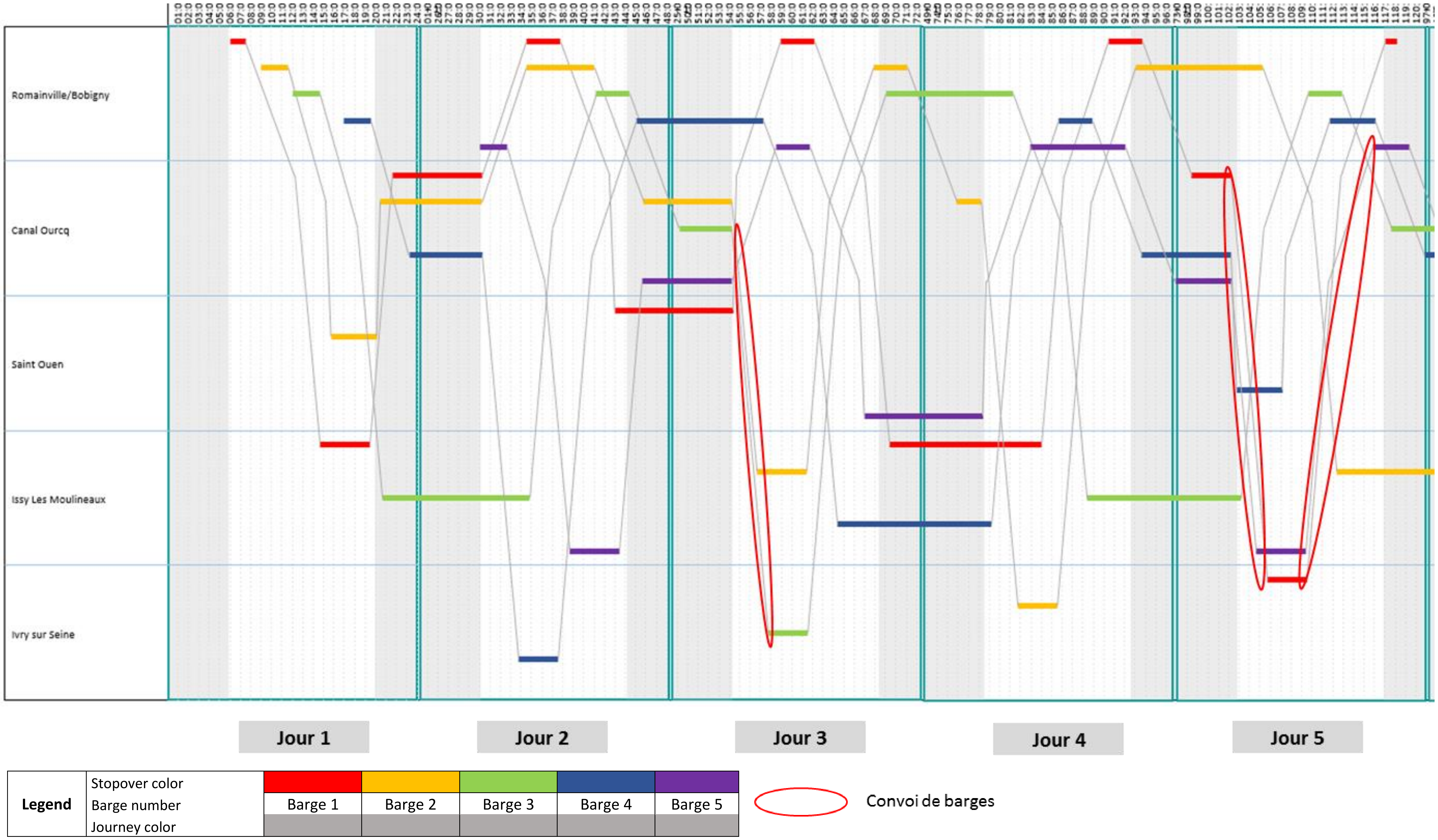

Figure 12 : Multiple case : modeling of the river transfer of barges over one week at each outlet

10.3 Annex 3 – Regulatory links

SAE J 2990/1 June 2016	Gaseous Hydrogen and Fuel Cell Vehicle First and Second Responder Recommended Practice
SAE J 2600 October 2015	Compressed Hydrogen Surface Vehicle Fueling Connection Devices
SAE J 2601 December 2016	Fueling Protocols for Light Duty Gaseous Hydrogen Surface Vehicles / Note: Revision A
Directive 2008/68/EC	Concerning the internal transport of dangerous goods.
Directive ATEX - Directive 1999/92/EC	Concerning the minimum requirements aimed at improving the safety and health protection of workers likely to be exposed to the risk of explosive atmospheres
REGULATION (EC) no 79/2009	Concerning the type-approval of motor vehicles running on hydrogen
NR566	Hull arrangement, stability, and systems for ships less than 500 GT
NR529	Gas fuelled ships
NI547	Guidelines for fuel cell systems onboard commercial ships
NR320	Certification scheme of materials and equipment for the classification of marine units
NI525	Risk-based qualification of new technology - methodological guidelines
NR266	Requirements for survey of materials and equipment for the classification of ships and offshore units
NR467	RULES FOR THE CLASSIFICATION OF STEEL SHIPS
NR217	Rules for the Classification of Inland Navigation Vessels
2018-900	of October 22, 2018 created a section 1416 "Storage or use of hydrogen" in the nomenclature of classified installations (ICPE - described in phase 2).