H2SHIPS

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

Development of a tool for the feasibility analysis of innovative propulsion systems for Inland Waterway vessels.

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Abstract

The exploitation of the inland waterways for commercial use is considered in Rhine and Danube regions as a key factor to decrease the road congestion and reduce the pollutant emissions due to transportation sector. Today, almost 100% of inland vessels are fuelled by gasoil and in order to bring together the targets regarding a better exploitation of the existing waterways and decarbonisation of the whole transportation sector the development of new and zero-emission propulsion systems need to be investigated.

The aim of this work has been that of developing an approach for the feasibility analysis of the application of fuel cell based propulsion systems onboard Inland Waterway vessels and analyse the potential and the limits of these applications. A market research on hydrogen production has been carried out in order to estimate the most plausible cost of hydrogen for supply chains dedicated to the European Inland Waterway network, but also to make some considerations on the most plausible future scenarios.

The core of this work has been the development of a model which allows estimating and comparing the weight, the volume and the Total Cost of Ownership of different propulsion systems considering, as inputs, data regarding vessel geometry, speed, load and a specific operational profile (Origin-Destination distance, number of roundtrip for year).

The propulsion systems which have been considered are:

- Electric engine powered by a battery system
- Electric engine powered by a fuel cell system
- Electric engine powered by a hybrid power supply (Fuel Cell+Battery)
- Internal combustion engine fuelled by Diesel
- Internal combustion engine fuelled by LNG

The usage of the model has been simplified thought a user interface which can be used for entering the inputs and receiving the results.

Besides, the model has been used to make some considerations on the application of fuel cell based solutions onboard representative IWW freight vessels in order to investigate the technical and the economic feasibility and evaluate how future potential scenarios can affect the economic competitiveness of the fuel cell based solutions

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List of Abbreviations

CH2	Compressed Hydrogen
EU	European Union
IWWT	Inland WaterWay Transport
LH2	Liquid Hydrogen
LNG	Liquefied Natural Gas
TCO	Total Cost of Ownership

1 Introduction

The commercial use of inland waterways is considered by EU as a key factor to reduce road congestion in areas where rivers and canals can be exploited, IWWT has the potential to be the most economic, fuel efficient and environmentally friendly inland transport mode and so contribute to the cut of emission in the overall transportation sector. The European IWWT system has an overall length of 41 500 km and covers almost the 6% of the overall inland freight transport with a transport capacity of almost 160 billion ton-km. This transportation mode assumes a crucial importance for the economies of regions where the Inland Waterways are branched and connect important industrial hubs or cities.

In the Netherlands, for example, the IWWT share covers almost 47% of the overall inland freight transport. For these regions the pollutant emissions due to IWWT have a not negligible impact on the environment, as demonstrated by the emission limits in force today for this sector which since 2002 have reduced even of 80%.

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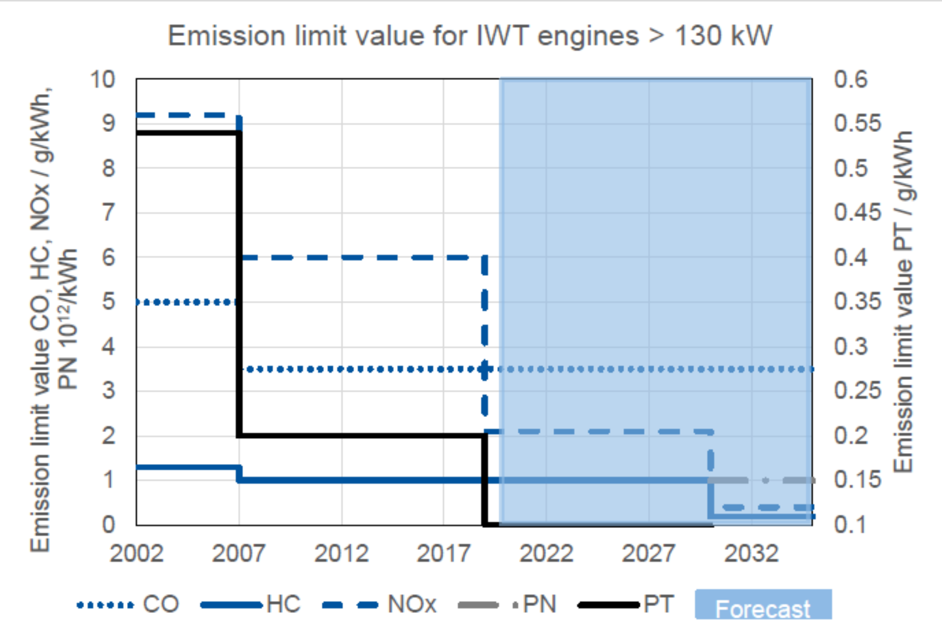

Figure 1 — Emission Limit Values for EU Inland Waterways

This context implies the need to evaluate the application of innovative propulsion systems which allow to overcome diesel engines with electric propulsion systems powered by fuel cells and batteries.

The aim of this work has been that to create a tool to test the technical feasibility of innovative solutions, estimating the weight and the footprint required by the components of the propulsion systems and the Total Cost of Ownership in order to evaluate the economic viability of each solutions.

The Propulsion Systems under analysis are:

- Electric engine powered by a battery system
- Electric engine powered by a fuel cell system
- Electric engine powered by a hybrid power supply (Fuel Cell + Battery)
- Diesel
- LNG

The choice of these systems has been done with the aim of considering the most widespread technology today, Diesel propulsion system, and comparing it to the ones which are expected to play a bigger role in this sector in a near (LNG), or remote future (Fuel Cell and Battery). In this analysis the propulsion system will be described without going in technical details not connected to the model's results and considering, for each propulsion system, the most established technology or, in the case of innovative propulsion system the ones which have been evaluated as more

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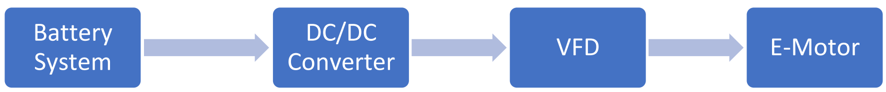
viable. All the components that have been supposed to be shared by each propulsion system, as for example the propeller and the mechanical system for the transmission from the prime mover, have been neglected since they don't add value to the analysis.

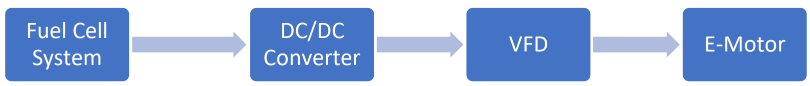
2 Propulsion system modelling

The first step towards the dimensioning of a propulsion system has been that of evaluating the components which most influence the results of the models, and so the Capex, the weight, and the footprint. Technical feasibility analyses and scientific articles have been used for the modelling as well as for the evaluation of the parameters for the dimensioning (weight and footprint estimation) and the cost analysis.

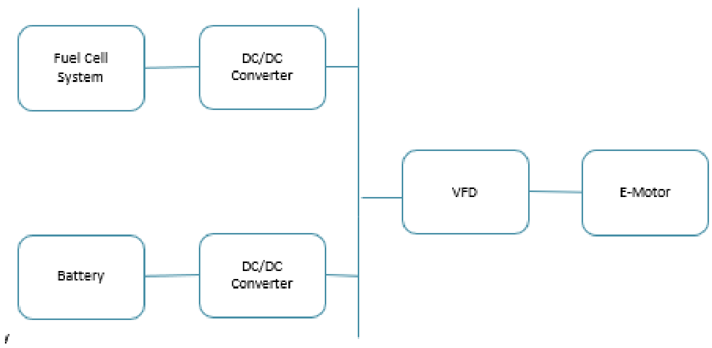
- Battery based Propulsion System



- Fuel Cell based Propulsion System



- Hybrid System



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- Diesel and LNG propulsion system

The weight, the footprint and the acquisition cost of each components has been estimated with parameters or linear relations, which represent the weight, or the volume occupied by each component for unit of installed power or in the case of fuel storage, for unit of fuel stored. The selection of these parameters has been done considering technical reports or catalogues of suitable and available on the market items. The latter approach consisted in the analysis of the relation between the weight or volume of real items, as in the case of e-motor and diesel engine; this has led to the definition of linear relations between installed power and volume and weight. An overview of the parameters used has been provided as an attachment of this report.

3 Tool Interface and working logic

The structure of the model has been created on the basis of the following inputs:

1. Vessel size and type
   a) Hull Length
   b) Hull Breadth
   c) Hull Draught
   d) Vessel type
2. Speed and Load
   a) Max Load Capacity
   b) Average Load Capacity
   c) Max speed
   d) Average speed
3. Propulsive efficiency
   a) Shaft Efficiency
   b) Propeller Efficiency
4. Operational Profile
   a) Origin-Destination Distance
   b) Number of intermediate stops
   c) Number of round trips for year
5. Hydrogen Storage

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The working logic of the model can be described by 5 steps:

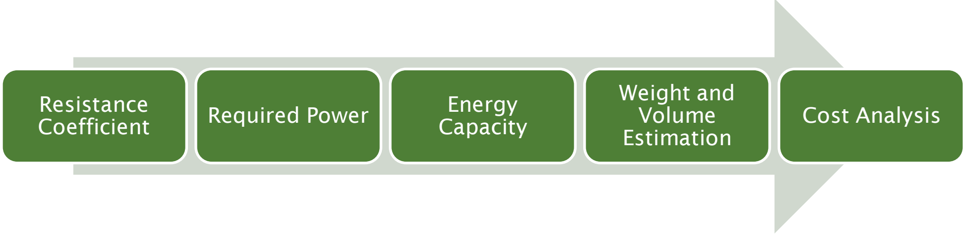

Figure 2 — Tool working logic

Considering the data regarding the vessel geometry the resistance coefficient has been estimated thought a method which have been elaborated considering data regarding real vessels. These data have been used to estimate linear relations between the resistance coefficient and the underwater hull volume of 4 classes of vessels, the underwater hull volume is calculated considering vessel's dimensions and coefficient of form unique for each class of vessel.

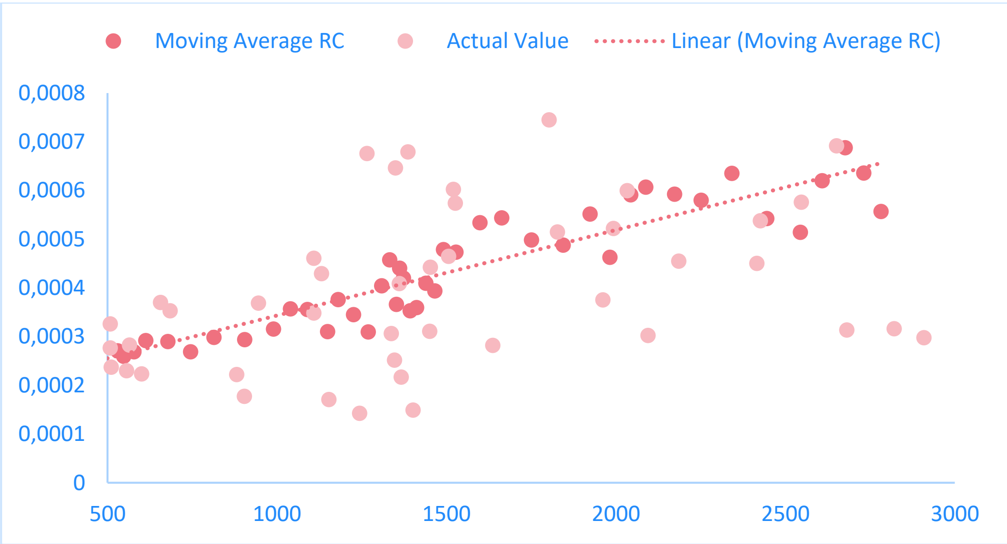

Figure 3 — Cargo: Resistance Coefficient-Underwater hull volume

The resistance coefficient and the max speed in calm water have been used to estimate the power requirements thought the following formula:

$$R = C\frac{1}{2}\rho v^2 A_s \qquad\qquad P_E = C\frac{1}{2}\rho v^3 A_s$$

Equation 1, Installed Power without hull and propeller efficiencies

Where:

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- *C= coefficient of total hull resistance*
- *ρ=water density*
- *As= wetted surface area of the underwater hull*
- *v= max speed in calm water*

This approach is limited to the few inputs which are provided by the user, the results are reliable in the ranges of speed, volumes and powers described in the table below.

	Volume Range (m^3)	Power Range	Max speed range $\frac{Km}{h}$
Cargo	0-1500	<2 MW	12-20
Tanker	0-4000	<2 MW	17-20
Push Boat	0-600	<2 MW	13-14
Passengers	0-2000	<2 MW	18-30

Table 1 — Estimation validity range per ship type

The aim of this method is to provide to the user a way to estimate the vessel's installed power if it is not yet known and so if the tool is used for the pre-dimensioning of a propulsion system. The max speed in calm water must be chosen considering the conditions of the navigation and it is considered as a parameter to overestimate the power when the geometry of the river or the current are particularly difficult.

The installed power will be evaluated considering also the propeller and the shaft efficiency.

The energy capacity has been evaluated as the energy required to the vessel to navigate from the origin to destination port in upstream. For alternative solutions it has been given the possibility to enter one or more intermediate bunkerings in order to reduce the total weight and the total volume occupied by hydrogen storage system. The fuel consumption in upstream, required to size the fuel storage system, and the overall consumption in one year of navigation have been dimensioned considering a unique operational profile which describe the average power during the round trip and the average power during upstream navigation as a function of the installed power.

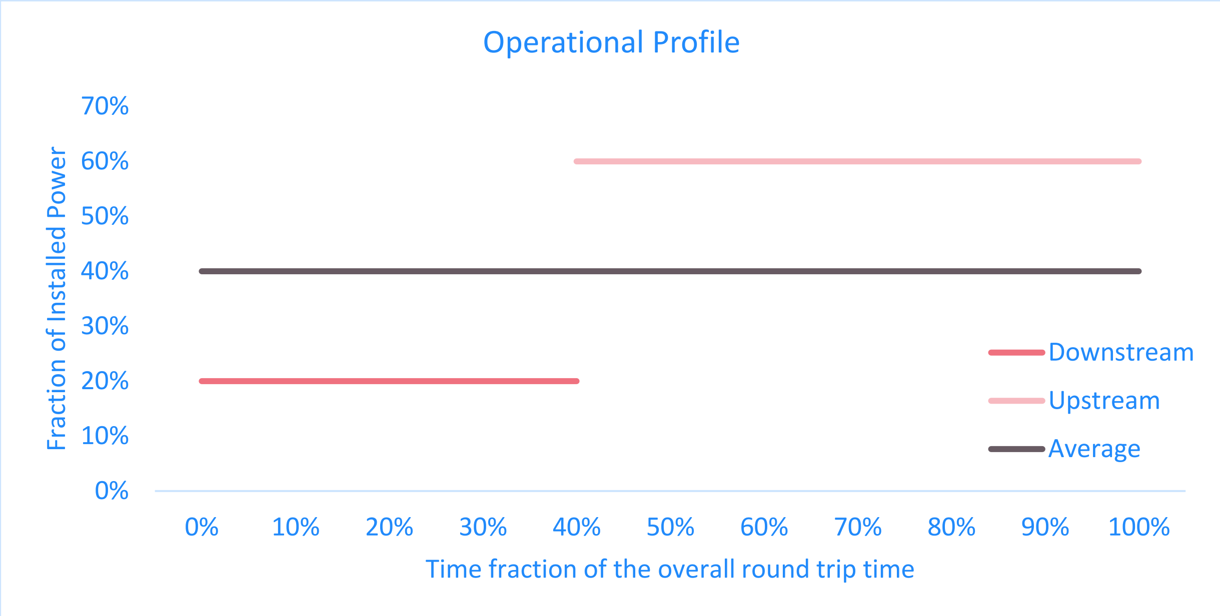

Figure 4 — Operational profile

Using the energy required to navigate from two subsequent bunkerings and the installed power the components of the different propulsion system have been estimated. For hydrogen storage system 6 alternatives can be selected:

- Compressed Hydrogen 700 bar
- Compressed Hydrogen 500 bar
- Compressed Hydrogen 350 bar
- Liquid Hydrogen
- Ammonia storage + Cracking
- Metal Hydrides

For all the solution PEM technology has been considered and so for Ammonia system a cracking system has been included.

A user interface has been created in order to make easier the usage of the tool, it has been developed in Visual Basic and is characterized by two sections, one dedicated to an expert user an one dedicated to a standard user. The main differences between the two sections are that, by the expert user section, it is possible to change the parameters of the model and enter the installed power if it is already known. The user interface has been created in order to be self-explanatory and a detailed description is provided in the attached guide.

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For the economic analysis the TCO (Total Cost of Ownership) approach has been used and it has been estimated both the TCO during the whole lifetime and respect to a single year.

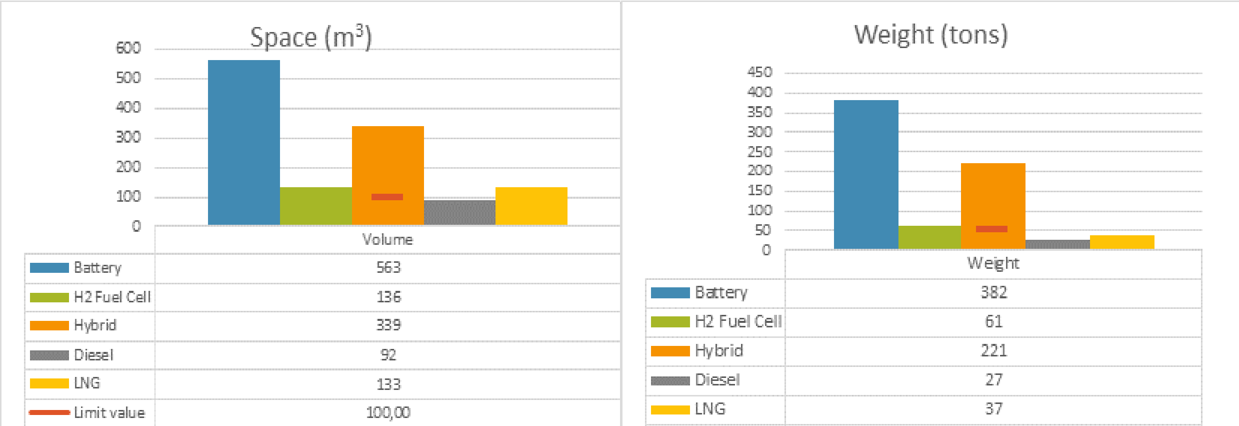

Figure 5 — Example of weight and Space Analysis Results display

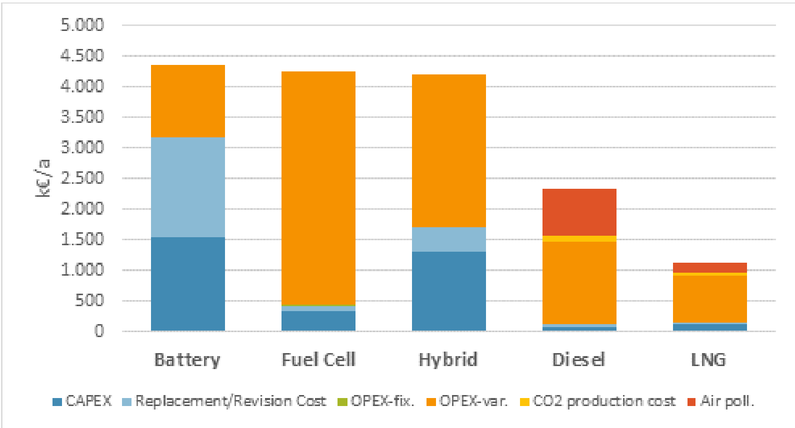

Figure 6 — Example of Annual Total Cost of Ownership Display

4 Case studies Analysis

The tool has been used to make some considerations on the technical and economic feasibility of the innovative propulsion systems under analysis onboard of some representative vessels used for IWW freight transportation in Rhine regions. The data have been collected from the report published for the project PROMINENT called "*Identification of the fleet, typical fleet families &operational profiles on European inland waterways".* The approach used consists, at first, in the comparison of the main parameters which determine the weight, the volume and the cost of each solutions

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and after in the evaluation of the results estimated by the model using the input data of the dataset.

The graphs reported below referred to the weight and the volume occupied by each propulsion system for unit of installed power and energy capacity in the overall system.

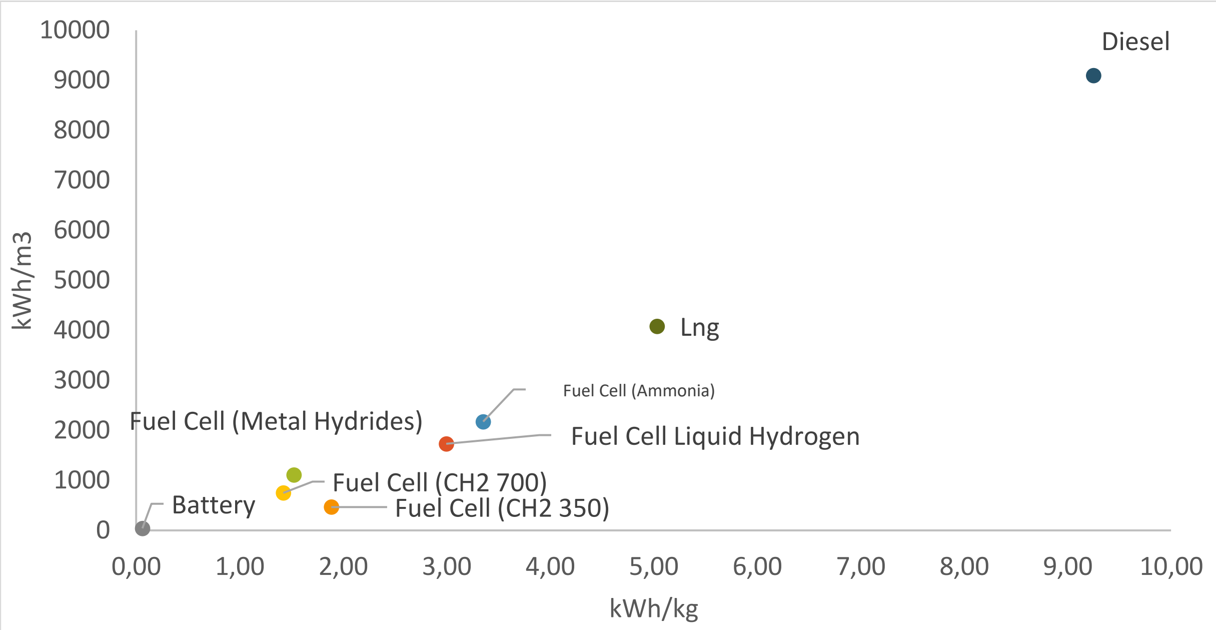

Figure 7 — Storage system weight and Volume per unit of stored energy

Storage System (tank + fuel + auxiliaries)	kWh/kg	kWh/m3
Batteries	0,06	30
Ammonia	3,35	2175
Metal Hydrides	1,53	1110
CH2 350	1,89	466
CH2 500	1,68	599

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CH2 700	1,42	749
Liquid Hydrogen	3,00	1732
Diesel	9,25	9098
LNG	5,03	4084

Table 2 — Storage system weight and Volume per unit of stored energy

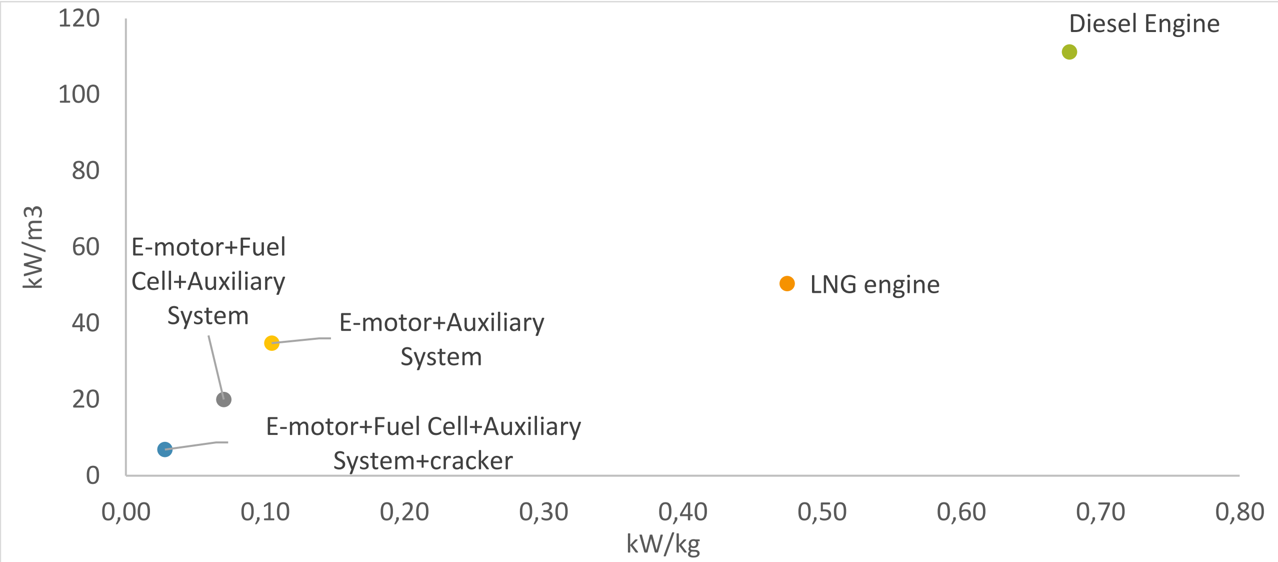

Figure 8 — Weight and Volume Parameters for unit of installed power

	kW/kg	**kW/m3**
Diesel Engine	0,68	111
LNG engine	0,47	50
E-motor + Fuel Cell + Auxiliary System	0,07	20
E-motor + Auxiliary System	0,10	35
E-motor + Fuel Cell + Auxiliary System + Ammonia Cracker	0,03	7

Table 3 — Weight and Volume Parameters for unit of installed power

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Battery-based solutions require the highest mass and volume for unit of energy stored, diesel is the most performing solution both respect to weight and volume. The storage of hydrogen through ammonia carrier allows to reduce the weight and the volume of the tank, but the cracking system will reduce this advantage especially when high power and so high cracking rates are required to the system. Liquid hydrogen represents the most interesting solution in terms of weight and footprint, according to the parameters used in this model

Compressed hydrogen storage requires the highest volumes for the storage of unit of hydrogen, even if 700 bar is used as storage pressure.

The average composition of the total weight and volume is synthesized in the following table using the results estimated for a generic vessel with an installed power of 2500 kW and an energy capacity of 87 MWh.

	Storage	**E-Motor + AE**		**tons**
Battery	98%	2%		1474
			Fuel Cell	
Fuel Cell (Ammonia)	20%	70%	9%	127
Fuel Cell (Metal Hydrides)	61%	26%	13%	93
Fuel Cell (CH2 350)	56%	29%	15%	82
Fuel Cell (CH2 500)	59%	27%	14%	88
Fuel Cell (CH2 700)	63%	25%	12%	97
Fuel Cell Liquid Hydrogen	45%	37%	18%	69
	Storage	**Combustion Engine**		
Diesel	72%	28%		13
LNG	77%	23%		23

Table 4 — Composition of the Total weight

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	Storage	E-Motor+AE		m³
Battery	97%	3%		514
			Fuel Cell	
Fuel Cell (Ammonia)	8%	81%	12%	90
Fuel Cell (Metal Hydrides)	35%	37%	28%	39
Fuel Cell (CH2 350)	56%	25%	19%	57
Fuel Cell (CH2 500)	50%	29%	21%	50
Fuel Cell (CH2 700)	44%	32%	24%	45
Fuel Cell Liquid Hydrogen	26%	43%	32%	34
	Storage	**Combustion Engine**		
Diesel	27%	73%		6
LNG	27%	73%		14

Table 5 — Composition of the Total volume

The weight of the energy storage system represents in all the solutions the biggest fraction of the overall weight of the propulsion system, the only exception is for fuel cell system powered by ammonia. The weight of the battery system is mostly determined by the battery stacks while for fuel cell system even if the storage assumes lower fraction respect also to traditional systems it still maintains value around 60% for metal hydrides and compressed hydrogen and below 50% for liquid hydrogen. The analysis of the volumes of each component shows that the energy storage system remains the most consistent part for battery system and compressed hydrogen, for ammonia powered system it is the cracker to absorb most of the volume occupied, while for liquid hydrogen and metal hydrides there is a balance between the volume fraction of the storage system and other components.

These results are in part influenced by the overestimation factors used for the volumes of the fuel cell system, battery system and combustion engines due to clearances required for access and maintenance. These factors have been derived from literature and are equal to 5 for combustion engines and 2 for fuel cell and battery system.

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The weight and space estimations done on the dataset show that battery-based solutions are too heavy and too bulky to be applied onboard vessels used for IWW freight transportation. Fuel cell-based solutions are instead promising because the difference with diesel solutions are not so high, in particular for mass requirement it has been noted that the total max payload, on this kind of vessels is rarely exploited, and so it can be supposed to reserve part of this difference for an increase of the mass of the propulsion system. **Considering the calculations done in this analysis, reducing the max payload of a minimal fraction, 3%, all the fuel cell solutions can be applied for the routes under analysis**.

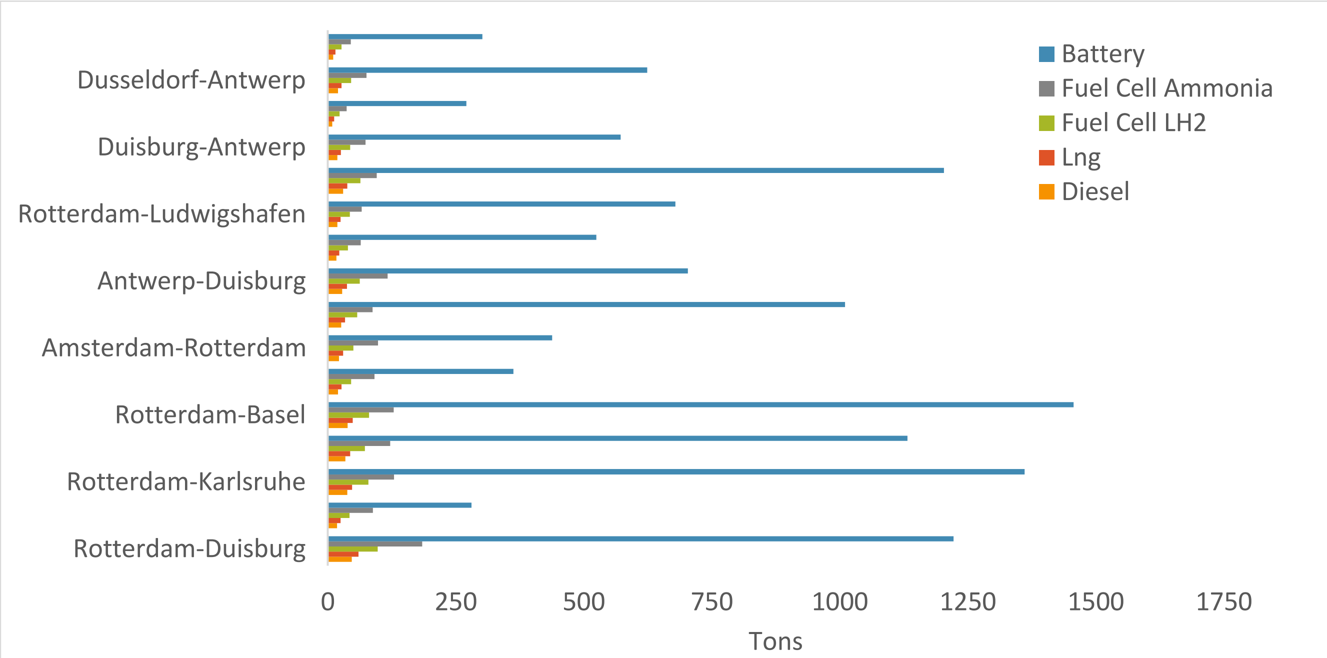

Figure 9 — Mass requirements estimated for the routes of database

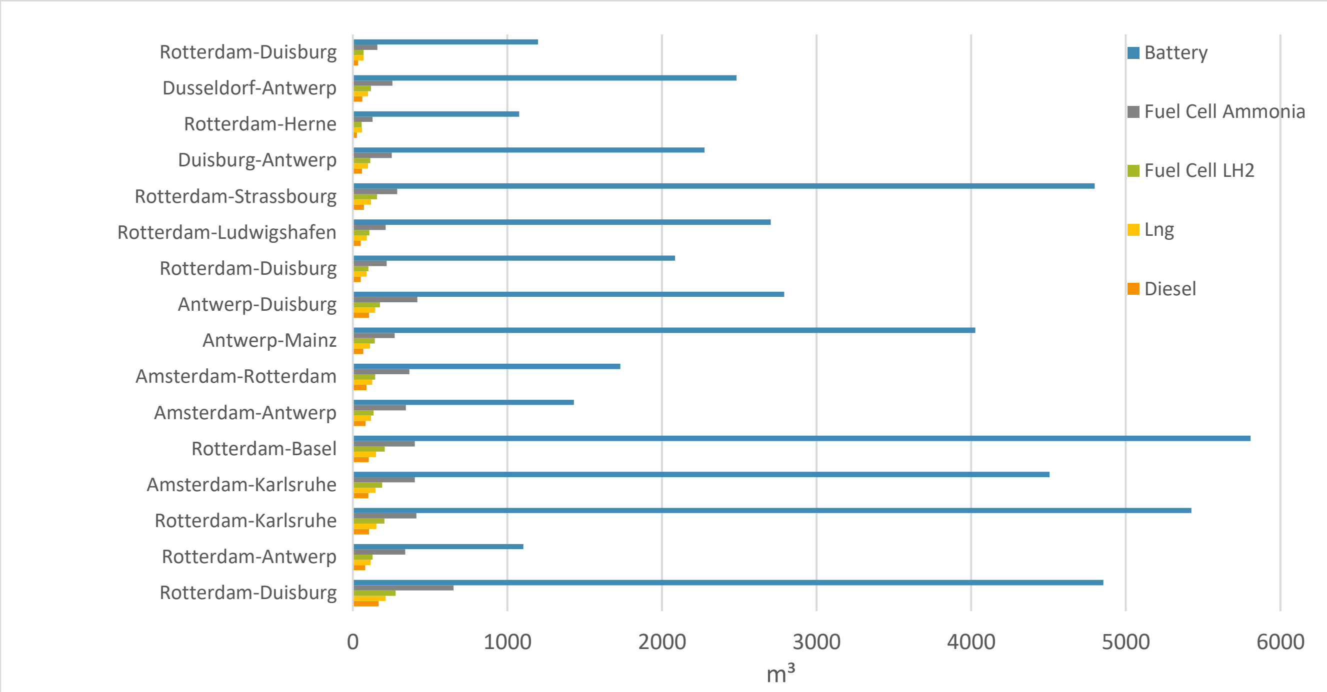

Figure 10 — Space requirements estimated for the routes of database

For the Volume analysis no hypothesis can be done on the available spaces onboard the vessels, because of the lack of useful data, and so the conclusions limited to the definition of an arbitrary limits, fixed at 1,5 times the volume occupied by diesel propulsion systems. Fixing these limits, it has been noted that in order to make most of the fuel cell solutions viable, one intermediate bunkering should be planned during a O-D trips of a distance below 300 km and 2 bunkerings for distance above 300 km. Considering the results reported below Ammonia volume does not respect the volume limit value and so it has been evaluated as a no viable solution.

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	LH2	CH2 700	CH2 500	CH2 350	Metal Hydrides	Ammonia	LNG
Rotterdam-Duisburg	41%	72%	86%	106%	55%	270%	27%
Rotterdam-Antwerp	47%	61%	67%	76%	53%	308%	42%
Rotterdam-Karlsruhe	37%	74%	91%	114%	53%	244%	44%
Amsterdam-Karlsruhe	38%	70%	84%	104%	52%	255%	44%
Rotterdam-Basel	37%	78%	96%	122%	55%	238%	46%
Amsterdam-Antwerp	47%	65%	73%	85%	55%	303%	43%
Amsterdam-Rotterdam	46%	67%	76%	89%	55%	298%	41%
Antwerp-Mainz	44%	88%	107%	134%	63%	250%	64%
Antwerp-Duisburg	46%	75%	87%	105%	58%	284%	38%
Rotterdam-Duisburg	63%	107%	126%	154%	82%	300%	73%
Rotterdam-Ludwigshafen	51%	90%	107%	131%	68%	275%	77%
Rotterdam-Strasbourg	43%	91%	112%	142%	63%	238%	62%
Duisburg-Antwerp	58%	99%	117%	142%	75%	294%	63%
Rotterdam-Herne	89%	134%	153%	181%	108%	361%	133%
Düsseldorf-Antwerp	58%	102%	121%	149%	77%	290%	63%
Rotterdam-Duisburg	75%	112%	128%	152%	90%	338%	101%

Table 6 — Volume Increase in percentage respect to Diesel solution

The economic analysis has shown that the main cost driver is the fuel cost; the fractions of each cost components, reported in the table below, are evaluated considering the annual TCO and a lifetime of 5 years for a vessel of 2500 kW, an energy capacity of 87 MWh and an annual fuel consumption which corresponds, in terms of energy provided to the propeller, at 10 GWh. These input values correspond each to the max value of the features which estimate the cost of vessels in the database. If the min values are instead considered, the percentage of the fuel cost will reduce but still will remain the most consistent fraction. In addiction it is obvious that considering longer lifetime the fuel cost will increase its share on the overall cost.

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	Fuel Cell + E-Motor + Aux	**Storage Capex**	**Opex (Fuel cost)**
Liquid Hydrogen	13,1%	2,5%	84,4%
Compressed Hydrogen 350	14,0%	7,1%	78,9%
Compressed Hydrogen 500	13,4%	8,0%	78,6%
Compressed Hydrogen 700	12,8%	8,8%	78,4%
Metal Hydrides	11,7%	16,1%	72,2%
Ammonia	24,4%	0,6%	75,0%
	Battery System	**E-Motor + Aux**	**Opex (Electricity cost)**
Battery	96%	2%	2%
	Engine	**Tank**	**Opex (Fuel Cost)**
Diesel Solution*	7%	1%	92%
LNG Solution*	19%	2%	78%

Table 7 — Annual TCO components

*CO2 tax and externalities not included.

In the following image it is compared the annual TCO of each types of propulsion system for a specific vessel described in the database, as it can be seen the annual TCO of Diesel varies between 40-50% of the TCO evaluated for fuel cell-based solutions while the LNG represents the cheapest solution.

Type	Cargo
Commodity	Container
Installed Power	1304 kW

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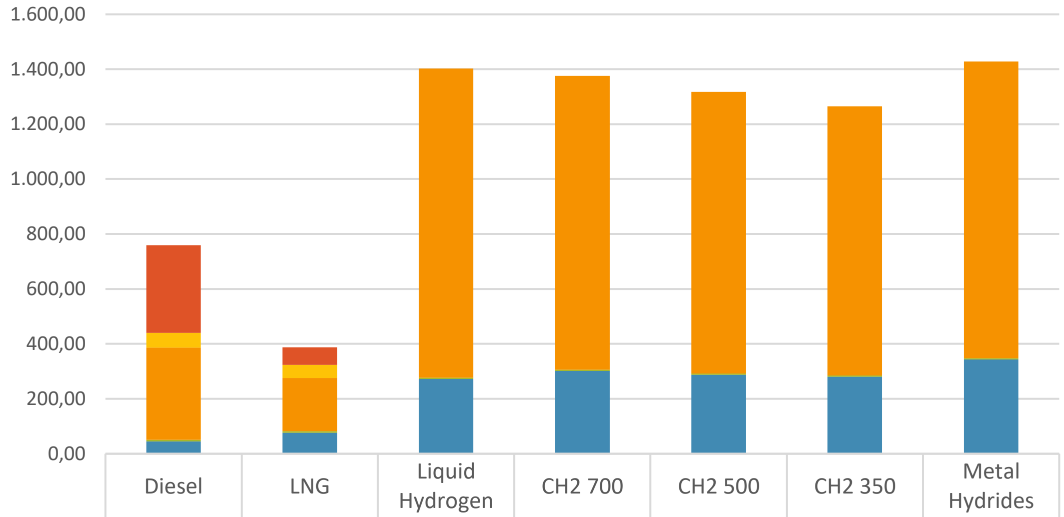
Average power	726 kW
Energy Consumption upstream	30968 kWh
Payload Carried	2710 t
O-D distance	510 km
N. round trips	55
Average speed	10 km/h

Table 8 — Case study input parameter



	Diesel	LNG	Liquid Hydrogen	CH2 700	CH2 500	CH2 350	Metal Hydrides
Air poll./a	320.190	64.038					
CO2 production cost/a	53.365	48.028					
Replacement/Revision Cost	-	-	-	-	-	-	-
OPEX-var./a	335.507	193.241	1.126.262	1.069.948	1.024.898	979.848	1.081.211
OPEX-fix./a	5.764	5.764	4.456	4.456	4.456	4.456	4.456
CAPEX	44.957	76.980	272.259	301.820	287.968	280.273	343.035

Figure 11 — Case study's annual TCO result

The solutions are compared on a lifetime of 10 years, as it can be seen there are no replacement costs in this time fraction for any solutions, Battery solution is the most expensive and it is not reported here since as explained the weight and the volume limit its application for this type of vessels.

Hydrogen solutions have an overall cost which varies in a range which is narrow if compared to the cost difference with Diesel and LNG systems. Liquid hydrogen

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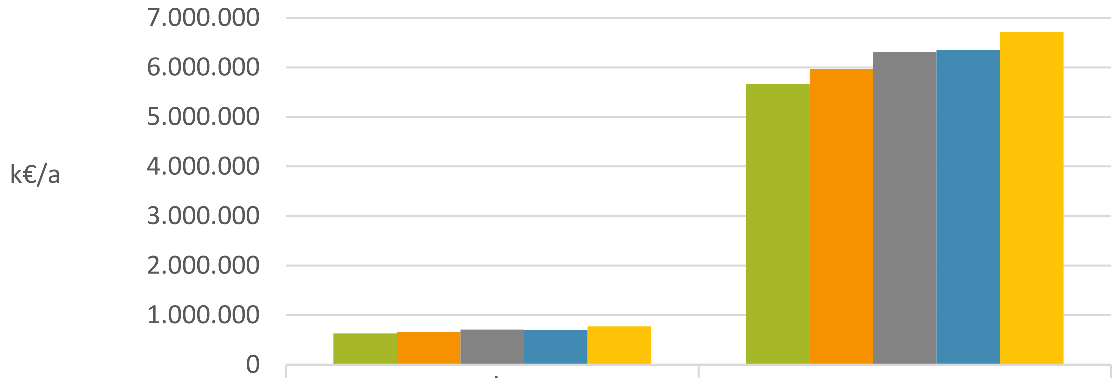
storage has the lowest Capex but the cost for kg of liquid hydrogen is also more expensive respect to other solutions, metal hydride solution is the most expensive because of the high Capex due to the hydrogen storage and, despite the fact the refuelling cost for unit of kg of hydrogen is the lowest 8€/kg, the loss due to the desorption process accounts for almost the 20% of the hydrogen stored and so the cost for kWh, provided to the e-motor, is comparable to the compressed hydrogen at 700 bar. Compressed hydrogen at 350 bar is the solution which, after Liquid Hydrogen, has the cheapest storage cost and, after the Metal Hydride solution has the lowest cost for kg of hydrogen. At the end, considering the energy and the power requirements typical of an IWW freight vessel, it can be concluded that compressed hydrogen at 350 bar is the cheapest alternative to Diesel and LNG propulsion system, but it is also the solution which require more efforts in terms of redesigning of spaces onboard the vessel.



	min	max
Compressed Hydrogen 350	628.726 €	5.669.985 €
Compressed Hydrogen 500	662.933 €	5.965.093 €
Compressed Hydrogen 700	706.086 €	6.312.086 €
Liquid Hydrogen	692.358 €	6.353.345 €
Metal Hydrides	771.733 €	6.717.016 €

Compressed Hydrogen 350 Compressed Hydrogen 700 Liquid Hydrogen Metal Hydrides

Figure 12 — Variation of TCO for fuel cell solutions considering typical input data valid for IWW freight vessel

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5 Scenario Analysis

At a first analysis it has been concluded that fuel cell-based solutions at the actual state of the art are not economically viable because of the big difference in the TCO values estimated. For this reason, they have been investigated future potential scenarios where the main cost parameters, which influence the total cost, have been changed according to the KPIs stated by important associations involved in projects for the development of hydrogen-based technologies, U.S. Department of Energy and Hydrogen Europe. A mid-term and a long-term scenario have been defined considering decreasing hydrogen prices, whose values have been fixed considering the main cost drivers of the supply chain.

Fuel Cell Capex	**Scenario 0**	**Scenario mid-term**	**Scenario long-term**	**Source**
Fuel Cell System Cost €/kg	1000	750	600	KEY PERFORMANCE INDICATORS Hydrogen Europe
Fuel Cell Storage 700 bar €/kg	530,00	400,00	300,00	
Fuel Cell Storage 500 bar €/kg	350,00	264,15	198,11	
Fuel Cell Storage 350 bar €/kg	250,00	188,68	141,51	
Fuel Cell efficiency system	0,56	0,6	0,65	
Liquid Hydrogen Cost	10	8	5,6	Based on own estimation considering the main cost drivers of the supply chain
Cost at nozzle 700 bar €/kg	9,5	6	4	
Cost at nozzle 500 bar €/kg	9,1	5,7	3,9	
Cost at nozzle 350 bar €/kg	8,7	5,4	3,7	
Metal Hydrides	8	5,5	4,5	

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Diesel price	0,71	0,9	1,1	Data on Diesel price variations in Germany
LNG	0,6	0,6	0,6	
Co2 price	25	50	100	IEA parameters for sensitivity analysis

Table 9 — Scenario Analysis Parameters

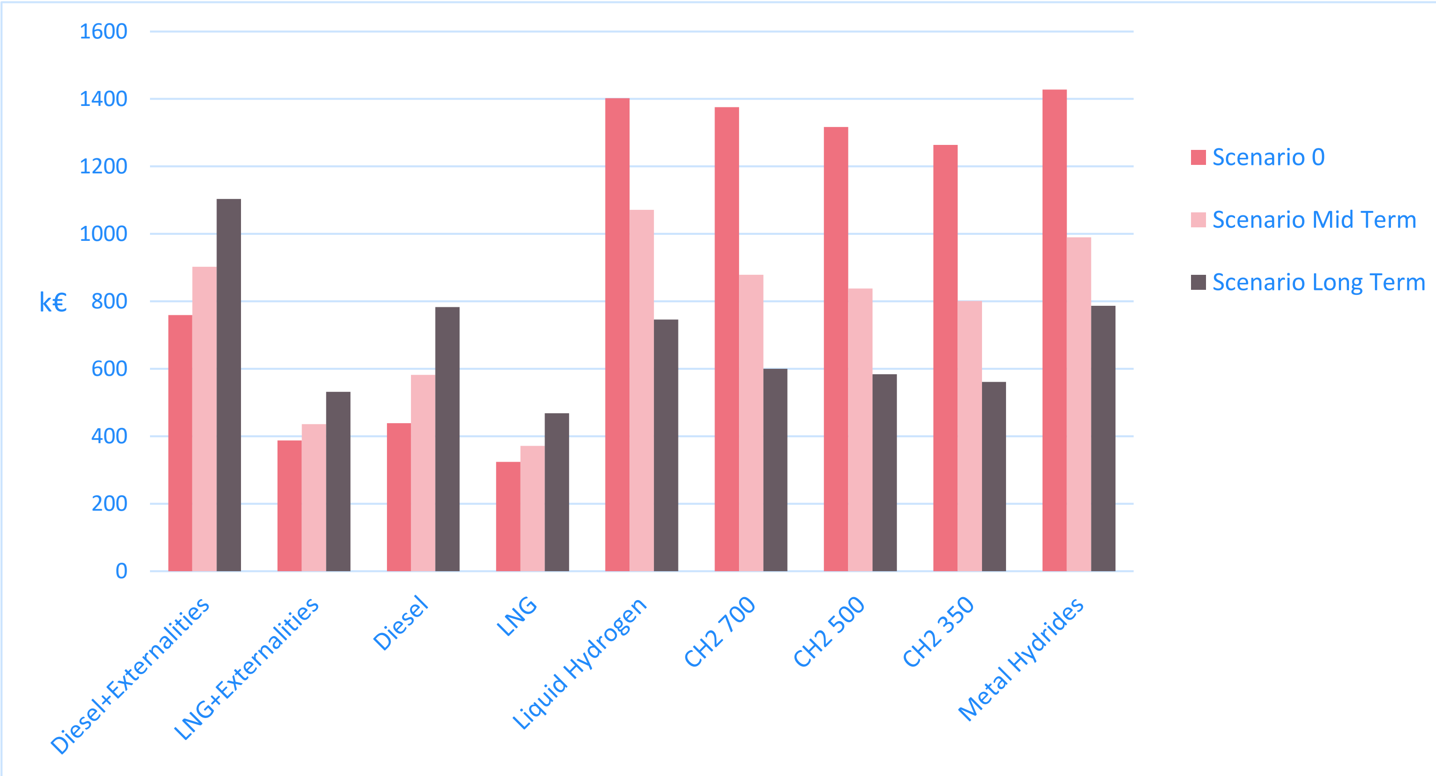

Figure 13 — Scenario Analysis Results

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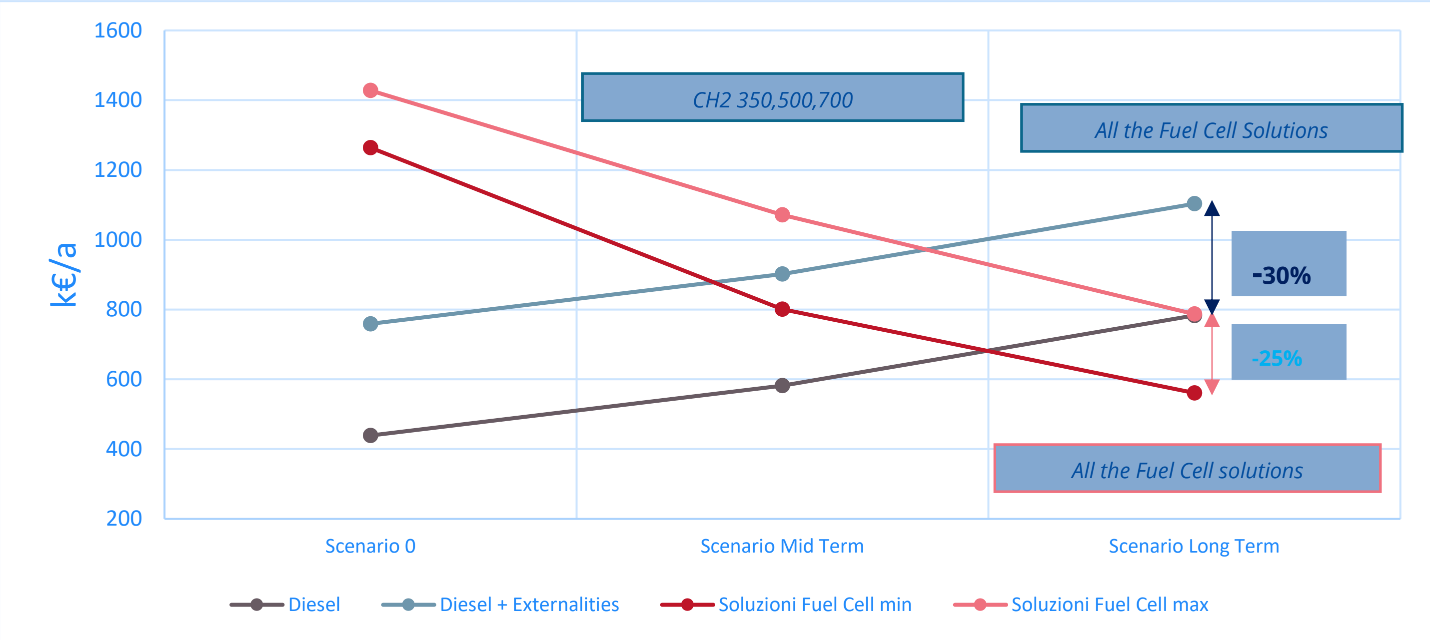

Figure 14 — Scenario Analysis Results Comparison

The main results which have been derived from the scenario analysis are:

- The future costs of hydrogen solutions can be cut considering a consistent reduction in hydrogen cost, the analysis on the future developments of hydrogen supply chain has shown that consistent cost reductions in hydrogen production cost and refuelling station can be expected in a mid- and long-term scenario and so the TCO of the fuel cell solution is expected to decrease as well.
- The solution based on compressed hydrogen are the ones with the highest cost reduction and are expected to remain the cheapest solutions also in the long-term scenario. These solutions are further interesting, under an economic point of view, since considering a mid-term scenario they are cheaper than Diesel solution if the external cost due to the air pollution is considered.
- In the long-term Scenario all the fuel cell solutions are expected to be cheaper or comparable to diesel solutions even if air pollution cost is not considered; in particular compressed hydrogen is estimated to be between 5% and 30 % cheaper, according to the hydrogen compression pressure, while liquid hydrogen and metal hydrides are comparable to the cost estimated for Diesel solution.

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Appendix 1: list of parameters

Shaft efficiency	0.99	(Man D.)
Propeller efficiency	0.72	
E-Motor	0.98	' (Kyunghwa Kim)
DC-DC Converter	0.98	
Speed Controller	0.97	
Battery round trip efficiency	0.95	(Pro, s.d.) (Karaduman, 2020)
Battery Depth of Discharge	0.8	(Team)
Battery-Aging and Degradation (KWh)	0.2	(Guenther, 2012)
Diesel engine efficiency	0.35	Own estimation
LNG dual fuel engine	0.45	
Fuel Cell efficiency	0.56	FC wave Ballard
Fuel Cell-Aging and Degradation (KW)	0.1	(Jouin)
Diesel lower heating value	11.83 kWh/kg	https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html
LNG lower heating value	13.5 kWh/kg	
Hydrogen lower heating value	33.3 kWh/kg	
Diesel density	0.846 kg/l	
LNG density	0.428 kg/l	
Weight and Space Parameters		

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Specific power (mass). Diesel engine. $Weight = a \cdot Power + b$		
a	0.15	Avg. own data collection
b	239	Avg. own data collection
Power density (volume). Diesel engine. $Volume = a \cdot Power + b$		
a	134	Avg. own data collection
b	193	Avg. own data collection
Specific power (mass). Fuel Cell system	0.23 kW/kg	FC Wave Ballard
Power density (volume). Fuel Cell system	101 kW/m3	
Specific energy (mass). Battery system	0.1 kWh/kg	(Man M. E.) Product :AKASYSTEM 15 OEM 37 PRC
Energy density (volume). Battery system	100 kWh/m3	
Specific power (mass). Electric motor. $Power = a \cdot Weight + b$		
a	0.24	Avg. own data collection
b	-280	Avg. own data collection
Power density (volume). Electric motor. $Power = a \cdot Volume + b$		
a	370	Avg. own data collection
b	-60	Avg. own data collection
Specific power (mass). LNG. $Power = a \cdot Weight + b$		
a	0.11	Avg. own data collection
b	181	Avg. own data collection
Power density (volume). LNG. $Power = a \cdot Volume + b$		
a	133	Avg. own data collection

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b	-648	Avg. own data collection
Specific power (mass). Converter. $Power = a \cdot Weight + b$		
a	0.3	Avg. own data collection
b	-79	Avg. own data collection
Power density (volume). Converter. $Power = a \cdot Volume + b$		
a	201	Avg. own data collection
b	-220	Avg. own data collection
Specific power (mass). VFD. $Power = a \cdot Weight + b$		
a	0.58	Avg. own data collection
b	-66	Avg. own data collection
Power density (volume). VFD. $Power = a \cdot Volume + b$		
a	201	Avg. own data collection
b	-220	Avg. own data collection
Factor mass H_2 storage. 70 Mpa kgH2/kg system	0.0446	(Boateng)
Factor volume H_2 storage. 70 Mpa kgH2/m³ system	22.5	
Factor mass H_2 storage. 35 Mpa *kgH2/kg system*	0.06	
Factor volume H_2 storage. 35 Mpa $kgH2/m^3 system$	14	
Factor mass H_2 storage. 50 Mpa kgH2/kg system	0.053	Avg. own data collection

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<table>
<tr><td>Factor volume H_2 storage. 50 Mpa
kgH2/m³system</td><td>18</td><td></td></tr>
<tr><td>Diesel Tank volume for 1 liter of fuel
m3 storage/liter Diesel</td><td>0.0011</td><td rowspan="10">(Hydrogen Europe)</td></tr>
<tr><td>Diesel Tank specific weight
Kg storage/m3storage</td><td>374*(Tank Volume)^-0.22</td></tr>
<tr><td>LNG Tank volume for 1 liter of fuel
m3storage/liter LNG</td><td>0.0013</td></tr>
<tr><td>LNG Tank specific weight
Kg storage/m3storage</td><td>1192*(Tank Volume)^-0.3</td></tr>
<tr><td>Liquid Hydrogen Tank specific weight
Kg storage/m3storage</td><td>976 x Tank Volume ^-0,164</td></tr>
<tr><td>*Liquid Hydrogen volumetric storage density*
Kg H2/m3 storage</td><td>52</td></tr>
<tr><td>*NH3 cracker specific weight*
kg/kW Cracker</td><td>11.2</td></tr>
<tr><td>*NH3 cracker specific volume*
M3/kW Cracker</td><td>0.05</td></tr>
<tr><td>*NH3 tank volumetric storage density*
KwhNH3/m^3</td><td>2891</td></tr>
<tr><td>*NH3 tank specific weight*
Kg/m3</td><td>90.6</td></tr>
<tr><td>*Metal Hydride storage system gravimetric Capacity*
Kg Storage/kg H2</td><td>18.18</td><td rowspan="2">(Motyka)</td></tr>
<tr><td>*Metal Hydride storage system volumetric Capacity*
Kg H2/m3storage</td><td>40</td></tr>
</table>

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Cost Parameter		
Diesel engine + gearbox €/Kw	244	(Hydrogen Europe)
Diesel Tank €/kg (storage)	3	
LNG engine + gearbox €/Kw	425	
LNGTank €/m3LNG(storage)	3377	
Electric Motor (€/KW)	120	(INDanube, 2020)
DC-DC Converters (€/KW)	170	(Kyunghwa Kim)
VFD (€/KW)	170	
O&M Diesel and LNG annual cost €/Kw/y	4.4	
Battery System Cost €/KWh	500	(Man M. E.)
Fuel Cell System Cost €/Kw	1000	(Battelle)
Compressed Hydrogen Storage System Cost 700bar €/kgH2	530	(Ahluwalia)
Compressed Hydrogen Storage System Cost 500bar €/kgH2	460	Own Estimation
Compressed Hydrogen Storage System Cost 350bar €/kgH2	390	(Hydrogen Europe) (U.S Department of Energy)
Compressed Hydrogen Cost at nozzle 700 bar €/kgH2	9.5	Own estimation based on hydrogen supply chain analysis

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Compressed Hydrogen Cost at nozzle 500 bar €/kgH2	9.1	
Compressed Hydrogen Cost at nozzle 350 bar €/kgH2	8.7	
Liquid Hydrogen Storage System Cost €/kwh storage	13,974*storage(kg)^-0,206*2	(Hydrogen Europe)
Liquid Hydrogen Cost €/kgLH2	10	Own estimation based on hydrogen supply chain analysis
Ammonia Cost €/kg	0.85	Own estimation based on hydrogen supply chain analysis
Ammonia Tank Cost (€/kg tank)	3	(Hydrogen Europe)
Ammonia Cracker Capex €/kW Cracker	423	
Metal Hydrides Storage System €/kgH2	888	(Motyka)
Metal Hydrides Refueling Cost €/Kg H2	8	Own estimation based on hydrogen supply chain analysis
Diesel Price €/kg	0.8	(Statistisches Bundesamt)
LNG Price €/kg	0.6	Truck-to-ship Rotterdam (Titan LNG, s.d.)
Electricity cost €/kWh	0.15	(Eurostat e.)
Lifetime Fuel Cell	30000 *hours*	FC wave Ballard
Lifetime Battery	1500 *cycles*	AKASYSTEM 15 OEM 37 PRC
Revision interval engine	30000 *hours*	(Prominent-e, 2018, S. 30)
Fuel cell replacement cost	20% of Fuel cell System cost	Own Estimation
Battery Replacement cost €/kWh	250	Own Estimation

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Internal Combustion engine revision cost €/Kw	63	(TNO)
CO_2-emission factor for diesel	50 g CO2/tkm	(EcoTransIT World Initiative)
CO_2-emission factor for LNG	45 g CO2/tkm	(Transport & Environment, 2018)
Cost factor for CO_2 emission	25 *€/tCO₂eq*	(CE Delft-f, 2019, p. 44)
Air pollution	(CE Delft-a, 2019)	

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