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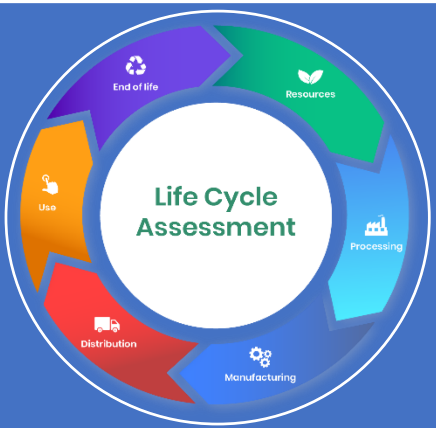
LIFE CYCLE ASSESSMENT OF AMMONIA/HYDROGEN MARINE ENGINES

CAHEMA

Concepts of ammonia/hydrogen engines
for marine application

Dr. Tuan Dong

WP4 framework



Life-cycle assessment

- Air pollutants
- Greenhouse gas emissions

Cost-benefit analysis

Benefit of ammonia/hydrogen engines

Public health

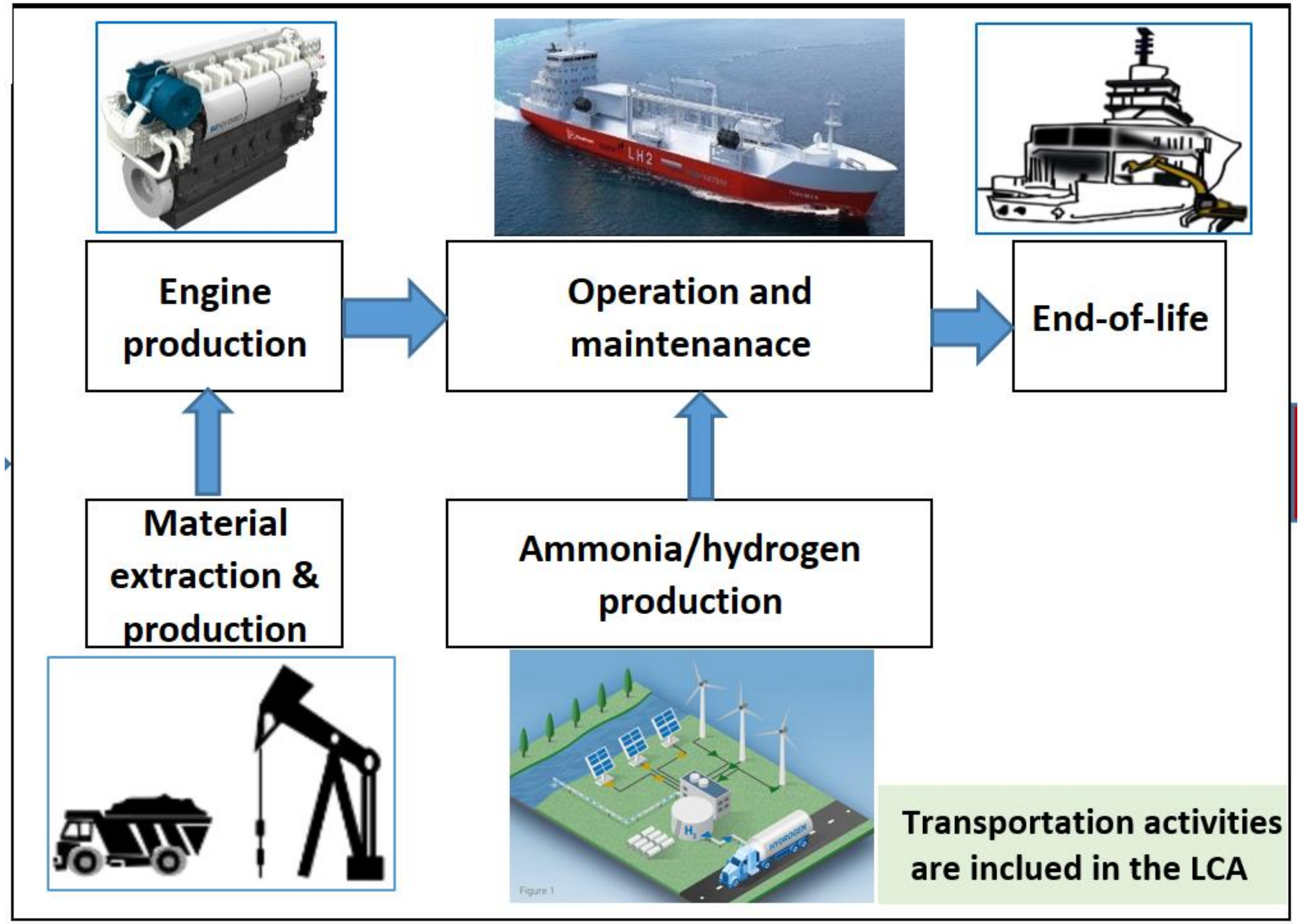
Effects of using ammonia/hydrogen engine on public health

Ammonia/Hydrogen engines for marine application

Life cycle assessment (LCA) and socio-economic cost in CAHEMA

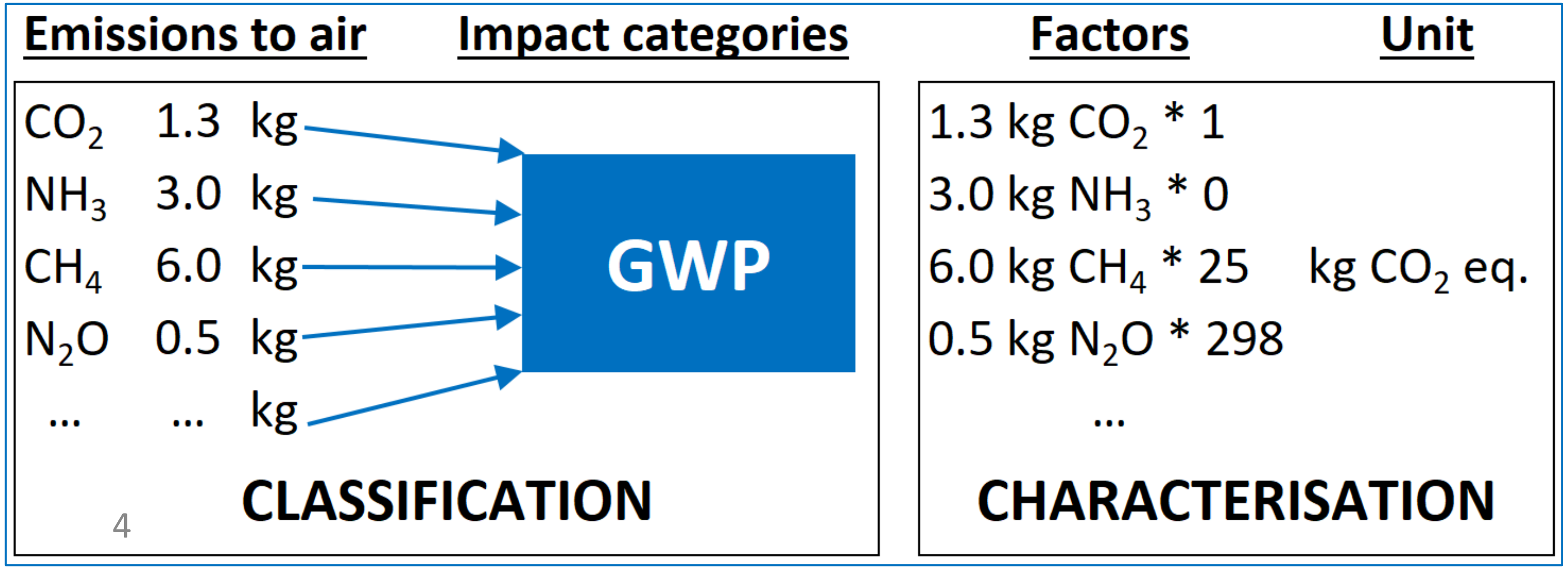
- The life cycle phases consist material extraction & production (for marine engines), ammonia/hydrogen production, transportation activities, operation and end-of-life.

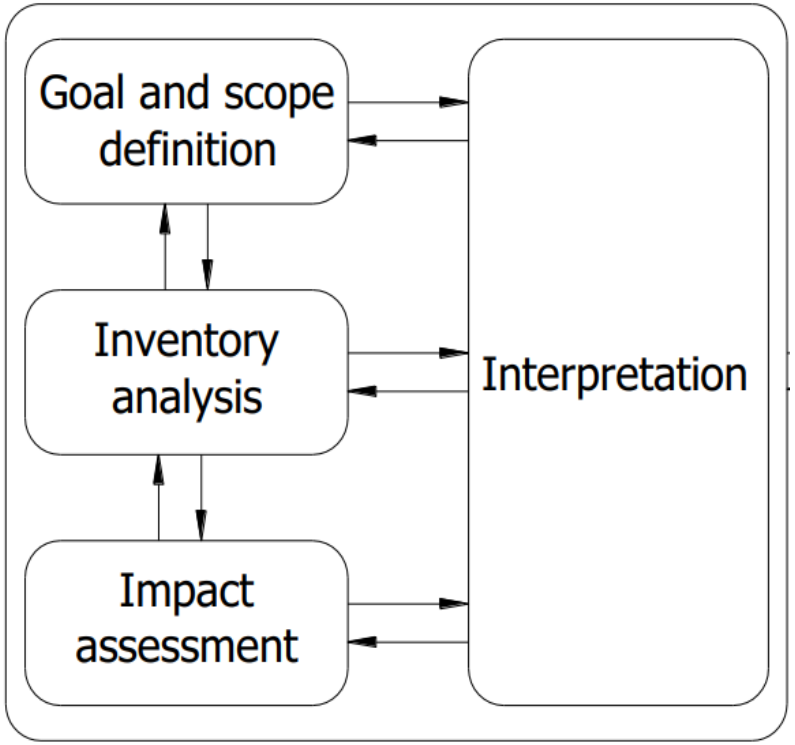
- Preliminary findings show that the ship operation phase dominates the environmental impacts and emissions in the ship's life cycle (more than 90% for global warming potential (GWP).



Life cycle assessment (LCA) and socio-economic cost in CAHEMA

- To evaluate GWP and socio-economic benefits of ammonia/hydrogen engines (for both “green” and “blue” ammonia/hydrogen).
- To recommend for emissions and environmental impacts regulations on the basis of a cost-benefit analysis comparing the economic cost of engine and emissions abatement technologies





LCA framework (ISO 14040, 2006)

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LCA - Five scenarios

- Scenario 1 (Base case scenario): 100% MDO
- Scenario 2: 98.5% H2 and 1.50% MDO
- Scenarios 3: 95% NH3 and 5% MDO

(Scenarios 2 & 3 include "blue" and "green" H2 and NH3)

Scenarios	Items	Units	MDO	NH3	H2
	Energy content	MJ/kg	42.6	18.6	120
	SFC	g/kWh	163.0	373.3	57.9
Scenario 1 100% MDO	Energy	kWh	1	0	0
	Mass	kg	0.1630	0.0000	0.0000
Scenario 2 98.5% H2 and 1.50% MDO	Energy	kWh	0.015	0	0.985
	Mass	kg	0.0024	0	0.057
Scenario 3 95% NH3 and 5% MDO	Energy	kWh	0.05	0.95	0
	Mass	kg	0.0082	0.3547	0

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LCA – Scope definition

- Product system: two-stroke engine (information provided by *Stolt Tanker*)
- Functional unit: grams emission/kWh delivered to the propeller shaft
- System boundary: fuel production & transportation (well-to-tank), engine operation (tank-to-wake), material extraction and production, engine end-of-life
- Primary emissions: CO_2, CH_4, N_2O, NO_X, CO, NMVOC, SO_X, PM_{10}, $PM_{2.5}$, Black carbon, H_2 slip, NH_3 slip
- Environmental indicator: Global warming potential (GWP)

LCA – Assumptions

- H_2 and NH_3 are produced in Yara (Norway)
- Fuels are transported by ocean-going vessels with the distance of 800 km
- Renewable energy in this study: Electricity from wind
- Energy used for liquefaction process: 0.836 kWh/kgNH_3; 10kWh/kgH_2
- Energy used for Haber-Bosch (H-B) process: 1.17 MJ/kgNH_3
- 90% of CO_2 is captured in CCS
- The amount of H_2, NH_3, CO_2 in SMR and H-B process are calculated based on SMR and H-B chemical reaction.
- The ship will be retired and dismantled after 25 years operating by sea
- Waste generation and management during the ship's life cycle, and malfunction of engines are ignored.

Emission factors (EFs)

- EFs of MDO are taken from IMO fourth GHG report
- EFs of H2 and NH3 for CO2, CH4, CO, SOX, PM, black carborn are zero
- EFs of N2O, NOX, H2 slip and NH3 slip are from literatures.

Emissions	MDO	H2	NH3
CO2	3.20600	0.00000	0.00000
CH4	0.00001	0.00000	0.00000
N2O	0.00018	0.00015	0.00033
NOx	0.05671	0.02333	0.02033
CO	0.00259	0.00000	0.00000
NMVOC	0.00240	0.00000	0.00000
SOX	0.00137	0.00000	0.00000
PM10	0.00090	0.00000	0.00000
PM2.5	0.00083	0.00000	0.00000
Black carbon	0.00038	0.00000	0.00000
H2 slip	0.00000	0.00800	0.00000
NH3 slip	0.00000	0.00000	0.00950

Hydrogen’s colors

Color	GREY HYDROGEN	BLUE HYDROGEN	TURQUOISE HYDROGEN*	GREEN HYDROGEN
Process	SMR or gasification	SMR or gasification with carbon capture (85-95%)	Pyrolysis	Electrolysis
Source	Methane or coal	Methane or coal	Methane	Renewable electricity

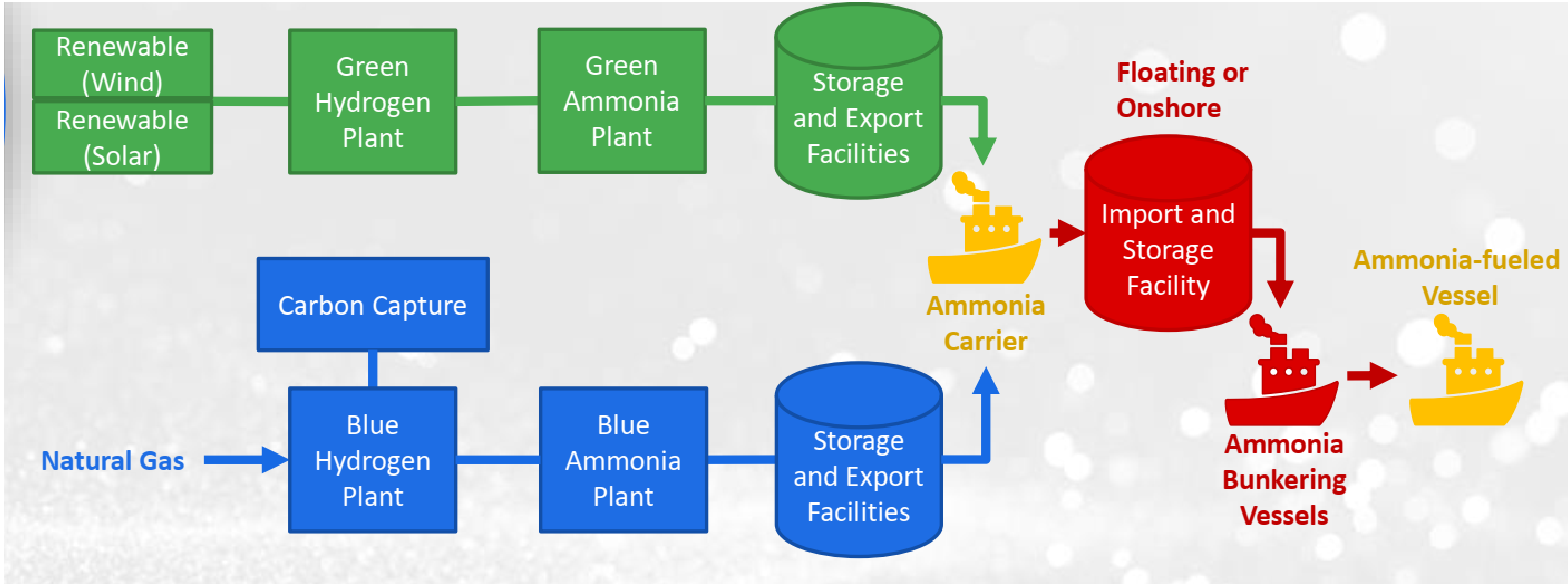
Note: SMR = steam methane reforming.

** Turquoise hydrogen is an emerging decarbonisation option.*

Source: International Renewable Energy Agency

- Notes: The difference between gray hydrogen and blue hydrogen is the carbon capture storage (CCS) with 85-95% CO2 reduction

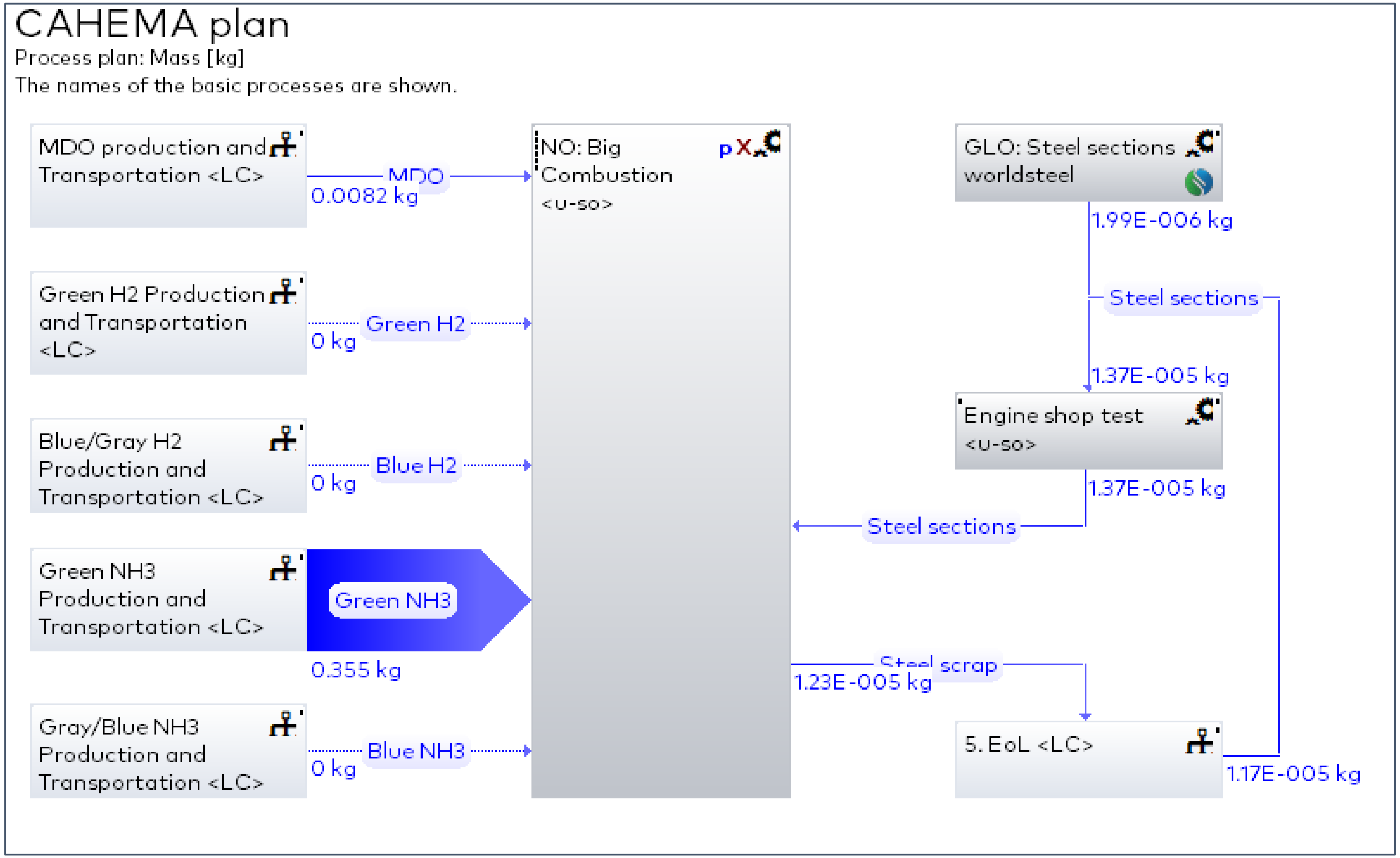
Ammonia production pathways



Source: International Renewable Energy Agency

LCA in GaBi software application

- GaBi – Sphera is used to obtain the LCA results
- Database/Data are availble in the software and data providers



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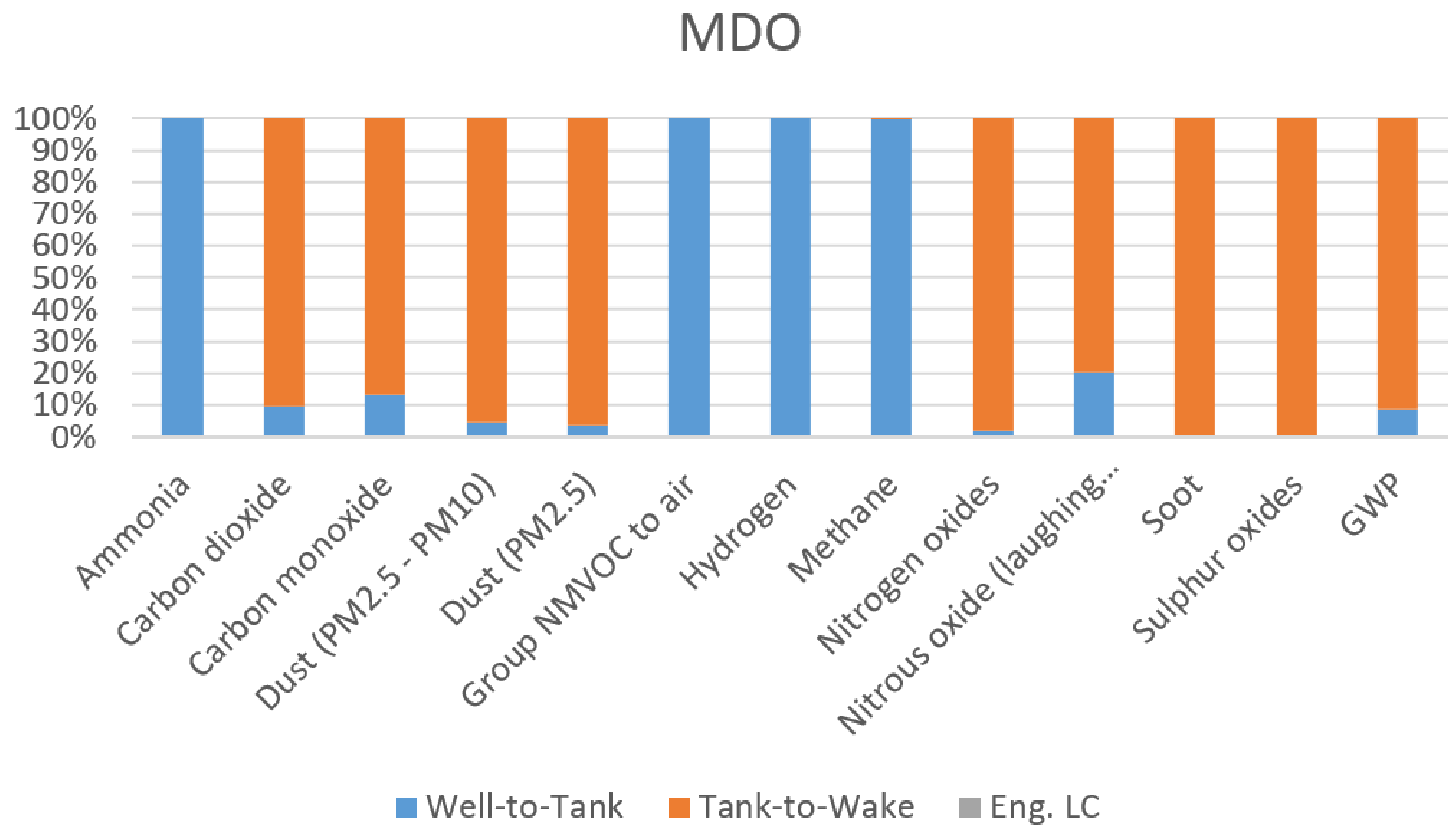
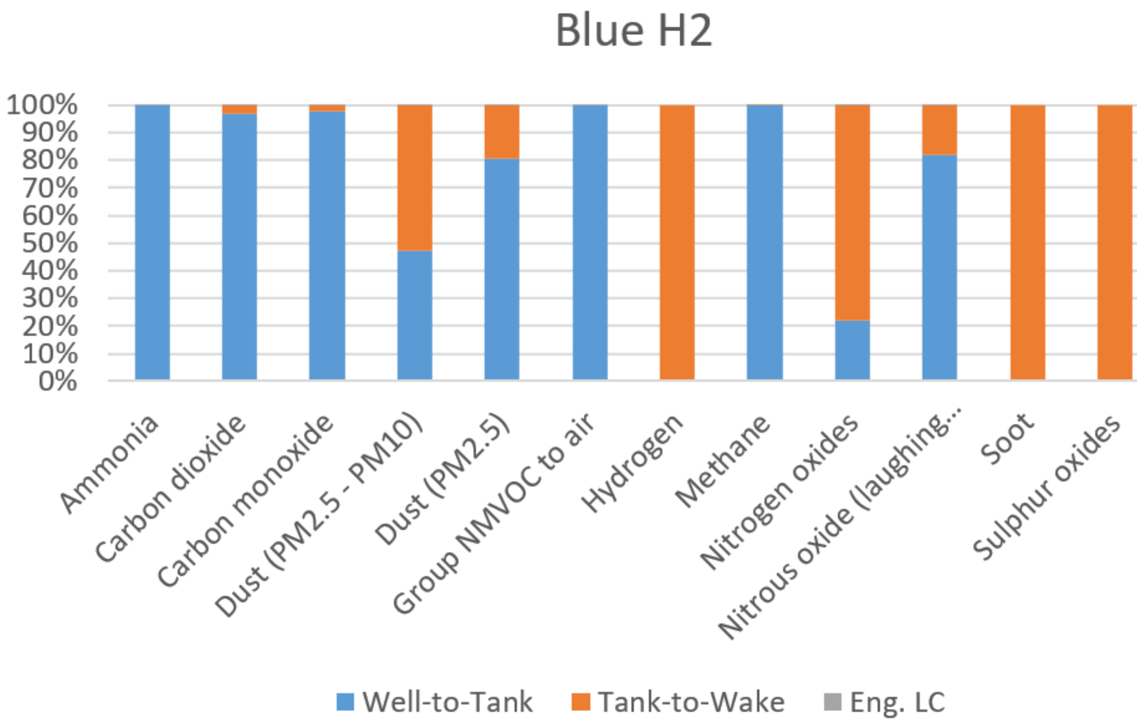
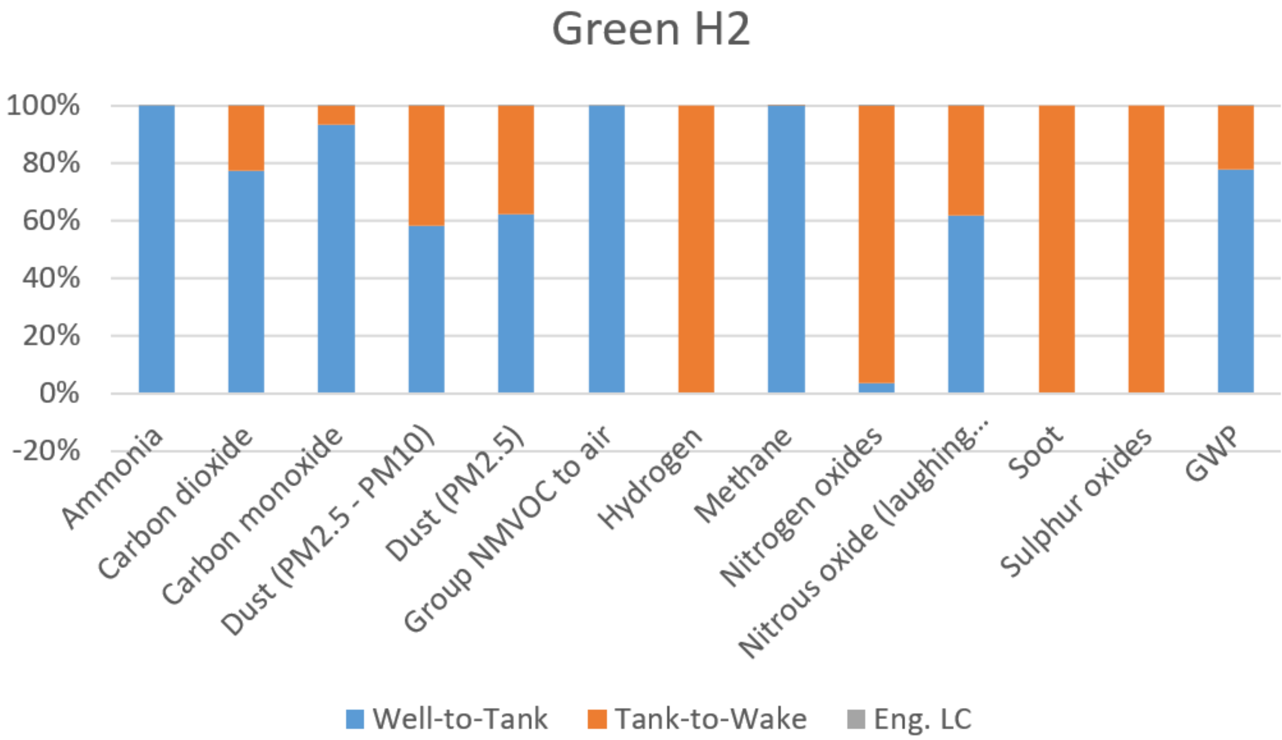
MDO – LCA phases contribution

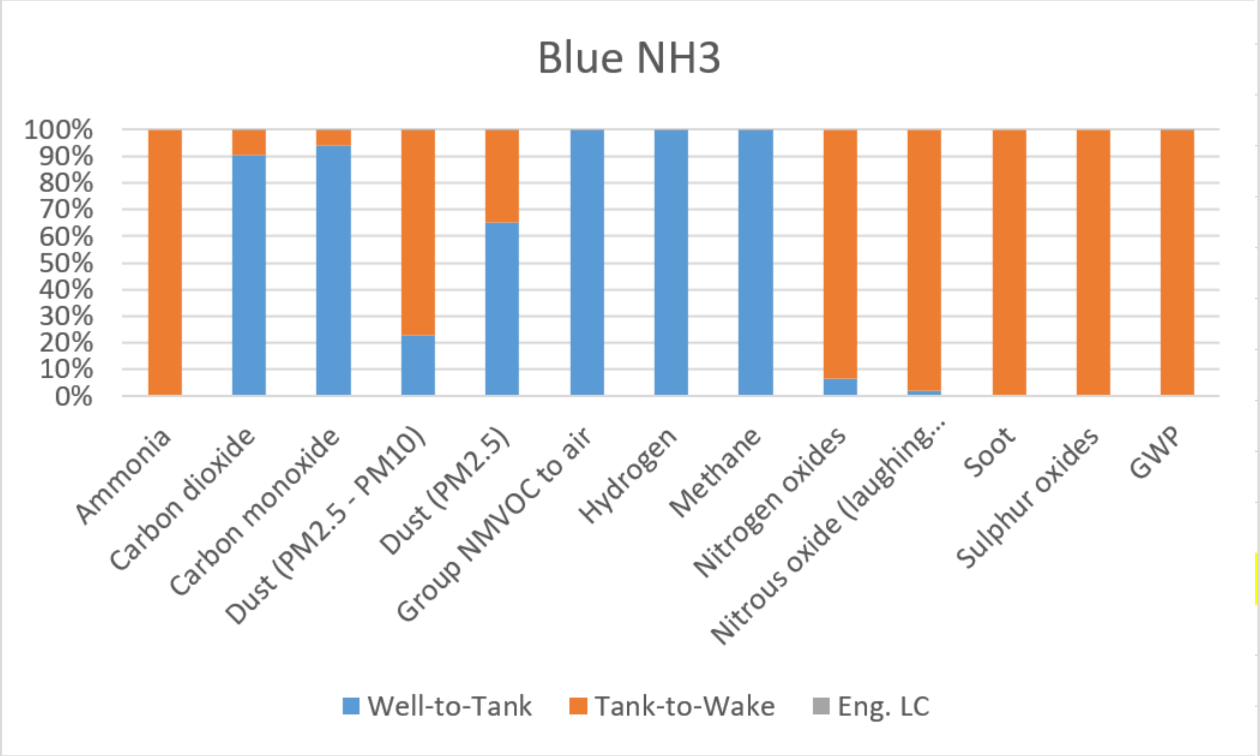


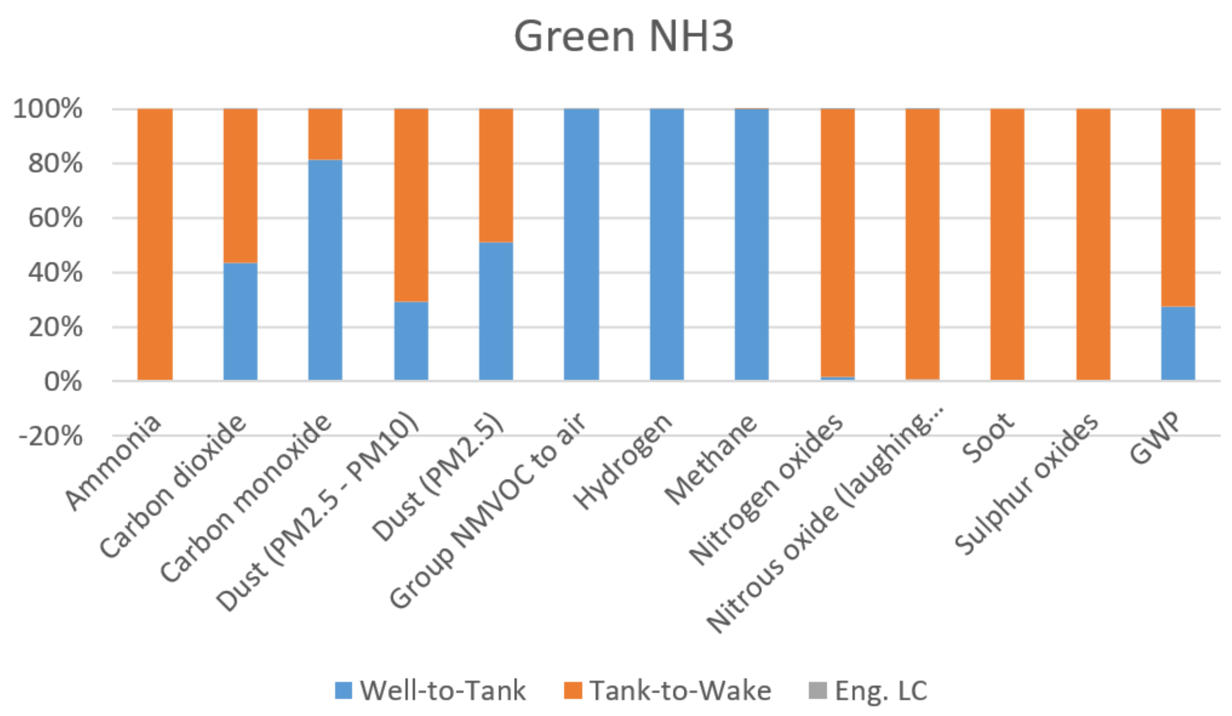
Blue and green H2 – LCA phases contribution





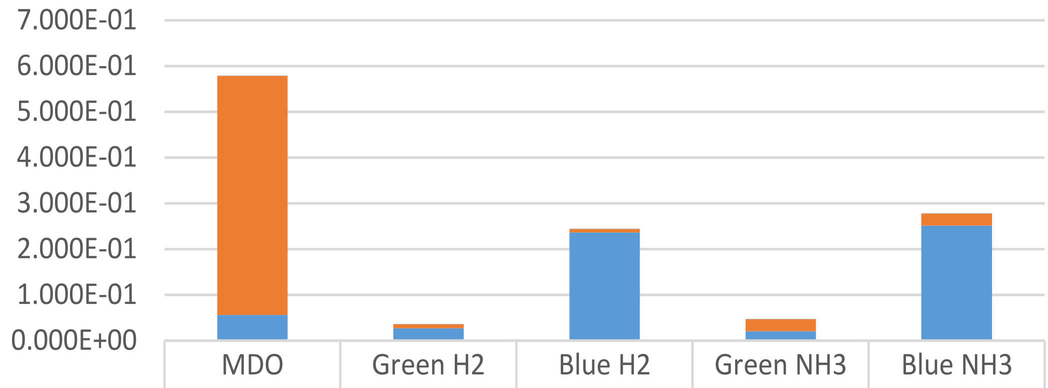
Blue and green NH3 – LCA phases contribution





Life cycle emissions – CO_2 and GWP

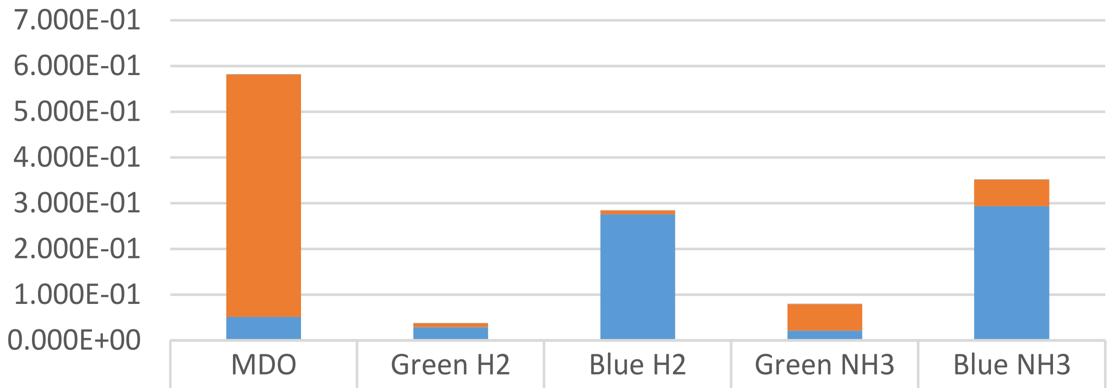
Carbon dioxide



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	7.160E-06	7.160E-06	7.160E-06	7.160E-06	7.160E-06
Tank-to-Wake	5.230E-01	8.020E-03	8.020E-03	2.630E-02	2.630E-02
Well-to-Tank	5.550E-02	2.705E-02	2.359E-01	2.019E-02	2.508E-01

Well-to-Tank Tank-to-Wake Eng. LC

GWP



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	7.570E-06	7.570E-06	7.570E-06	7.570E-06	7.570E-06
Tank-to-Wake	5.300E-01	8.130E-03	8.130E-03	5.770E-02	5.770E-02
Well-to-Tank	5.120E-02	2.869E-02	2.758E-01	2.158E-02	2.936E-01

Well-to-Tank Tank-to-Wake Eng. LC

Scenarios	Indicator	kg CO2 eq./kWh	Comparisons
MDO	GWP	5.82E-01	100.0%
Green H2	GWP	3.68E-02	6.3%
Blue H2	GWP	2.84E-01	48.8%
Green NH3	GWP	7.93E-02	13.6%
Blue NH3	GWP	3.51E-01	60.3%

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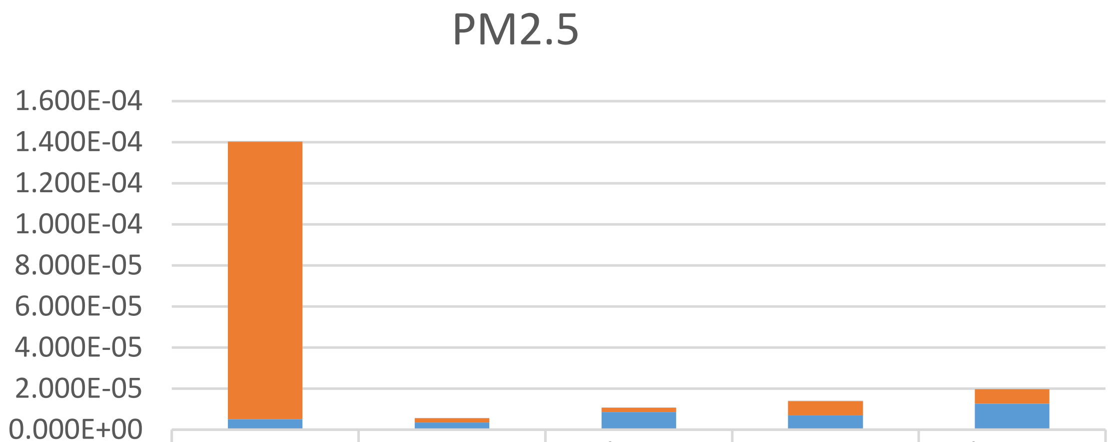
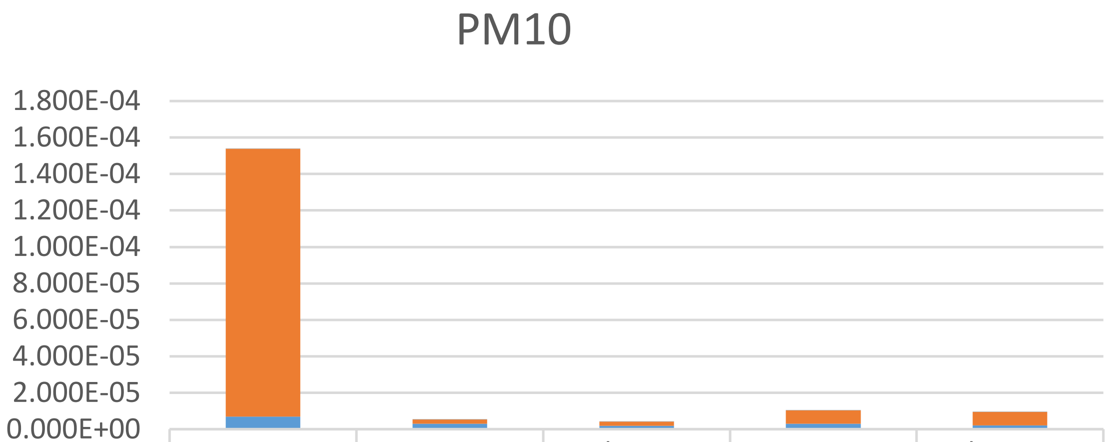
Life cycle emissions – PM



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	6.040E-10	6.040E-10	6.040E-10	6.040E-10	6.040E-10
Tank-to-Wake	1.350E-04	2.080E-06	2.080E-06	6.810E-06	6.810E-06
Well-to-Tank	5.100E-06	3.408E-06	8.598E-06	7.046E-06	1.276E-05

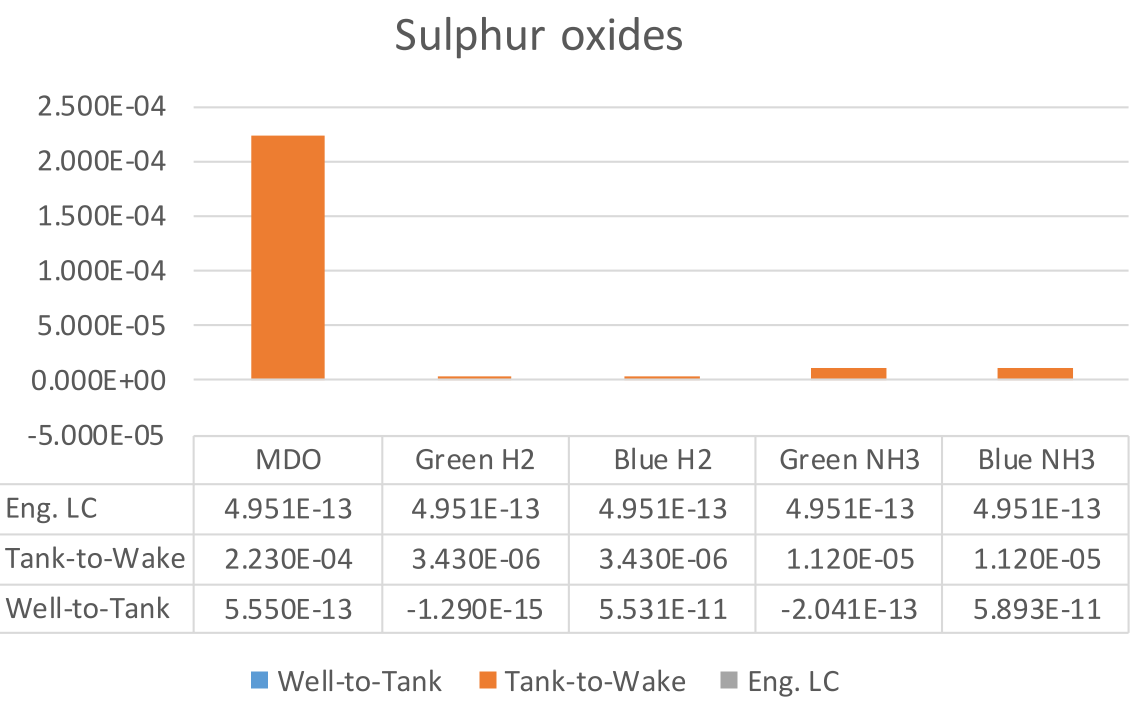
Well-to-Tank   Tank-to-Wake   Eng. LC



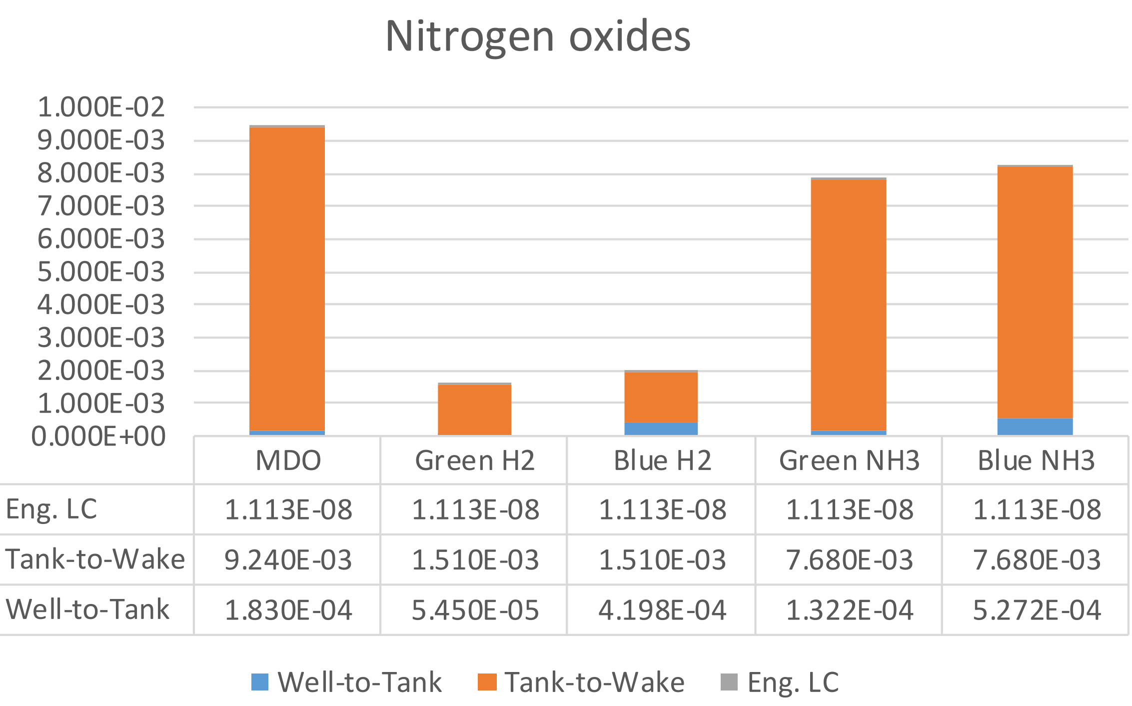
	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	4.280E-10	4.280E-10	4.280E-10	4.280E-10	4.280E-10
Tank-to-Wake	1.470E-04	2.250E-06	2.250E-06	7.380E-06	7.380E-06
Well-to-Tank	6.940E-06	3.136E-06	2.016E-06	3.029E-06	2.199E-06

Well-to-Tank   Tank-to-Wake   Eng. LC

Life cycle emissions – SOX and NOX

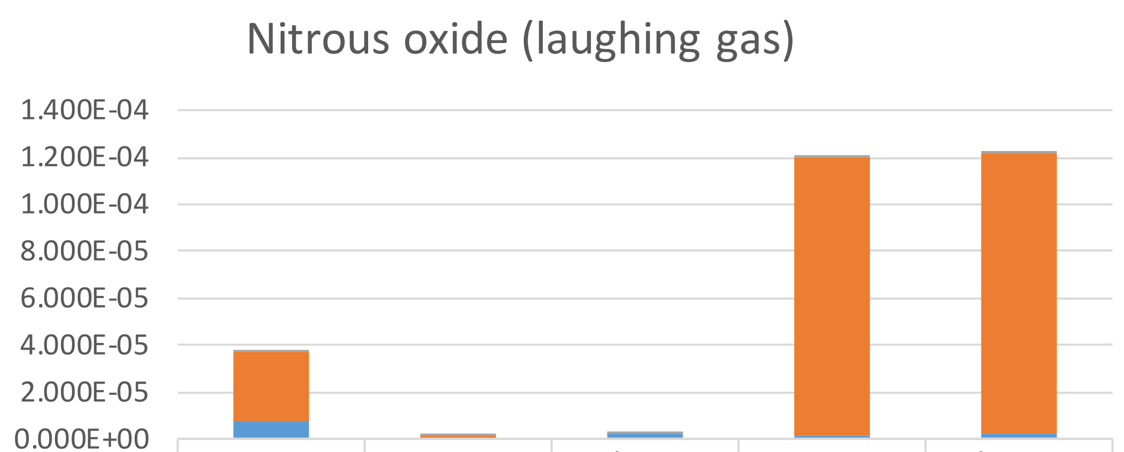


	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	4.951E-13	4.951E-13	4.951E-13	4.951E-13	4.951E-13
Tank-to-Wake	2.230E-04	3.430E-06	3.430E-06	1.120E-05	1.120E-05
Well-to-Tank	5.550E-13	-1.290E-15	5.531E-11	-2.041E-13	5.893E-11

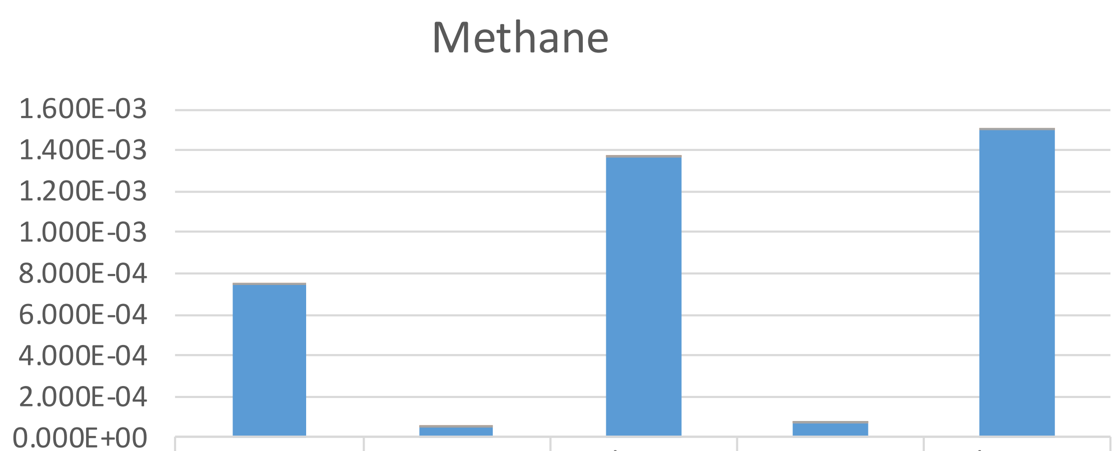


	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	1.113E-08	1.113E-08	1.113E-08	1.113E-08	1.113E-08
Tank-to-Wake	9.240E-03	1.510E-03	1.510E-03	7.680E-03	7.680E-03
Well-to-Tank	1.830E-04	5.450E-05	4.198E-04	1.322E-04	5.272E-04

Life cycle emissions – N2O and CH4



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	1.803E-10	1.803E-10	1.803E-10	1.803E-10	1.803E-10
Tank-to-Wake	2.930E-05	4.500E-07	4.500E-07	1.190E-04	1.190E-04
Well-to-Tank	7.430E-06	7.320E-07	2.034E-06	1.006E-06	2.494E-06



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	1.205E-08	1.205E-08	1.205E-08	1.205E-08	1.205E-08
Tank-to-Wake	1.630E-06	2.500E-08	2.500E-08	8.200E-08	8.200E-08
Well-to-Tank	7.460E-04	4.860E-05	1.371E-03	7.260E-05	1.498E-03

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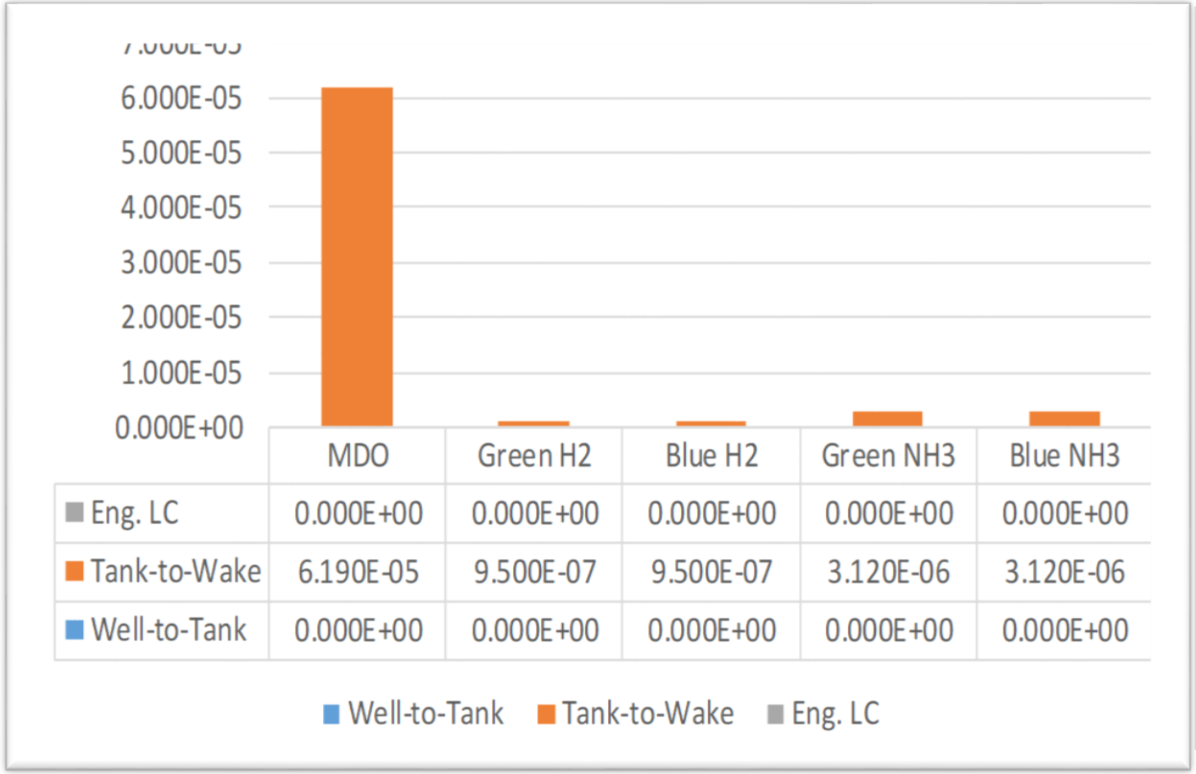
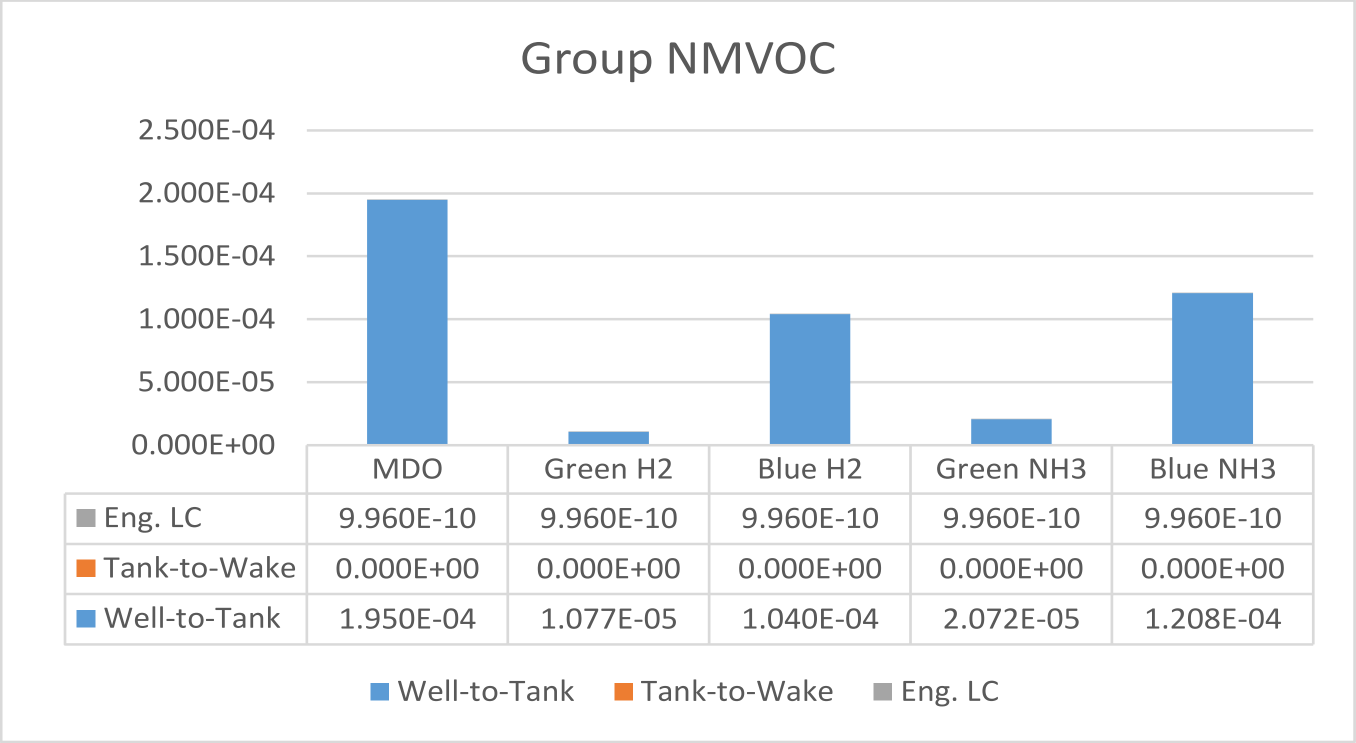
Life cycle emissions – BC & NMVOC



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Tank-to-Wake	6.190E-05	9.500E-07	9.500E-07	3.120E-06	3.120E-06
Well-to-Tank	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00



	MDO	Green H2	Blue H2	Green NH3	Blue NH3
Eng. LC	9.960E-10	9.960E-10	9.960E-10	9.960E-10	9.960E-10
Tank-to-Wake	0.000E+00	0.000E+00	0.000E+00	0.000E+00	0.000E+00
Well-to-Tank	1.950E-04	1.077E-05	1.040E-04	2.072E-05	1.208E-04

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Selective Catalystic Reduction (SCR)

Unit: kg emissions/kWh

Scenarios	CO2 equiv.	SOX	NOX	PM	Notes
100% MDO (LSF)	5.82E-01	2.23E-04	9.42E-03	2.94E-04	
MDO + SCR					Assuming 90%NOX reduction
95% Blue ammonia + 5% MDO	3.51E-01	1.12E-05	8.21E-03	2.91E-05	
95% Blue ammonia + 5% MDO + SCR					Assuming 90%NOX reduction
95% Green ammonia + 5% MDO	7.93E-02	1.12E-05	7.81E-03	2.43E-05	
95% Green ammonia + 5% MDO + SCR					Assuming 90%NOX reduction
98.5% Blue hydrogen + 1.5% MDO	2.84E-01	5.36E-05	1.83E-03	8.33E-06	
98.5% Blue hydrogen + 1.5% MDO + SCR	2.84E-01	5.36E-05	1.83E-03	8.33E-06	No SCR required!
98.5% Green H2 + 1.5% MDO	3.68E-02	3.29E-06	1.55E-03	5.13E-06	
98.5% Green H2 + 1.5% MDO + SCR	3.68E-02	3.29E-06	1.55E-03	5.13E-06	No SCR required!

Conclusion

- Emissions from fuel transportation and the LCA of engine's material are inconsiderable; most emissions come from fuel production and engine operation. This is because of a huge amount of fuel is consumed in the life cycle.
- The base case scenario (MDO) has highest amount of emission in most of primary emissions (excl. N_2O, H_2 slip and NH_3 slip)
- The rate of MDO used for pilot injection increases the environmental impacts.
- Generally, H_2 and NH_3 are more environmentally-friendly than the base case scenario (100%MDO)
- Blue H_2 and NH_3 has higher amount of CH_4 due to the electricity consumed in the production process.

H_2 and NH_3

- NH_3 has higher environmental impacts than H_2 (excl. H_2 slip)
- SCR will be used in case of using NH_3 as marine fuel; this could increase the environmental impacts and cost because of the use of urea
- The length of voyage could increase the environmental impacts of H_2 scenario
- The green solutions could significantly reduce emissions more than blue H_2 and NH_3

Next plans

- Sensitivitive analysis
  - Emission factors
  - Rate of MDO used for pilot injection process
  - Rate of H_2 slip, depends on number of operating day and % of boil-off H_2 (0.1%-1% per day)
  - Rate of CO_2 captured in CCS technology (from 85% to 95%)
  - Energy demand for H_2 liquefaction (from 6 to 10kWh/kgH2)
- Include CSR in LCA (15g of urea per 1 kWh could reduce 90% NOX)

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SUSTAINABLE DEVELOPMENT GOALS

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