

System-level comparison of ammonia, compressed and liquid hydrogen as fuels for polymer electrolyte fuel cell powered shipping

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Supplementary material A- Mass and energy balance calculations

According to the first law and second law of thermodynamics, the mass balance, energy balance and exergy balance for steady-state processes can be expressed as follow,

$$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i \quad (SI. 1)$$

$$\dot{Q} - \dot{W} = \Delta \dot{E}_{KE} + \Delta \dot{E}_{PE} + \Delta \dot{H} \quad (SI. 2)$$

$$\Delta \dot{H} = \dot{H}_{out} - \dot{H}_{in} = \sum_{out} \dot{n}_i \widehat{H}_i - \sum_{in} \dot{n}_i \widehat{H}_i \quad (SI. 3)$$

$$\dot{Q} \left(1 - \frac{T_0}{T}\right) + \sum_{in} \dot{m}_i ex_i = \sum_{out} \dot{m}_i ex_i + \dot{W} + \dot{E}_{Xd}$$

For ideal gas and constant pressure liquid, the specific enthalpy ($\widehat{H}_i$) can be calculated as [59]:

$$\widehat{H}_i = \int_{T_0}^{T_i} C_{p,i} dT + \Delta \widehat{H}_{f,i}^0 \quad (SI. 4)$$

where T_i is the temperature of component i ; T_0 is the reference temperature (298.15K); $\Delta \widehat{H}_{f,i}^0$ is the standard specific heat of formation of component i at 298.15K and 1atm; $C_{p,i}$ is the specific capacity.

The specific exergy (ex) is the sum of the specific physical exergy (ex_{ph}) and chemical exergy (ex_{ch}), which can be computed by [16],

$$ex_{ph} = \widehat{H} - \widehat{H}^0 - T_0(\widehat{S} - \widehat{S}^0)$$

$$ex_{ch} = \sum x_i ex_{ch,i}^0 + RT_0 \sum x_i \ln(x_i)$$

where $\widehat{S}$ is the specific entropy, x_i is the molar fraction of species i and $ex_{ch,i}^0$ is the standard chemical exergy of species i .

Table SI.1- Mass and energy balance of the main component in the designed hydrogen and ammonia system

Component	Reaction	Mass Balance	Energy Balance	Exergy Balance
Fuel cell stack	$2H_2 + O_2 \rightarrow 2H_2O$	$\dot{n}_{H_2} = \frac{I \cdot N_{cell} \cdot 2H_2}{n_{H_2} \cdot F}$ $\dot{n}_{O_2} = \frac{I \cdot N_{cell} \cdot 3O_2}{n_{O_2} \cdot F}$ $\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\dot{Q}_{natural\ convection} + \dot{Q}_{radiation} + \dot{Q}_{coolant} = \Delta \dot{H} + PWR_{stack}$ $\dot{Q}_{natural\ convection} = h_{amb} \cdot A_{stack} \cdot (T_{FC} - T_{amb})$ $\dot{Q}_{radiation} = \epsilon \cdot \sigma \cdot A_{stack} \cdot (T_{FC}^4 - T_{amb}^4)$ $\dot{Q}_{coolant} = C_{p,coolant} \cdot (T_{coolant,out} - T_{coolant,in}) \cdot \dot{n}_{coolant}$ $E_{FC} = E_{oc} - V_{act} - V_{conc} - V_{ohm}$ $PWR_{stack} = N_{cell} \cdot E_{cell} \cdot I$	$\dot{E}_{Xd} = \sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i - \dot{Q} \left(1 - \frac{T_0}{T_{FC}}\right) - PWR_{stack}$
Blower/Compressor	None	$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\dot{H}_{out,gas} - \dot{H}_{in,gas} = \dot{W}$	$\dot{E}_{Xd} = \dot{W} - (\sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i)$

Liquid pump	None	$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\dot{W} = \frac{w_{isen} \cdot \sum_{in} \dot{m}_i}{\eta_{isen}}$ $w_{isen} = \frac{kRT_{in}}{k-1} \left[\left(\frac{P_{out}}{P_{in}} \right)^{(k-1)/k} - 1 \right]$ $\dot{H}_{out} - \dot{H}_{in} = \dot{W}_{pump}$ $\dot{W}_{pump} = \frac{w_{pump,isen} \cdot \sum_{in} \dot{m}_i}{\eta_{pump,isen}}$ $w_{pump,isen} = v \cdot (P_{outlet} - P_{inlet})$	$\dot{E}_{Xd} = \dot{W}_{pump} - (\sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i)$
Ammonia cracker	$NH_3 \rightarrow 0.5 N_2 + 1.5 H_2$	$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\dot{Q} = \sum_{out} \dot{n}_i \widehat{H}_i - \sum_{in} \dot{n}_i \widehat{H}_i$	$\dot{E}_{Xd} = \sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i + \dot{Q} \left(1 - \frac{T_0}{T_{cracker}} \right)$
Burner	$4NH_3 + 3O_2 \rightarrow 6H_2O + 2N_2$ $4NH_3 + 5O_2 \rightarrow 6H_2O + 4NO$ $4NH_3 + 7O_2 \rightarrow 6H_2O + 4NO_2$ $H_2 + 0.5 O_2 \rightarrow H_2O$	$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\dot{Q} = \sum_{in} \dot{n}_i \widehat{H}_i - \sum_{out} \dot{n}_i \widehat{H}_i$	$\dot{E}_{Xd} = \sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i - \dot{Q} \left(1 - \frac{T_0}{T_{cracker}} \right)$
SCR reactor	$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O$ $2NO_2 + 4NH_3 + O_2 \rightarrow 3N_2 + 6H_2O$	$\sum_{in} \dot{m}_i = \sum_{out} \dot{m}_i$	$\sum_{in} \dot{n}_i \widehat{H}_i = \sum_{out} \dot{n}_i \widehat{H}_i$	$\dot{E}_{Xd} = \sum_{in} \dot{m}_i ex_i - \sum_{out} \dot{m}_i ex_i$

Table SI.2- Mass and energy balance of the main component in the designed hydrogen and ammonia system [1]–[5]

Parameters	Estimated Values
Number of electrons transferred per mole of hydrogen (n_{H_2})	2
Number of electrons transferred per mole of oxygen (n_{O_2})	4
Stoichiometric ratio of hydrogen (z_{H_2})	1.2
Stoichiometric ratio of air (z_{O_2})	2
Hydrogen loss due to purging	1.00%
Ambient temperature (T_{amb}), K	298.15
Stack heat transfer area (A_{stack}), m ²	31kW stack (water taxi): 1 m ² 198kW stack (cargo ship): 6 m ²
Stack emissivity(ϵ)	0.8
Stefan-Boltzmann constant (σ), W/(m ² K ⁴)	5.67E-08
natural convective heat transfer coefficient ($h_{ambient}$), W/m ² K	6

* The parameters are assumed the same for water taxi and cargo ship case studies if not mentioned specifically.

Table SI.3- Parameters for pump, blower and compressor mass and energy balances [6], [7]

Equipment	Pressure ratio	Isentropic efficiency (η_{isen})
Hydrogen recirculation pump	1.28	80%
Air blower to the fuel cell	1.2	75%
Coolant pump for the fuel cell	1.18	70%
Air compressor to the burner	2	75%
Liquid ammonia pump	1.02	70%

Table SI.4- Parameters for reactor and separator mass and energy balances [8]–[15]

Equipment	Operating temperature °C	Operating pressure 10 ³ Pa	Conversion
Ru/Al ₂ O ₃ ammonia cracker for water taxi	873.15	350	99.95%
Ni/Al ₂ O ₃ ammonia cracker for cargo ship	873.15	350	99.9%
Ammonia/hydrogen Burner	1873.15- 1973.15	205	Concentration in the outlet: 30ppmv H ₂ 400ppmv NO;0.2ppmv NO ₂ ;85ppmv NH ₃
Membrane separator	623.15	343	-
SCR reactor	533.15	205	90%

Table SI.5- constants for specific capacities [16]

Reference states: 298.15K and 1atm; $C_{p,i} = a + b \cdot T + c \cdot T^2 + d \cdot T^3$

	a	b	c	d	$\Delta \hat{H}_{f,i}^0$ (10 ³ J/mol)	$ex_{ch,i}^0$ (10 ³ J/mol)
H ₂	0.02714	0.0000093	-1.381E-08	7.645E-12	0	236.09
N ₂	0.03115	-0.00001357	2.68E-08	-1.168E-11	0	0.72
Water(g)	0.03224	0.00001924	1.055E-08	-3.596E-12	-241.82	9.5
Water (l)	0.07243	0.0000104	0	0	-285.83	0.9
Oxygen	0.0291	0.00001158	-6.076E-09	1.311E-11	0	3.97
Particulate Matter (PM)	0.1674				0	6.36
CO ₂	0.0198	0.00007344	-5.602E-08	1.7115E-11	-393.52	19.87
NH ₃ (g)	0.02731	0.00002383	1.707E-08	-1.185E-11	-46.19	337.9
NO	0.02935	-9.378E-07	9.47E-09	-4.187E-12	90.29	88.9
Ar	0.0208				0	11.69

Supplementary material B - Fuel cell power calculation

The PEMFC generates electrical power by electrochemical reaction between oxygen and hydrogen. The anodic, cathodic and overall reaction of the PEMFC are expressed as,



The maximum voltage provided by the fuel cell (i.e. open circuit potential) can be given by the Nernst equation ,

$$E_{oc}(V) = 1.229V + (T_{FC} - 298.15K) \frac{\Delta S_0^0}{nF} + \frac{RT_{FC}}{2F} \ln[p_{H_2} p_{O_2}^{1/2}] \quad (SI. 8)$$

where R is the universal gas constant, T_{FC} is the fuel cell temperature in K, F is the Faraday's constant, n is the number of the electrons transferred per mole of fuel reacted, ΔS_0^0 is the standard (1 atm and 298.15K) entropy change of the fuel cell reaction, p_i is the partial pressure of species i in atm.

In practice, the fuel cell potential is smaller than the open-circuit potential because of the losses, including activation loss (V_{act}), concentration loss (V_{conc}) and the ohmic loss (V_{ohm}) [18]. The actual fuel cell voltage (E_{FC}) can be calculated as,

$$E_{FC} = E_{oc} - V_{act} - V_{conc} - V_{ohm} \quad (SI. 9)$$

The activation potential of the fuel cell can be simplified as [19],

$$V_{act} = \frac{RT_{FC}}{n \alpha F} \ln \left(\frac{i}{i_{oc}} \right) \quad (SI. 10)$$

where i is the current density in A/cm^2 , α is the charge transfer coefficient and i_{oc} is the exchange current density for cathode in A/cm^2 .

The concentration voltage loss of the fuel cell can be approximated as [20],

$$V_{conc} = \frac{RT_{FC}}{nF} \cdot \left(1 + \frac{1}{\alpha} \right) \cdot \ln \frac{i_L}{i_L - i} \quad (SI. 11)$$

where i_L is the limiting current density.

The ohmic loss of the fuel cell is directly proportional to the current density (i),

$$V_{ohm} = i \cdot R_{ohm} \quad (SI. 12)$$

R_{ohm} depends on the membrane thickness (t_m) and membrane conductivity (σ_m) and can be calculated as [21],

$$R_{ohm} = \frac{t_m}{\sigma_m} \quad (SI. 13)$$

The membrane conductivity is [21],

$$\sigma_m = (0.005139 \cdot \gamma_m - 0.00326) \cdot e^{(1268 \cdot (\frac{1}{303} - \frac{1}{T}))} \quad (SI. 14)$$

where γ_m is the water content and can be determined from average relative humidity (RH),

$$\gamma_m = 0.048 + 17.81 RH - 39.83 RH^2 + 39.85 RH^3 \quad (SI. 15)$$

The fuel cell stack voltage can be calculated by multiplying the fuel cell voltage with the number of the fuel cells (N_{cell}) in the stack:

$$E_{stack} = N_{cell} \cdot E_{cell} \quad (SI. 16)$$

The electrical power generated by the stack (PWR_{stack}) then can be obtained from:

$$PWR_{stack} = N_{cell} \cdot E_{cell} \cdot I \quad (SI. 17)$$

Table SI.6- Parameters for the fuel cell voltage and power model [1], [2], [22]–[24]

	31kW Fuel Cell Stack for water taxi	198kW Fuel Cell Stack for cargo ship
Rated power, kW	31	198
Operating temperature of the fuel cell (T_{FC}), K	328.15	328.15
Operating pressure of the fuel cell (P_{FC}), kPa	110-120	110-120
Number of electrons transferred per mole of fuel (n)	2	2
Charge Transfer Coefficient (α)	0.5	0.5
Fuel Cell Active Area, cm^2	500	500

Exchange current density for cathode (i_{oc}), A/cm ²	0.000001	0.000001
Limiting Current Density of the Fuel Cell (i_L), A/cm ²	1.1	1.1
Relative Humidity in the Stack (RH)	95%	95%
Membrane Thickness (t_m), cm	0.01	0.01
Number of cells	122	754

Supplementary material C– Tank volume and mass calculation

1. Calculate the inner volume of the tank

$$V_{inner\ volume} = \frac{V_{fuel}}{\text{Maximum capacity of the tank}} \quad (\text{SI. 18})$$

2. Assume torispherical tank, the inner diameter (D_{inner}) of the tank can be calculated from [25],

$$V_{inner\ volume} = 2 * 0.0778 D_{inner}^3 + \pi \left(\frac{D_{inner}}{2} \right)^2 \cdot D_{inner} \cdot R \quad (\text{SI. 19})$$

where R is the tank length to diameter ratio.

3. The thickness of cylindrical shell (load bearing layer) thickness can be calculated by [25],

$$t_{load-bearing,shell} = \frac{P \cdot r}{S \cdot E - 0.6 P} + t_c \quad (\text{SI. 20})$$

where P is the inner pressure of the tank in psig, r is the inner radius of the tank in inch, S is the allowable stress of the tank material in psi, E is the joint efficiency, which is assumed as 85%, t_c is the corrosion tolerance in inch, which can be assumed as 0.15 inch.

4. The thickness of torispherical head (load bearing layer) thickness can be calculated by [25],

$$t_{load-bearing,head} = \frac{0.885 P \cdot L_{crown}}{S \cdot E - 0.1 P} + t_c \quad (\text{SI. 21})$$

where L_{crown} is the crown radius of head in inch, which is the same as head diameter for the torpspherical design.

5. Outer volume of the tank is then given by [25],

$$V_{outer} = \left(\frac{D_{inner}}{2} + t_{load-bearing,shell} + t_{leakage} + t_{insulation} + t_{protection,shell} \right)^2 \pi L + 0.842 \cdot (D_{inner})^2 \cdot 2 \cdot (t_{load-bearing,head} + t_{leakage} + t_{insulation} + t_{protection,head}) + 2 * 0.0778 D_{inner}^3 \quad (\text{SI. 22})$$

where $t_{leakage}$ is the leakage protection layer, such as the high-density polymer layer in the hydrogen tank; $t_{insulation}$ is the heat insulation layer to reduce heat transfer; $t_{protection,shell}$ is the protection layer for the shell; $t_{protection,head}$ is the protection layer for the head.

Supplementary material D - Summary of the results from mass and energy balance models

Table SI.7- Summary of the results from the mass and energy balance model for the water taxi systems at sea

	Propulsion load factor	Time spent	Propulsion Power	Auxiliary Power	Mass flow rate of H ₂ or NH ₃ fuel	Stack Efficiency	Power generated by the stack
		%	10 ³ W	10 ³ W	10 ⁻³ kg/s	%LHV	10 ³ W
GH ₂ PEMFC system	100%	75%	25	1.7	0.44	57%	29.5
	15%	25%	3.75	1.1	0.07	68%	5.3
LNH ₃ system	100%	75%	25	2.1	3.2	56%	29.9
	15%	25%	3.75	1.2	0.6	68%	5.4

Table SI.8- Summary of the results from the mass and energy balance model for the cargo ship systems at sea

	Propulsion load factor	Time spent	Propulsion Power	Auxiliary Power	Mass flow rate of H ₂ or NH ₃ fuel	Stack efficiency	Power generated per stack
		%	10 ³ W	10 ³ W	10 ⁻³ kg/s	%LHV	10 ³ W
GH ₂ PEMFC system	100%	1%	21770	1552.0	413.3	55%	194.2
	65%	32%	14150.5	1281.2	248.6	61%	128.4
	55%	15%	11973.5	1214.3	207.8	62%	109.6
	35%	24%	7619.5	1089.1	131.3	65%	72.3
	25%	15%	5442.5	1030.2	95.3	66%	53.6
	15%	10%	3265.5	973.6	60.6	68%	35.0
	5%(maneuvering)	1.75%	1088.5	1942.8	41.7	69%	24.5
	2%(Idle)*	1.25%	435.4	687.2	15.5	69%	25.6
LH ₂ PEMFC system	100%	1%	21770	1588.6	414.5	55%	194.6
	65%	32%	14150.5	1317.2	249.4	61%	128.7
	55%	15%	11973.5	1250.3	208.6	62%	110.0
	35%	24%	7619.5	1125.0	132.0	65%	72.6
	25%	15%	5442.5	1066.1	95.9	66%	53.9
	15%	10%	3265.5	1009.4	61.2	68%	35.3
	5%(maneuvering)	1.75%	1088.5	1978.5	42.2	69%	24.8
	2%(Idle)*	1.25%	435.4	723.0	16.0	69%	26.4
LNH ₃ PEMFC system	100%	1%	21770	1940.7	3023.4	55%	195.9
	65%	32%	14150.5	1542.6	1842.2	61%	129.6
	55%	15%	11973.5	1444.6	1550.8	62%	110.7
	35%	24%	7619.5	1261.4	1005.2	65%	73.2
	25%	15%	5442.5	1175.2	748.4	66%	54.4
	15%	10%	3265.5	1092.5	501.5	68%	35.7
	5%(maneuvering)	1.75%	1088.5	2047.3	366.8	69%	25.2
	2%(Idle)*	1.25%	435.4	733.7	184.6	65%	74.1

*When the cargo ship is at the idle stage, only 50 stacks are at work for the GH₂ and LH₂ PEMFC systems and 18 stacks are at work for the LNH₃ PEMFC system to reach the minimum working power of the stacks.

Supplementary material E- Power loss contribution of the designed PEMFC systems

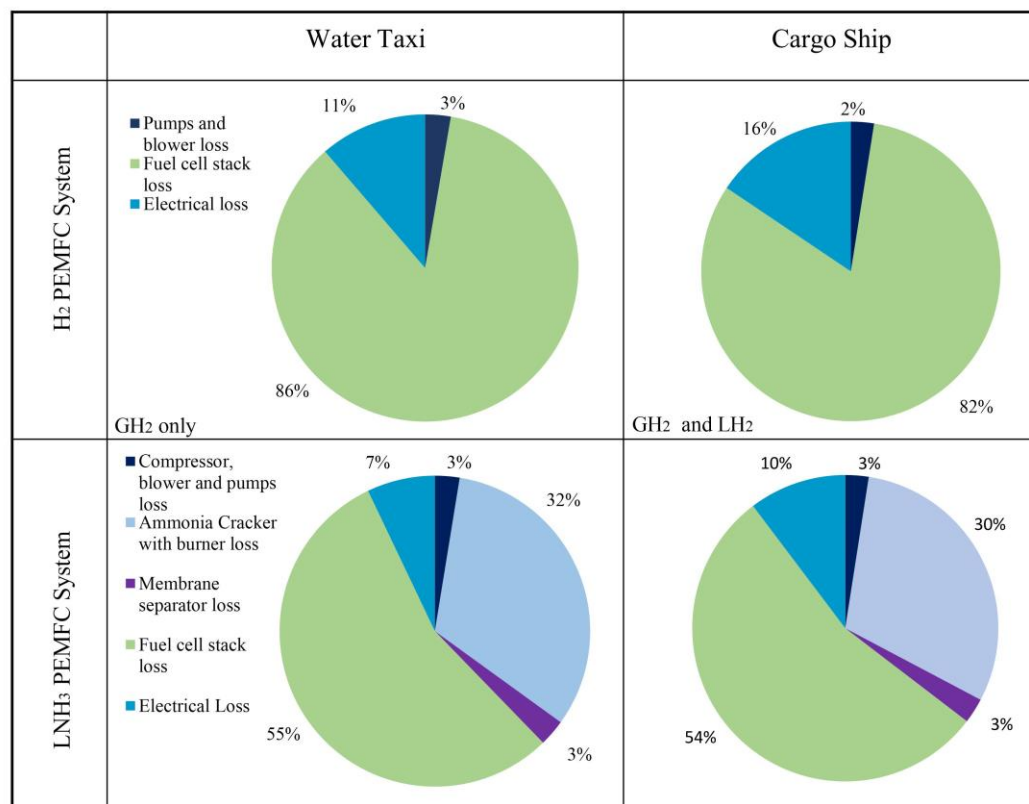
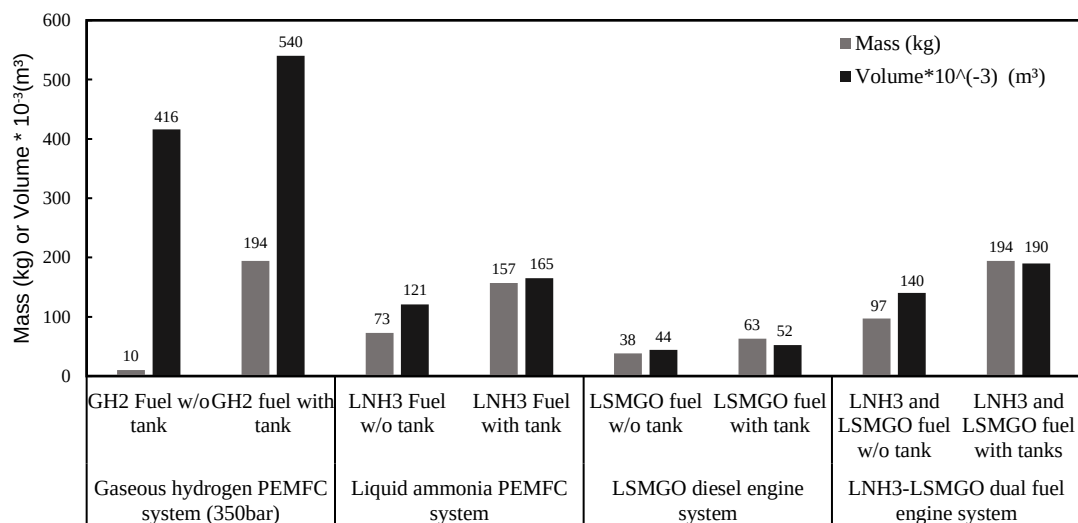


Figure SI.1- The power loss distribution under full propulsion load condition for the water taxi and cargo ship PEMFC systems. Note: For water taxi, the efficiency distribution is only for the GH₂ PEMFC system whereas for the cargo ship, the efficiencies are for both GH₂ and LH₂ PEMFC systems, which give similar power loss distribution based on the analysis; electrical loss includes the loss of the controller, sensor, converter, inverter, transformer, drive, gearbox, motor. (1.5 column)

Supplementary material F - Mass, volume and cost of the main components applied in the water taxi and cargo ship GH₂, LH₂ and LNH₃ systems

(a)



(b)

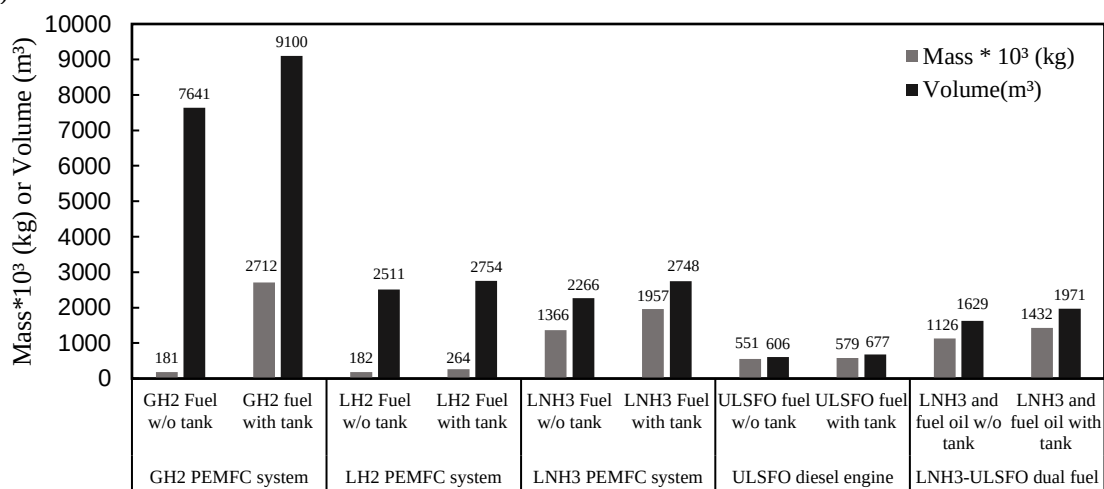


Figure SI.2- Fuel tank mass and volume analysis of the (a) 12-passenger water taxi (b)2600TEU cargo ship

Table SI.9- Mass, volume and cost of the main components applied in the water taxi and cargo ship GH₂, LH₂ and LNH₃ systems

Equipment	Water taxi				Cargo ship				Reference
	Mass	Volume	CAPEX	O&M costs	Mass	Volume	CAPEX	O&M costs	
	kg	L	£	£/year	tonne	m ³	k£	k£/year	
GH ₂ fuel tank *	194	540	3914	39	2712	9100	65952.7	659.5	[26]
LH ₂ fuel tank*	-	-	-	-	264	2754	38515.9	385.2	[27]
LNH ₃ fuel tank *	157	165	130	-	1957	2748	412.6	4.1	[28]
Fuel cell stack: Hydrogenics HD-30 fuel cell stack for water taxi and Hydrogenic-180HD Fuel Cell stacks for cargo ship	71	76	23560	942	0.7	1.2	148.9	5.9	[1], [2], [29]
Air Blower for the fuel cell	1.6	2.5	684	68.4	1.2	0.8	7.6	0.4	[30]–[33]
Air Filter for the fuel cell	2.3	19.6	81	24	0.2	1.4	0.6	0.2	[34], [35]
Coolant Pump for the fuel cell	2.2	5	122	12	0.2	0.6	10.6	0.4	[36], [37]
Coolant Filter for the fuel cell	0.5	0.9	19	-	0.07	0.1	4.3	-	[38]
Coolant Reservoir for the fuel cell	0.3	1.5	30	-	0.3	1.3	0.4	-	[27]
Keel Cooler for the fuel cell	24.2	10.8	380	76	25.2	25.8	183.8	9.2	[39], [40]
Cathode Demister for the fuel cell	4.3	6.2	432	32	0.7	11.5	38	0.4	[41], [42]
Battery for the GH ₂ PEMFC system	5	2.4	319.2	9.6	5	2.4	319.2	9.6	[43], [44]
Battery for the LH ₂ PEMFC system	-	-	-	-	5.5	2.6	351.1	10.5	[43], [44]
Battery for the LNH ₃ PEMFC system	15	7.1	957.6	38	15	7.1	957.6	28.7	[43], [44]
Converters	11	16.9	3800	38	9	8.5	3308.3	33	[29], [45], [46]
Propulsion System (include Motor and Drive)	80	100	7535	75	94	180.2	6618.1	66.2	[47], [48]
LNH ₃ pump	0.5	1.5	185	19	0.04	0.04	1	0.05	[37], [49], [50]
LH ₂ pump	-	-	-	-	1.8	1.7	5.5	0.3	[40], [51]
LH ₂ evaporator	-	-	-	-	1.2	0.8	36.1	1.8	[40], [52]
Back-up electrical LH ₂ evaporator	-	-	-	-	0.1	0.06	26.6	1.3	[53]
Heat exchangers to evaporate and heat up LNH ₃	11.1	5.8	203	40	9.4	6.4	313.0	15.6	[40], [52], [54]
Back-up electrical heater for LNH ₃ evaporation	3	0.4	760	38	0.53	0.24	100.2	5	[40], [54], [55]
Air compressor for ammonia burner	2	20	1900	190	16	42.8	60.8	3	[32], [56], [57]
Ammonia cracker with burner	10.3	8.3	18334	182	38	12	3296.8	33.0	[47], [58]
Pd membrane	4.1	5.2	742	56	4.2	5.2	747	7.5	[59], [60]
Ammonia sorption column	0.3	0.4	233	70	0.2	0.3	169	1.7	[61], [62]
SCR reactor	0.4	1.6	137	4	0.4	1.6	10.4	0.3	[63], [64]

* The volume and mass of the fuel tank includes the volume and mass of the fuel at the beginning of the journey.

Supplementary material G - Operational emissions of different water taxi and cargo ship power systems [65]–[71]

Table SI.10- Operational emissions of different water taxi and cargo ship power systems [65]–[71]

		EF_{NO_x}	NO_x	NO_x	EF_{SO_x}	SO_x	SO_x	EF_{PM}	PM	PM	EF_{NH_3}	NH_3	NH_3
	WT	g/kwh	kg/year	g/p-km	g/kwh	kg/year	g/p-km	g/kwh	kg/year	g/p-km	g/kwh	kg/year	g/p-km
	CS	g/kwh	kg/year	g/TEU-km	g/kwh	kg/year	g/TEU-km	g/kwh	kg/year	g/TEU-km	g/kwh	kg/year	g/TEU-km
GH ₂ or LH ₂ PEMFC system	WT	0	0	0	0	0	0	0	0	0	0	0	0
	CS	0	0	0	0	0	0	0	0	0	0	0	0
LNH ₃ PEMFC system *	WT	-	1.6	0.002	0	0	0	0	0	0	-	0.0012	2 E-06
	CS	-	2103	0.003	0	0	0	0	0	0	-	4.4	6.3E-06
HFO diesel engine system	WT	6	317.8	0.4	9	476.6	0.6	0.5	26.5	0.03	0	0	0
	CS	ME:14 AE:9	ME: 874900 AE: 55153 Total: 930053	1.3	ME:9 AE:12	ME: 562436 AE: 73537 Total: 635973	0.9	ME:1.4 AE:1.4	ME: 87490 AE: 8579 Total: 96069	0.1	0	0	0
LSMGO diesel engine system (for WT) or ULSFO diesel engine system (for CS) *	WT	0.6	31.8	0.04	0.3	15.9	0.02	0.3	15.9	0.02	0	0	0
	CS	ME:1.4 AE:0.9	ME: 87490 AE: 5515 Total: 93005	0.1	ME:0.3 AE:0.4	ME: 18748 AE: 2451 Total: 21199	0.03	ME:0.4 AE:0.4	ME: 24997 AE: 2451 Total: 27448	0.04	0	0	0
NH ₃ -LSMGO dual fuel engine (for WT) or NH ₃ -ULSFO dual fuel engine (for CS)	WT	2.4-15	127.1- 794.4	0.2-1	0.03	1.6	0.002	0.04	2.1	0.003	20	1059.2	1.4
	CS	14.4	988141	1.4	0.03	2120	0.003	0.04	2745	0.004	20	13724 18	2
NH ₃ -LSMGO dual fuel engine (for WT) or NH ₃ -ULSFO dual fuel engine (for CS) *	WT	0.24- 1.5	12.7- 79.4	0.02- 0.1	0.03	1.6	0.002	0.04	2.1	0.003	0.02	1.1	0.001
	CS	1.4	98814	0.1	0.03	2120	0.003	0.04	2745	0.004	0.02	1372	0.002

All the systems marked with * are with aftertreatment, which includes the SCR and ammonia sorption column; WT is water taxi; CS is cargo ship; ME is main engine; AE is auxiliary engine; g/p-km is gram/passenger-km; HFO is heavy fuel oil (2.7 mass% S); LSMGO is low-sulfur marine gasoil (0.1 mass% S) ; ULSFO is ultra-low sulfur fuel oil (0.1 mass% S)

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