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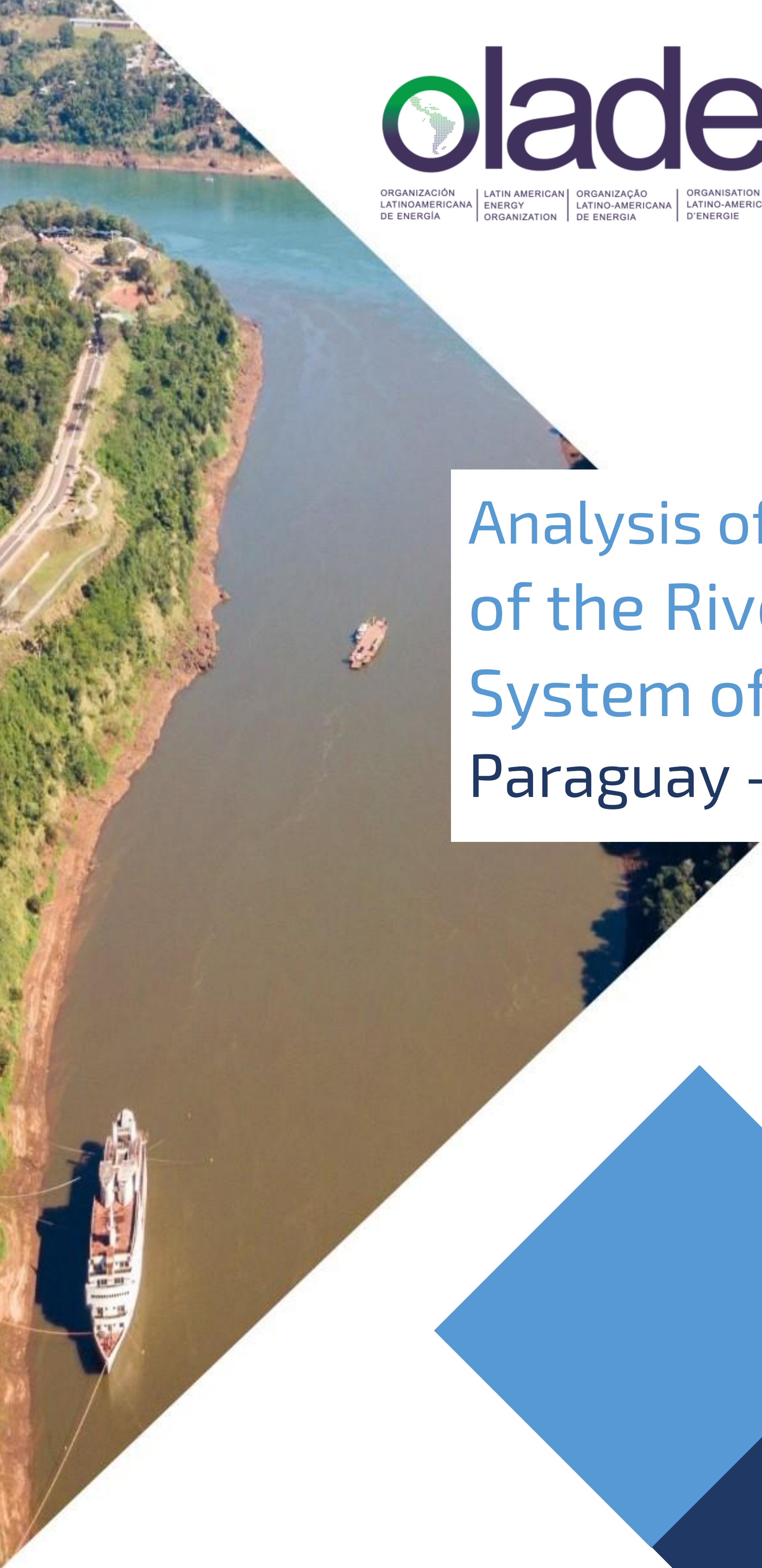

Analysis of Fuel Substitution of the River Transportation System of the Paraguay - Paraná Waterway

Technical Report

November 2020

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This Report was commissioned and coordinated by the Inter-American Development Bank (IDB) through Roberto Aiello, Principal Specialist of the Energy Division (ENE). Helpful comments were provided by Michelle Hallack and Luis Carlos Perez Martínez (IDB/ENE).

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Executive Summary

This study's main objective, within its scope, is to make a first approach to the replacement of bunker fuels used in the Paraguay - Paraná Waterway with more sustainable and environmentally friendly energy alternatives. To do this, replacement options such as natural gas, electricity or hydrogen were evaluated. However, considering the feasibility and current trends, the analysis of the potential substitution by Natural Gas has been deepened. It should be noted that a complete life cycle analysis was not performed to determine the greenhouse gas emissions associated with the use of the fuel alternatives that were evaluated.

The Waterway runs from north to south from the Brazilian city of Puerto Cáceres, in the state of Mato Grosso, before flowing out into the Paraná delta in front of the Nueva Palmira port, located in the district of Colonia, Uruguay. The countries that share this river system - Argentina, Bolivia, Brazil, Paraguay and Uruguay - created the Intergovernmental Committee of the Waterway (CIH - Comité Intergovernmental de la Hidrovía). Between 1988 and 2010, the transport of goods multiplied, from 700 thousand to almost 17.4 million tons per year, to exceed the current 36 million.

The major part of the traffic is based on cargo of grains, minerals, transportation of fuels, alcohols and vegetable oil. The Waterway has an intense traffic of medium-sized ships up to Rosario. Upstream the transit is carried out through small barges. The most used modality is by barge trains. A convoy can transport in total, up to 25,000 tons. It is estimated that there are about 13,000 annual trips of this type of convoy.

Gas Oil and Fuel Oil consumption is about 80,000 m^3 per year, and among the main consumers are the already mentioned high-power push boats. If the consumption of marine fuel in ports and roads, close to the waterway, is added, the consumption of these fuels exceeds 800,000 m^3 per year. This would-be volume replaceable by cleaner fuels, in line with international trends. The current supply of fuels in the Waterway is produced mainly from Argentine ports.

In addition, it should be noted that, in comparison with other modes of freight transport, the Waterway turns out to be more efficient than land or rail transport.

Considering the currently available technologies, this study provides some evidence that Natural Gas would be the most appropriate fuel in the short term to replace the marine fuels that are used today in the Waterway. The indications that support the option for Natural Gas are summarized below in three groups:

a) **Price:** It is inferred that the price per calorie of Natural Gas would be lower than that of the replaced fuels, as is the case in the International Market for Liquefied Natural Gas (LNG), in its use as bunker fuel and with the price projections of said product. This would allow a saving of close to 50% in total operating costs, compared to the use of standard heavy fuel oil.
b) **Sustainability:** LNG offers prospects for a 25% reduction in CO_2 emissions, the complete elimination of sulfur emissions and close to 90% reduction in nitrous gases compared to currently used marine fuels.
c) **Technological maturity:** Currently, there are ships that already run-on LNG as the main source and sustained growth is projected. In addition, considering that the transportation mode on the Waterway north of Rosario is, for the most part, through convoys of barges, it has been found that these can be adapted to store LNG in tanks

with appropriate capacities. Shipyards were identified that have designed tugboats capable of operating with LNG.

Natural Gas is an option supported by the integration and uses of regional resources:

Arguments in favor of the use of Argentine Natural Gas:

The Vaca Muerta Unconventional Field, in the province of Neuquén, Argentina, could ensure the supply of Natural Gas to replace the Gas Oil and Fuel Oil that are used today in the Waterway and in nearby Ports. The criteria considered in this argument are:

a) The volume of Natural Gas reserves in Vaca Muerta, estimated as sufficient for 150 years, at the current consumption level according to the Argentine Institute of Petroleum and Gas.
b) The diversity of top-level international companies that operate in the different productive fields of said formation.
c) The incremental production and export projections of Natural Gas for the coming years in said training.
d) The liquefaction plant in operation (Tango FLNG), in Bahía Blanca, Argentina (with the capacity to produce 0.5 million tons per year of LNG) that constitutes a first strategic step for the development of a natural gas liquefaction project from Vaca Muerta.
e) The accumulated experience in the use of Compressed Natural Gas (CNG) for vehicles and the projects in execution of the use of LNG, in Trucks and Omnibuses.
f) The volumes of Gas Oil and Fuel Oil to be replaced, estimated at 80,000 m3/year, turn out to be quantities that can be supplied comfortably.
g) The current technological development of companies for liquefaction and transportation through virtual LNG pipelines on a small scale.

Other regional options, Bolivia and Brazil:

As analyzed in the present study, it is also possible to source from the Natural Gas Fields in Bolivia, but in small volumes, and most likely only to satisfy the demand in the northern part of the Waterway. It is anticipated that the availability of Natural Gas in Brazil's pre-salt area could only materialize in the long term, once the "*Floating LNG*" projects are completed in the *offshore* of its deep waters. It is presumed that Brazil will continue to be a net importer of Natural Gas for a considerable time.

Other technological options for the medium and long term:

In the last chapter of the Study, other sources of energy are analyzed, such as Biodiesel, Hydrogen, and other clean sources, as possible fuels in ships on the Waterway.

Regarding Biodiesel, it is believed that it will be incorporated into bunker mixtures in a progressive and natural way, given that IMO specifications are increasingly restrictive in the permitted sulfur content. In this case, the mixtures with HF gas oil or Fuel Oil can be made in the refineries since the facilities are already prepared for *blending* biodiesel with vehicular gas oil. And the same logistics used today for the distribution of bunker fuel would be used in the Waterway with practically no need for investments in infrastructure. One barrier to the use of biodiesel is its high cost.

Likewise, abundant information was obtained from ships powered by Solar Energy and Green Hydrogen obtained by electrolysis of water, and converted into Water in fuel cells that deliver electrical energy for the operation of their engines. Regarding the use of solar and wind energy in medium/large size vessels, there are several successful cases that are shown in the present study. It is considered that the opportunities for the use of Hydrogen in the ships in the Waterway could arise in the medium/long term and would require a more detailed analysis.

The roadmap of the proposed substitution process should have synergies with the initiatives that are being generated to supply Natural Gas, both compressed and liquefied, to home users, service stations and electricity generation plants located in the Northeast of Argentina, giving lead to possible economies of scale and complementarities. It will also be necessary to consider the inertia in the substitution of marine fuels for LNG at the international level, which would impact other ports near the Waterway, such as Campana, Capital Federal, La Plata and Montevideo.

The necessary investments in LNG infrastructure to start the substitution process are not significant, and are related to the reception and dispatch of the new fuel in the ports, in the ships to be transformed and eventually those necessary to build and set up small scale or portable liquefaction plants.

1. Introduction and Background

The Paraguay - Paraná Waterway runs from Brazil to the south, starting from the Brazilian city of Puerto Cáceres in the state of Mato Grosso, and ending at the delta of the Paraná River, in front of the port of Nueva Palmira, in the district of Colonia, Uruguay. The countries that share this river system — Argentina, Bolivia, Brazil, Paraguay and Uruguay — in a first stage promoted studies to determine the economic, technical and environmental feasibility of the necessary improvements to guarantee the sustainable use of the water resource, creating the Intergovernmental Committee of the Waterway (CIH). The transport of goods multiplied between 1988 and 2010, from 700 thousand to almost 17.4 million tons per year, to exceed the current 36 million.

Although numerous improvement works have been proposed and executed in the Waterway, it was not possible to identify any previous study about replacing bunker fuels with Natural Gas or other sources of clean and renewable energy, as it is proposed to analyze in this study, led by the IDB and OLADE.

2. Current situation of the Waterway

2.1. Main characteristics of the Waterway

Taking its website as a source of information, and as can be seen in Figure 1, the Paraguay - Paraná Waterway consists of the construction of a navigable channel through the Paraguay, Paraná rivers and some of their tributaries. The main goal is to allow the navigation of barges of great draft and large volumes of cargo 365 days a year. To achieve this goal, it has been necessary to rectify the route (eliminating meanders), widen it (eliminating riparian vegetation), make it safer (by signaling), eliminate islands and islets (dynamiting them) and deepen it (dredging the river bed).

Figure 1: Map of the Paraguay - Paraná Waterway

Source: Intergovernmental Committee of the Waterway Paraguay - Paraná (http://www.hidrovia.org/es/mapas)

The length of the Paraguay - Paraná Waterway for each country and main grain ports:

- **BRAZIL: 890 km, 26%**
- **BOLIVIA - BRAZIL: 48 km, 2%**

- **BRAZIL - PARAGUAY: 322 km, 9%**
- **PARAGUAY: 567 km, 16%**
- **ARGENTINA - PARAGUAY: 375 km, 11%**
- **ARGENTINA: 1240 km, 36%**
- **TOTAL - 3442 km, 100%**

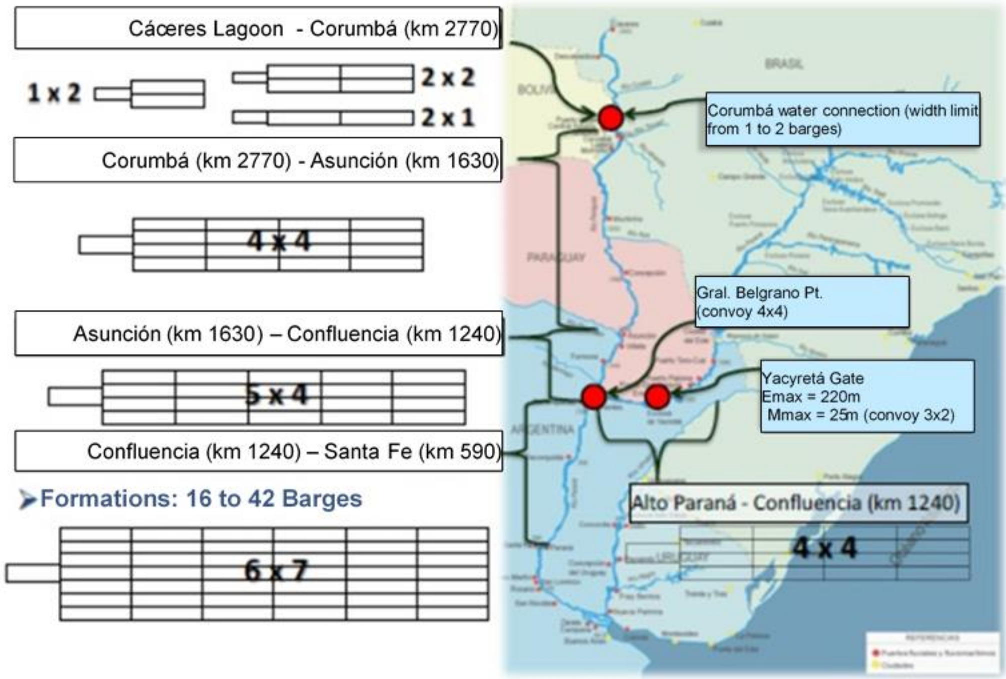
The following grain ports can be found on this route: *Cáceres, Curumba and Ladario in **Brazil**; Aguirre in Bolivia; Concepción and Asunción in **Paraguay**; Barranqueras, Reconquista, Santa Fé, Paraná, Diamante, San Martín, San Lorenzo, Rosario, Villa Constitución, San Nicolás and San Pedro in **Argentina***.

Figure 2 shows a map of the navigable drafts according to the geographical location along the Waterway and, in consistency with this, Figure 3 shows the typology of the convoys admitted along the Waterway.

Figure 2: Navigable Drafts

Source: Ministry of Agriculture, Livestock and Fisheries (2016).

Figure 3: Typology of Convoys admitted by draft



Source: Ministry of Agriculture, Livestock and Fisheries (2016).

2.2. Advantages of using the Waterway

River transport has greater advantages than rail and road transport due to its lower investment and maintenance cost, lower energy consumption, higher load capacity and lower transport costs for long distances, as detailed in the following paragraph. River transport is a highly profitable means compared to land transport: to transport a ton of merchandise based on each liter of fuel consumed, a truck travels 23 km, the railroad 90 km and a barge or ship between 250 and 300 km. In terms of towing power, a barge is equivalent to 37 wagons or 50 trucks, each convoy of barges is made up of approximately 15 units.

Over distances of up to 300 km, it is convenient to use the truck; from 300 km to 800 km, the railway and above 800 km, it is convenient to use river transport by barges. A barge train equates to 36 barges or 1,500 tons (ton) of grain to each barge, totaling of 54,000 tons of grain. A barge train is equivalent to 1,080 railway wagons (50 tons) and 1,928 trucks (28 tons). According to data provided by the Ministry of Agriculture, Livestock and Fisheries of the Argentine Republic, the estimated rate for the transportation of grains, oils and by-products is USD 0.10 per ton/km by truck; USD 0.045 per ton/km by rail and USD 0.02 per ton/km by barge.

If the improvements introduced in recent times in the markings and in the depth for navigation (determinant in 34 feet) are added to the natural benefits, it is noted that they allowed the transit of larger vessels with the result of a lower cost of freight (economy of scale) of about $ 6 to $ 8 per ton.

Furthermore, the incorporation of new technology and new port terminals have improved the flow of merchandise destined for export, making it possible to increase exports in the ports of the Waterway and a greater competitiveness of regional products in international trade.

2.3. Evolution of the operational capacity of ports

An example of this evolution, considering the years 1990 and 2007 as a base, is observed in the volume of storage of grains/solid by-products in the ports of the Waterway, which grew from 1.5 million tons to almost 8 million, while ship loading rates increased from 23 thousand tons per hour to 54 thousand.

This expansion of the operational capacity of the ports has allowed the exports of the "*Up-River*" sector to also increase from about 13.5 million tons to about 54 million grains and pellets without causing additional storage costs or delays in the stays of the ships.

To this information provided by Mr. Carlos Ibáñez from the Directorate of Agrifood Markets, an in-person interview is added with the *Ambassador Luis Niscovolo*, who was *CIH Executive Secretary* at the time of preparing this study, in order to add details of the current operation of the Waterway and contribute his vision regarding the replacement of marine fuel currently used by LNG or other clean and renewable energy sources.

From his position as Executive Secretary, he encourages working within the framework of the international conventions "Marpol" of the International Maritime Organization. And it is precisely in this context that CIH officials are actively working to adapt these marine environmental standards to river transport along the Waterway.

He adds that the Waterway has a more or less intense traffic to Rosario for the loading and unloading of agricultural products, fuels and auto parts. Upstream the transit is carried out through small barges. The most used modality is by barge trains. A convoy can have up to 25,000 tons. He states that push boats of 4,000 to 6,000 HP are used. There are about 13,000 annual trips of this type of convoy. The main operator is Paraguay, since of the 2,500 barges and 300 push boats that navigate the Waterway, 75% belong to that country. He also points out that he presumes that Bolivia will be increasingly using the Waterway as an outlet to the sea.

It indicates that the Waterway Agenda contemplates the use of more environmentally friendly fuels in the short and medium term. And these terms can be shortened if the supply of clean energy and lower operating cost for the Waterway can be ensured. Finally, he points out that lowering the cost of freight by using cheaper fuels such as LNG will be important to attract more merchandise to be transported through the Waterway.

2.4. Movement of ships and sale of bunker fuels

As indicated before, around 2,500 barges, 300 Push Boats (R/E) trunk lines and 50 self-propelled vessels circulate on the Waterway. The trunk lines are those that load bunker fuel along the Waterway. The international definition of bunker applies to Gasoil or IFO (*Intermediate Fuel Oil*) fuels, which do not pay taxes for ships that engage in international traffic. The barges do not load fuel for their own consumption, since they do not have their own propulsion. The trunk lines are push boats with powers of 4,000 to 6,000 HP. Most of these R/E consume Gas Oil, but there are about 12 units that can burn IFO or Gas Oil, indistinctly. The companies that have push boats that burn IFO are Hidrovía; P&O and Naviera Yeruti.

The major part of the traffic is grain/ore cargo. The grains come from Paraguay or Bolivia and the mineral from areas of Bolivia and Brazil, all in the Rio de La Plata. There is also container traffic that takes place in self-propelled ships or in convoys made up of an R/E and a very large barge. This container traffic occurs mainly between Asunción, Buenos Aires and Montevideo. Finally, there is the traffic of liquid fuels (mainly gasoline and diesel) from the Rio de La Plata area to Asunción and Bolivia. There is also movement, although to a lower extent, of Alcohols and Vegetable Oil.

What is relevant for this Study is that, to carry out all this transport, the push boats and self-propelled boats load bunkers in the cheapest place they can find, which is typically in Argentina.

There is even a network of intermediaries who buy from the Refining Companies in Argentina and resell to the shipowners in northern ports of the Waterway (Asunción is a natural place for ship maintenance, crew change, refueling, etc.). For the reasons already mentioned, the market volumes have been estimated from the statistics of the Argentine Secretary of Energy, according to the tables indicated below.

Table 1: Sales and Prices of Bunker Fuels in Waterway and Nearby Ports, on the Argentine Coast

Exchange rate in June 2019: 1 USD = 45 Argentine pesos

Location / Bunker port	Derived	Wholesale operator	Channel of commercialization	Price excluding taxes	Price including taxes	Reported volume (m3)	Exempt
Zárate-Zarate Port Complex - D. Dock - Campana	Blend 70-30	PAN AMERICAN ENERGY LLC, ARGENTINE BRANCH	International bunker	16,947	16,947	10,348.40	NO
	Gas Oil Grade 2B		International bunker	27,371	27,371	3,898.17	NO
	Gas Oil Grade 2	YPF S.A.	International bunker	25,738	25,738	181.00	NO
	Total June 2019					**14,417.57**	
	Estimated Annual Total Zarate Complex					**187,428.41**	**M3/year**
San Lorenzo Complex - San Martín - Rosario - Gral Lagos - Punta Alvear and Villa Constitución (WATERWAY)	Gas Oil Grade 2B	PAN AMERICAN ENERGY LLC, ARGENTINE BRANCH	Cabotage bunker	25,688	36,168	861.15	NO
	Gas Oil Grade 2B		International bunker	26,487	26,487	5,255.91	NO
	Fuel oil	Shell Argentina	International bunker	18,477	18,477	362.44	
	Gas Oil Grade 2	YPF SA				181.0	
	Total month of June 2019					**6660.5**	
	Estimated annual total for the San Lorenzo Ports Complex (WATERWAY)					**79,926 m3/year**	
Federal Capital	Gas Oil Grade 2	YPF S.A.	International bunker	38,323	38,323	871.00	NO
	Blend 70-30		International bunker	18,822	18,822	3,065.00	NO
	Total month of June 2019					**3936 m3**	
	Estimated annual total CF port					**47,232 m3/year**	

Puerto La Plata	Blend 70-30	YPF S.A.	International bunker	19,087	19,087	29,342.00	NO
	Fuel oil	SHELL COMPAÑIA ARGENTINA DE PETRÓLEO S.A.	International bunker	18,791	18,791	23,252.90	YES
		Total month of June 2019				52,594.9	
		Estimated Annual Total in Puerto La Plata				**631,138.8 m3/year**	

Source: Secretary of Energy of the Argentine Republic**.**

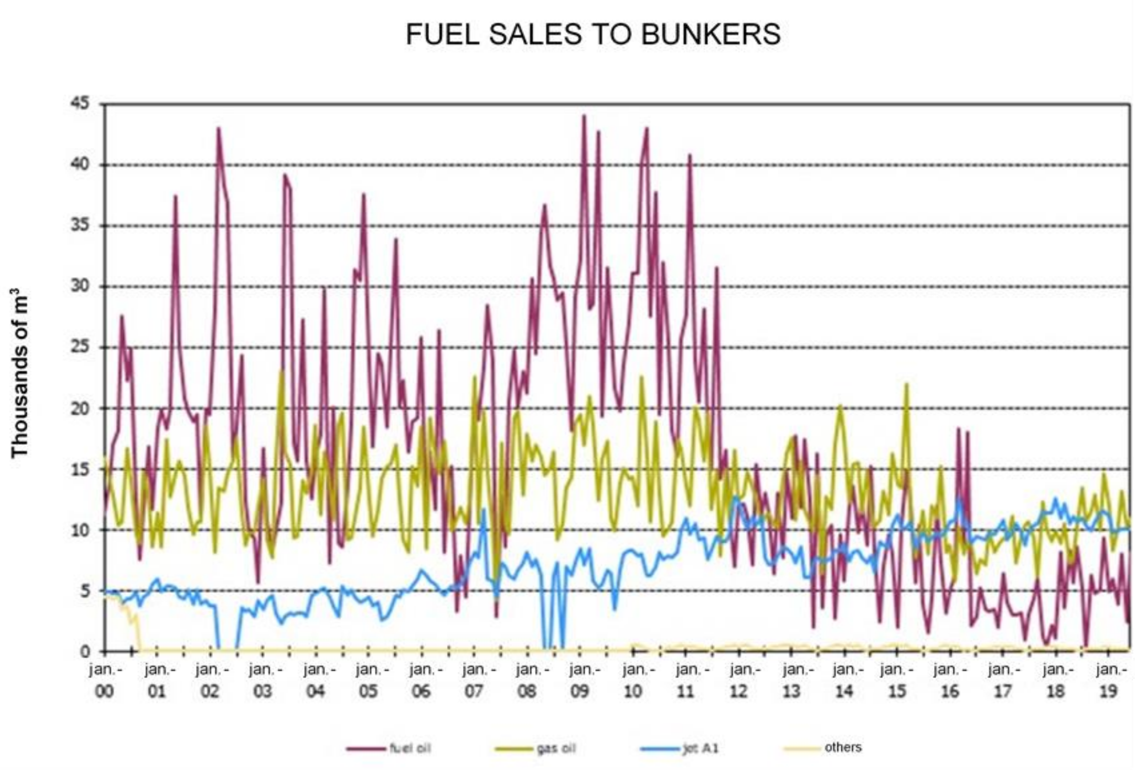
Table 2: Total sales of IFO blends (RMG 380) in all Argentine ports. June 2019.

Company	unit	Argentine ports	IFO blends (RMG 380)
		All	
Trafigura Argentina S.A.	(m3)		
	(Ton)		17,258.09
PAN AMERICAN ENERGY SL	(m3)		
	(Ton)		15,594.00
Polipetrol S.A.	(m3)		
	(Ton)		78.00
SHELL C.A.P.S.A.	(m3)		
	(Ton)		19,990.00
YPF S.A.	(m3)		
	(Ton)		13,189.00
General total for June 2019			66,109.09
Annual general total (estimated)			793,308 m3/year

Source: Argentine Secretary of Energy

See specifications of bunker fuels in the Waterway in Annex 1.

Figure 4: Official statistics of bunker fuel sales in the Oriental Republic of Uruguay



Source: Ministry of Industry, Energy and Mining (MIEM), Oriental Republic of Uruguay

Paraguay does not produce marine fuels. And it has not been possible to identify official statistics on imports or sales of bunker fuels in the Waterway.

2.5. Dynamics of circulation and fuel supply in the Waterway in the Rio de La Plata

The Waterway is navigated from south to north through the Río de la Plata, which has an approximate length of 150 nautical miles (one nautical mile is equivalent to 1,852 km), from the confluence of the Río Paraná and the Río Uruguay, at the height of Martín García Island, to the imaginary line drawn straight from Punta del Este (Oriental Republic of Uruguay) and Punta San Antonio (southern end of Samborombón Bay in the Province of Buenos Aires).

Within the Río de La Plata it is possible to distinguish two main areas with regard to the entry of ship traffic; the Landing and the Common Zone.

- **Landing**: it is located 16.8 miles south of Montevideo and is used as an anchorage area where it waits for the decongestion of river traffic and as a Pilot and Beacon

Station. In this sector, the ships obligatorily take the River Pilot and continue their march towards the west.

- **Common Zone or Anchorage area**: it is an anchorage and maneuvering sector used as ship waiting area with destination of port of Buenos Aires or upriver in case of congestion. It is located between Km 37 and Km 57 - at the height of the city of La Plata. That is, between the Banco Chico pass and the access to the Buenos Aires Canal and the Miter Canal.

Finally, in this Zone, ships have the possibility of refueling in open waters using barges. These self-propelled barges, with an average capacity of about 3,000 m3 of fuel, transfer bunker fuel by pumping, mainly starting from the La Plata Refinery in Puerto de La Plata or the Shell Refinery in Dock Sud.

Upon reaching the Common zone or anchorage area, the self-propelled barges transfer the bunker "ship to ship" by pumping. At the same time, they can supply gas oil for consumption by the generators inside the ships.

The quality of fuel for large merchant and cruise ships is according to ISO 8217 2005 and its name is ISO-F.RMG 380 (also called 70/30). The total market is in the order of 80,000 tons/month (m3/month).

It is difficult to determine how much of that volume of fuel powers ships entering or leaving the Waterway and how much powers those entering the port of Buenos Aires or La Plata. What can be affirmed is that most of the fuel consumed by these ships when navigating the Waterway is supplied outside of its limits. And the main reason is that they must navigate by roads with low draft and prefer to enter the Waterway with the strictly necessary fuel, and resupply in the Anchorage Area in the manner indicated above, when leaving already loaded with merchandise. Whatever the case may be, it is very difficult that this volume of fuel or its eventual replacement that is more environmentally friendly, can be supplied within the Waterway in the future as long as there are limitations in the draft.

2.6. Main navigation channels in the Rio de La Plata

From Landing to Common Zone through the “Canal Punta Indio”, whose limits are indicated by a set of buoys, there is a width of 600 meters and its draft is approximately 34 feet. To cover the journey from the Common Zone to the Paraná and Uruguay Rivers, at kilometer 37 the “Barra de Farallón” Channel is born. From there you can opt for the Martín García Canal route bordering the homonymous island, which is made up of a set of channels that include anchoring areas for waiting for favorable water levels, since the action of the winds permanently modifies the depth.

The inauguration of the Mitre Canal in 1976 meant an important change for the entrance to the Paraná River, allowing the transit of ships with greater draft and better conditions for navigation. It is located at the km 12 from the access to the Buenos Aires canal and 56 km from the "Paraná de las Palmas". The carrying out of dredging works that led to

34 feet of draft the determinant of the passage in the channel, instead of the historical 28 feet, has notably favored the system and international trade.

2.7. Navigation on the Paraná River

The Paraná river originates in the Republic of Brazil and is formed by the confluence of the Grande, Tieté, Paranponema and Iguazú rivers, receiving at the km 1,245 the waters of the Paraguay River. For the purposes of commercial navigation, the River is subdivided into three sectors: the Alto Paraná (from the km 1,245 to the km 597 - City of Paraná); the Paraná Medio (from the km 597 to the km 420 - City of Rosario) and the Lower Paraná (from Rosario to its mouth in the delta of the Río de la Plata. Through this river you can navigate with a draft of 34 feet (determinant of the Mitre Canal) to the port of San Martín (Province of Santa Fe), continuing with 22 feet to the port of Santa Fe. From there, following the Paraguay River, the drafts only allow the transit of barges with a depth of 11 feet, which decreases as one moves north, until reaching 8 feet in the port of Cáceres.

Barges of 1,500 gross tons are generally used as part of convoys with a maximum of 20/25,000 tons of cargo. The Tieté-Paraná branch is impossible to navigate in its entirety due to the lack of a system of locks at the Itaipú dam in order to bridge the 115-meter drop. However, navigation is carried out on the Argentine side to Puerto Iguazú with an approximate draft of 8 feet, there it is transshipped to truck, and then by barge in the Piracaciba-Itaipú Waterway in Brazil.

The following sources of supply of Gas Oil HF have been identified for the push boats of the convoys in the Waterway. From the Argentine Republic, the sources of production of Gas Oil HF are the La Plata and San Lorenzo refineries, belonging to YPF; the Axion Refinery of the PAE group, and the Shell Refinery of Dock Sud. From Uruguay there is ANCAP's La Teja Refinery. It is possible that there is also a proportion of imported fuel by International Traders (Trasfigura; Vitol and recently Energías del Paraná, among the ones with the largest volume), but its quantification exceeds the scope of this preliminary study. This gas oil, with more sulfur content than that used in motor vehicles, has the international designation DMA-ISO 8217/2005 (See specifications for HF gas oil in Annex 1).

As inferred from the summary prepared with data from the Argentine Secretary of Energy, extrapolating from the month of June, the estimated annual volume that is distributed and consumed in the transit of barges and push boats within the limits of the Waterway, is of the order of 80,000 m^3.

The most important supply points are: Campana (with 3 terminals: Axion, Trasfigura Petromining 6 km downstream from Campana), San Lorenzo and Asunción (Petropar terminal in Villa Elisa and Trasfigura has its own port).

The San Lorenzo refinery supplies the Port of the same name through pipes. While the other refineries mostly use self-propelled barges that are loaded in ports close to them and then unloaded into tanks at their corresponding terminals.

There is the possibility of refueling Gas Oil HF in Paraguayan ports, through the Reception and Dispatch Terminals owned by both Petropar and Trasfigura (the company that bought the infrastructure from Petrobras). But it has not been possible to identify official sales and price statistics.

2.8. Freight Carrier Preferences

The large grain ships that load in the ports of Rosario and its surroundings prefer to stock up during the mooring and simultaneously with the loading of merchandise in said ports to reduce the time spent in the area.

However, limitations in the waterway's draft force large vessels to refuel in anchorage areas or other *topping off* areas, and circulate through the Waterway with the least amount of fuel possible. Due to the inherent characteristics of this river system, it is not expected that this situation will change in the short term.

The grain ships that enter the Waterway are usually of the Panamax Type, with the potential to load up to 60,000 tons of cereal, but due to restrictions on the waterway's draft, they only load 45,000 tons. To be more efficient and navigate with all its cargo potential, the waterway's draft should reach 41 feet.

3. International specifications on liquid fuels for ships

Below, and as general information, the types of marine fuels that are have been in the world and the trends in international specifications are described.

Marine gasoil (MGO) is a distilled product, 100% of fossil origin, without the addition of additives or residues. The MGO can be used in four-stroke engines and generators. This fuel meets the specifications of the ISO-F DMA standard and the required sulfur limit for all European ports (1000 ppm or 1% sulfur).

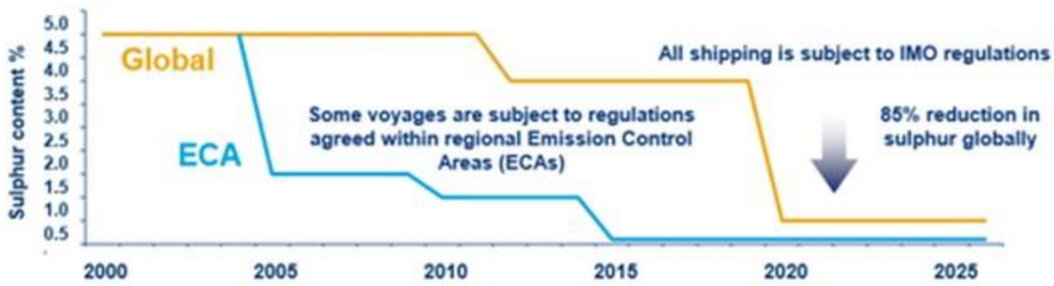
ISO-F-RMG 380 This is the most widely used product. Meets the specifications of the ISO 8217:2010 standard. Intended for slow and semi-fast engines (up to 4.5% sulfur).

ISO-F-RMG 380 Low sulfur Fuel with a sulfur content of less than 1.0%. It is used in controlled emission zones - CEPA. Meets the specifications of the ISO 8217:2010 standard. Intended for slow and semi-fast engines.

Intermediate Fuel Oils (IFO) IFO fuels are obtained by mixing bunker fuel, MGO and IFO with low sulfur content to comply with the limits defined by the ECA. Intended for slow and semi-fast engines.

Wood Mackenzie (2019a) describes the situation derived from the new specifications for marine fuels, established by the International Maritime Organization (IMO), and which began to apply from January 2020.

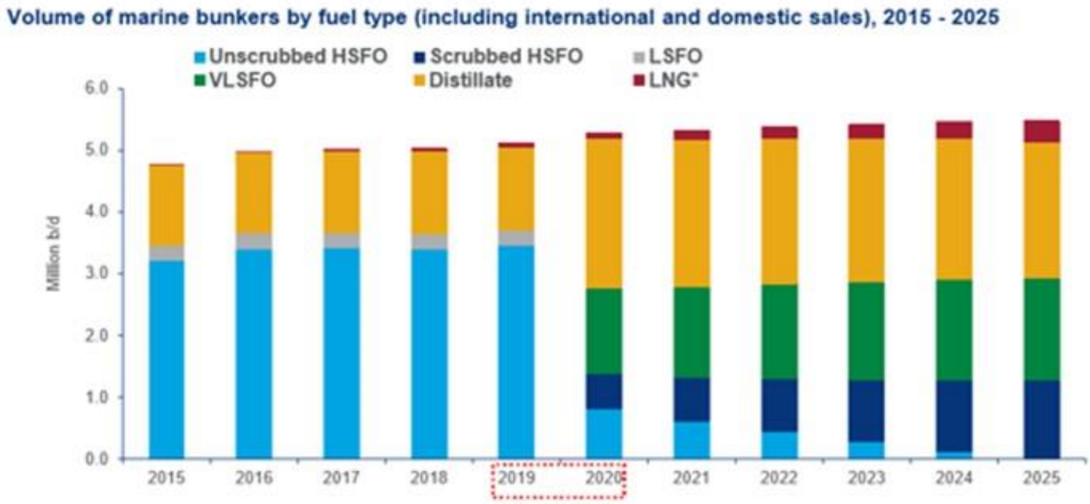
Figure 5: Evolution of sulfur content in marine fuels in accordance with international regulations



Source: Wood Mackenzie (2019a)

As can be seen in Figure 5, there is an 85% reduction in the sulfur content of the IMO specifications, which began to apply in January 2020. The impact of these IMO specifications in the demand for Marine Fuels can be seen in Figure 6.

Figure 6: Impact of the new IMO specifications on the global demand for marine fuels



Source: Wood Mackenzie (2019a)

In the first place, it is necessary to highlight that the global demand for marine fuels is between 4.5 and 5 million barrels per day, which means about 5% of the total demand for petroleum derivatives (which is around 90 million barrels per day).

It can be seen in Figure 6 that the demand for High sulfur Fuel Oil (HSFO) is reduced as of 2015 and by 2024 it is projected that it will be practically nil. At the same time, it is clearly seen that the demand for marine fuel with low sulfur content is progressively increasing, such as the so-called: Vacuum Low sulfur Fuel Oil (VLSFO); the High sulfur Fuel Oil with countercurrent washing, (Scrubbed HSFO), the Low sulfur Fuel Oil (LSFO) and the distillates (Distillate).

The interesting thing about the data that appears in this graph is that *as of 2015 a demand of almost 100,000 BOE/day for LNG as marine fuel begins to appear*. And the demand projection indicates a growing use of LNG as a Bunker. Indeed, this projection is confirmed later in this study, since it is possible to see the various LNG-fueled ship manufacturing projects, both completed and in progress. As will be seen, the demand for LNG Bunker is projected to reach 9 million tons per year in 2025, and 35 million tons per year in 2035.

Likewise, a study was recently published by the classification society Det Norske Veritas (DNV GL - Maritime, 2014), which focuses on the economic and environmental benefits of LNG as an alternative fuel for maritime transport and which reaches the following conclusions:

"LNG is currently a commercially viable fuel to be used in maritime transport."

"It can enable savings of 45% in total operating costs compared to those using standard heavy fuel oil and offers prospects for a 25% reduction in CO_2 emissions, complete elimination of sulfur emissions and close to 90% reduction in nitrous gases".

Below, the state of situation in which the use of alternative energy sources in river transport is found is analyzed.

4. The use of alternative energy sources in river transport

4.1. The structure of river transport

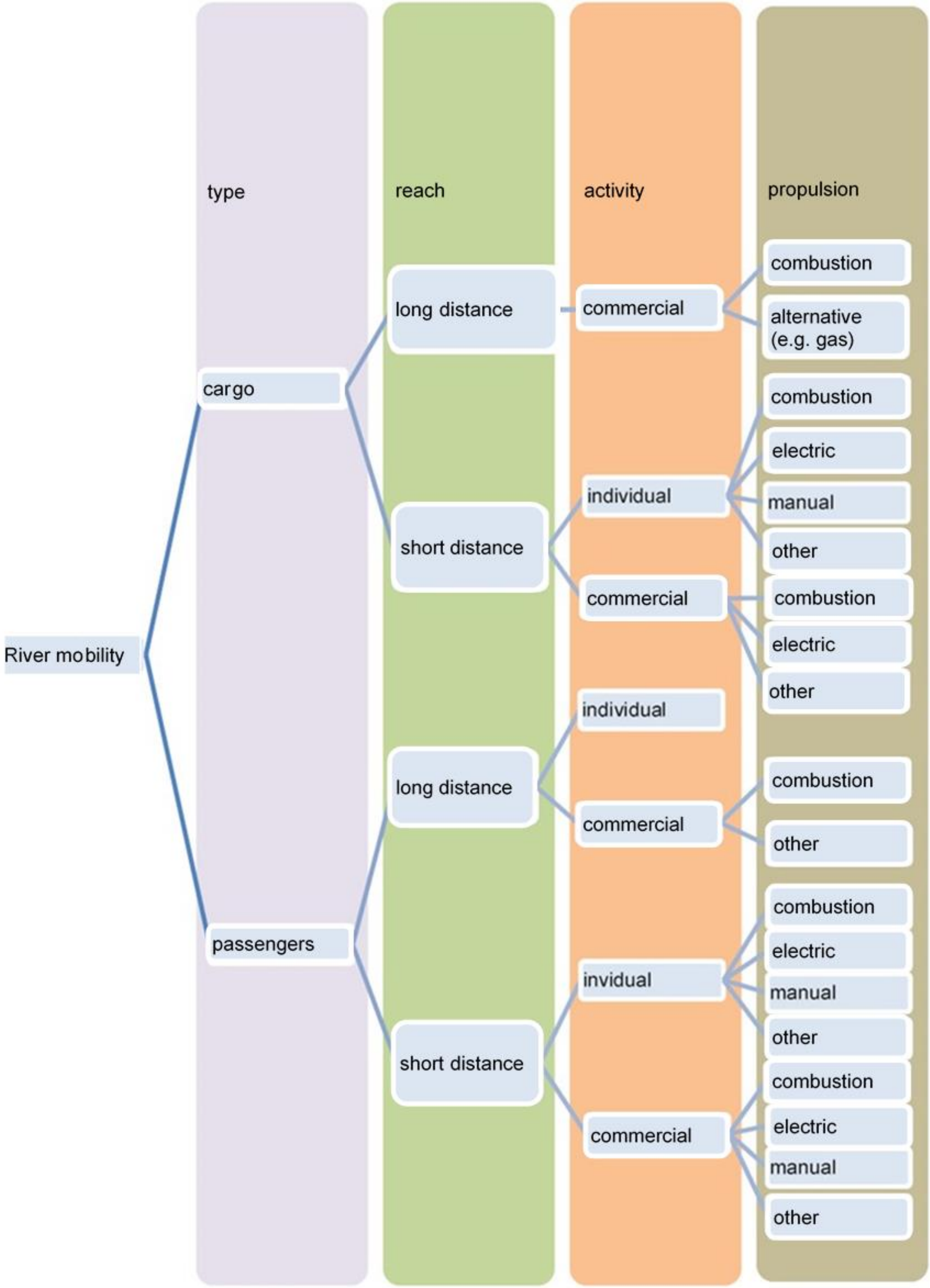
There are a number of subsystems that can be characterized and differentiated in river navigation by their different dimensions: passengers and goods, geographical scope, activity and type of propulsion (Jaimurzina and Wilmsmeier 2017). Figure 7 shows the complexity of the types of services according to the defined dimensions.

River navigation plays an important role in Latin America, although it is still underdeveloped in its scope, from local to international cabotage. Jaimurzina and Wilmsmeier (2017) highlight that "*in parts of the region, river navigation not only has an important capacity to transport cargo to and from production centers in the interior of the continent, it is also the only form of communication for a large part of the millions of citizens that inhabit it*." These authors also argue that inland navigation is "*a central component of identity, crucial to indigenous peoples regardless of their nationality, and an integration factor since the main rivers and hundreds of tributaries of different magnitudes penetrate the region through the thousands of kilometers of inland waterways*."

In the context of this work, the propulsion dimension plays a preponderant role in the discussion. Jairmurzina and Wilmsmeier (2017) differentiate some options, however, in this study the alternative fuel options such as LNG and LPG are omitted.

The need to consider the dimensions described above for the potential for technological adaptation should be highlighted. This potential also depends on the formality or informality present in each specific subsystem and the availability and openness of the actors towards change. The receptiveness towards change is defined by cultural differences, the level of training of the actors, economic or purchasing power, and previous experiences.

Figure 7: Inland navigation dimensions



Source: Jaimurzina and Wilmsmeier, 2017

4.2. Alternative energies in river transport

As already highlighted, river transport is perceived as a cleaner and more efficient mode of transport compared to other means. However, with some exceptions, as of today in

South America almost 100% depends on liquid petroleum-based fuels, mainly Marine Diesel, IFO 380 and, for smaller ships, gasoline. Recognizing the atmospheric pollution of these fuels, especially those with high sulfur content (esp. IFO 380), the International Maritime Organization (IMO) has pushed for stricter regulations for fuels in the seas and rivers.

Along with the search for more sustainable development and transportation systems, several alternative fuel options have been developed that can contribute significantly to reducing the carbon footprint of the shipping industry (Eide, et al., 2012). On the other hand, in the future the use of these fuels offers the potential to generate greater efficiencies and economic savings for the sector. However, the transition towards the use of alternative fuels is still yet emerging in the Southern Cone. Consequently, in order to face a process of transformation of the sector towards a more sustainable fuel use regime, it is necessary to evaluate and contrast global development with current realities in the region. Table 3 presents a list of alternative fuels that are part of the current discussions, defining the main pros and cons and determining the scope of application within the river sector.

Table 3: Summary of alternative fuels (see details in Annex 5).

Fuel	Positive	Negative
Low-sulfur fuels	Comply with current regulations; current availability	It is still a fossil fuel; availability
Methanol/biomethane	CEESA recommended fuel; dual fuel concept	Low flash point; toxic in contact with skin
Biodiesel	Dominant biofuel; can increase the flash point of other fuels when mixed, increasing safety	Degradation over time; Currently heavily dependent on palm oil
Renewable diesel derived from hydrogenation (HDRD)	Legally permitted to be used in existing vehicles and diesel infrastructure; good low temperature performance	Limited availability; only a few actors on the scoreboard
Algae biofuel	Potential to be produced on a large scale; safe like diesel	The current cost of fuel is prohibitive for general use; limited availability; lower calorific value
Liquified petroleum gas (LPG)	Available in the market; good supply infrastructure	Heavier than air; Danger of explosion; top quality product; little experience in use as marine fuel
Liquefied natural gas (LNG)	Available in the market; government support	Cost of adaptation; fuel storage volume; energy density 60% of diesel

Biomethane	Chemically identical to LNG. More environmentally friendly fuel for having zero net CO_2 emissions; better quality than fossil LNG	More expensive, competes with arable land for food
Electricity	More efficient than diesel in energy conversion; can be used to refuel ships during their stay in port reducing emissions at terminals (*cold ironings*)	Low energy density due to dependence on on-board electricity or on-board battery storage; high capital cost (batteries)
Hydrogen	Best storage energy-to-weight ratio of all fuels	Commercial engines not available and under development; fuel could be expensive to produce, transport and store

Source: Various authors, adapted.

Throughout this work, the focus has been placed on LNG and the options for the use of electricity and hydrogen as alternative fuels will be discussed in less detail, since they are not commercially mature technologies and currently are not widespread in river applications. However, they could be potentially promising in a few years.

5. LNG as an alternative fuel

5.1. Marine engines and alternative fuels

Today, the vast majority of ships use diesel engines similar in principle to those in cars, trucks and locomotives. However, marine fuels are different in many ways. The viscosity of marine fuels is generally much higher - up to 700 cSt, while highway diesel fuel rarely exceeds 5 cSt. The quality of fuels for marine use is generally much lower and the quality band is much wider than that of fuels used in land transport.

Therefore, marine engines must accept many different fuel grades, often with high sulfur levels that would seriously impair the function of exhaust gas recirculation (EGR) and catalyst systems in automobile engines (McGill et al., 2013).

Different fuels with different autoignition temperatures require different types of engines. The following fuels work in diesel engines (Florentinus et al., 2012):

Biodiesel, vegetable oil, DME (dimethyl ether), LPG (gas to liquid), biofuel and hydrogen-treated vegetable oil. The compression ratio is much lower (typically 1:11) compared to 1:20 for compression ignition (Diesel).

The following fuels work in Otto engines (Florentinus et al., 2012): Gasoline, ethanol, methanol, natural gas (LNG); Biomethane (both in compressed form (CNG) and in liquid form (LNG)); Hydrogen marine engines have a typical proven service life ranging from 10 years (for high-speed) to over 20 years for low-speed engines.

The robust technology even allows them to operate for up to 50 years with proper maintenance. Different fuels in the same engine type only need relatively minor adjustments in terms of fuel lines, filters, and injectors.

However, converting a diesel engine to Otto requires major adjustments and large parts of the engine need to be rebuilt. Therefore, engine manufacturers play an important role in the introduction of alternative fuels, as they provide the guarantee that engines will run on fuels with specific properties (Florentinus et al., 2012). MAN B&W already offers a low-speed marine gas engine and Rolls Royce has a medium-speed marine gas engine that meets Tier III NOx limits that went into effect in 2016 (McGill et al., 2013).

MAN also confirms the viability of using liquid biofuels in their MAN medium-speed diesel engines, originally designed for heavy fuel oils (Florentinus et al., 2012).

5.1.1. Impact on reducing emissions

LNG contributes significantly to the reduction of emissions of SOx, NOx, particulate matter (PM) compared to traditional fuels. However, CO_2 reduction can vary. It is important to note that in this Technical Report a complete life cycle analysis was not performed to determine the greenhouse gas emissions associated with the use of the fuel alternatives that were evaluated.

CO_2 savings are lower than could expected based on energy content when the engine type needs to be changed from Diesel to Otto; for example, when switching from diesel to CNG, LNG, ethanol or hydrogen. Marine diesel engines are approximately 30% more efficient than Otto engines, due to their higher compression ratio.

Switching from diesel to compressed natural gas (CNG) (Otto) results in a combined emission reduction of 10 - 15% of CO_2: when gasoline and diesel are burned simultaneously in a Diesel engine, the CO_2 savings are as high as can be expected based on energy content. This technology involves two fuel systems on the ship.

Typically, a small amount of marine fuel oil is used as a pilot fuel to initiate the ignition process, followed by combustion of the selected alternative fuel. The ship can run on a variable combination of the available fuels (DNV GL - Maritime, 2014). For example, a variation from 100% diesel up to 97% LNG and 3% diesel is possible, resulting in high CO_2 savings and high variable cost savings.

As an example, the following comparisons can be made:

The LNG vs. Diesel Comparison:

- CO_2 reduction up to 25% (in case of zero *methane slip*[1])
- PM reduction up to 100%
- NOx reduction up to 90%
- SOx reduction up to 95%

The comparison of LNG with LPG (liquefied petroleum gas)

- GHG emissions reduction up to 15%
- PM reduction up to 10%
- NOx reduction up to 50%

It is important to consider that the use of LNG reduces greenhouse gas (GHG) emissions by around a quarter compared to Marine Diesel Oil (MDO), commonly known as marine gas oil, or heavy gas oil (HFO). However, higher emissions from the LNG supply chain and unburned methane from the ship's engine can actually negate GHG gains.

At present, low-pressure LNG engines based on the dual-fuel Otto cycle represent the cheapest option in terms of Capex to comply with regulations such as the energy efficiency requirements of the *Energy Efficiency Design Index* (EEDI). However, these low-pressure LNG options must take precautions to avoid methane emissions (*methane boiling off*) that generate GHGs.

Using as an example a 183 m long medium range (marine) tanker with a 37,000-ton design, of which there are approximately 1,500 worldwide, the best LNG technology available - dual fuel high pressure engines operating on the diesel principle - meets all regulatory requirements at a cost of about $ 9-10 million. However, the cheapest option, the low-pressure Otto cycle, only costs about $ 5 million. Thus, the conversion costs of LNG-powered ships must consider the best technology including the investment necessary to “eliminate” *methane slip* throughout the value chain. The use of bio methane generates performance improvements in relation to additional CO_2 emissions.

Alternative fuels that have the potential to reduce emissions below required levels may play an important role in the future as substitutes for HFO and MDO. Both the demand for low-sulfur fuels and the need to reduce greenhouse gas emissions can be addressed

[1]*Methane slip* is methane that is not burned in the engine's combustion chamber and escapes into the atmosphere through the engine's exhaust. Its presence mitigates the benefits of LNG use due to the emissions it produces.

by introducing low-carbon alternative fuels, provided that these fuels and the necessary technology are offered at competitive prices.

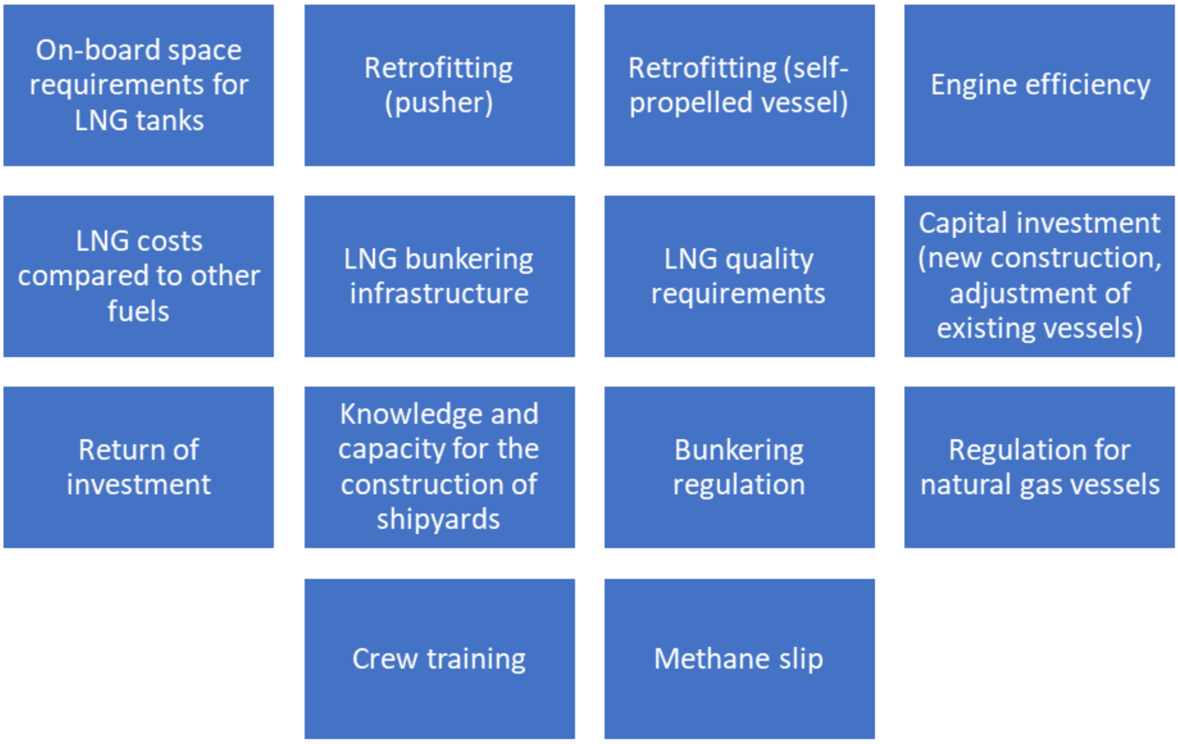
Other fuels that could play a role in the future are liquefied petroleum gas (LPG), dimethyl ether (DME), biomethane, synthetic fuels, hydrogen (especially for its use in fuel cells), renewable diesel derived from hydrogenation (HDRD) and pyrolysis oil, and other fuels such as low sulfur diesel (ULSD) that can be used to comply with regulations.

5.1.2. Barriers to the implementation

The implementation of a new fuel in inland waterways carries significant technical, financial, legal, and training barriers. The most important aspects are financial, followed by technical ones. One barrier from an environmental point of view is the *methane slip*. However, there are no logistical barriers among the barriers.

Capital investment is the aspect that most influences the implementation of LNG in river navigation in the near future, but also adaptation aspects, the costs of LNG compared to other fuels and the return on investment are important points for the introduction of LNG. It is important to highlight that this transition requires the collaboration of multiple actors from the public and private sectors.

***Figure 8**: Mosaic of barriers to the implementation of LNG as a fuel in inland navigation*



Source: Compiled by authors

Each of the barriers will be discussed in more detail in the following subsections.

Tank space requirement for new construction and ship adaptation

The size of the fuel tanks in the ships directly affects the productivity of the ships because it limits the volume or weight of the cargo to be transported. LNG has a volume 1.8 times greater than diesel, and if the entire LNG engine system and the cylindrical-shaped fuel tank are included on board, the space required is even three or four times greater than the conventional petroleum system. This especially impacts the adaptation of existing ships, whose design does not consider tanks of this type and size. In new ships, modern designs allow different options of locating the tank. For example, it is possible to place the LNG tank vertically in the heart of the ship (center of gravity), in such a way that this aspect presents a compromise relationship between cost reduction, the impact on the environment and the economic performance of the ship.

Retrofitting (pusher)

Only part of the existing ship fleet is suitable for retrofitting with LNG. For some ships it is not possible to install an LNG tank due to space restrictions (see previous item). Therefore, depending on the type of ship and the operation, an adaptation may be feasible, but is not expected to become a major activity. The other problem is that the cost of adaptation can even be higher than in the case of new constructions. It is assumed that the potential for adaptation to LNG of existing pushers is limited, because they do not have enough space to install a larger volume LNG tank than those already installed. Since the ships on the waterways navigate long distances and remote areas with few options for refueling, these ships require a large storage capacity. The key problem in this case is finding space for the fuel tank, since for stability reasons it must be placed in the gravitational center of the ship where the engine room is usually located. The probability that this issue will be resolved for existing ships is low, so LNG as a fuel will be driven for the most part by new constructions.

Retrofitting (Self-propelled vessel)

In line with the previous items, only a part of the existing fleet of ships is suitable for retrofitting for LNG, and it is difficult to generalize the potential due to the high variety in the fleets, in such a way that an individual evaluation of each ship is required. The potential for adaptation will depend on the age and length of the ship, as well as the type of construction of the ship. Tankers and container ships are beneficial for tank storage, although the additional weight of the LNG tank will decrease the net cargo of the ship. However, beyond the issue of space, the challenge of the cost of adaptation prevails, which is higher than in the case of new constructions.

Gas engine efficiency

The efficiencies of LNG fueled marine engines are good. They can be classified into three groups: (i) Lean Burn Spark Ignited (LBSI) engines (LBSI) and dual-fuel engines (DF); (ii) high pressure gas injection (300-350 bar) and (iii) low pressure gas injection. High pressure gas injection engines are not used in waterway ships. Therefore, in Lean Burn

Spark Ignited (LBSI) engines and in low pressure gas injection engines the thermal efficiency is very high at full load and low at partial load. However, gas-electric propulsion, such as that installed in new ships, does not carry the problem of efficiency under partial load.

Quality requirements for LNG

The quality of LNG, like that of any fuel in an open fuel market, can vary. The methane number is the parameter used to quantify the knocking tendency of a gas and is especially relevant when using natural gas as motor fuel. It is generally recognized that knocking problems are avoided in facilities with a methane index greater than 75 - 80. For cogeneration applications, engine characteristics are specified for gases with a methane index greater than 65 - 75. When the methane index is between 55 and 65, it is recommended to take measures to prevent the engine from knocking. For a methane index lower than 55, the best option is to take the engine out of service.

LNG refueling infrastructure

A critical challenge for the development of LNG as a ship fuel is the current lack of fueling infrastructure and established distribution networks for the supply of LNG to waterway ships. In Europe, the Directive 2014/94/EU regulates that countries must provide LNG refueling stations until December 31, 2030. However, there is currently no strategy in the waterways to develop a supply network and the corresponding infrastructures in the rivers. An interesting document is the LNG Master Plan for river navigation in Europe. Today there are four LNG bunker stations on the river Rhine. Today the most common supply is truck-to-ship fuel supply (e.g., ports of Rotterdam, Amsterdam, Mannheim). Another option is ship-to-ship refueling2.

Cost of LNG compared to other fuels

From the perspective of the logistics operator, the price of LNG is not the most important factor, but the price is relative to the alternatives; that is, the comparison with the MDO or HFO, etc. The retail price of LNG for end users is not the same as the price for large LNG suppliers. The price is mainly related to the costs of extraction, liquefaction and large-scale transportation. To this price must be added the specific cost of small-scale distribution (for example, the cost of transportation to stations, bunker solutions, service stations or other supply systems). For inland waterway fleet operators, fuel costs represent a significant part of annual operating costs.

The fuel costs of a waterway ship easily represent more than 40% of the total annual costs. The prices of the different fuels show a wide variation. The relative differences, taking the MDO as a reference, between the fuels can be the following[3]:

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[2]For details see http://www.lnggot.com/tags/lng-bunkering/ (concept under approval by DNV).

[3]Note: this table is for reference purposes. It is to be expected that there is a high geographical and temporal variability.

Table 4: Relative differences between fossil fuels

Fuel Type	***Max***	***Average***	***min***
MDO	100	100	100
LSFO	63%	70%	73%
HFSO	58%	67%	70%
LNG	48%	52%	58%

Source: Compiled by authors

Unlike diesel, the quantity of LNG is expressed in kilograms and not in liters. Several studies show that LNG is an economically interesting alternative to diesel, when the ship's annual diesel consumption is around 500,000 l (425 tons) per year. Supply and logistics costs must always be added to these prices.

Capital Investments

As already stated, it is possible to convert diesel engines to use LNG as a substitute fuel or to replace the old diesel engine with a gasoline or dual fuel engine. The investment depends on the power of the engine and the size and type of the ship. An investment of approximately 1.2 million euros can be assumed for the entire LNG system for a waterway ship in the European case (as of 2018). This includes the costs of the engine, a tank system, and LNG preparation equipment such as the cold box and installation. Operating costs depend on the evolution of LNG prices, the fuel contract and the general energy consumption of the ship on its route. Due to the high investment, it is better to install the LNG on board of larger ships with high energy/fuel consumption.

The investment costs related to the machinery of an inland waterway LNG ship are higher than the investment costs related to the machinery of a diesel ship for river navigation. This is partly due to the higher material costs (esp. The LNG tank), the greater safety requirements that must be respected and the low market integration (absence of economies of scale). In relation to the last point, it is also important to highlight that the knowledge in the shipyards of the region for these types of machinery is still limited. Thus, to address this barrier, it will also be necessary to work on updating the knowledge in shipbuilding in the countries of the Southern Cone.

Given these high costs, the probability that an operator adopts this technology depends significantly on the market in which it is operating. According to European studies, the LNG technology could be economically viable for new ships that sail more than 5,000 engine hours per year, in which case the payback time would be around five years, over an alleged price advantage of 20% of LNG compared to with diesel.

As with all fuels, the sailing range of an LNG-fueled ship depends on the capacity of the fuel storage tank. For example, the EIGER-NORDWAND ship has a fuel storage tank with a capacity of 60 m3, which allows the ship to sail from Rotterdam to Basel and vice versa (approximately 1,700 km) without the need to refuel.

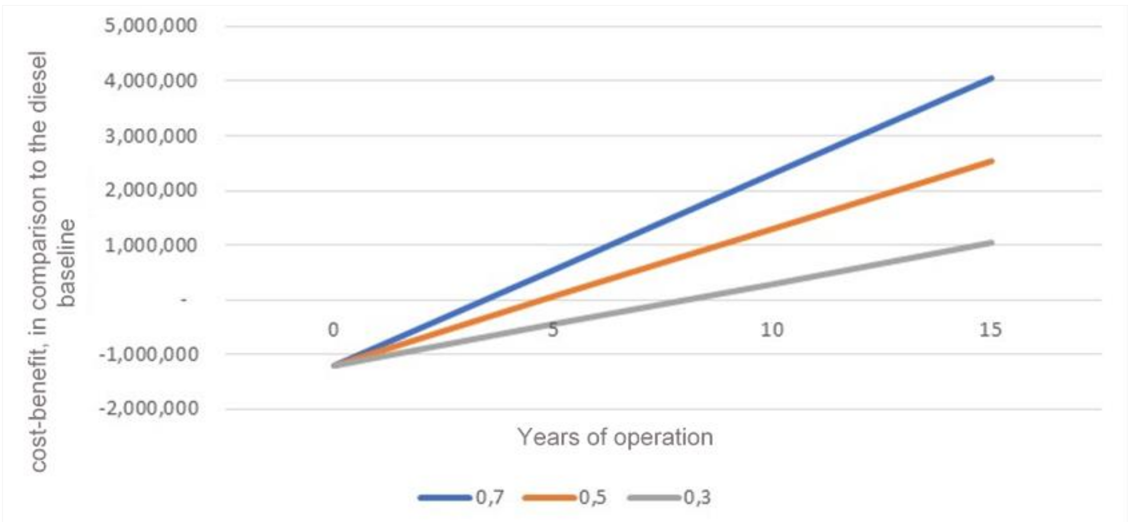
This question is important for the region under study, since the ships usually travel long distances. However, restrictions on 24/7 sailing could limit the attractiveness of the conversion. Consequently, the most relevant factor to promote investments in LNG rests on economic considerations, beyond the inherent environmental benefits.

In this context, it is important to highlight the possibility that dual fuel solutions with 80% LNG and 20% diesel as a combination of fuels allow savings of at least 20% in fuel costs compared to conventional diesel engines. This generates benefits that compensate greater investments in LNG technology and, in particular, investments in fuel tanks and the engine. However, it can only be considered a "bridge solution" because it obviously has limited positive impacts in environmental terms.

Return of Investment

The level of fuel consumption is crucial as it influences the payback time required to recover the high investment costs. Payback times (for additional investment costs) for dual-fuel propulsion are in the range of 4 to > 10 years, depending on operating hours and average power at a LNG price of 80% diesel. It can take up to 15 years for 100 percent LNG solutions, depending on the price difference. The return on investment depends, on the one hand, on capital investment costs and, on the other, on fuel cost savings. Small boats with fewer operating hours have less fuel economy than pushers with very high fuel costs due to their intensive use.

Figure 9: Return on investment - gas price scenarios (Euro / m³)



Note: considering a consumption of 500 thousand m³ per year

Source: EICB (2017).

Figure 9 emphasizes that the attractiveness of adapting to LNG is highly correlated with the difference in prices of different fuels and not the price level itself.

Regulation on fuel supply

The supply of LNG is not yet regulated. For example, there are no standards for the following points: (i) definition of the LNG fuel supply process, (ii) LNG fuel supply procedures, (iii) interfaces between the LNG ship and the facility, (iv) LNG fuel supply port operations, (v) LNG fuel supply safety distances, (vi) LNG fuel supply risk assessment and risk acceptance criteria, (vii) LNG fuel supply during loading/unloading and embarkation/disembarkation of passengers, (viii) emergency plans related to the LNG fuel supply. However, there are good references to LNG use projects in the region, such as the Buquebus that transports passengers between Argentina and Uruguay.

Regulation of gas ships

The IGF code (IMO MSC 391 (95)) has been in force since January 2017 for ships that use LNG. Phase 2, in development until 2021, is dedicated to fuel cells (*methyl* and *ethyl*) and will enter into force only in 2024. The IGF code establishes the guide for the respective technological installation. However, there are no specific regulations for river navigation, so the temporary solution is to use the IGF code or the rules of the certifiers (DNV, Lloyd's, BV, GL), which are based on IMO regulations.

Crew training Gas tanker/gas-propelled ship

The transport of LNG in tankers is not regulated, as is the use of LNG as fuel for waterway ships. A very significant development is that the International Society of Gas Operators for Tankers and Terminals (SIGTTO) has created a new organization - the Society for Gas as Marine Fuel (SGMF) - that focuses on natural gas maritime transport industry. This will greatly contribute to the standards of the crew and those involved in the safe handling of gas.

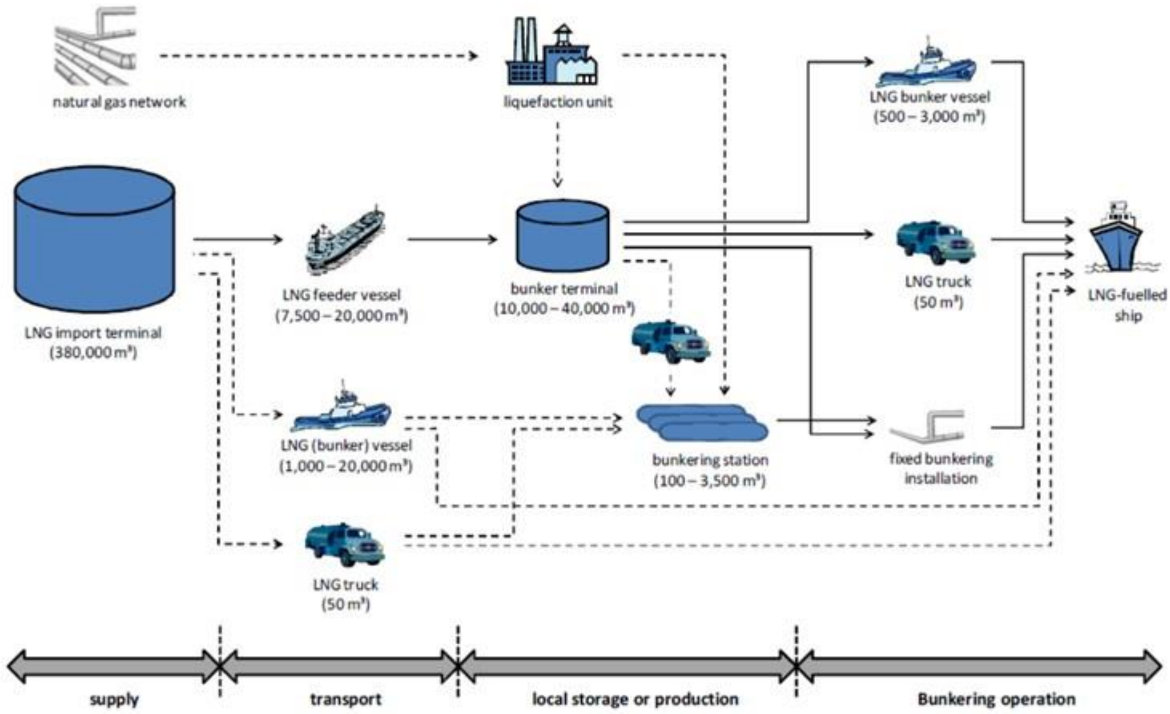
Methane slip

Methane leakage is called *methane slip*. The GHG balance from the use of LNG is advantageous only if this slippage can be considerably limited compared to the use of heavy fuel oil or diesel. Indeed, the combustion of methane causes about 28 percent less CO_2 compared to diesel, although this is a theoretical technological potential. To maximize the reduction of greenhouse gas emissions with the use of LNG, it is necessary to minimize methane slippage from engines. LNG is highly compressed and cooled to -162 °C and has about one sixth the volume of gaseous natural gas. Gas combustion in conventional or dual-fuel engines tends to generate methane slip, which can be minimized by demanding control. There are solutions to reduce *methane slip* with specific catalysts.

LNG supply practices

As seen in Figure 10, LNG supply operations are characterized by the interaction of multiple stakeholders and different regulatory contexts. This poses a challenge on different levels.

Figure 10: Schematic representation of LNG bunkering practices



Source: EMSA (2018).

The next chapter develops this topic in more detail. It is worth commenting here that the European Maritime Safety Agency (EMSA) published a reference guide on LNG bunkering (see EMSA, 2018), which in combination with the LNG Master Plan[4] for river navigation establishes a good basis to develop a strategy for the countries participating in the Waterway.

5.1.3. Relevant examples of LNG-fueled ships

While LNG carriers, LNG terminals, truck loading facilities and fueling infrastructure represent the "supply" and sourcing side of the regional LNG fuel market, ships and vessels propelled by LNG represent the "demand" side. There is currently no significant fleet of LNG-fueled ships in the region under study.

[4]For more details see: http://www.lngmasterplan.eu/

The "pioneers" of LNG propulsion have been ships, transporters, service vessels, push boats, harbor ships and patrol ships in Norway. A pioneering case of the use of LNG-fueled ships in South America has been the Buquebus company.

Box 1: Francisco catamaran ferry

Francisco is a high speed catamaran ferry built in 2012 by the Incat shipyard in Tasmania. It was acquired by Buquebus to operate the international route that connects Buenos Aires with Montevideo, navigating the Río de la Plata.

Wärtsilä manufactured the two axial hydrojets that power the ferry. The system was designed to be installed inside the stern, thus saving space. The propulsion system controls the steering angle, rudder position, and impeller speed; It can be operated alternatively with joystick control or on autopilot.

It has the capacity to transport 1,000 passengers and 150 vehicles.

Source: For more details see*: https://www.motorship.com/news101/ships-and-shipyards/lng-fuelled-catamaran-pushes-frontiers-in-ferry-powering*

While the deployment of LNG-fueled ships is focused on ships operating in geographically restricted areas, an expansion in use can be observed in recent years.

The development of the fleet was driven by the establishment of emission control zones (ECAS; emission control areas) in the North Sea, the Baltic Sea, North America and the US Caribbean. USA, and the introduction of NOx Cap Level III for newly built ships in the North American/Caribbean export credit agencies of the United States.

Globally, 47 LNG-fueled maritime ships entered into operation in 2017-18, bringing the total number of LNG-fueled ships in operation to 143. These new ships include the world's first two LNG dredgers, the world's first container ship (also for exploitation in Northern Europe), the world's first LNG cruise ship (the Aida Nova), the world's first LNG shuttle to operate in the Mediterranean, and the first LNG cargo ship in Asia.

In the context of river navigation, a good example is the Rhine-Danube, where the first concerted efforts emerge from 2013 with the LNG Master Plan for the Danube. This plan defines goals for the development of the LNG-fueled fleet[5]. In 2016, six LNG-fueled ships were in operation.

[5]See: https://www.prodanube.eu/download-pdi?layout=edit&id=127

Table 5: Examples of LNG-fueled ships in Europe

NAME	ARGONON	GREENSTREAM AND GREENRHINE	EIGER NORDWAND	SIROCCO	ECOLINER
TYPE	Tanker type C (chemicals)	Tanker type C (chemicals)	Container coupled convoy	Tanker type G (LPG-tanker)	Tanker
ENI NUMBER	02334277	02335315/02335378	02324957 (Eiger) / 02326710 (Nordwand)	02335784O	02336631
OWNER	Argonon Shipping BV, Zwijndrecht	CV NFT I-Tanker 1, IJsselmuidenC.V. NFT I-Tanker 2, IJsselmuiden	Danser Switzerland, Basel	Chemgas Barging S.a.r.l., Luxemburg	QaGroup, Netherlands
YEAR OF CONSTRUCTION	2011	2013	2000 (retrofit 2014)	2013	2015
LENGTH	110m	110m	104.92m (Eiger) + 73.45m (Nordwand)	110m	110m
BEAM	16.2m	11.44m	11.45m	11.4m	11.5
DRAFT	5.13m	3.46m	2.55m (Eiger) + 2.29m (Nordwand)	2.7m	3.6m
BOWING	6100 ton	2877 ton	5300 ton/348 TEU	1692	3100
ENGINE	Engine: 2 x Caterpillar 3512 (B) DI-TA electronic, 1119 kW, 1600 rpm	4 x Scania SGI-16M gas generator sets, 285 kWe	2 x Wärtsilä 6L20 DF, 900 kW	2 x Wärtsilä 6L20 DF, 900 kW LNG-application	4 x Stamford with gas engine, 280 kW
LNG APPLICATION	Dual fuel (80% LNG and 20% diesel)	LNG Electric	Dual fuel (99% LNG and 1% diesel)	Dual fuel (99% LNG and 1% diesel)	LNG Electric

Sources: Vlootschouw, Vereniging De Binnenvaart, Weekblad Schuttevaer, Argonon Shipping, Interstream Barging, Danser Group, Chemgas, Sandfirden and Damen

In 2011, Argonon was the first waterway ship to start sailing on LNG. It is a tanker that operates predominantly in the ports of Rotterdam and Antwerp.

The first LNG ships for river navigation were the sister ships Greenstream and Green Rhine, which are commissioned by Interstream and sail for Shell on a trajectory between Basel and Rotterdam. Sirocco is a dual fuel tanker commissioned by Chemgas Shipping that carries out the transport of LPG in the Rhine area.

Here are some recent examples of gas-fueled ships on inland waterways.

Figure 11: 3 Examples of LNG ships for inland navigation and their technical characteristics

MS EIGER-NORDWAND RETROFIT

Operator: DCL Barge B.V.
Location: Netherlands, Rhine
Organisers: DCL Barge, Koedood, Wärtsilä
In operation: 2014

ⓘ www.danser.nl

Vessel type: inland container vessel
ENI: 02324957
Vessel size: 105 × 11.45 m (L × W), Draught (max): 3.55 m
Propulsion: 2 dual-fuel Wärtsilä 6L20DF, 900 kW each at 1,200 rpm
Tank capacity (LNG): 60 m³ (gross) sufficient for the roundtrip Rotterdam - Basel
LNG tank: Vacuum-insulated double-wall pressurised tank IMO type C
Benefits: fuel consumption reduction by approximately 20 %

MS SIROCCO

Operator: Chemgas Barging s.a.r.l
Location: Luxemburg, Rhine
Organisers: Chemgas Barging
In operation: 2015

ⓘ www.chemgas.nl

Vessel type: LNG-fuelled type G tanker
ENI: 02324789
Vessel size: 110 × 11.40 m (L × W), Draught (max): 3.15 m
Propulsion: Single 8L20DF Wärtsilä main engine capable of running on LNG & marine gasoil
Tank capacity (LNG): 88 m³ (gross)
LNG tank: Single wall independent vacuum-insulated pressure tank with design pressure of 10 bar

RPG BRISTOL
RPG STUTTGART
RPG STOCKHOLM

Operator: Shell Trading BV
Location: Netherlands, Rhine
Organisers: Plouvier Transport NV/ Intertrans Tankschiffahrt AG
In operation: 2017

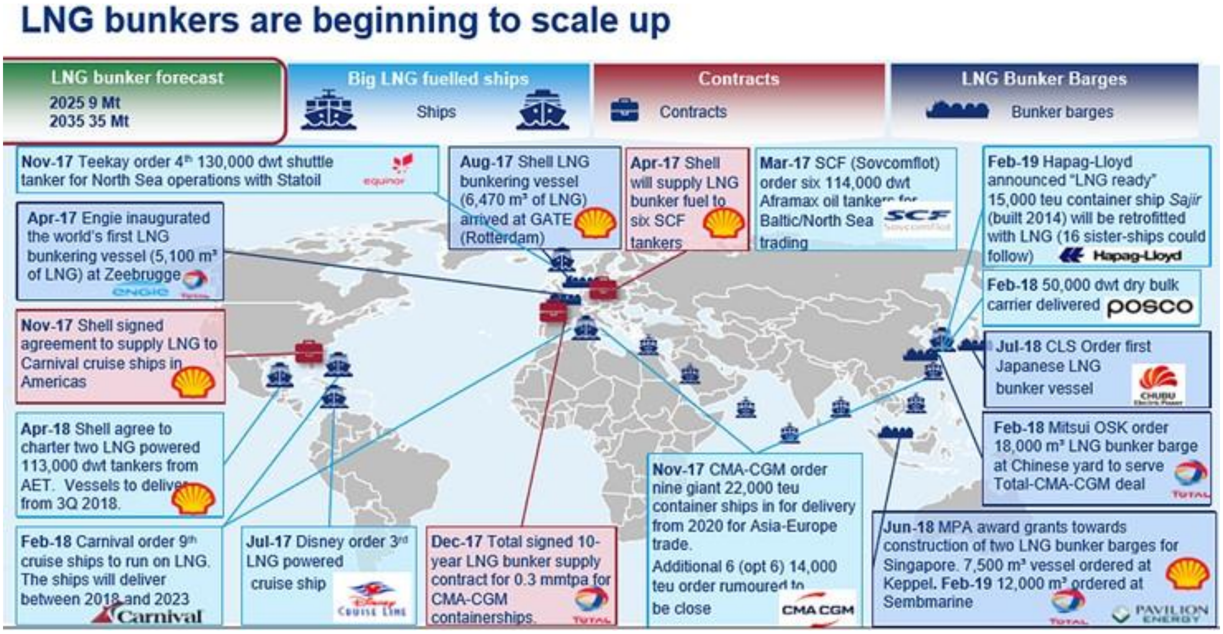
ⓘ www.plouvier.be

Vessel type: LNG-fuelled type C tanker
ENI: 02337327
Vessel size: 110 × 11.4 m (L × W), Draught (max): 3.21 m
Propulsion: Wärtsilä 6L20 DF dual fuel engine , 1100 kW
Bunker capacity (LNG): 60 m³
LNG tank: Wärtsilä LNGPac

Source: www.plouvier.be

In addition to these examples in Figure 12, some other relevant cases are presented.

Figure 12: LNG bunker has started to grow



Source: Wood Mackenzie (2019a)

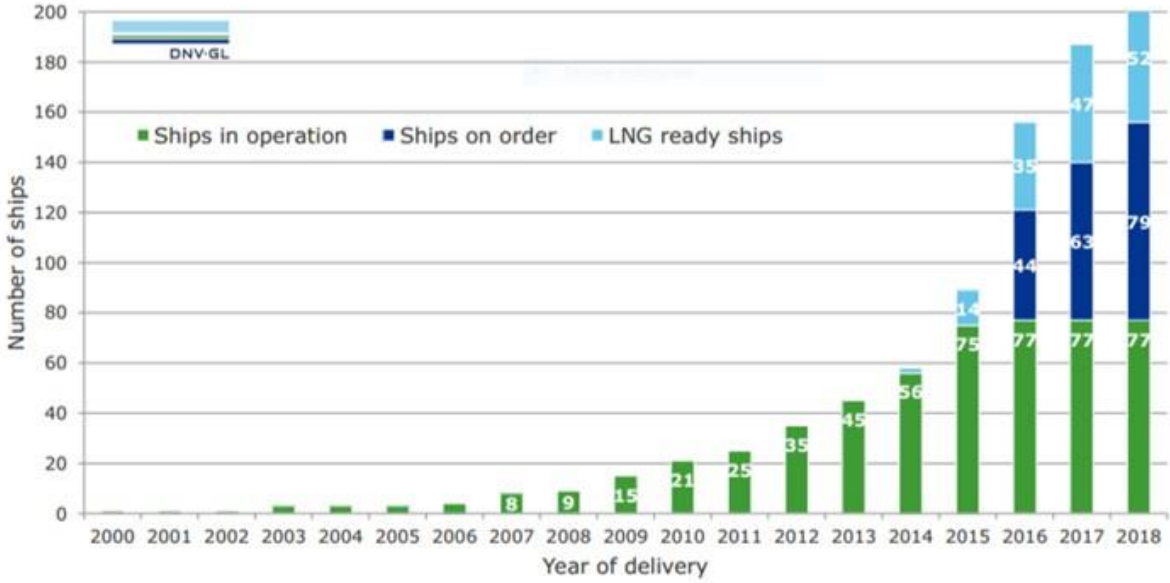
Likewise, it is worth noting that ***Hapag Lloyd's* 15,000 TEU MV Sajir** ship will be prepared to operate with LNG, after the *MAN Energy Solutions* company carries out the pertinent work, thanks to which it is expected to refuel the ship with a combination of LNG and heavy fuel oil. The refurbishment includes improvements to the current container ship engine, which will allow it to operate with dual functionality, combining heavy fuel oil and LNG, thus making the 15,000 TEU MV Sajir the first ship to receive these improvements. Following the conversion, *Hapag-Lloyd* will become the first shipping company to adapt a large container ship to gas propulsion.

Sajir will be the first of the fleet of 17 ships belonging to *Hapag Lloyd* that will be converted in order to reduce CO_2 emissions between 15% and 30%, as well as to reduce the emission of sulfur and other particles by at least 90%.

5.1.4. Recent evolution of the fleet and its characteristics

The global LNG fleet has seen significant growth in recent years, with even greater expansion than what was projected. In total, there are around 121 LNG-fueled ships in operation and the most significant types are car/passenger ferries and container supply ships. In addition to the examples already cited, some links to other relevant cases of LNG ships are shown in the bibliography.

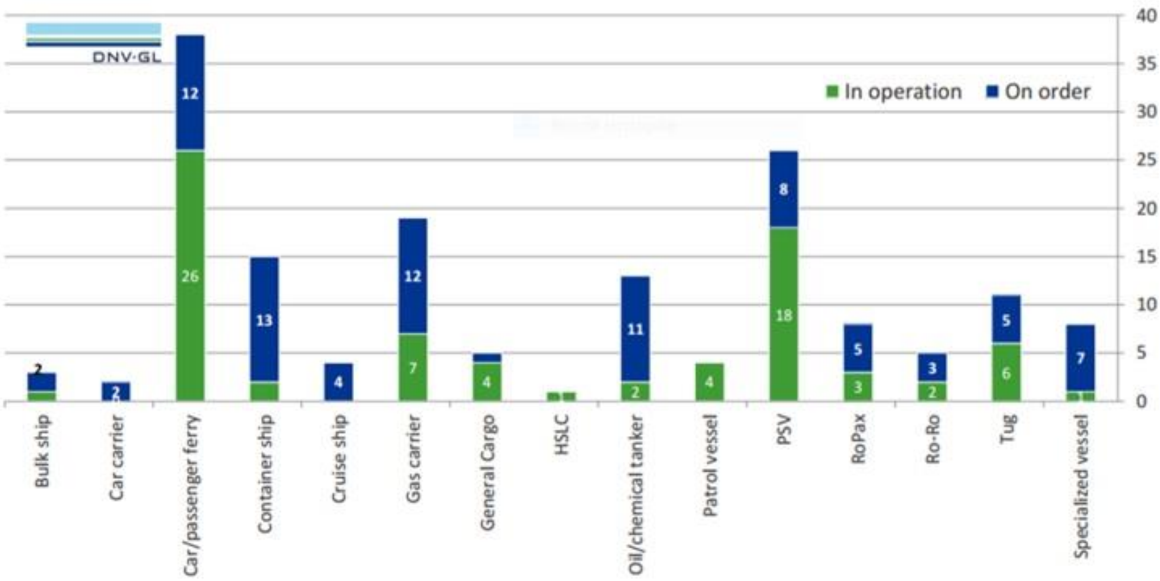
Figure 13: Ships transformed to LNG and in the manufacturing process



Source: DNV GL - Maritime (2014).

Since March 2016, 86% of the LNG-fueled fleet operates in Europe, with Norway being responsible for almost 70% of the fleet, as the Norwegian Parliament adopted, in 2006, a fiscal policy on NOX emissions, as well as a NOX fund, created to assist in the design and construction of alternatives. However, the situation is changing considerably as, due to the adoption of ECT regulations, Europe and the United States are responsible for 83% of the new confirmed LNG ship construction projects.

Figure 14: Ships converted to LNG (by type)



Source: DNV GL - Maritime (2014).

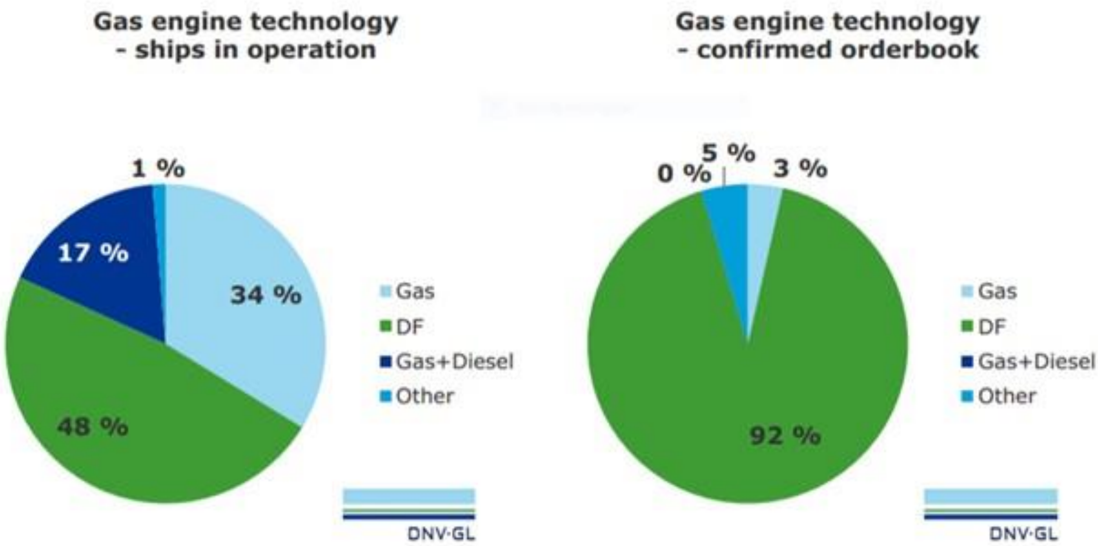
According to what can be seen in Figure 14, there are already 6 LNG-fueled push boats and 5 with construction order. About 300 push boats circulate on the Paraná - Paraguay waterway, and this precedent on a global level must be taken into account.

As an impulse for the replacement of Liquid Fuels with LNG, it is interesting to mention the Rio Paraná Sur Shipyard, which, with the contribution of the Employers' Center, proposes units fueled by LNG that imply savings of 68%. The Rio Paraná Sur shipyard (ARPS) has just been awarded a special mention in the 2019 Carlos Armero Sixto Award for its design for the construction of an LNG-fueled push tug.

A telephone conversation has been held with *Mr. Emiliano Paz, a member of the Board of Directors of said Shipyard*, who in addition to confirming the news has indicated that, although there are a couple of parties interested in building an LNG tug, they have doubts if there will be availability and logistics for supplying the new fuel, that reaches at least as far as the Port of Asunción.

Regarding the type of drive solution for each boat, dual engines are the most chosen for those under construction order, as can be seen in Figure 15. In addition, within the ships that are already operating there are a significant number that use Gas engines.

Figure 15: Technologies used in marine engines



Source: DNV GL - Maritime (2014).

5.1.5. Some general comments

Currently the use of LNG has become a technically viable option as an alternative fuel for river transport. We have seen that, while still emerging, a growing number of ships are being converted or from their own construction are being equipped with LNG propulsion systems. Despite the volatility of oil prices, this form of propulsion has an interesting acceptance in different types of ships. A good part of the responsibility for the consolidation of knowledge and the transferability of the experience of maritime transport to river navigation and from the regions with more experience in the subject (for example, in Europe and Asia) lies with the development agencies and the governments of the region.

However, technological diversity introduces in all cases an increase in the complexity of the systems. Furthermore, the low-flashpoint nature of LNG highlights concerns about the risk and safety of a fuel that is not only physically different from traditional petroleum fuels, but also brings additional operational challenges in relation to its transportation, provisioning and use.

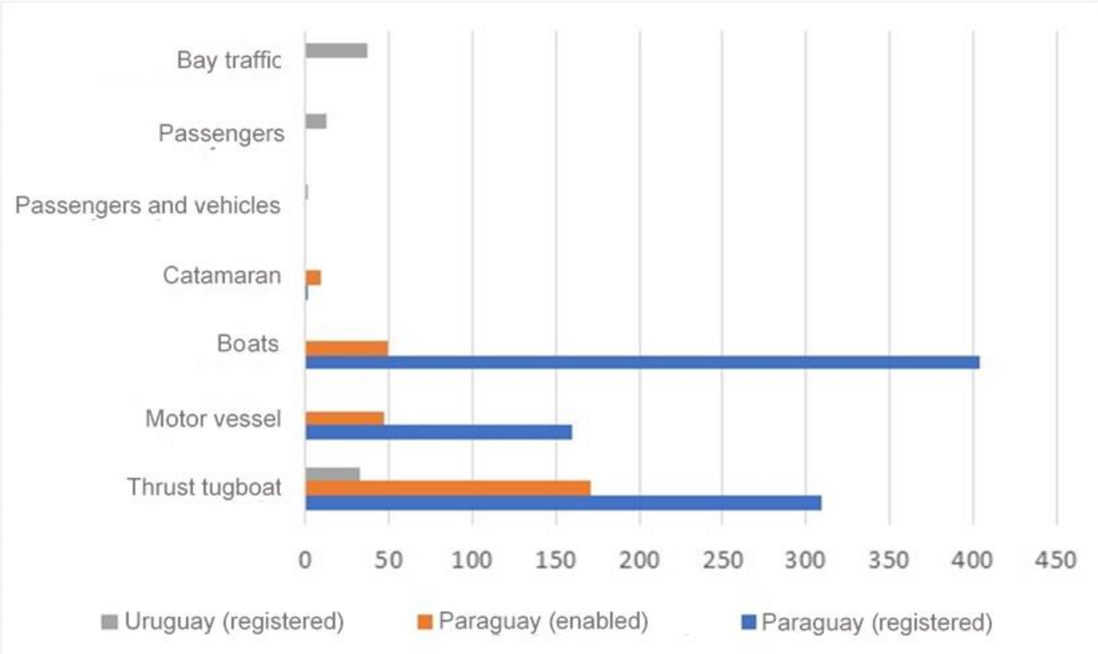
There is an International Code of Safety for Ships that use Gases or other Low-Flashpoint Fuels (IGF Code) since 2017[6], and also a regulatory framework of reference for inland waterways in Europe. The IGF Code contains mandatory regulations for the disposition, installation, control and surveillance of machinery, equipment and systems that use low-flashpoint fuels, initially focusing on LNG. The Code addresses all areas that need special consideration for the use of low-flashpoint fuels, adopting a goal-based approach, with objectives and functional requirements specified for each section that form the basis for design, construction and operation of the ships that use this type of fuel. A corresponding regulatory framework for river navigation in the study region has yet to be developed.

On the other hand, there is still no Strategic Plan or *Masterplan* (such as the one considered in Europe) for the development of the use of LNG in the navigation of the Waterway.

In order to establish a first estimate of the conversion demand potential in the region, Figure 16 summarizes the current river navigation fleet of Paraguay, Uruguay and Bolivia.

[6]For details see: http://www.imo.org/en/OurWork/Safety/SafetyTopics/Pages/IGF-Code.aspx

Figure 16: Self-propelled inland navigation fleet in Uruguay and Paraguay, number of ships by type



Source: ECLAC, 2017

First, the potential of the fleet to be converted is limited to self-propelled ships. The data show a significant difference between registered and licensed ships in the case of Paraguay. At first glance, more than 350 ships are identified to be analyzed in detail for their conversion potential. For this analysis, it was not possible to have information from Argentina since it was not available from public sources.

An important hypothesis when considering conversion potential is that LNG is not a suitable alternative to diesel in all types of ships. Therefore, it will be necessary to select the appropriate types of ships based on their characteristics and the most suitable types and models for which such conversion is economically feasible must be identified.

In previous studies, the potential fleet is selected based on the annual fuel consumption, which must be at least 500 m^3. This volume is taken as a threshold, considering calculations made in Europe to recover investment in LNG.

This threshold can be seen as the first and most important condition for investing in an LNG facility. Thus, in order to identify the ships that meet the requirement, it is necessary to identify the consumptions of the ships that operate on the Waterway. It is to be expected that long navigation distances will favor the conversion investment as the threshold is exceeded.

6. Other potential fuels

6.1. Biodiesel as a marine fuel

Brazil's National Agency for Petroleum, Natural Gas and Biofuels (ANP) held a public hearing in 2011 to discuss the experimental addition of biodiesel to diesel used in ships.

Currently, marine diesel in Brazil does not receive the addition of biodiesel in the proportion of 5% in conventional, as determined by law for land vehicles. However, the resolution under discussion only deals with the experimental use in research projects, and not with the commercialization of the biofuel. This means that the blending will be carried out only during the test periods defined and authorized by the ANP. A major concern is how the mineral diesel blending with biodiesel will behave in environments highly exposed to humidity. Biodiesel absorbs water from the air very easily, which could cause problems with ship engines. The ANP resolution requires that all tests record the negative effects caused by water contamination of fuel. No regulations have been identified in Argentina, Paraguay and Uruguay on the use of biodiesel in ships.

However, it is believed that in the near future the addition of Biodiesel in bunker fuels will be produced gradually, due to the restrictions on the sulfur content in the IMO specifications.

What is possible is that the pressure of environmentalists around the world guides the production of Biodiesel using, as raw material, vegetable oils whose production does not cause destruction of forests (as is currently happening in Indonesia with palm oil) and also towards vegetables such as rapeseed oil, whose emissions during production are lower than those of other types of oil. In addition, these types of oils do not interfere in the food chain, as happens with soybean, sunflower and corn oil. The main barrier to its use could be its high cost and sale price.

6.2. Electric vessels

Obviously, the use of electricity as a propulsion source for vessels substantially reduces the level of emissions compared to the use of fossil fuels, although this depends on the electricity generation system with which the batteries used are charged. If the electricity is generated by renewable sources (such as wind, photovoltaic or hydro-kinetic energy), the reduction in emissions of all gases is 100%.

In the case of electric vessels, the indication of power is expressed in kilowatts (kW). There are electric motors for ships from about 500W (for example, canoes) up to more than 750 kW (for example, ferries).

The efficiency of electric motors is significantly higher than in traditional combustion engines. This difference is more noticeable in small ships, where the overall efficiency of an outboard motor is between 5% to 15%, while this same efficiency for an electric outboard motor is between 30% to 56% (depending on the producer).

For electric propulsion, there are three variants of energy supply: (a) through a direct electricity generation system on board, for example photovoltaic; (b) through the use of batteries that are recharged during non-operating times (during the stay at the dock, for example), or (c) a combination of the previous variants.

Lithium-based batteries are currently the best option to generate the energy necessary to guarantee electric mobility since (i) they store much more energy than other batteries, (ii) they can work with high currents (a decisive advantage for electric motors), (iii) they do not lose capacity, (iv) they provide electrical energy reliably —even at low temperatures—, (v) they do not develop a "memory effect", (vi) they allow more cycles than lead-based batteries and, mainly, (vii) they have a reduced weight due to the physical characteristics of the non-metallic mineral.

The advantages of lithium batteries include:

- Very high energy density,
- Long lifespan
- Robust
- Highest quality and safety standards

The life span of a lithium battery depends on its age and, to a lesser extent, on the number of operating cycles. The annual capacity loss is 2 to 4% at an ambient temperature of 25 °C. The aging process is accelerated if the battery is exposed to high temperatures. Lithium batteries can be used at high ambient temperatures, but it is best to store them in a cool place whenever possible.

Today's batteries have a significantly lower energy density than gasoline or diesel. However, during the combustion process a considerable percentage of the energy stored in gasoline is dissipated, while electric motors drive the propellers more efficiently because their torque curve is more appropriate. On average, electric motors make use of the energy they receive up to 10 times more efficiently to propel propellers in water. The specific energy density of different energy carriers in Wh per kg can be compared as follows: 11,944 Wh/kg gasoline, 120Wh/kg lithium battery and 25Wh/kg lead battery.

However, when navigating with electric motors, considerably less energy is available than that of a combustion engine, so it is necessary to make the most of the limited energy available. Therefore, the overall efficiency that considers all losses, including those of the propeller, is the most important parameter to describe the performance of an electric propulsion system for ships.

Given the energy storage restrictions, the scope of application is mainly for short sailing distances. Some recent developments in the application of electric boats are described below.

Relevant examples of nautical electromobility in various parts of the world and for different applications can be found in Annex 3 of this document.

6.2.1. Some comments on electric propulsion

Almost all ferries of this size and with these trip characteristics (frequent and short crossings) are considered suitable for battery electric propulsion. In Norway, at least 80 other ferries on 60 different crossings are considered suitable for electrification.

The integrity of a battery power system poses particular challenges in terms of cost, production, life span, recycling, power supply, and type of power source used. Other aspects include the limited storage capacity and efficient on-board battery storage.

Similarly, as in the case of LNG, the countries do not have an electrification strategy for their water transport services. In addition, navigation services in most countries are not considered in the laws promoting electromobility in general (an exception is Colombia, which considers all modes in the electromobility law).

6.3. Sailing on Hydrogen

It should be noted that hydrogen is the most abundant element in nature, but it is associated with other elements to form more complex molecules and, therefore, to produce it, we must consume energy. The method most used today, especially for its industrial applications, is "*Reforming*" from fossil hydrocarbons (oil, gas and coal), covering 93% of the demand. But it can also be obtained by electrolysis, from water and electricity, which provides a product of higher purity, applicable directly to fuel cells. In turn, these electrolysers are capable of operating at variable power, helping to stabilize the electrical grid, absorbing the natural variations of wind and photovoltaic generators (see Annex 2).

This method today satisfies 4% of demand, but is projected to reach 20% in 2025. The strong increase expected makes this segment of the industry, associated with the hydrogen economy, an area of great global economic interest.

For its application in transport there are two options:

1. By means of hydrogen internal combustion engines, which are characterized by having a construction similar to conventional internal combustion engines, and which develop their potential by igniting hydrogen within the combustion chamber. In this case, hydrogen obtained by *reforming* Natural Gas can be used.

2. Through electric motors that are powered by the energy produced by hydrogen fuel cells. These are characterized by their differential construction with an electric motor powered by "fuel cells", which generate the electrical charge by supplying hydrogen accumulated in high pressure tanks.

Currently, the duo formed by hydrogen and the fuel cell is emerging as an important part of the solution to the world's energy problems in the medium and long term. Today 55 million tons of hydrogen are produced, which are applied in industry; 96% is of fossil origin, through the reforming of natural gas, crude oil and coal. It is estimated that the future energy system will incorporate hydrogen in different applications, with transport being the main one. It is estimated that the demand will rise to 550 million tons by the year 2050; This will result in a great development of this industrial sector and in turn, a notable reduction in emissions.

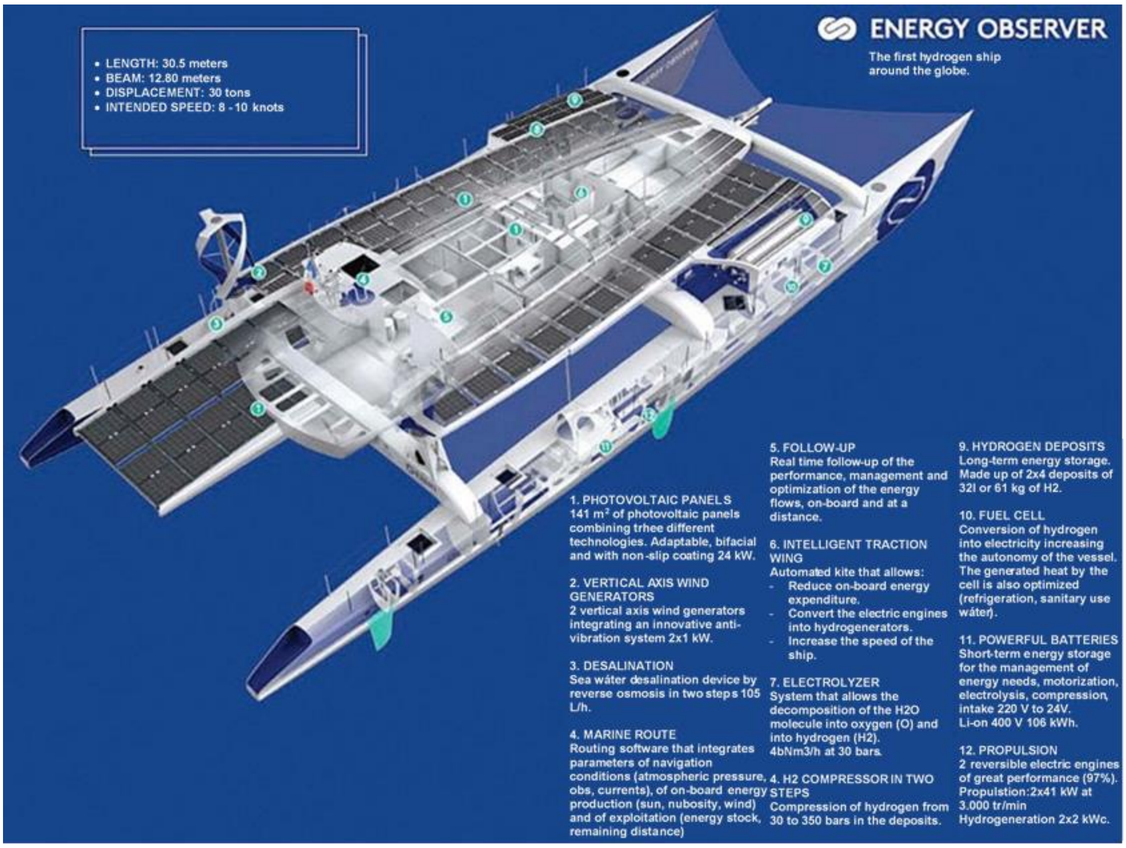
Hydrogen electric vehicles, which generate electricity on board using fuel cells, are the most advanced car configuration today. They are already commercially available globally, albeit in initially small quantities.

The ship named **Energy Observer** (Figure 25) is a catamaran sponsored by **Toyota** and other companies and is capable of moving solely and exclusively with hydrogen and renewable energy. That is, from solar and wind energy, generated by waves, to hydrogen generated from seawater.

This hydrogen-based energy technology is not new, we have already seen it in buses, cars, trains, etc. In fact, **Toyota uses it in their Mirai car** and now they have adapted it to this boat, this being the first time it has been used at sea to produce hydrogen directly during navigation.

Annex 2 details how a hydrogen fuel cell works and Annex 3 comments on hydrogen storage and its difficulties.

Figure 25: The Energy Observer (the first hydrogen ship)



Source: www.energy-observer.org

It has also been identified that the ABB company will make the world's first hydrogen-powered riverboat possible. As published, ABB will provide a power and propulsion solution for a newly built ship that will operate on the Rhone River in France and will run exclusively on hydrogen fuel cells. ABB strengthens its position as the marine market leader in hydrogen cell technology through its role in FLAGSHIPS, an EU-funded initiative to deploy zero-emission commercial-use ships for land transport and short sea shipping.

It is also possible to consider systems based on solar energy that can be applied in low-power catamaran-type ships with a large deck area. And those catamarans could be dedicated to fishing, tourism, or entertainment. In this sense, Paraguay, by virtue of the great availability of electricity, would have exportable surpluses that could be used for this purpose. Indeed, the fact of participating in both the Itaipú and Yacyretá generation plants places Paraguay in an excellent position with regard to the use of electrical energy in ships that circulate on the Waterway. Until now, its exports are carried out through high voltage lines. But it could lead a project to store that electrical energy different from the batteries that are currently used. The opportunity would be to produce hydrogen by electrolysis, store it in pressure tanks and thus become a supplier of this product to ships.

In summary, for the option of hydrogen as a substitute fuel, it would be necessary to carry out a detailed study of the opportunities for its supply, in a region where these systems are not currently being used and presumably a reasonable time will elapse before it can be applied in ships such as high-powered tugboats on the Waterway.

6.4. Sustainable replacement opportunities in the river transport system

Considering a relevant case, it is worth noting that the European goal is to have LNG supply in all river navigation ports that are part of the TEN-T Core Network. This objective is part of the LNG Master Plan, which seeks to establish a cooperation platform between the public and private sectors to create a harmonized regulatory framework for the use of LNG as fuel and cargo in river navigation. The main goals of this plan include:

- Identify the savings, costs and benefits of using LNG,
- Transfer knowledge of the maritime sector to inland navigation,
- Develop technical concepts for new and existing ships that can be reconditioned,
- Run pilots and tests,
- Develop a roadmap for the transition from the use of alternative fuels (with special emphasis on LNG)

The budget for this plan is 80.5 million Euros for studies, tests and pilots on the River Rhine and Danube.

Another example is China, which also developed a comprehensive strategy for the transition to the use of LNG, including a regulatory framework, a policy of subsidies to strengthen the shipbuilding of gas-powered ships, and a plan for the construction of LNG supply stations in the ports of Beijing, the Hangzhou Canal, the Yangtze River and the

Pearl River. Successful implementations in China include: a supply pontoon and supply barges.

The desire to reduce emissions in the transport sector has led to stricter regulations globally. However, the implementation of these strict regulations has not progressed in the same way in the river transport of the Waterway.

It is important to note that technologies to adapt alternative fuels are available and, as we have highlighted, there are already numerous examples of the feasibility of this change, using these fuels as “drop-in” or “dual fuel”. The current trend involves the challenge of substituting one fossil fuel for another (electricity and hydrogen being exceptions), in such a way that a shift towards the LNG use does not present a decoupling of dependence on fossil fuels.

Due to its availability in the subregion, LNG represents an interesting alternative, which does not eliminate, but does reduce GHG emissions. However, such adaptation requires not only the change of engines or the development of new constructions, but also the deployment of the supply infrastructure to guarantee the availability of fuel along the rivers.

Methanol has also been considered an option by shipping lines due to the low cost of engine retrofitting. The shift towards LNG and methanol is interesting because there are non-fossil alternatives such as biomethane (bio-LNG) for both fuels. Thus, the same supply concepts can be used in the implementation of these alternatives. These fuels can be thought of as transitional fuels towards non-fossil solutions. However, the use of biofuels requires sufficient availability of (sustainable) biomass for production, as well as effective and efficient production processes. An example of effective production in the region can be the first installation of the Biogastiger Project in Ecuador. An advantage of the use of biofuels can be decentralized production (when there is sufficient availability of local biomass), which could reduce costs in transporting the supply.

Currently a range of alternative fuels are available and they have been approved for use in river navigation. Additionally, as we have detailed, there are numerous implementation examples, including some within South America.

The shipbuilding industry plays an important role, given that the proposed fuel substitution leads to the development of new businesses and markets, as well as the development of new, more efficient and sustainable designs. The replacement also requires new infrastructures and supply and provisioning networks in the ports, in addition to the piers.

Another relevant factor to take into account in the process of adaptation to alternative fuels is based on the investment decisions that the owners of the ships and the operators in the sector will adopt. They would need to acquire a certain level of confidence about the operation of the new technology and the availability and quality of the substitute fuel. It is important to study in greater detail the impacts, barriers and financial instruments that will affect the potential for conversion to alternative fuels.

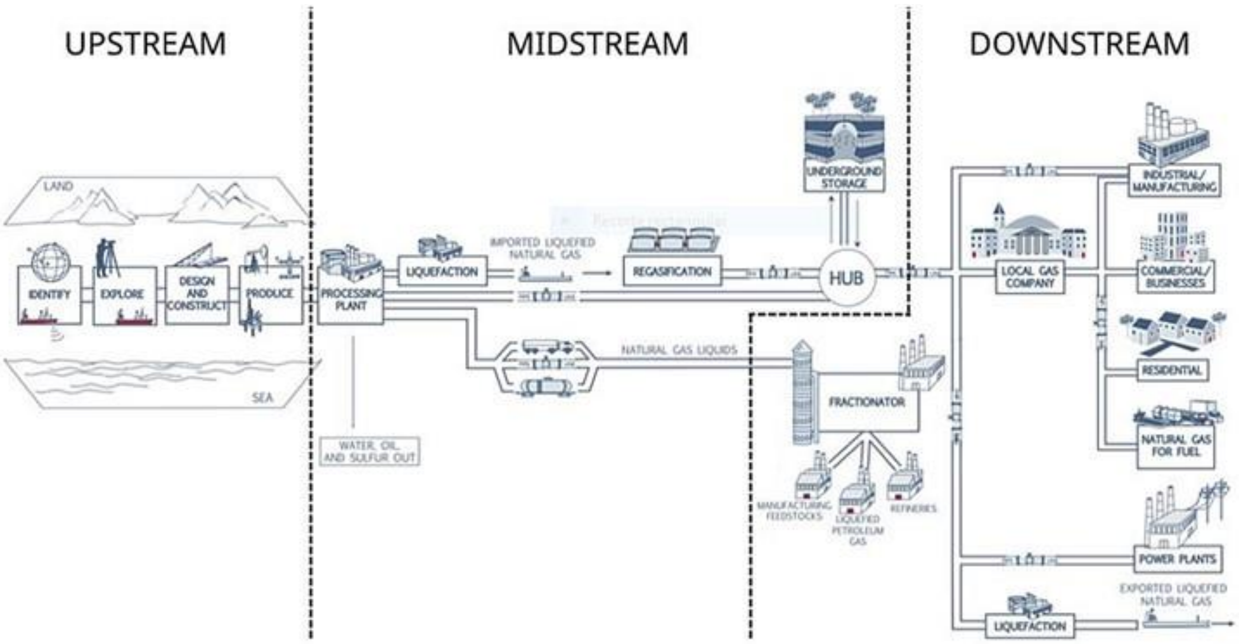
As we have mentioned, it is already technologically feasible to take river navigation towards a more sustainable path. However, before proclaiming that these technologies can “revolutionize” both the economic and environmental performance of the sector, it is necessary to build a roadmap debated among the multiple actors involved for the technological conversion, since the entire chain of value and the changes that would be generated by the adoption of these “new” fuels. The review of the regulatory frameworks and their adjustments are another key aspect of this development. Finally, all the key stakeholders should be brought together (in various instances) for a detailed discussion and coordination of the views of the various stakeholders, including shipyards, energy producers, ports, river transport operators, ship owners and other intervening parties to outline common visions and actions that are directed towards what is desirable and possible.

7. Natural Gas supply and transportation chain, some experiences

The classic supply and transportation system for Natural Gas is the one shown in Figure 26. Outside the reach of gas pipelines, natural gas compressed to about 200 atmospheres of pressure (CNG) is transported by truck, train or barge, in suitable containers that withstand those pressures. When the fields in which Natural Gas is produced are far from the ports to be exported in the Liquid state, the product is transported by pipeline to that place and a liquefaction plant is installed there, and then unloaded to the classic LNG tankers. It is transported by ship in a tanker of steel with 9% nickel, at low pressures (maximum 6 to 8 bars). The temperature of the liquid is kept at -163 °C.

LNG Bunkering configurations are very different from traditional liquid fuels. The LNG bunkering in the tanks is based on different processes from those corresponding to the loading of liquid fuels due to the physical differences between the two. In effect, LNG is a cryogenic liquid at temperatures of approximately -163 °C, that is, it remains in a liquid state and has boiling points at very low temperatures, becoming, as we know, gases at normal temperatures and pressures. Transporting LNG is like transporting a boiling liquid that can be very volatile and is therefore more dangerous to handle and store. Vapors generated in typical oil or liquid fuel bunkers are not considered as hazardous as they have flash points above 60 °C, while LNG vapors can form explosive clouds in confined spaces. This requires special handling of the steam when it is supplied.

Figure 26: Natural gas value chain

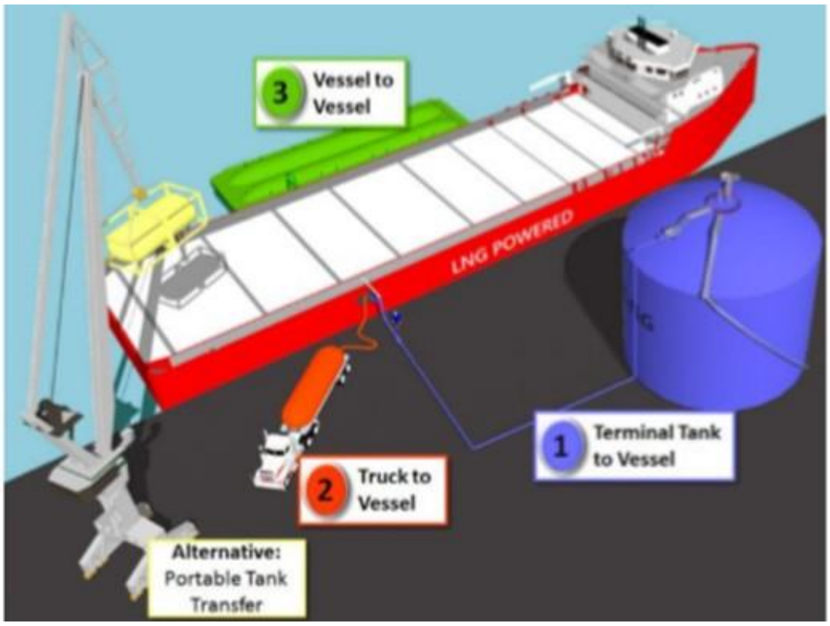


Source: Gas Natural Fenosa.

In Spain, the advantages of this fuel for transport, especially maritime transport, have led the port authorities, in collaboration with some of the most relevant companies in the sector, to make a significant effort to expand the range of services they offered up to the moment. Among the improvements registered, included within the European CORE LNG project and coordinated by Enagás, are the adaptation of the regasification plants to offer LNG bunkering services to ships, as well as the study of new logistics solutions for small-scale liquefied gas.

According to the data provided by Enagás, any terminal in the Spanish port system can supply LNG to ships through tanks (“*Truck to Vessel*”) or containers (“*Container to Vessel*”), two of the modes used for the supply or loading of liquefied gas in ships, as shown schematically in figure 27 below.

Figure 27: LNG transfer scheme "Truck - Ship" and "Tank - Ship"



Source: Enagás.

For its part, Gas Natural Fenosa, in conjunction with a Norwegian group, has developed a unique system in the world for the transfer of LNG (liquefied natural gas). This infrastructure is a floating system, recognized with different patents and exclusively, consisting of a platform that has a joint system compatible with any type of LNG tanker. Once connected to the ship, the LNG is transferred, safely and efficiently, to land through floating cryogenic hoses. Both the joint system that has been applied *offshore* for the first time in the world and the floating cryogenic hoses, constitute two milestones that highlight the innovative aspect of the platform.

The infrastructure, implemented in collaboration with the Norwegian technologist Connect LNG, has been designed and manufactured in a record time of 6 months, in a shipyard in Brevik (Norway), from where it was towed to the Norwegian town of Herøya where the first unloading operation was carried out with absolute success, which has proven its functionality, versatility and speed of commissioning.

This system, which appears in a photograph in Figure 28, called DirectLink LNG, allows the discharge of liquefied natural gas from *ship to shore* without the need for expensive fixed infrastructures (port and dock, for example) and with minimal environmental impact. In this way, it responds to the need of those customers who require natural gas supply in locations where today it is not economically or environmentally viable, making it possible for this energy to reach remote or difficult-to-access places, facilitating opening of new markets. This solution does not require any type of modification in the existing LNG tankers and allows reducing the access times to energy in the market and for the recipients.

Figure 28: "Retractable" dock for mooring of ships and LNG transfer

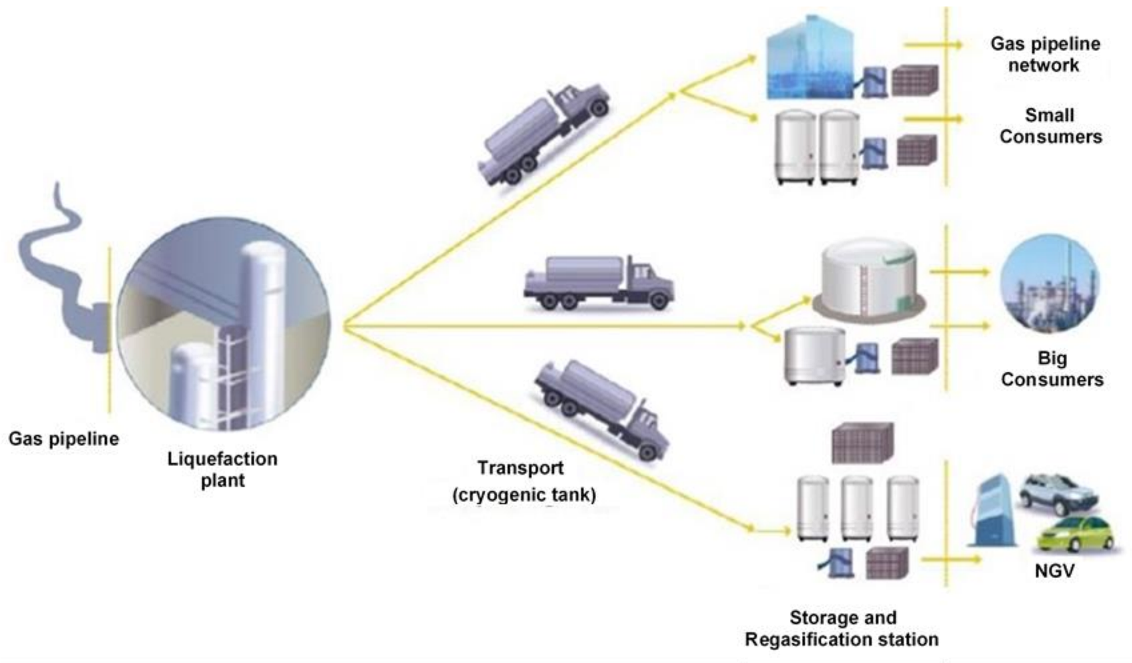
Source: GAS NATURAL FENOSA.

7.1. Virtual Gas pipelines

A few years ago, a transportation system called "Virtual Gas Pipeline" was developed, see diagram in Figure 29.

Natural gas is processed in relatively small, chassis-mounted liquefaction units. These units capture natural gas from pipelines or directly in reservoirs, liquefy it, and pack it in isotanks. These are transported by truck to areas where there are no home distribution networks, however there is a thermal generation station or consumption center. The isotank is deposited in the Central's tank park and with the help of vaporizers, it goes back to the gaseous state and is thus consumed in that Consumption Center.

Figure 29: Scheme of a "virtual" gas pipeline



Source: https://www.bnamericas.com/es/noticias/los-gasoductos-virtuales-ganan-terreno-en-peru

This system is used for distances of up to 600 km and is widely used today in various parts of the world, as it allows "market development". Once economically justified, transport by truck is replaced by a gas pipeline.

8. Current fuel supply system for vessels in the main ports

Part of this section is based on interviews with relevant personalities who are directly or indirectly involved in the processes of production, commercialization and logistics for the supply of liquid fuels in the Waterway. In this sense, consultations were made with the director of one of the most important refineries in Argentina, a Planning and Supply Manager of a medium-sized refinery, the Manager of a Bunker, the director of a medium-large Oil and Gas company and several managers of international consulting firms.

8.1. LNG supply system of the Ferry “Papa Francisco”

The appearance of the Ferry "Papa Francisco" of the Buquebus company, which uses LNG in its propulsion, was a real novelty in the transit of passengers between both banks of the Rio de la Plata and is a relevant precedent to highlight in the framework of this study. The ferry was built entirely in aluminum and has a capacity to transport up to a thousand passengers and 150 vehicles. It is powered by turbines similar to those used in jet skis and can develop speeds of up to 50 knots. It consumes between 30 and 35 Tons of LNG per trip (between 67 and 78 m3).

The LNG is supplied from a small-scale liquefaction plant built for this purpose in the town of San Vicente, 90 km from the Federal Capital, and has a liquefaction capacity of 90 m3/day. The LNG is transported by truck in Iso Tanks that are bunkered to the Ferry in Puerto Madero. The ferry has two LNG tanks on both sides and they can be refueled independently

The ship operates regularly in Dársena Norte, jurisdiction of the Port of Buenos Aires. There was no specific regulation regulating the supply of this fuel from a truck to a ship when it entered service. Therefore, the AGP provisionally granted “the first authorization to bunker LNG from a tanker truck to the ship”.

While successive extensions were extended to the shipowner so that it could continue operating, the feasibility of incorporating the standards ISO 18683 (guidelines for systems and facilities for supplying LNG as fuel for ships) and ISO 20519 (specification for the supply of ships fueled with LNG), and the Ministry of Energy adopted them within the framework of resolution 438/2019.

9. General characteristics of the LNG supply system

9.1. Identification of Natural Gas supply sources

For a better understanding of the opportunities for substituting fuels such as Gas Oil HF or RMG 380, face-to-face meetings and telephone conversations were held with different relevant experts related to the possible supply of Natural Gas. To do this, they interviewed a Gas and Energy Strategic Planning Manager of one of the main Argentine oil and natural gas companies, a LNG Project Manager of a medium-large Argentine company, a Manager of new business companies of medium size, the Secretary General of the *International Gas Union* (IGU), the General Manager of the consulting company Wood Mackenzie in Argentina, the Country Manager of the Petrobras Company and the Production Manager of a regasification company in Canada.

As a summary of information published on the web and of the conversations held, it can be concluded that in the region the Southern Cone has three main basins that could supply the Natural Gas necessary to replace fuels such as Gas Oil HF or the RMG 380 used in the Waterway and in other ports located in Cuenca del Plata, such as Buenos Aires, Montevideo and Tierra del Fuego.

One of them is the Zona Faja Plegada of Bolivia, the other is the Brazilian pre-salt area and the third is the Vaca Muerta unconventional field, in Argentina. Although we should not rule out other sources such as the Austral basin in Argentina or imported LNG such as the one that goes to the Argentine and Brazilian ports, where there are several floating LNG regasification units operating and NG injection in the gas pipeline networks of both countries.

In a first analysis that should be verified in subsequent studies, Bolivia's NG reserves would not be sufficient and there are no indications that a Liquefaction Plant will be installed on a worldwide scale by Bolivia. In addition, lately there have been difficulties to supply the volumes contracted by Argentina and Brazil. However, considering Puerto Suarez and Bolivian or Paraguayan ports upstream of the Waterway, with a demand that is presumed to be reduced volumes of LNG, there could be some opportunity to supply it through small scale NG Liquefaction plants. The natural gas for these plants could be taken from nearby gas pipelines and, in this way, supply the barges and push boats that transport goods to that area.

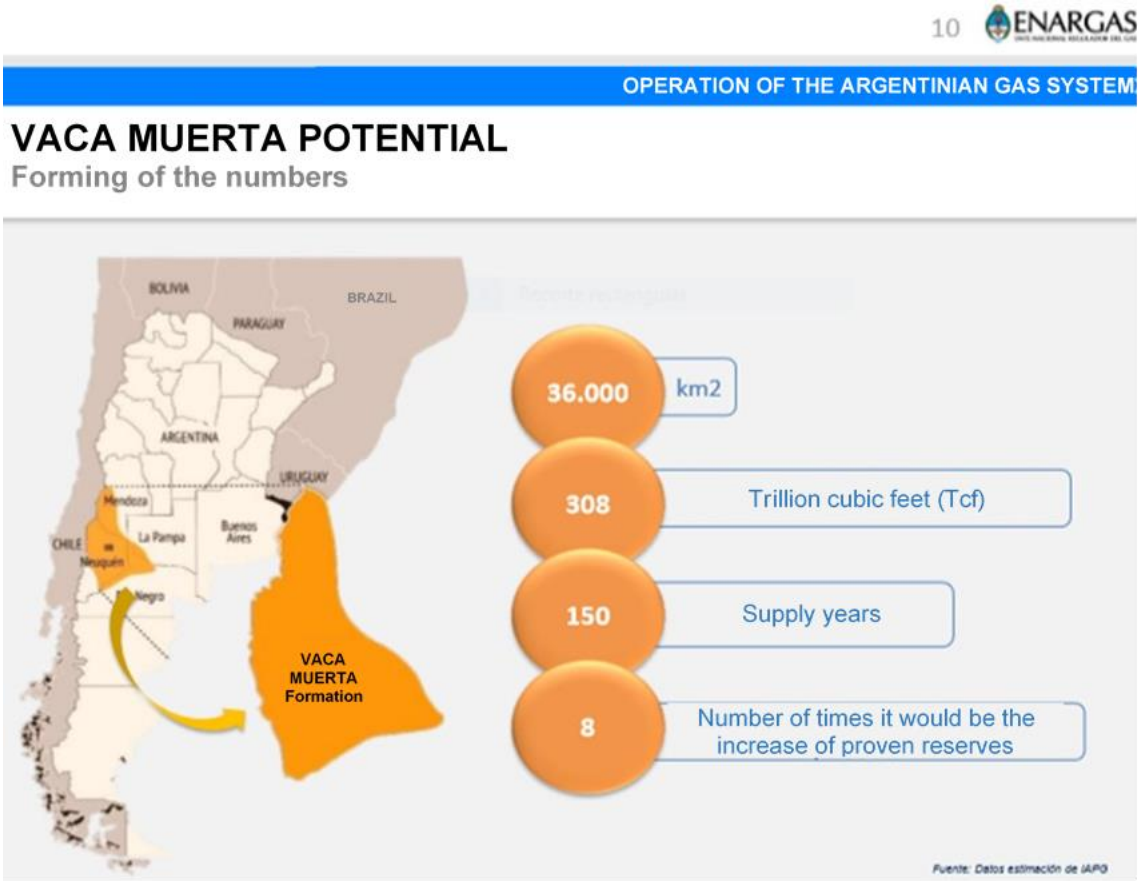
The natural gas that is produced in association with oil in the Brazilian pre-salt area reaches the territory by gas pipeline and is consumed by internal demand. However, it is known that there are studies to develop liquefaction projects in floating units in situ of the NG produced in the pre-salt area, for its export to international markets - but not how these could be carried out in the short term. There are three LNG reception and regasification terminals in Brazil, which, like the one that receives the same product in the port of Escobar, in Argentina, could be a source of LNG supply to Puertos de Santos and Rio de Janeiro, but it would be very difficult as a supply to ports of the Waterway. In short, it is presumed that Brazil will continue to be an importer of Natural Gas and it is unlikely that it will be able to supply the demand that originates from the Waterway, since it should first meet its own.

Regarding the potential of the unconventional Natural Gas reservoir in Vaca Muerta in Argentina, some data are reproduced below based on a presentation made by the former Secretary of Energy of the Argentine Republic, Mr. Enrique Lopeteguy. The presentation concludes with the statements that appear in Figure 30. In the first part it is stated that Argentina resumes its Natural Gas exports to neighboring countries; then it is indicated that Natural Gas exports will gradually increase. Finally, the contract is announced to order a Floating Liquefaction unit with capacity for 2.5 million M3/day of NG or 0.5 Million Tons per year of LNG ([3]).

Figure 30: Conclusions of the Minister of Energy of Argentina

Source: Lopetegui (2019), Secretary of Energy, Argentine Republic.

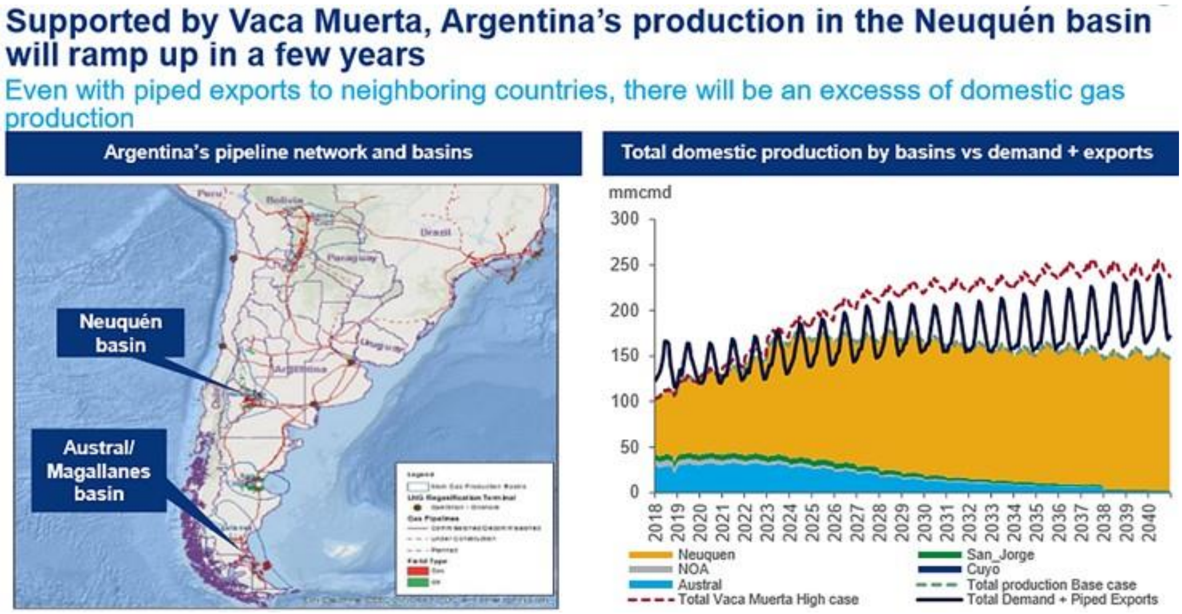
Figure 31: Potential for Vaca Muerta



Source: ENARGAS Argentina.

As can be seen in Figure 31, according to estimates by the Argentine Institute of Oil and Gas, the reserves of the Vaca Muerta formation would guarantee 150 years of supply. There is also evidence that by 2025 the YPF Company would build a global-scale LNG plant in the port of Bahía Blanca. This arises both from interviews with relevant experts from companies linked to the sector, as well as from international consultants, who have carried out specific studies on the competitiveness of a facility such as the one proposed there.

Figure 32: Projection of natural gas production and exports in Argentina



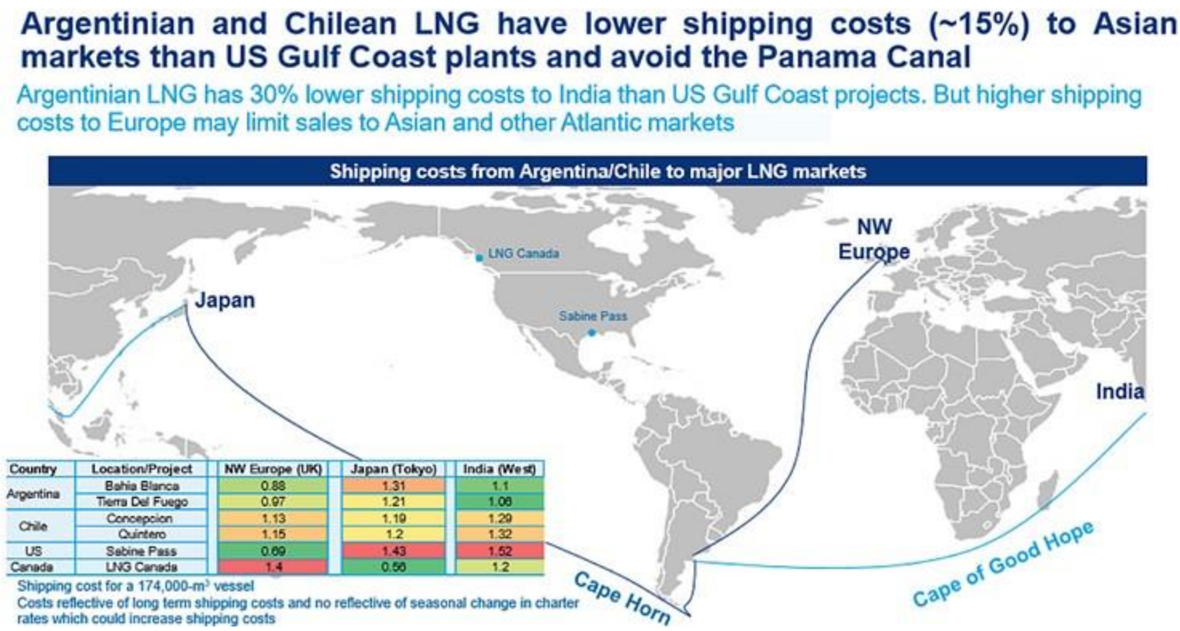
Source: Wood Mackenzie (2019b)

Based on the analysis carried out based on the available information, the most appropriate source of supply for Natural Gas, both to supply the local market in Argentina and its export to other international markets, would be the **Vaca Muerta Unconventional Field** located in the province of Neuquén.

As shown in Figure 32, the incremental production and export projections of Natural Gas in the Vaca Muerta Formation for the coming years are significant when considering the availability of LNG to potentially supply ships on the Waterway.

Finally, it is necessary to point out that the LNG exported from Argentina would have competitive prices internationally (Figure 33). Likewise, as evidenced in Figure 34, another important factor to consider is the diversity of top-level international companies that operate in the different productive fields of said formation.

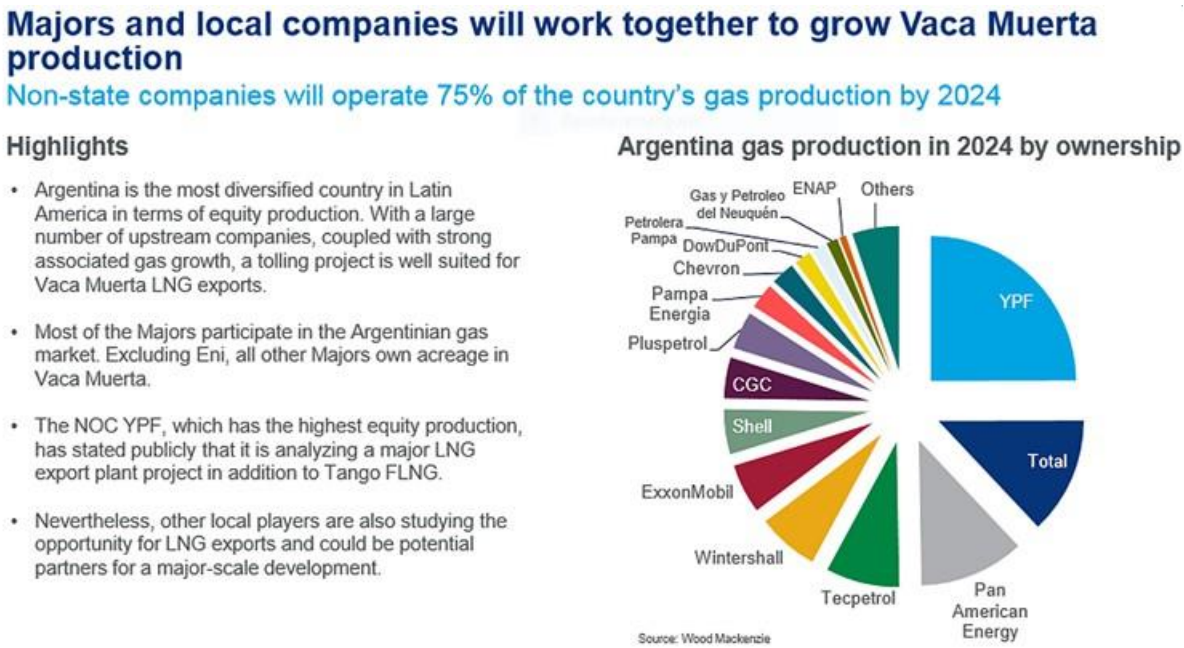
Figure 33: Freight costs from Bahía Blanca to Japan, Europe and India



Country	Location/Project	NW Europe (UK)	Japan (Tokyo)	India (West)
Argentina	Bahia Blanca	0.88	1.31	1.1
	Tierra Del Fuego	0.97	1.21	1.06
Chile	Concepcion	1.13	1.19	1.29
	Quintero	1.15	1.2	1.32
US	Sabine Pass	0.69	1.43	1.52
Canada	LNG Canada	1.4	0.56	1.2

Source: Wood Mackenzie (2019b).

Figure 34: International and local companies working in Vaca Muerta



Source: Wood Mackenzie (2019b).

It should be remembered that most of the ships that circulate on the Waterway are supplied by the "BUNKER Internacional" Marketing channel, as shown in Table 1 based on the information obtained from the Secretary of Energy of the Argentine Republic. This means that users do not pay ITC taxes on the fuels they purchase through that channel and, for the country of origin, these sales are considered as exports.

The transformations to LNG by large cruise ships belonging to leading international companies (discussed in the previous chapter) would force the availability of LNG in the short/medium term in various ports of the Argentine Republic. Otherwise, many cruise ships that operate on LNG would not be able to reach Buenos Aires or Tierra del Fuego, as ships powered by traditional fossil fuels currently do.

The decision, embodied in the resolution 438/2019 and published in the Official Gazette, adopts the international ISO standards in relation to the operations of transferring and supplying LNG to ships from tanker trucks, mainly.

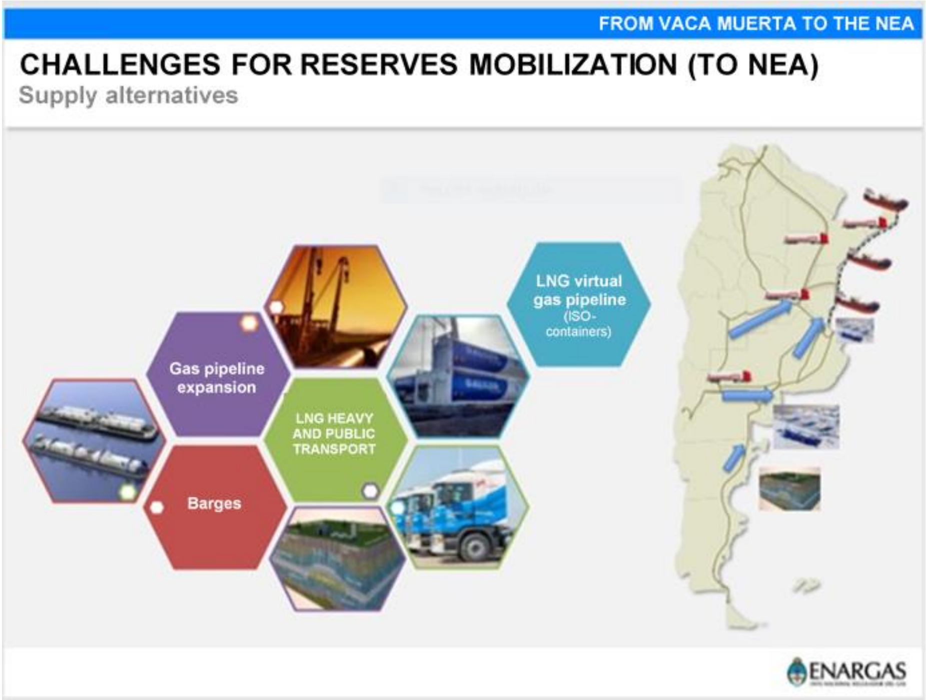
9.2. LNG transportation system that would need to be considered

In accordance with the aforementioned international experience, several options could be considered for the transportation of Natural Gas from the field to the Waterway:

1. For the initial stages of the project, the Galileo Company's distribution network could be used, which would use trucks with isotanks, which would come directly from Neuquén (virtual gas pipeline). The isotanks that supply service stations in places near the refueling ports for ships and push boats would be transported directly to the ports. Then they could be loaded with appropriate cranes to the barges that transport other fuels upstream of the Waterway, in order to supply LNG to ports such as Asunción del Paraguay. In other cases, the isotank on the ship's deck would fuel the ship's engines.
   Likewise, and by pumping from isotanks on land, the LNG could be transferred to appropriate tanks provided by the modified ships to be fueled by LNG. Since it is LNG captured from reservoir vents, it would have a very competitive price compared to HF Oil Gas.

   The Argentine Gas Regulatory Body (ENARGAS) has outlined the movement of Natural Gas towards the Northeast of Argentina, where the bunker fuel supply ports are located (see Figure 35). The basis of such a system is that there are more than 3 million potential Natural Gas users in that area.

Figure 35: Mobilization of Natural Gas reserves to the Argentine NEA



Source: ENARGAS

2. The Natural Gas that has been transported by existing Gas Pipelines to the vicinity of a fuel supply port on the Waterway (San Lorenzo, for example) could be extracted and liquefied in the portable units mentioned in this study. Once packaged in isotanks, the procedure would be similar to that indicated in the previous paragraph.

3. When the quantities consumed in the Waterway and in nearby ports increase, it could be transported by LNG tankers from the liquefaction plant located in Bahía Blanca (see Figure 36).

Figure 36: Characteristics of the liquefaction plant in Bahía Blanca: Advantages and Disadvantages

Source: Wood Mackenzie (2019b).

4. Given that an imported LNG unloading and regasification dock is located in Escobar, the feasibility of building a retractable dock like the one indicated above could be evaluated, and proceed directly to unloading the LNG to self-propelled vessels or tugboats. The other option is that, if the LNG loading dock is built in trucks in that place, (whose basic engineering is under development), it is used to load isotanks from the LNG tanker.

   These isotanks could be transported by truck to the port of San Lorenzo and from there they would supply ships converted to LNG, with systems similar to those already indicated. Having the support of the LNG imported in Escobar has the advantage of ensuring supply in the winter, which is when the greatest demand for NG is produced at a household level in Argentina, and at competitive prices, given that this country is "against the season", with respect to the northern hemisphere, from where the ships arriving at Escobar are mostly supplied.

9.3. Required investments in infrastructure

In the case of using LNG as a substitute fuel, this initiative is automatically aligned with the LNG supply and distribution initiatives that are part of the government Agenda and that are already underway in the Argentine Republic. Therefore, investments in specific infrastructure for this project will be limited. And that means that this option has competitive advantages compared to other substitute energy alternatives, which do not have the level of development that Natural Gas has, (both compressed and liquefied), in that country.

Therefore, it is likely that it will be necessary to invest in LNG reception and dispatch infrastructure in the ports destined for this purpose on the Waterway, with investment amounts much lower than those necessary for the basic infrastructure and necessary to produce, transport and liquefy Natural Gas.

For this project, the following would be needed: (i) cranes for loading or unloading isotanks; (ii) pipes and pumps when it is necessary to transfer directly to the ships' LNG tanks, and in general (iii) investment in facilities that do not imply significant expenses.

Also, as was considered in the previous chapter, it will be necessary to invest in the modification of ships and the construction of new vessels.

It is insisted that the really significant investments will be those destined to the Production of Natural Gas in Field, in the facilities for the treatment of gas at the wellhead; in the trunk gas pipelines to transport Natural Gas to the liquefaction plant or consumption centers: the liquefaction plant itself and the port facilities for its operation with LNG tankers, etc. In any case, the amortization of these investments will be included in the price of the LNG that will go to the Waterway, but diluted in a significantly higher volume, which will result from the comprehensive project at the country level.

10. Analysis limits

This study is of preliminary nature. Based on what has been analyzed, the use of LNG as a fuel for the propulsion of ships would be, due to its technical and market characteristics, an adequate replacement option. This study configures a first approach to the subject, but in future instances the project should be divided into stages and try to better evaluate the volumes of fuel involved and make a quantitative analysis consistent with the estimation of the number of vessels that could be readjusted in a first stage of implementation of the replacement project. Likewise, the different LNG distribution logistics alternatives should be analyzed and evaluated with a view to optimize the replacement offer.

11. Recommendations

The list of energy options or alternatives to fuels that are currently used should begin, if possible, with the lowest cost of transforming the ship/lowest price of substitute fuel, and highest relative environmental benefit. Attention should be kept on the transformations that are being carried out at the global level, such as those mentioned in the previous paragraph, in order to identify possible synergies between relevant international initiatives and those of the Waterway.

Information transparency: It is evident that, in order to facilitate a consistent state of knowledge on the subject, one should be in a position to offer pertinent information to potential interested parties, such as the cost estimates of the refitting of the ships, the most probable prices of the substitute fuel (which, certainly, should be less than the one currently used) and concomitantly, various analyzes on the repayment periods of potential investments. In summary, each owner / shipowner should have a detailed description of the considered “business model”, with a description of the cost/benefit equation that encourages them to undertake initiatives with a view to retrofitting their ships.

Regulatory changes: In parallel, the necessary regulatory changes must be analyzed, such as to guarantee adequate safety standards in supply and logistics operations with the new fuel. There is already a precedent in Argentina, a country that adopted the European Union regulations for the transport and transfer of LNG from trucks to ships, and in this way significantly accelerated the process. In this sense, similar processes should be promoted in the other CIH member countries. IMO codes are a good reference.

Due to the volumes that have been identified that are consumed within the Waterway, the roadmap of the implementation process should be attentive to the initiatives that are being generated in the same region to supply Natural Gas to home users and power plants, and thus take advantage of the synergies of these initiatives, with those of fuel changes in transportation by the Waterway. Precisely, opportunities have been identified to supply residential users who today do not have access to Natural Gas (there are more than 3 million home users in that condition) in the northeastern areas of

Argentina, the south of Bolivia and the north of Uruguay. A project to replace fuels for ships with LNG on the Waterway, such as the one outlined in this study, could generate enormous economies of scale if both types of initiatives could be made compatible and complemented.

It will also be necessary to take into account that there is already an inertia in the change of marine fuels at the international level that would be impacting ports near the Waterway, such as Campana, Capital Federal, La Plata and Montevideo, and that it would be desirable to align with these initiatives and avoid developing an independent substitution policy for ships that circulate within the Waterway.

In addition, grain producers that use the Waterway demand a greater draft and claim losses of more than 100 million dollars per year for that reason. An alternative fuel with a lower price and a short amortization period for the Shipowner would mean a palliative in the volume of losses by allowing to reduce transportation costs.

It has also been found that the most efficient transport is a “multimodal” type, such as that carried out in other countries. Well, it would not be difficult to make the use of the same alternative fuel compatible between the fleet of trucks and / or the train and the boats, to reach the transoceanic ship. It has been seen that in Chile and Argentina there are companies that manufacture heavy transport vehicles that run on LNG, and they are already bringing these models to both countries (IVECO, SCANIA, VOLVO, and Mercedes Benz, among others).

Along the same line, the Shipyards that have already shown interest in transforming vessels for the LNG usage should be contacted, and these initiatives should be leveraged with a Financing Program for modifications with credits from international organizations that promote the economic development of the Region and that, at the same time, try to mitigate the impact of Climate Change.

More information and studies: Finally, studies should be carried out to deepen the substitution line with Hydrogen / Electric Power, and begin to evaluate sources of supply, transport and conversion of ships fueled by these sources. For the complete determination of the greenhouse gas emissions associated with the use of each of the fuel alternatives, it will be necessary to carry out respective life cycle analyzes in each case to establish a homogeneous comparative analysis base.

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Annex 1: Current specifications of bunker fuels in the Waterway

GAS OIL HF

1. TECHNICAL SPECIFICATION

DENOMINATION: GASOIL HF		**CODE: 4064**
RECOMMENDATION: Fuel for Diesel cycle motors DMA category – ISO 8217/2005 (1)		
Operate in dispatch Terminals		
PARAMETER	VALUE	METHOD
Density at 15°C	0,8300 – 0,8850	ASTM D 1298 / 4052
Distillation 50% Distilled, °C 90% Distilled, °C., max	 Report 370,0	ASTM D 86
Sulfur, /w, max.	0,200	ASTM D 4294/2622/5453
Corrosion s/ Cu plate, (3 h at 50°C), max.	3	ASTM D 130
Viscosity at 40°C, cSt.	2,000 – 4,500	ASTM D 445
Cetane index, min.	45,0	ASTM D 976
Flash point, °C, min.	60.0	ASTM D 93
Color, max.	3,0	ASTM D 1500
Conradson Coal, (s/10% dist.), %w, max.	0,30	ASTM D 189 / 4530
Water and Sediments, % vol., max.	0,10	ASTM D 1796
Ashes, % weight, max.	0,01	ASTM D 482
Pour Point, °C, max(*) (*) Southern Zone (see table)	0 (summer) -6 (winter)	ASTM D 97/5950
Appearance: -Period May – September at 15°C (winter) -Period October – April at 20°C (summer), max.	 Clean and Shiny 1	ASTM D 4176 Procedure 1 Procedure 2
Biodiesel content, %vol	Report	EN 12078

Source: YPF (https://www.ypf.com/productosyservicios/Descargas/Gas-Oil-HF.pdf).

MARINE FUEL OIL RMG 380

1. TECHNICAL SPECIFICATION

DENOMINATION: MARINE FUEL OIL RMG 380		**CODE: 4079**
RECOMMENDATION: Fuel for big marine engines and for energy generation in boilers		
STANDARDS: Category ISO – F – RMG 380 of the ISO 8217/2005 (1)s		
SPECIFICATIONS		
Viscosity at 50°C, cSt.	250 – 380	ASTM D-445
Density at 15°C, g/cm^3 (max.)	0,991	ASTM D-1298/4052
Pour Point, °C, (max.)	6,0	ASTM D-97/5950
Flash point, °C, (min.)	60,0	ASTM D-93
Water, % vol., (max.)	0,5	ASTM D-95
Ashes, %w, (max.)	0,15	ASTM D-482
Sulfur, %w, (max.)	**1,00**	**ASTM D-2622**/ISO 8754
Conradson Coal, %w, (max.)	15,0	ASTM D-189/4530
Vanadium, mg/Kg (max.)	200	ASTM D-5863/5709/ISO 14597
Aluminum+Silicon, mg/Kg (max.)	80	ASTM D-5184/ISO 10478/IP 377
Potential sediments, %w (max.)	0,10	ISO 10307-2 (Proc.A)
Extraction sediments, %w (max.)	0,50	ASTM D-473
Zinc, mg/Kg (max.)	15	ASTM D-7111/IP 501/IP 470
Phosphorus, mg/Kg (max.)	15	ASTM D-4951/IP 501/IP 470
Calcium, mg/Kg (max.)	30	ASTM D-7111/IP 501/IP 470

Source: YPF (https://www.ypf.com/productosyservicios/Descargas/RMG-380.pdf).

Annex 2 Examples of relevant nautical electromobility

Canada

The new fiberglass Templar C26 Cruiser with a fully electric powertrain is offered as a water taxi model that has been commercially certified for up to 12 passengers by the Canadian government. Gray Line Hop-on Hop-off Sightseeing Tour in Victoria, Canada recently placed an order for 12 vessels that will be used in the harbor tour business and will serve as quiet and eco-friendly dinner vessels. It is followed by a sedan version for long-range cruises and a light cargo commercial vessel. All will be built in the same 26 foot hull mold.

It has a fully electric propulsion system, consisting of a 10KW motor powered by a bank of six lithium-ion batteries. The base model's six-battery configuration provides up to seven hours of performance at a five-knot cruising speed, with the option of adding up to 10 batteries to increase range. Batteries can be recharged at the dock with a standard 15 or 30 amp plug or an optional sunroof can help with charging.

This boat does not generate noise or fumes or odors on the deck. In addition, it is virtually maintenance free and has no fuel costs, resulting in very low operating costs. With no fuel tanks or heavy combustion engine, the lightweight 5000-pound boat is towable by an SUV.

Figure 17: Templar 26, Canada

Source: Torqeedo, For more information visit: https://www.torqeedo.com/es/noticias-y-prensa/blog/blog-2019-10-02.html

Thailand

Thailand's first electric ferry started its service recently by the Bangkok Metropolitan Authority (BMA). The boat is part of the city's efforts to relieve congestion and improve air quality through investments in green transportation.

The 47.5-foot fiberglass vessel was repowered by MariArt Shipyard, replacing the current 205 horsepower diesel engine with two 10 kW Torqeedo Cruise electric outboards, each with six lithium battery banks and two rapid chargers. The 40-passenger ship is part of a fleet of ferries operated by BMA's Krungthep Thanakom Company (KT BMA) and operates a five-kilometer-a-day route between Hua Lampjong and Thewes Pier.

Figure 18: Electric ferry, Thailand

Source: Torqeedo. For more information visit https://www.torqeedo.com/es/noticias-y-prensa/blog/blog-2018-11-28.html

Spain

ECOCAT solar-electric aluminum passenger ferry entered service on the Spanish Mediterranean coast in 2018.

The 18-meter ferry, built by the Metaltec Naval shipyard in Cantabria, works with electricity generated by 120 photovoltaic solar panels on the roof of the ship. To maximize the area of solar panels for energy harvesting, Metaltec designed a set of retractable and deployable pneumatic wings. The propulsion system consists of two 50 kW electric motors, for a total of 100 kW, powered by eight BMW i3 30.5 kWh high-voltage lithium-ion batteries, four in each hull. The maximum speed is 9.7 knots (18 km/h). Normal operating speed is 7 knots (13 km/h).[7]

[7] https://www.europapress.es/cantabria/cantabriaxxi-00775/noticia-construido-cantabria-primer-barco-pasajeros-energia-electrosolar-europa-20180614151250.html,

Figure 19: EcoCAT, Spain

Source: https://emag.nauticexpo.com/sunshine-superstar/

The 120 passenger ship is 100% powered by solar battery system without auxiliary internal combustion engine. The ship's cruising range is eight hours of operation on batteries without sun. Operators expect an average of six 13 km trips a day.

Denmark

The *Ellen*[8] sails between the southern Danish ports of Fynshav to Soby on the island of Aero. The e-ferry is capable of carrying 30 vehicles and 200 passengers and is powered by a battery with a capacity of 4.3MWh, according to Swiss battery maker Lechanché, which provided the system. Danfoss Editron supplied Ellen's all-electric transmission, consisting of two 750kW drive motors and two 250kW drive motors controlled by DC/AC inverters. This innovative propulsion system means that the ferry significantly reduces noise and waves, adding to its eco-friendly credentials.

At almost 60 meters long and 13 meters wide and with a maximum speed of between 13 and 15.5 knots, it will reduce the travel time per direction to 55 minutes, compared to the 70 it takes for a fuel-powered vessel that currently operates in the route.

For one year, the e-ferry will avoid the generation of 2,000 tons of CO2, 42 tons of NOx, 2.5 tons of particulate matter and 1.4 tons of SO2.

The ship can sail up to 22 nautical miles between charges, seven times farther than was previously possible for an e-ferry. The e-ferry offers up to seven round trips per day.

The European Union, which supported the project, aims to deploy 100 or more of these ferries by 2030[9].

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https://www.eldiariomontanes.es/cantabria/ministra-transicion-ecologica-20180619134603-nt.html, https://www.youtube.com/watch?v=3sEBSnm8duk

[8] For details see http://e-ferryproject.eu/.

[9] https://www.euronews.com/2019/08/20/world-s-largest-all-electric-ferry-sets-sail-in-denmark

Figure 20: Electric ferries

Source: https://www.cnbc.com/2019/08/19/the-worlds-largest-all-electric-ferry-completes-maiden-voyage.html, https://new.abb.com/marine/marine-references/forsea

Beyond new construction there are examples of converting boats to electric propulsion.

The *Tycho Brahe* and *Aurora* ferries are operated by ForSea on a 4 km route between Denmark and Sweden; they have gone from running on conventional diesel engines to running on batteries, becoming emission-free electric ferries.

The conversion project for the two ferries, originally built in 1991, included the installation of a 4,160 kWh battery on board each vessel. The scope of the project also included battery racks, ABB's award-winning Onboard DC Grid ™ power distribution system, as well as energy storage control systems.

Tycho Brahe and Aurora move annually more than 7.4 million passengers and 1.9 million vehicles between Helsingør, Denmark, and Helsingborg, Sweden.

Norway

In 2012, the Norwegian Ministry of Transport launched a competition to convert the passenger and car ferry crossing the Sognefjord near Bergen into a low-noise, low-emission ferry.

The answer was a proposal for an electric ferry, loading at each dock. The fast charging system includes the installation of a battery system at each dock to facilitate high-power charging of the vessel without overloading the relatively weak network. The ferry is operated by Norled, a private ferry company.

The Ampere electric ferry entered into operation in early 2015. It crosses the fjord about 34 times a day, it has a capacity of 360 passengers and 120 cars. The 6 km crossing takes 20 minutes. The ferry's 1,000 kWh lithium-ion battery system is charged at each dock for about 10 minutes.

90% of electricity in Norway is produced from hydroelectric power (hydropower), which is practically free of pollutants and CO_2 emissions. This goes a long way towards making this concept environmentally friendly.

The owner and operator of the ferry is Norled. The ship was built by the Norwegian shipyard Fjellstrand. For an electric boat, it is very important to reduce energy consumption to the maximum. This is important to limit the battery size and charging power to reasonable values.

Figure 21: e-ferry Ampere, Norway

Source: https://news.cision.com/fi/capman-oyj/i/norled-ampere,c2628125

A reduction in energy consumption of around 30% was achieved by designing a thin and light aluminum catamaran hull and limiting the operating speed to about 10 knots per hour (18 km/h).

The CO2 reduction with the light electric ferry is estimated at 2,150 tons per year or a reduction of around 95% compared to a conventional diesel ferry. The light ferry uses 50% less propulsion energy than a conventional steel shuttle. Fuel costs are only 20% of operations.

The ferry uses around 1 million kWh of electrical energy per year. Electric propulsion is very attractive from an economic point of view, as the payback period is estimated to be around 5 years[10].

South America

In South America there are at least two interesting examples of the use of electricity as fuel in the river sector.

The Tapiatpia solar boat runs along the banks of Sharamentsa, in the province of Pastaza, Ecuador. The boat is the product of the KaraSolar project, an initiative that seeks to generate river public transport for nine Achuar communities in the Ecuadorian Amazon. The boat is built with fiberglass and unlike other electric river transport systems in the Amazon, it does not depend on recharging stations: its roof of solar panels gives it travel autonomy even at night, when its 12 batteries on board can operate the boat for three to six hours depending on the power to which the engine is subjected. The

[10] http://www.ppmc-transport.org/battery-electric-car-ferry-in-norway/

boat is socially, technically and economically self-sustaining and "has a useful life of about 20 years[11]".

The second project is a collective boat for 60 passengers on the Tigre River, Argentina. LINEAS DELTA seeks a solution for the sustainable propulsion of passenger ferries.

***Figure 22**: Tapiatpia - solar boat*

Source: https://charlienewland.co.uk/solarcanoe

For trips of about 60 km distance and a total duration, with stops, of max. 6 hours it is expected that 80% of the ship's driving time will be done at 12 knots of speed, 87 kW of electrical power. The remaining 20% of the time the speed is approximately 10 knots, which requires about 38 kW of electrical energy.

The boat will have the following motorization:

- 100 kW Heavy-Duty Drive Train with Shaft Drive Motor DB150i
- HV Battery bank 8xBMW i3, including cooling systems

Carbon emissions from the operation of electric motors depend on the energy mix of the local electricity grid. The energy conversion factor in Argentina is 0.39 kg CO_2per kWh. In comparison, diesel engines generate CO_2 emissions of between 0.75 and 0.9 kg of CO_2 per kWh of usable energy.

[11] https://www.elcomercio.com/tendencias/tapiatpia-embarcacionsolar-comunidadesachuar-amazonia-transporte.html

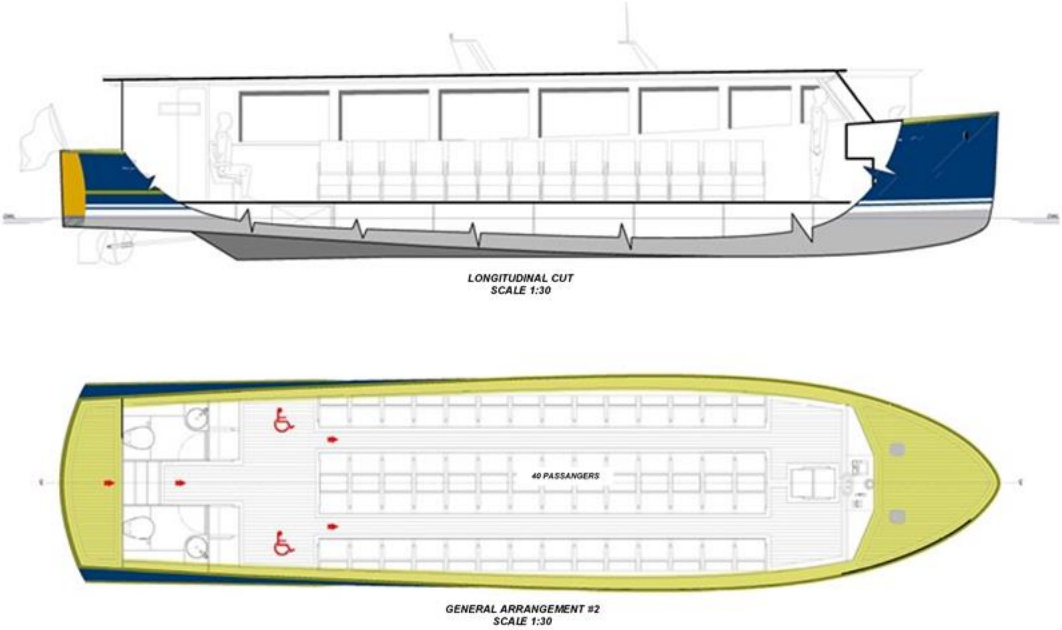
As the speed of the electric vessel is 15% lower (12 knots compared to 14 knots in the current solution), the project benefits from an additional 30% reduction in emissions. Consequently, CO2 emissions can be reduced by more than 70% with this project.

Conventional marine diesel engines emit significant amounts of harmful exhaust gases, NOx and PM. With the electric propulsion solution, these emissions can be completely eliminated locally.

For this project, a new marine engine complying with current standards (Scope 3) would emit, during operation at the same speed (15% reduced), approximately the same amount of harmful exhaust gases as 90 modern cars. Performance at the original 14 knots is compared to about 130 modern cars.

The parallel development of an onshore renewable energy project could reduce carbon emissions entirely.

Figure 23: Electric boat Tigre River



Source: Torqeedo

Other relevant cases

The Turanor:

The Swiss Raphael Domjan fulfilled his dream of creating the first ship that goes around the world solely with solar energy. This hydrodynamic catamaran has 703 solar panels throughout its deck, high-capacity saltwater-proof batteries and navigation systems to make the most of sunlight. The Turanor also has two emergency diesel engines, which according to its crew it has not needed. On the website of his company, PlanetSolar, Domjan offers details of the project, which has cost about 15 million euros, and a gallery of images and videos.

Solemar: solar catamarans "*made in Spain*"

The Solemar is an 80 passenger solar catamaran created by the Seacleaner Trawler shipyard, based in Mallorca. Its 16 solar panels located on the roof provide all the energy and feed 24 batteries to guarantee about 150 hours without the need for light. Its managers highlight its advantages: it does not emit oil residues, nor carbon dioxide (CO_2), nor noise and solar energy is free. It can be seen in the reservoirs of Castell de Guadalest (Alicante), Benagéber (Valencia) or in the pond of the Retiro Park (Madrid).

Sun21:

The Sun21 entered the Guinness Book of Records as the fastest ship to cross the Atlantic Ocean powered by solar energy. This catamaran of 20 people and 14 meters in length left Chipiona (Seville) in October 2006 and arrived in New York in May of the following year. With an average speed similar to that of a sailboat (12 km/h), it traveled more than 12,000 kilometers.

SolarSails:

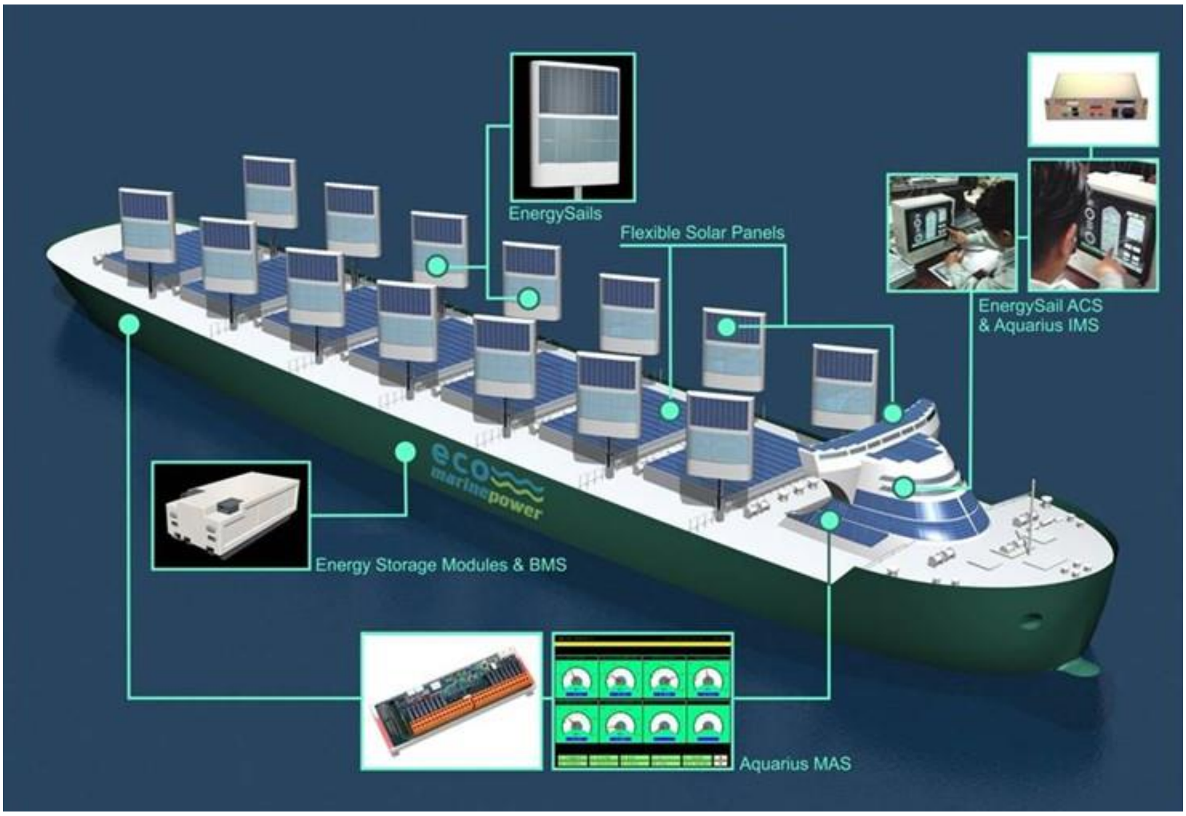
The Australian company SolarSailor has created everything from small tourist catamarans to private yachts, or even large commercial vessels. The characteristic that makes these "SolarSails" unique are their sail-like panels, which take advantage of the energy of the sun and the wind. In some other models, they also use a hybrid technology with conventional electric and combustion engines.

First freight ship designed to capture wind and solar energy

An interesting case to cite is the Aquarius MRE, the first freight ship with integrated solar and wind energy capture and storage, which is in the process of development. Currently, feasibility studies are being carried out on three large ships -Belgrano, Nord Gemini and Bulk Chile-, in which on-board tests will be carried out, in addition to data collection.

This will help determine aspects such as the power that this technology can provide and the size that solar installations could reach.

Figure 24: First freight ship designed to capture wind and solar energy



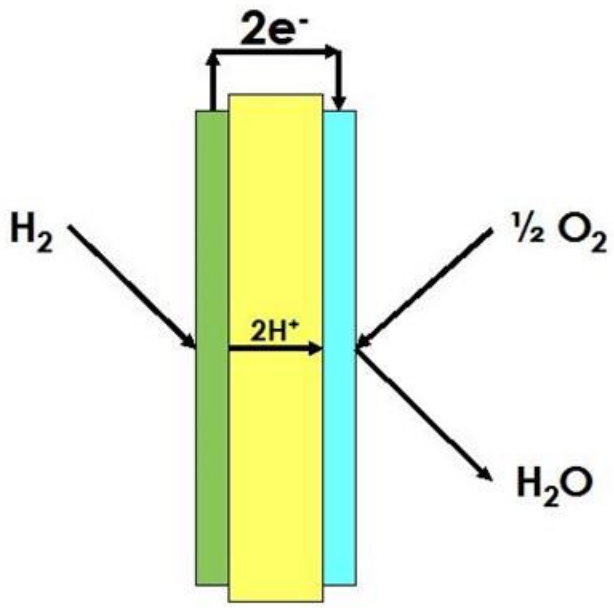
Source: New Ship with Rigid Solar Sails Harnesses the Power of Sun and Wind at the Same Time https://futurism.com/new-ship-rigid-solar-sails-harnesses-power-sun-wind-same-time

Once the study is finished, one of the vessels will be selected to start the testing phase of the system, which will last between a year and a year and a half. At the end of that period, and if the results are in line with the expectations generated about this technology, the substantial reduction of the carbon footprint of the maritime transport sector could be closer.

Annex 3: How does a hydrogen fuel cell work?

A fuel cell is capable of transforming the chemical energy stored in the reactants into electrical energy without having to go through the thermal and mechanical energy stages, which is why its efficiency is greater than that of the internal combustion engine. The idea is to collect the electrons that are transferred during the electronic reconfiguration that gives rise to the products and make them pass through a conductor, generating an electric current. To achieve this direct transformation, fuel cells use electrochemical reactions, which are not the same as chemical reactions. But how do you collect those electrons? The key is to separate the electron release reactions (oxidation reaction) and electron uptake reactions (reduction reaction), in this way the transfer of electrons occurs over a long journey. Thus, what is done is to separate the supply of the fuel and the oxidant, so that the electrons are released when the fuel oxidizes and these are conducted until they reach the place where the oxidant is reduced.

Figure A: Diagram of operation of a hydrogen fuel cell.



Source: Santiago (2016a).

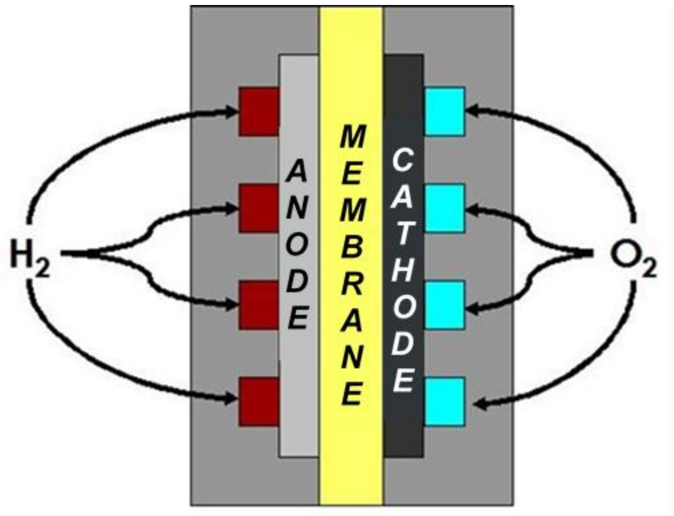
$$H_2 + 0.5\ O_2 \leftrightarrow H_2O \qquad (1)$$

$$H_2 \leftrightarrow 2H+ + 2e^- \qquad (2)$$

$$0.5\ O_2 + 2H^+ + 2e^- \leftrightarrow H_2O \qquad (3)$$

Let's look at equation (1), in it the combustion of hydrogen is presented, which is what would take place during a direct reaction of hydrogen with oxygen. However, if that reaction is separated into two that take place separately (2) and (3) we can take advantage of the flow of electrons. Equation (2) represents the oxidation of hydrogen (electrons are released), while in (3) the reduction of oxygen takes place (electrons are captured). Technically this is outlined in Figure A above. The fuel (hydrogen) is supplied to an electrode (anode) on which a catalyst is deposited that allows accelerating the oxidation reaction of the fuel. On the other hand, the oxidant (oxygen) is supplied to a different electrode (cathode) on which there is also a catalyst that makes it possible to increase the speed of the reduction reaction. As can be seen, between the two electrodes there is a membrane which has a double function. On the one hand, separate the flow of reactants since if they were mixed this would cause both reactions to take place on both electrons. Second, it acts as an electrolyte, which means it has free ions that can move around. Usually, this membrane is of the PEM (*Proton Exchange Membrane*) type, which means that it has free protons (H+).

Figure B: Independent feeding of reactants to each electrode through the channels of the supply plates.



Source: Santiago (2016a).

By joining the electrodes, there is a flow of electrons that can be used to power an electric motor, for example, as in the case of boats that work with hydrogen batteries. Obviously there are different configurations, catalysts and structures, but they are all based on the same concept, to separate the oxidation and reduction reactions.

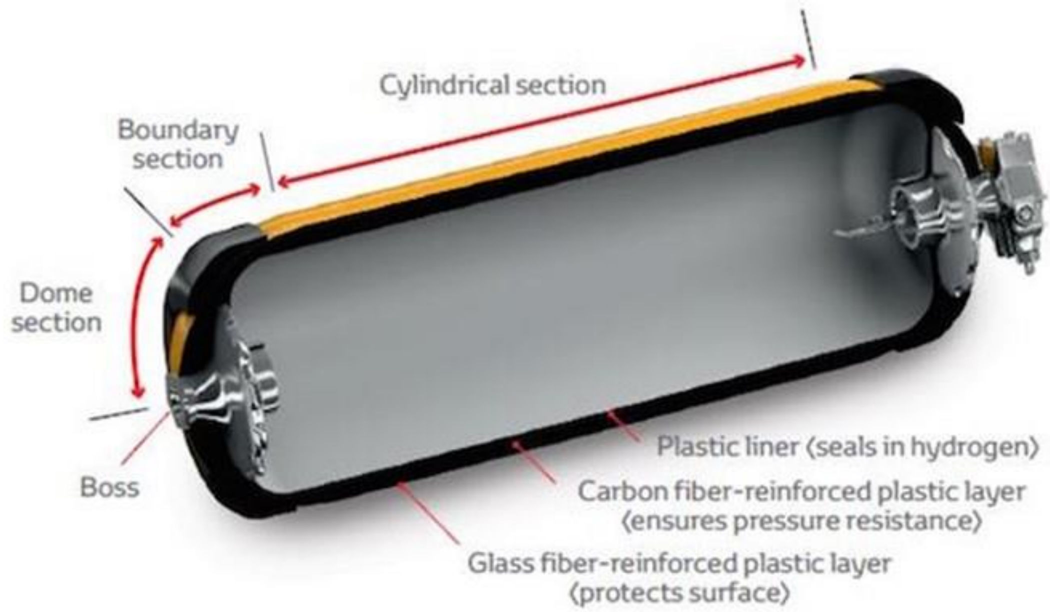
Annex 4 Methods for hydrogen storage

Following Santiago (2016), for a long time, the availability of a suitable system for hydrogen storage was one of the biggest obstacles to the large-scale use of hydrogen, especially in the Transport Sector. The problems for confining hydrogen derive from its physical and chemical characteristics, since although hydrogen is a fuel that has a high energy density per unit mass, it has a very low volumetric energy density, both in liquid and gaseous states. In addition, hydrogen has great diffusivity and permeability which makes it capable of diffusing even through solids, which entails both the loss of stored fuel that is discharged into the atmosphere, and the possible embrittlement of the metals used to confine the element, steel, for example.

Compared to other fuels, hydrogen requires larger tanks to store the same amount of energy. Due to the low density of hydrogen, its storage always requires large volumes and is associated with high pressures, with very low temperatures and/or in combination with other materials (much heavier than hydrogen itself).

The most common way to store hydrogen is in high pressure tanks. Typical storage pressures are 200 bar, 350 bar (standard years ago for tanks that were mounted on vehicles) and 700 bar, which is currently the standard used in the automotive industry. In laboratories, pressurized gases such as nitrogen or oxygen are usually stored in bullets or steel cylinders, however, these types of tanks are not practical for most hydrogen applications because they are very heavy. For this reason, light tanks have been developed based on composite materials, such as those mounted on the *Toyota Mirai* that have three layers. An inner layer made of a nylon-based plastic polymer with low hydrogen permeability. An intermediate layer of epoxy resin with carbon fiber that gives the tank structural rigidity. And finally, an external shell made of a fiberglass-based composite material to protect the tank from possible abrasions. In this way, by using composite materials, it is possible to significantly reduce the weight of the tanks to be shipped.

Toyota Mirai high pressure hydrogen tank



Source: Santiago (2016b).

Table: Volume required to store 1 kg of hydrogen at 20ºC as a function of pressure.

Pressure (MPa)	0.101325	200	350	700
Volume (L)	11934	68.4	42.7	25.7

Source: Santiago (2016).

Another option is to store hydrogen in a liquid state, however, for hydrogen to be in a cryogenic state it is necessary to maintain a temperature of -253 ºC. Therefore, to liquefy hydrogen a certain amount of energy is required to lower the temperature to 20.3 K above absolute zero, in addition, strongly insulated tanks are also needed to keep such a low temperature. This is a method of storing relatively large amounts of hydrogen. By this method, hydrogen cannot be stored for long periods of time, due to the cost of keeping hydrogen in a liquid state and the losses that may occur. BMW has developed and used liquid hydrogen technology in prototypes in which it has used small tanks.

The third option, which is currently one of the least used, however, one that is being studied the most is the storage of hydrogen in the form of metal hydrides. Various metals and alloys such as magnesium, titanium, iron, manganese, nickel or chromium form metal hydrides when in the presence of hydrogen. Hydrogen atoms are packed into the metal framework, thus higher hydrogen storage densities can be achieved than with compressed hydrogen. In a similar way to what happened with steel cylinders, the problem with this type of storage is that metals are very heavy per se, which can weigh on different applications in which weight is a determining factor. To release hydrogen from metal hydrides for use, heat is required, in fact, the waste heat generated by the fuel cell itself is sufficient to release hydrogen from the low temperature metal hydride lattice. Although, it is not released instantly.

To date, a solution to hydrogen storage has been achieved that appears to be good enough to be marketable, at least in the automotive sector. That is, tanks made of different layers of composite materials that allow the safe storage of hydrogen under pressure. However, there are a large number of lines of research open around hydrogen storage, because although a first solution to the problem has been achieved, it may not be the best or the cheapest. In addition, for applications other than automotive, it is possible that the use of cryogenic hydrogen, space applications, for example, or in the form of metal hydrides present a greater utility than compressed hydrogen.

Annex 5: Alternative Fuels for Vessels. Current technological options, their advantages and main challenges for their use in vessels.

Alternative Fuel	Technology	Advantages	Challenges
Liquefied natural gas (LNG)	Natural gas stored as a cryogenic liquid. The temperature required to condense natural gas depends on its precise composition, but is generally between -120 and -170 ° C (-184 and -274 °F). LNG carriers have used this alternative fuel for more than 40 years now, mainly as a result of conveniently making use of cargo vapors due to impossible 100% insulation effectiveness. On-board storage of LNG is typically a challenge for ship design. Engine concepts include gas-only engines, dual fuel 4-stroke and 2-stoke.	- **Environment**. Environmental gains, both in GHG emissions and other relevant substances such as NOx, SOx and Particulate Matter. - **Availability**. Increasing availability of natural gas sources. - **Energy content**. Energy density comparable to gasoline and diesel, expanding range and reducing refueling frequency. - **Promotion**. Significant number of first-movement initiatives with more than 60 (sixty). - **Profitable**. LNG achieves a higher reduction in volume than compressed natural gas (CNG) so that the (volumetric) energy density of LNG is 2.4 times greater than that of CNG or 60 percent that of diesel fuel.	- **GHG Impact**. LNG is mostly composed of Methane (CH4) - comparative impact of CH4 on climate change is more than 25 times greater than CO2 over a 100-year period. Careful consideration needs to be given to any form of methane release throughout the Well-to-Wake chain of LNG (i.e., over the life cycle of the fuel). - **Capital investment**. High investment costs. - **Supply**. The LNG supply infrastructure is still in the early stages of development. - **Safety**. Safety concerns associated to Low flashpoint and cryogenic nature of LNG.
Compressed natural gas (CNG)	Natural gas stored in high pressure tanks of 20 to 25 MPa (200 to 250 bar, or 3,000 to 3,600 psi).	- **Environment**. All the environmental benefits of LNG. - **Safety**. No associated cryogenic risks, compared to LNG technology. - **Small Vessels**. CNG can be a good considerable option for small crafts where the demanding systems associated to cryogenic temperatures and insulation cannot be afforded.	- **Energy Density**. Energy density 2.4 times lesser than LNG, making it an even bigger challenge for on-board storage. - **Technology**. Engineering barriers associated with high pressure / high capacity containers. - **Pressure**. Challenges for on-board management for the insulation of high-pressure containers.

Liquefied Petroleum Gas (LPG)	Liquefied petroleum gas is a clean-burning fossil fuel that can be derived from crude oil and natural gas; the bypass can be propane, butane, propylene and ethylene.	- **Environment**. Environmental gains, both in GHG emissions and other relevant substances such as NOx, SOx and Particulate Matter. - **Availability**. It is produced as a by-product of natural gas processing and oil refining. - **Energy content**. High octane rating and excellent properties for spark-ignited internal combustion engines.	- **Gas Composition**. LPG can vary widely in composition, leading to variable engine performance and cold starting performance. - **Gas Density**. Unlike natural gas, LPG is heavier than air, and thus will flow along floors and tend to settle in low spots, such as basements. Such accumulations can cause explosion hazards.
Methyl/Ethyl Alcohols (Methanol/Ethanol)	Colorless liquids that can be produced from natural gas, coal, biomass, or even CO2. STENA Germanica, a 240 meter long, 51,000GT Ro-Pax carrier, has undertaken retrofit conversion for the use of methanol as an alternative fuel under the project entitled "Methanol: The marine fuel of the future", a pilot action that was granted 50% support by the EC under the 2012 Trans-European transport network (TEN-T) multi-annual program.	- **Environment**. Emissions of sulfur (SOx) are reduced by roughly 99 percent, nitrogen (NOx) by 60 percent, particles (PM) by 95 percent and carbon dioxide (CO2) by 25 percent when compared to fuels currently available. - **Storage**. Fuel stored in liquid form, in atmospheric tanks (particular advantage when compared to LNG). - **Versatility**. Can be burned either on engines using the Otto cycle or on dual fuel Diesel engines. - **Hydrogen and fuel cells**. Methanol has the potential to provide a very good stable and safe Hydrogen carrier. Methanol can be used to produce hydrogen, and the methanol industry is working on technologies that would allow methanol to produce hydrogen for fuel cells.	- **Energy content**. Lower heating value compared to Diesel or LNG, resulting in lower performance when compared to other marine alternative fuels like LNG. - **Corrosiveness**. Fuel storage tanks and fuel distribution system equipment must be corrosion and damage resistant due to the corrosive nature of ethyl/methyl alcohols. Bunkering requires use of non-corroding hoses and stainless steel fuel tanks. - **Fire characteristics**. Methyl/Ethyl alcohols pose challenges to fire detection and firefighting techniques. With a flame which can hardly be seen it is important to develop quickly available and easy-to-use thermal imagery for fire visualization. Substantial research is ongoing in this area. - **Toxicity**. Methyl/Ethyl alcohols are toxic to humans when ingested or when their vapors are inhaled. - **Low viscosity**: The viscosity of DME is lower than that of diesel by a factor of about 20, leading to potential increased amount of leakage in pumps and fuel injectors.

Di-Methyl Ether (DME)	Di-Methyl Ether (typically abbreviated as DME), also known as methoxymethane, wood ether, dimethyl oxide, or methyl ether, is the simplest ether. It is a colorless gas, slightly narcotic, non-toxic, highly flammable at ambient conditions, but can be handled as a liquid when slightly pressurized. The properties of DME are similar to those of Liquefied Petroleum Gas (LPG). DME is degradable in the atmosphere and is not a greenhouse gas.	- **High oxygen content**. DME contains 35% oxygen by weight. Together with the absence of any C–C bonds it is responsible for its smokeless combustion, low formation and high oxidation rates of particulates. - **High cetane number**. DME has a high cetane number (N55) compared to diesel fuel (40-50), resulting in a low autoignition temperature and near-instantaneous vaporization. - **Low Boiling point**. Low boiling point (-25°C) leading to quick evaporation when a liquid-phase DME spray is injected into the engine cylinder. - **Low injection pressure**. DME vaporizes immediately during injection, due to its low boiling point, even though it is injected as a liquid. Therefore, the high fuel injection pressures, such as 50–150 MPa, used in modern diesel injection systems are not required for DME.	- **Energy content**. Low combustion enthalpy: The low calorific value of DME is only 64.7% of that of diesel (Ying et al., 2008), which necessitates a larger injected volume and longer injection period for DME in order to deliver the same amount of energy to that provided by diesel. - **Low viscosity**. The viscosity of DME is lower than that of diesel by a factor of about 20; causing an increased amount of leakage in pumps and fuel injectors. - **Low Boiling point**. Due to the low boiling point of DME (248 K), it is a gas under standard atmospheric conditions and therefore must be pressurized in a fuel system, including a storage tank, and handled like a liquefied gas. Thus, the low boiling point of DME requires a closed pressurized fuel system. The vapor pressure of DME, roughly the same as LPG, demands the same kind of handling and storage considerations as for LPG. - **Low lubricity**. The lower lubricity of DME when compared to diesel fuel may lead to wear problems (this is a similar concern with alcohol fuels). - **Long injection period**: The low liquid density and low calorific value require a higher volume of DME to be injected into the cylinder, compared with that for diesel fuel. 1.8 times the volume of diesel is required (to supply the same amount of energy), which requires a longer injection period. - **Sealing material**: Compatibility of DME with elastomer / plastics from sealing material needs to be carefully addressed in the design / retrofit of the engine. PTFE (Polytetrafluoroethylene) is one of the few elastomers with approved compatibility.

Diesel (biodiesel) (Note: biodiesel is biofuel. Other alternative fuels such as ethyl / methyl alcohols or DME can also be "biofuels". For the present table it was found advantageous to feature some of the potential biofuels separately due to their individual physical-chemical differences).	The use of diesel can be considered as an alternative when non-conventional feedstock or production methods are considered. Among the available alternatives are synthetic diesel obtained from natural gas, soybean and rapeseed methyl ester and synthetic biodiesel obtainable from biomass. Biodiesel can be derived from edible and/or non-edible crops and algae. Waste-generated biofuels have many benefits, but bear challenges in securing the necessary production volumes. Biodiesel can be mixed with conventional fossil fuels to form fuel blends for conventional engines.	- **Availability**. Wide variety of possible sources, from crops to organic waste. - **Bio-degradable**. Bio-degradability is another advantageous feature of biofuels, posing far less of a risk to the marine environment in the event of a spill. - **Emissions**. Biodiesel combustion in a conventional Diesel engine results in reduction of greenhouse gas emissions and particulate matter compared to HFO fuel. - **GHG Impact**. High potential for low impact in GHG effect. Reduction in CO2 equivalent emissions, when compared to traditional oil fuels, can go up to 65%. - **Carbon Self-sustainability**. Emission of carbon to the atmosphere can balance out with the potential for carbon-absorption in special dedicated systems.	- **Land Use**. Land use is an important parameter of the biofuel life-cycle environmental footprint; indicatively, the production of 300MTonnes of Oil Equivalent (TOE) biodiesel based on today's technology requires about 5% of the current agricultural land in the world. - **High production costs**. Still with insufficient economy of scale the production cost for biodiesel can be considerably high. It will also depend significantly on the availability and accessibility of biomass for fuel production. - **Physical-chemical stability**. Concerns related to long-term storage stability of biofuels on board ships, and issues with corrosion also need to be addressed. - **Monoculture**. Monoculture refers to practice of producing same crops year after year, rather than producing various crops through a farmer's fields over time. While, this might be economically attractive for farmers but growing same crop every year may deprive the soil of nutrients that are put back into the soil through crop rotation.

Synthetic and Paraffinic Diesel	Paraffinic diesel is a liquid fuel that can be created synthetically from raw materials such as natural gas (GTL), biomass (BTL) or coal (CTL); or by hydro-treatment of vegetable oils or animal fats (HVO). These high-quality fuels burn cleaner than conventional crude-oil based diesel fuels and are thus able to reduce local harmful emissions such as nitrogen oxides and particulate matter (i.e., less visible black smoke).	- **Environment**. Possible environmental benefits can be very advantageous, depending mainly on the process used to synthetize the fuel and whether a Carbon Capture System (CCS) is used. The life cycle of GHGs. - **Versatility**. Different Fuel compositions are possible, depending on the potential applications. Marine Fuels could benefit from synthetized process fuels. - **Cost-Benefit**. Without the need to make modifications in current diesel-engines, the introduction of synthetic fuels could be done without significant capital cost investment. - **Availability**. The broad number of potential sources for synthetization, and the diversity of production processes result in a higher available fuel source.	- **Environment**. The Environment, also presented as an "Advantage" can also be a clear disadvantage of synthetic fuels, especially with regards to GHG life cycle footprint of these fuels. Production processes can be the major contributor to this with a significant amount of energy used to synthetize paraffinic fuels. - **Sustainability**. Despite having the potential for significant environmental benefits, and to bring a cleaner and cost-effective alternative to oil-based fuels, synthetic fuels are still being produced from a finite source. A sustainable biomass source would be the way to make paraffinic/synthetic fuels a sustainable solution. - **Production costs**. Due to substantial/complex production chain, synthetic fuels can be costly when compared to oil-based fuels.

Shore Side Electricity (SSE)	Electricity supplied to ships through a connection to the local electrical grid. Shore side electricity has been defended by many institutions as the key solution to solve local environmental impact of shipping close to higher populated areas. Many different technical challenges and uncertainty about the demand for shore power supply have led, so far, to a fairly reduced adoption of this alternative solution.	- **Environment**. Local impact from SSE is immediately positive in terms of SOx, NOx and Particulate Matter emissions. GHG impact would depend on the specific CO2 emission factor associated to the available electricity supply. - **Noise reduction**. With connection to energy from the shore there would be no need to have the auxiliary engines running, leading to an immediate noise reduction on-board and in the port area. - **Work conditions**. Significantly improved working conditions, allowing for a more comfortable working environment on-board.	- **GHG Impact**. In countries with high CO2 emission factors for the electricity supply, the use of SSE from the national electricity grid would lead to more emissions than using the standard diesel generator on-board. - **Frequency**. The incompatibility 50 / 60Hz would have to be resolved by the installation of a frequency Converter. This would immediately lead to an increase in the investment cost associated to SSE infrastructure. - **Responsibility**. Should any accident occur on-board during switch-over, or during SSE connection period, who would be liable for electrical accidents potentially induced by the grid? - **Connectors**. No standardization exists on SSE connectors. This may cause incompatibility issues in different ports. - **Black-Out**. During switch-over operations from on-board to shore power supply, there is always a very short interruption. This may have operational implications, depending on the type of ship.

Using electricity from batteries	Electricity used from charged batteries, using on-board electrical power generation or shore supply (SSE). Many different on-board solutions for electrical power generation can be considered (co-generation, micro-generation, tri-generation) and still use opportunistic waste heat recovery to produce electricity. Renewable energy sources can also be considered for charging batteries. Whilst SSE represents a solution for the ship, connected, alongside, batteries provide electrical energy for the ship, sailing. It can be considered as an intermediate power storage / carrier with power that may have been produced on-board by many other means (diesel generators, fuel cells, solar panels, etc.).	- **Environment**. Depending on the operational profile and on the electrical power source used, it is possible to have combinations with a potential strong impact on the environment. Reduction of SOx, NOx and particulate matter with strong local impact. Particularly relevant for short distance ferries, connecting inland, port or coastal areas. - **Fuel savings**. Even for a ship producing its own electrical power, the use of electricity from batteries has the potential to reduce the fuel consumption considerably. - **Noise reduction**. A ship operating on batteries is inherently silent. Apart from the comfort for all those on-board it may also represent significant operational advantages. - **New Battery Technology**. Different battery technologies are being the subject of specialized research with the aim of increasing their power density (mainly reducing volume and weight). New battery solutions include metal-sulfur, where the metal is magnesium, sodium, or lithium or metallic oxygen, also referred to as metal-air where the metal is zinc, lithium or sodium. Lithium-air batteries are a promising area of research and development today.	- **Self-Discharge Rates**. Batteries (lead acid, zinc-carbon dry cell and the nickel-cadmium) have significant challenges related to self-discharge rates and memory effect. - **Charging times**. Duration for re-charging, especially if made during shipping, may present restrictive operational condition, depending on the ship type and profile. - **Cargo space**. The available cargo space on-board may be reduced, especially on those vessels who adopt a hybrid solution, with fuel storage and batteries installed. The impact of voluminous and heavy batteries is still a big concern in ship design. **-Life cycle cost**. The battery pack requires is limited to a total number of charge / discharge cycles.

Hydrogen	As an alternative fuel application, hydrogen is generally used in two ways: internal combustion or fuel cell conversion. In combustion, it is essentially burned as conventional gaseous fuels are, whereas a fuel cell uses the hydrogen to generate electricity that in turn is used to power electric motors on the vehicle. Hydrogen gas must be produced and is, therefore, an energy storage medium, not an energy source. The energy used to produce it usually comes from a more conventional source. Hydrogen holds the promise of very low vehicle emissions and flexible energy storage; however, many believe the technical challenges required to realize these benefits may delay hydrogen's widespread implementation for several decades.	- **Energy Density**. Liquid hydrogen, compressed at 700 bar, has a specific energy (KJ / Kg) more than 3 times higher than diesel/gasoline. - **Availability**. Hydrogen is a very abundant element in nature. It has however to be produced, involving significant cost. - **Environment**. Liquid Hydrogen generates no emissions to the atmosphere (does not contain SOx, CO2 or particulate matter). NOx can result from the combustion of H2 with air (O2 + N2) but not from Fuel Cells that only produce water (H2O). - **Versatility**. Through different production processes hydrogen can be obtained from many different sources making the production chain versatile. - **Non-Toxic**. Unlike many other fuels, Hydrogen is also non-toxic. - **Sustainability**. Hydrogen, as it was already pointed above, is widely available in the nature. It is a molecular element contained in many available sources. It is however not directly available and has to be produced by industrial processes. Currently, the majority of hydrogen is produced from fossil fuels by steam reforming or partial oxidation of methane and coal gasification with only a small quantity by other routes such as biomass gasification or electrolysis of water. However, there is good potential for hydrogen production if hydrolysis is chosen as the preferred way forward, along with energy from renewable sources. - **Diffusivity**. Hydrogen is lighter than air and diffuses rapidly. Hydrogen has a rapid diffusivity (3.8 times faster than natural gas), which means that when released, it dilutes quickly into a non-flammable concentration.	- **Reduced Experience**. Hydrogen has been largely untried in the marine industry for propulsion purposes. - **Safety**. Even though hydrogen is today largely understood and dealt with under very strict safety measures, it is still a gas with a low LFL (4% in air) and with the largest flammability range (from 4% LFL to around 70% UFL). - **Infrastructure**. There would be the need for a substantial hydrogen supply, distribution and bunkering infrastructure to make it viable for the marine industry. - **Cost**. Production Costs pose a challenge to Hydrogen viability as an alternative fuel, especially when compared with other fuels. - **Storage**: Hydrogen storage is today a significant area of discussion and research. An important fundamental note is that whilst hydrogen holds a high specific energy (MJ/Kg), its Energy Density (MJ/m3) is quite low. Thus, to carry a similar amount of energy onboard to that of hydrocarbons would require a very large tank volume. Compression and / or liquefaction are therefore the two strategies most commonly applied to achieve a satisfactory storage of energy for mobile applications. Research is ongoing in other areas and strategies for Hydrogen storage, either chemically or physically. In chemical storage, ongoing research areas include: Metal Hydrides, Non-Metal Hydrides, Carbohydrates, Synthesized Hydrocarbons, Liquid Organic Hydrogen Transporters (LOHC), Ammonia, Borane Amine Complexes, Liquids Ionic imidazolium, Phosphonium borate, Carbonite substances, Organometallic scaffolds, Encapsulation.

Fuel Cells	Fuel cells are not, by themselves, an alternative fuel. In fact, they are an excellent engine, transforming the electrochemical potential energy of hydrogen (H2) into electrical energy that is then stored in batteries. Among the different technologies are: • alkaline fuel cell (AFC), • proton exchange membrane fuel cell (PEMCF), • High temperature PEMFC (HT-PEMFC), • Direct Methanol Fuel Cell (DMFC), • phosphoric acid fuel cell (PAFC), • Molten Carbonate Fuel Cell (MCFC) • solid oxide fuel cell (SOFC)	- **Environment**: Fuel cells are hydrogen consumers. Water is the only product of Fuel Cells operation (when no reforming is considered). Liquid Hydrogen generates no emissions to the atmosphere (does not contain SOx, CO2 or particulate matter). NOx can result from the combustion of H2 with air (O2 + N2) but not from Fuel Cells where only fresh water (H2O) results. - **On-board energy integration**. Fuel Cells are electrical energy production units. They can be used in different arrangements favoring different ship design arrangement options. - **Noise**: With no mechanical work involved and no combustion processes, Fuel Cells are silent and have the potential in applications.	- **Power density**, **MJ/m3 (or specific power, MJ/kg)**: fuel cells have relatively low power outputs compared to internal combustion engines, for installations of the same volume/weight, although recent developments with hybrid cycles gave rise to the possibility for higher power solutions. - **Reforming**: When the storage of hydrogen is not considered along with the fuel cell installation reforming needs to be considered. By reforming methanol, LNG. - **Hydrogen**. The storage and use of hydrogen on board is not yet regulated and is only possible through alternative design arrangements. - **Energy Efficiency/Waste Heat recovery**: High temperatures are a characteristic associated to the operation of fuel cells (in particular MCFC, SOFC and HT-PEM). Waste heat recovery strategies have the potential to increase significantly the energy efficiency of fuel cells. - **Low responsiveness to load variations**. Fuel Cells have a slow response to load variations. Batteries can be used for “buffering”.

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