Overview of Hydrogen Supply Chain & Cost Analysis

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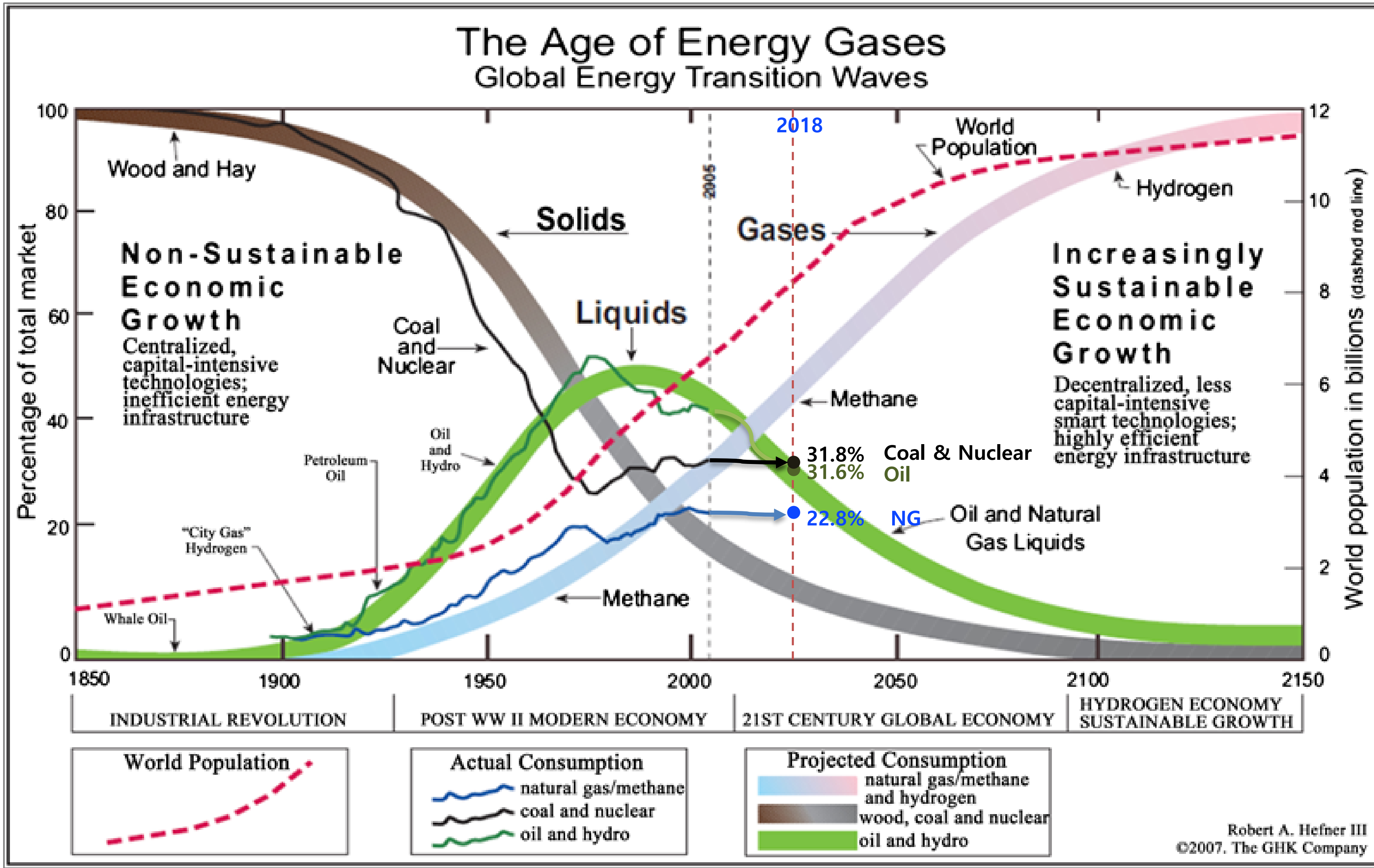
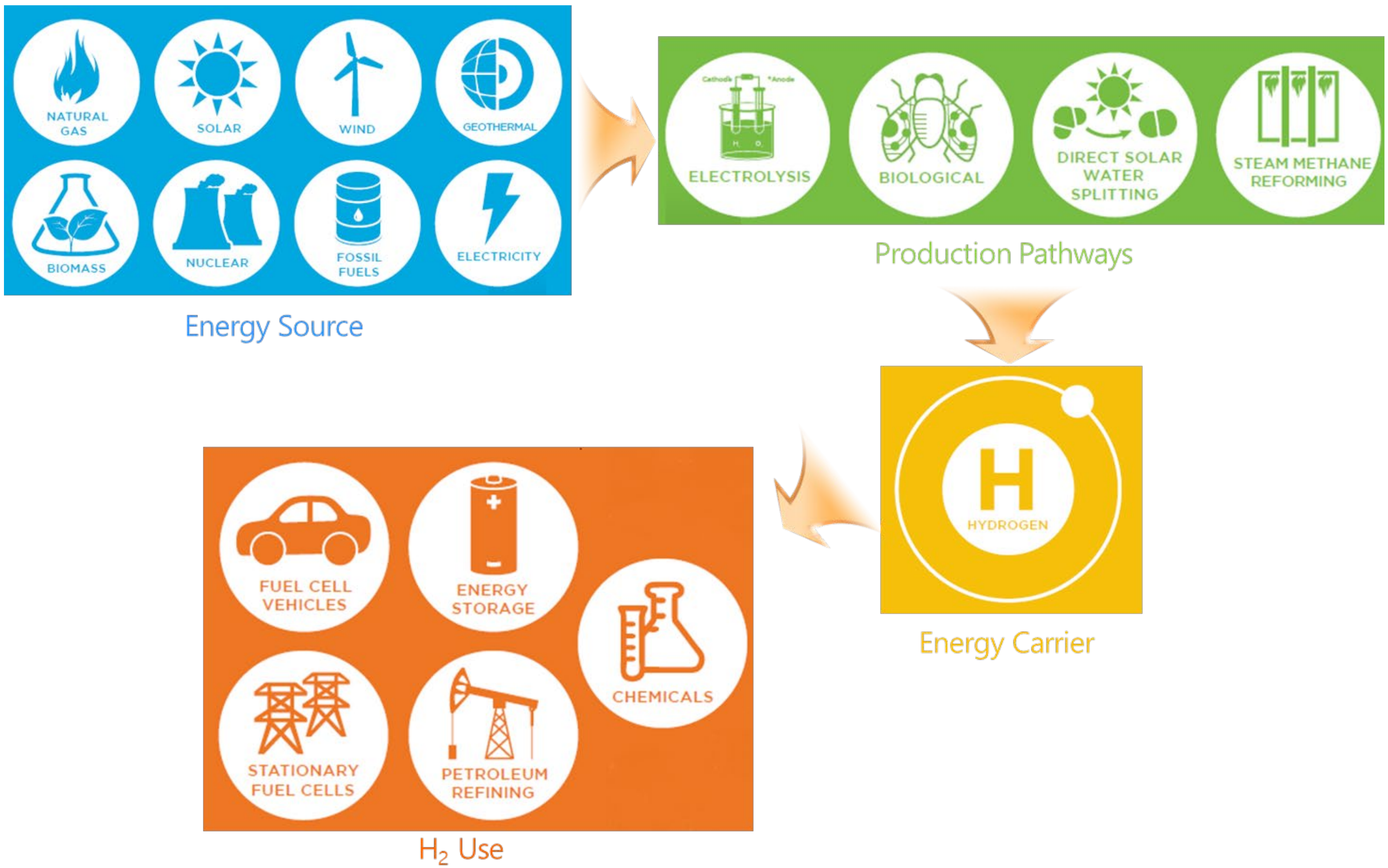
Energy Transition



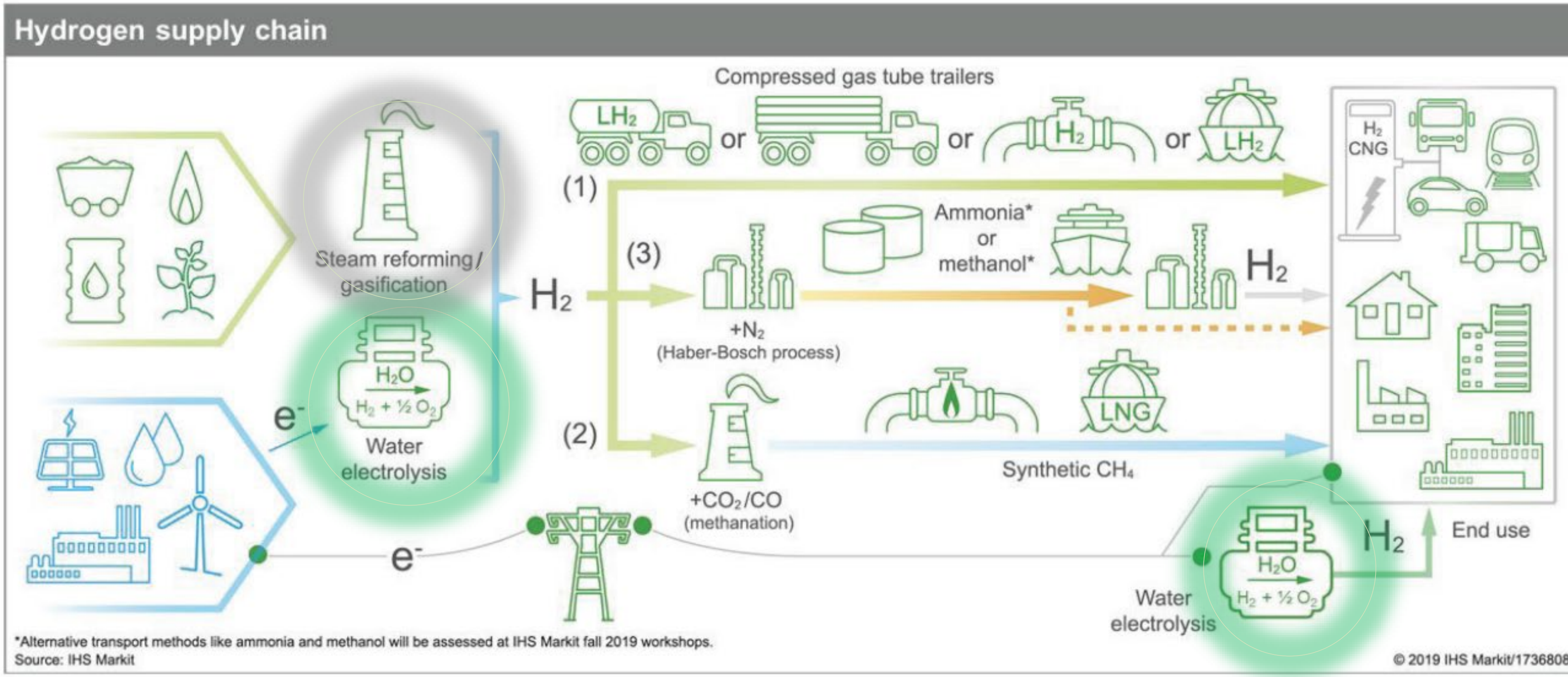
Hydrogen : Energy Carrier



Source : https://energy.gov/sites/prod/files/2017/09/f36/fcto-infographic-h2-energy-carrier-sept17.pdf

Hydrogen Supply Chain

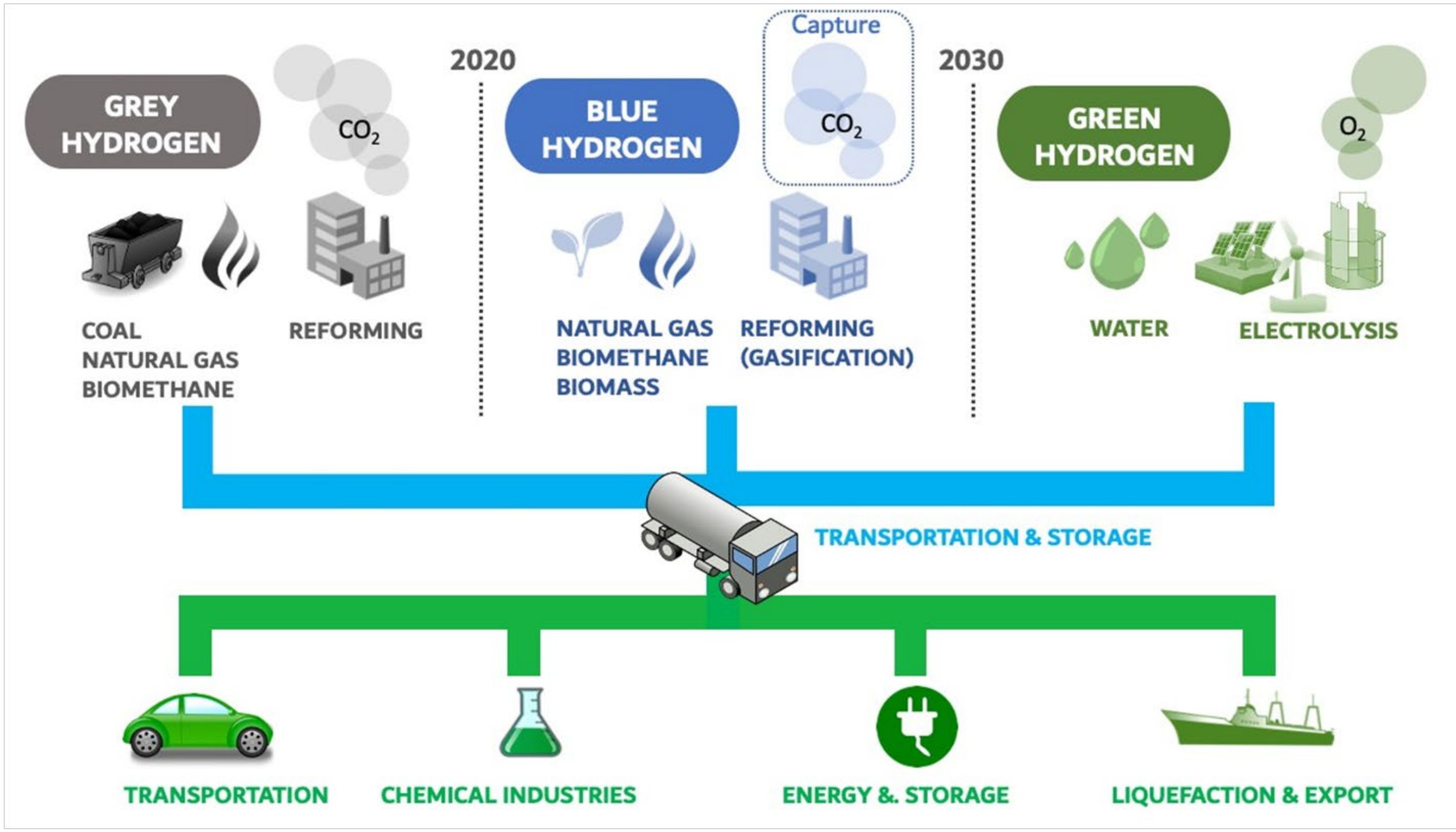
Production – Delivery/Storage - Utilization



HOW TO

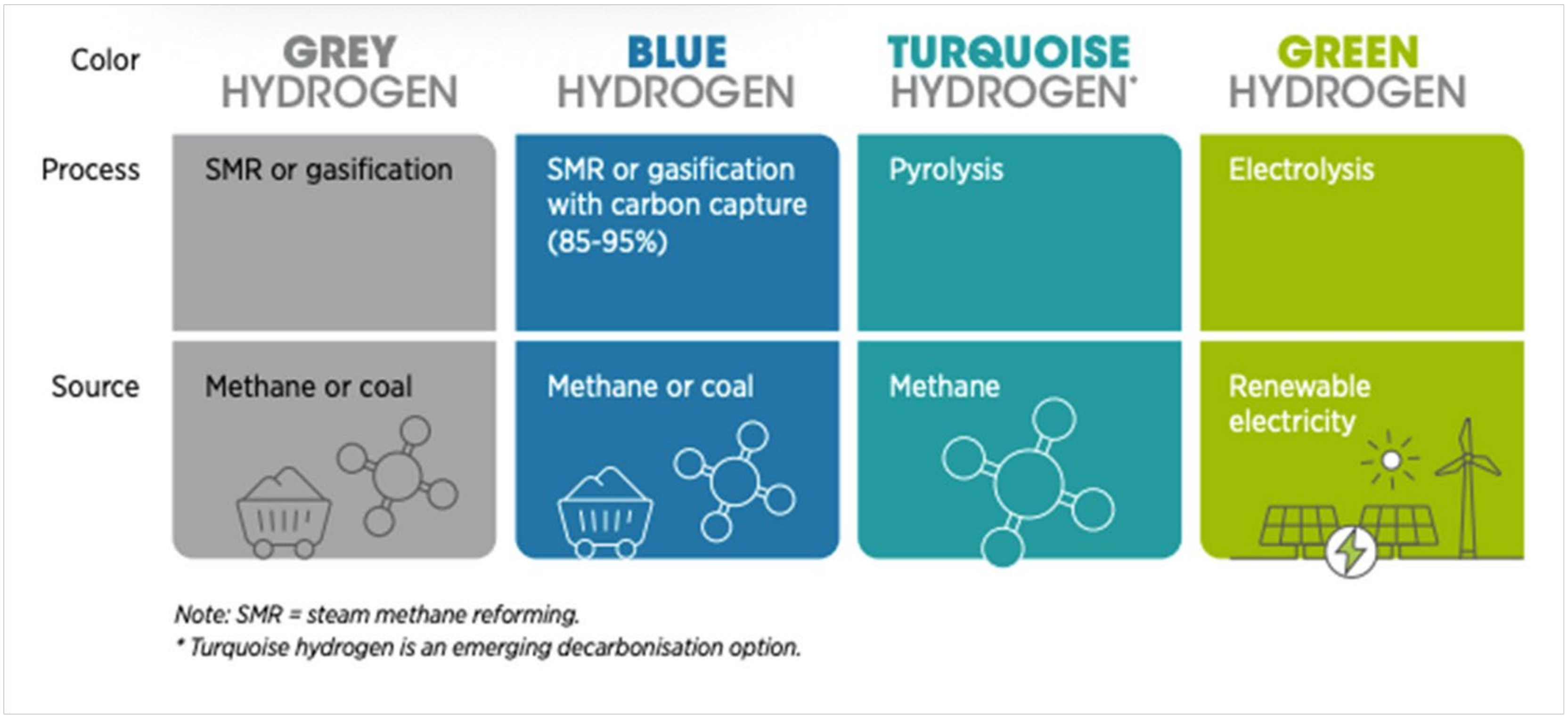
Hydrogen Production Technology(1)

Gray H2	Blue H2	Green H2

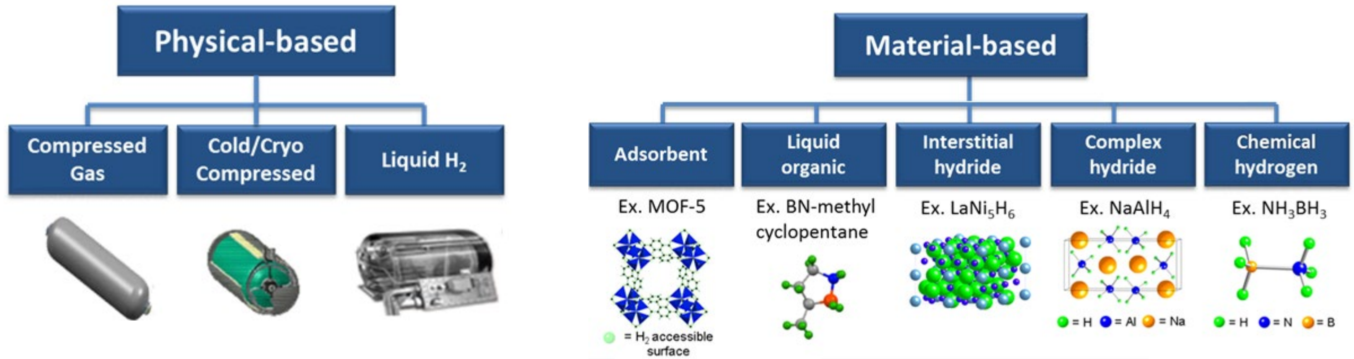


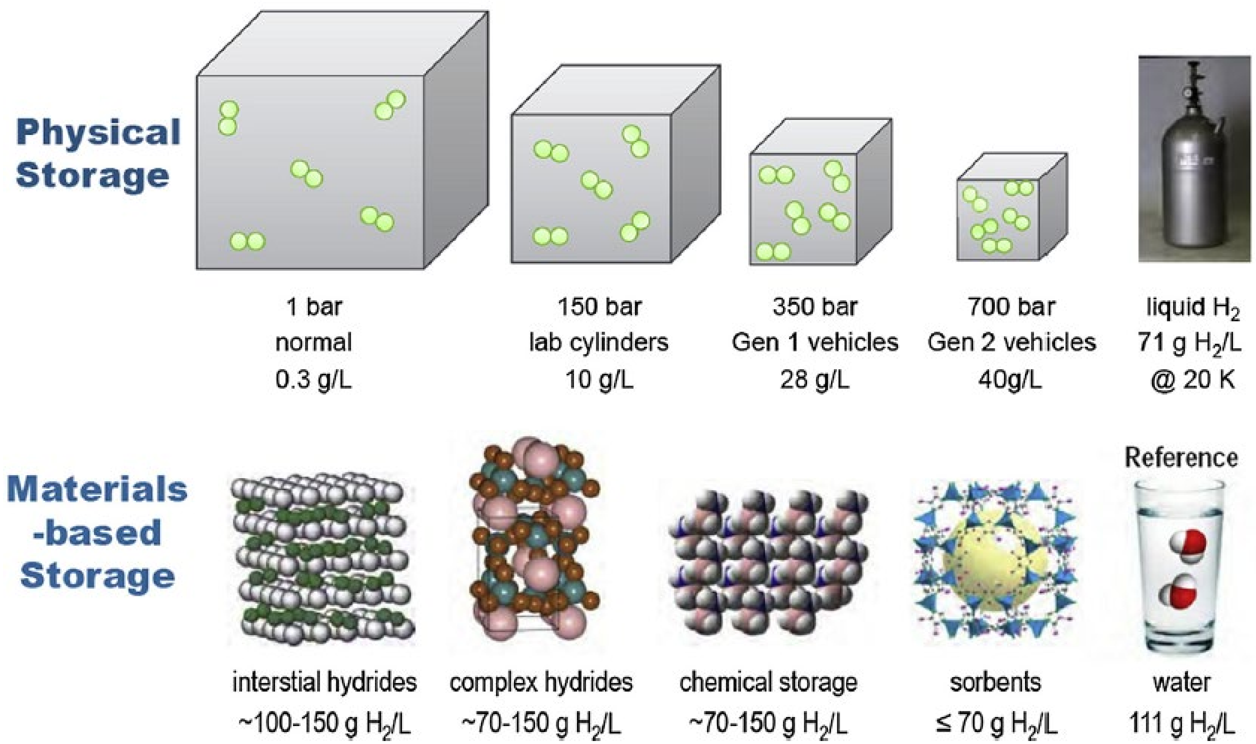
Hydrogen Production Technology(2)

Gray H2	Blue H2	Turquoise H2	Green H2

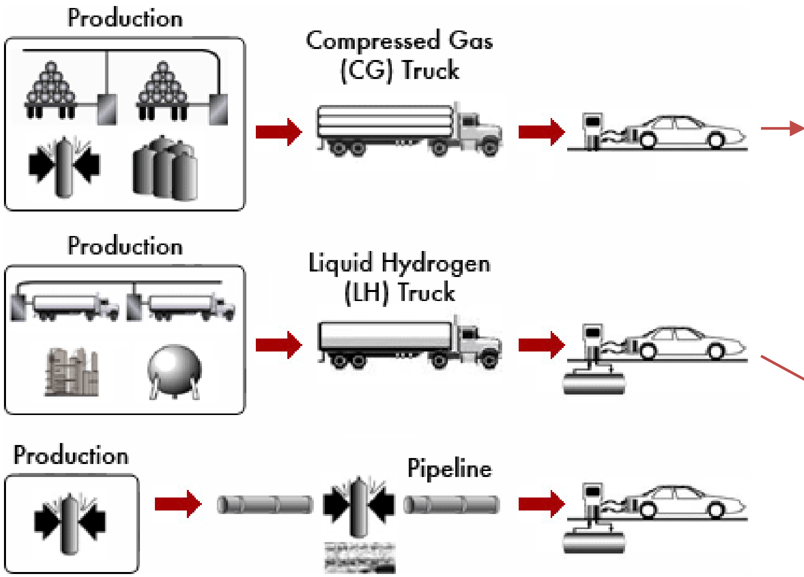


Hydrogen Storage & Delivery

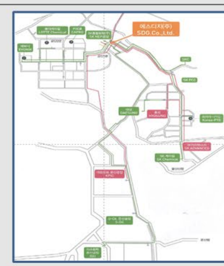




Hydrogen Storage & Delivery

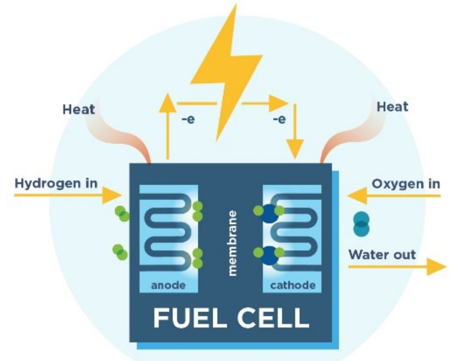


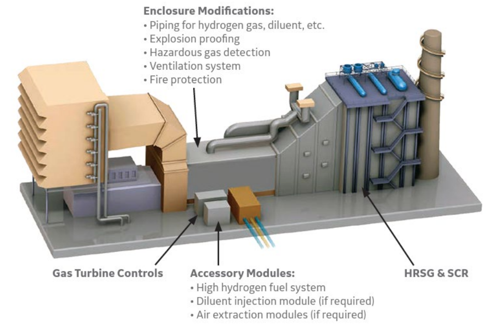
200Bar(Type 1)	450 bar(Type 4)
 	
• Cylinder : 1,200/2,290 (L) • Hydrogen capacity : 180/340 (kg) • Weight : 31 ton	• Cylinder : 1,845 L • Hydrogen capacity : 950 kg • Weight : 20 ton

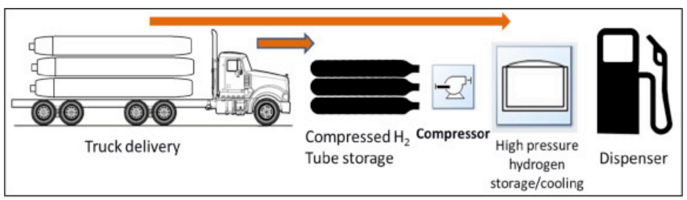
Ulsan(Deokyang)	Ulsan(SPG)	Ulsan(SDG)	Hydrogen pipeline
42.4 km	26.6 km	30 km	
			 - Depth 1.2m - Diameter 15cm

- Hydrogen pipeline : about 200 km built around petrochemical complexes (Ulsan, Yeosu, Daesan)

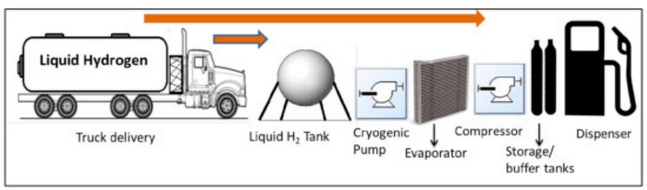
Hydrogen Use







(a)



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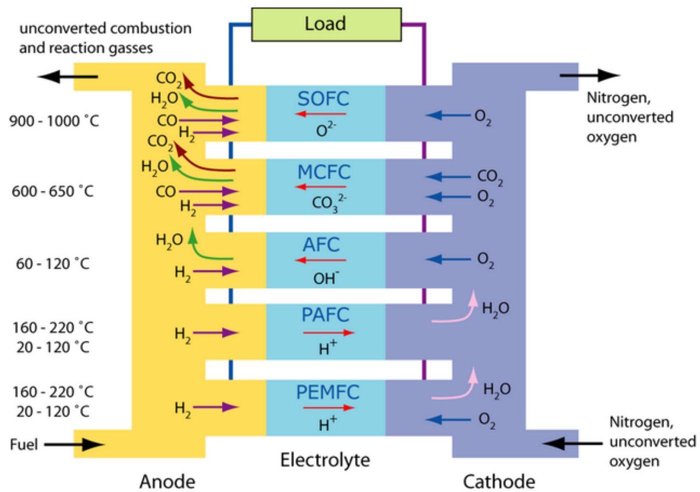
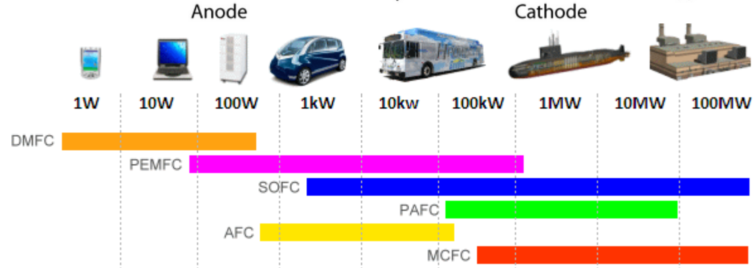
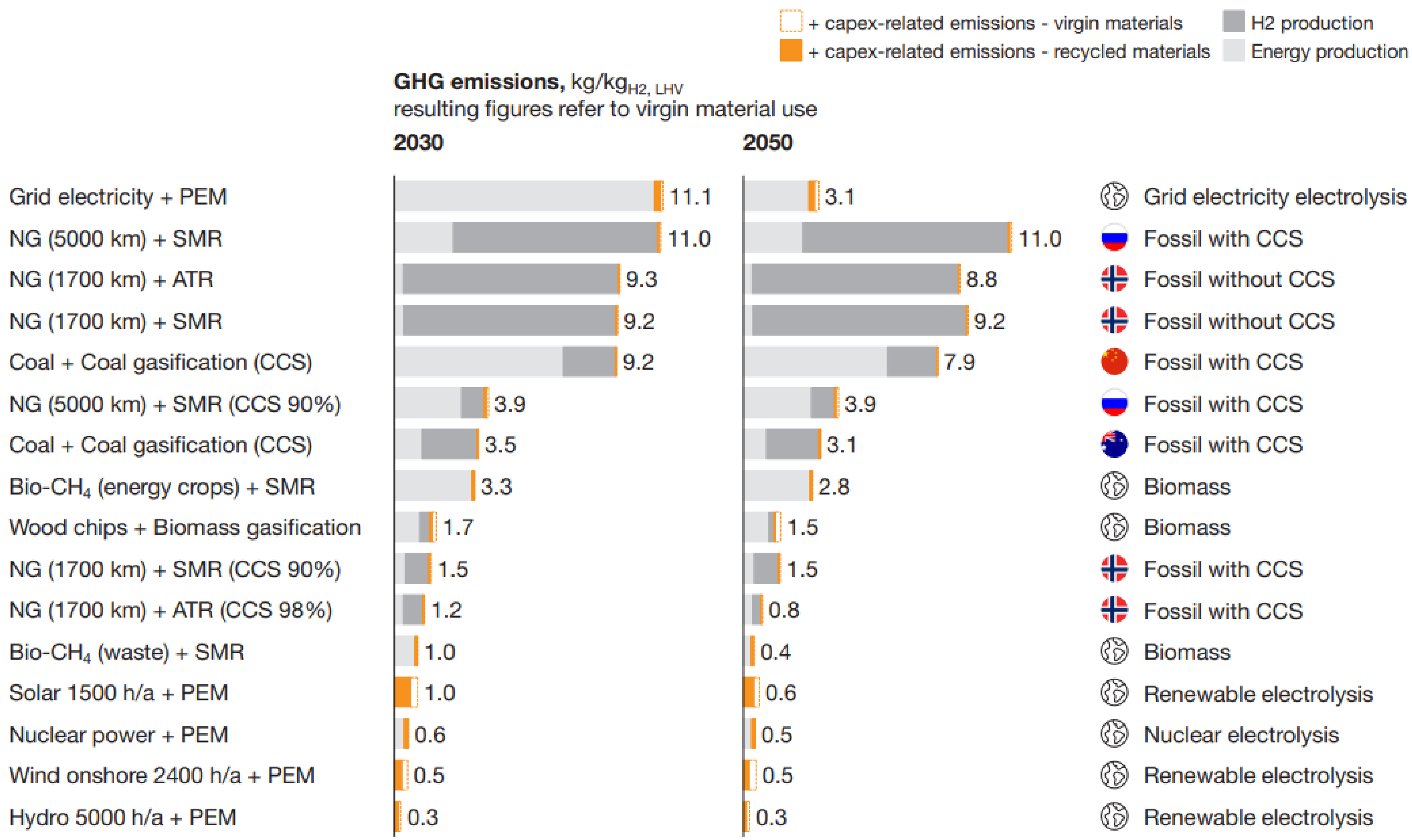




Greenhouse gas emission by Hydrogen production technologies



Source: Hydrogen Council, LBST

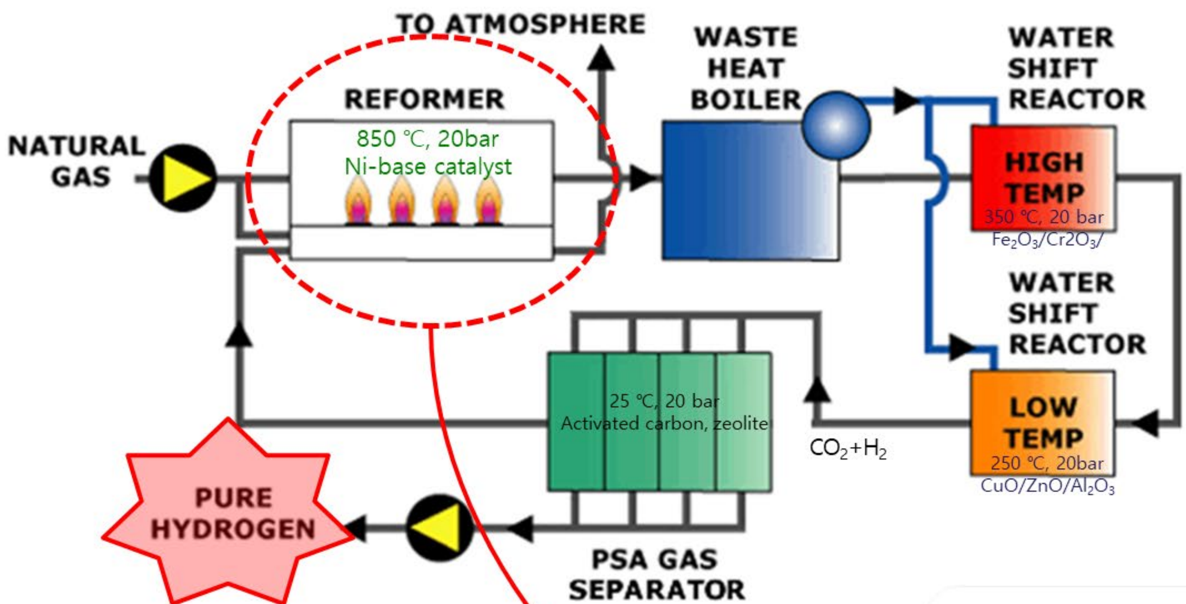
I. Hydrogen Supply Chain

II. Hydrogen Production Technology

III. Hydrogen Cost Analysis

IV. Sector Coupling & P2G

Grey Hydrogen : from Natural Gas



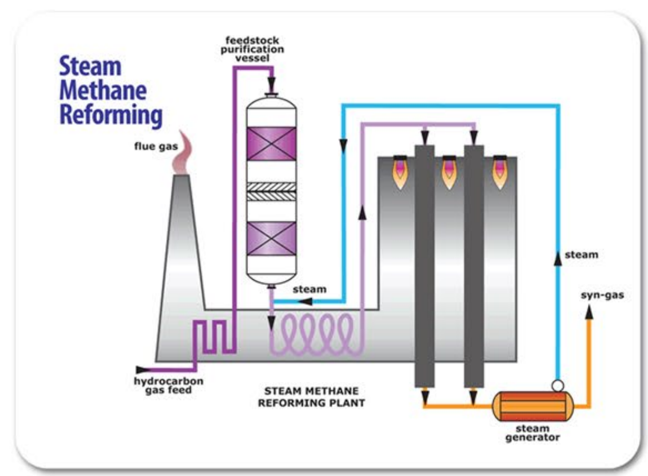
Reforming reaction

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2$$

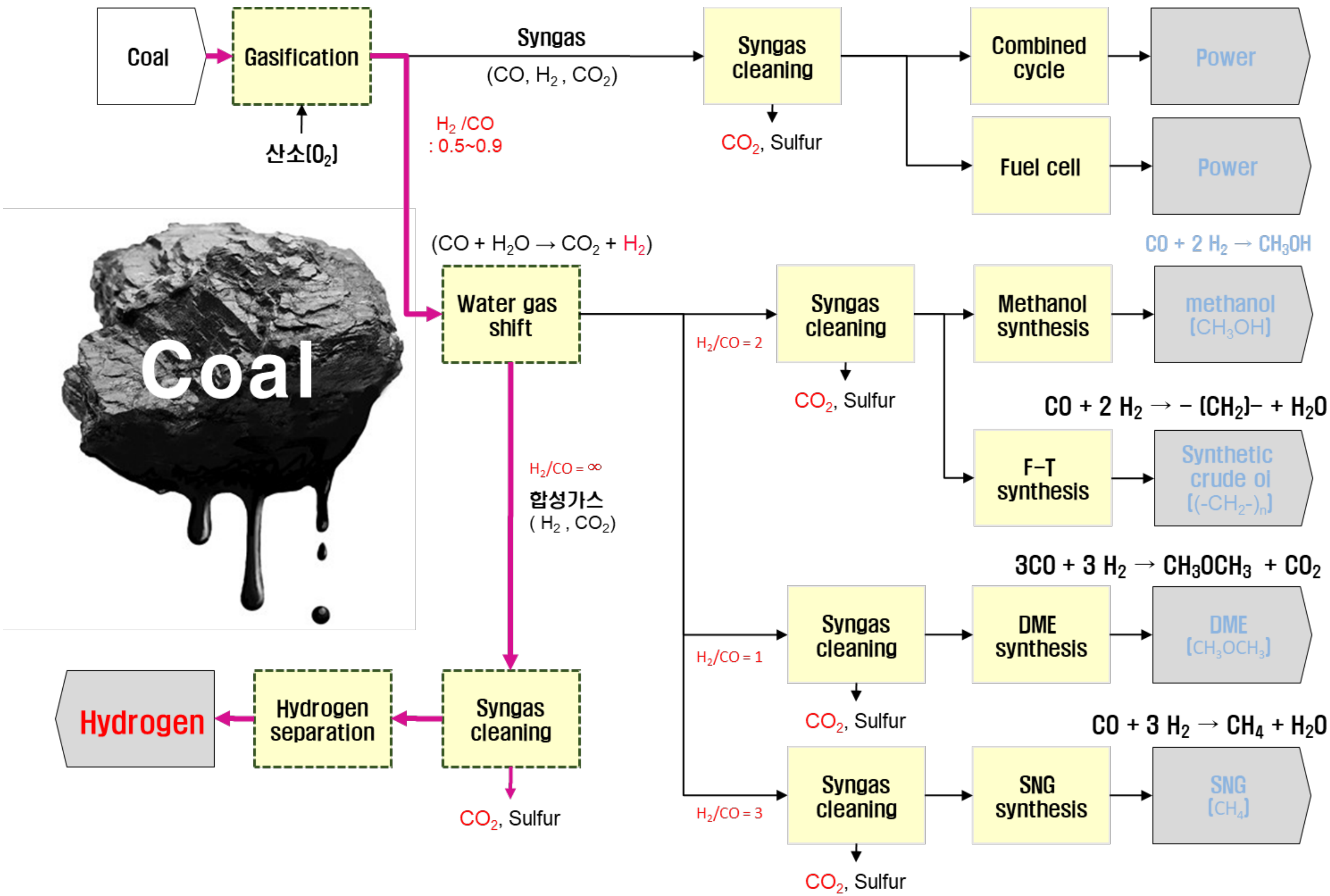
Water gas shift reaction

$$CO + H_2O \rightarrow CO_2 + H_2$$

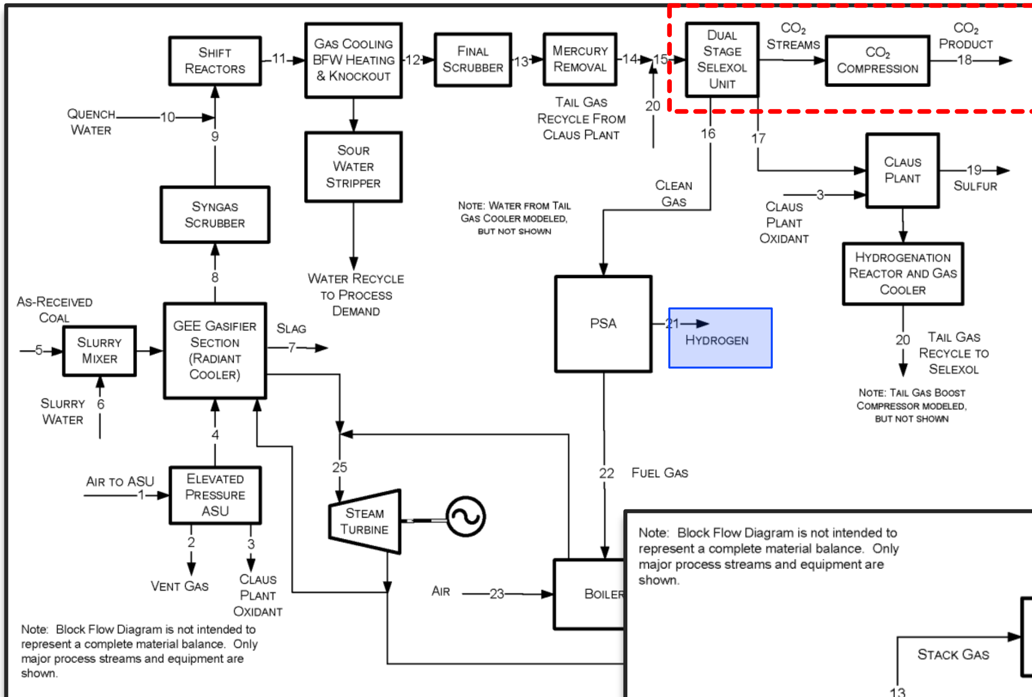


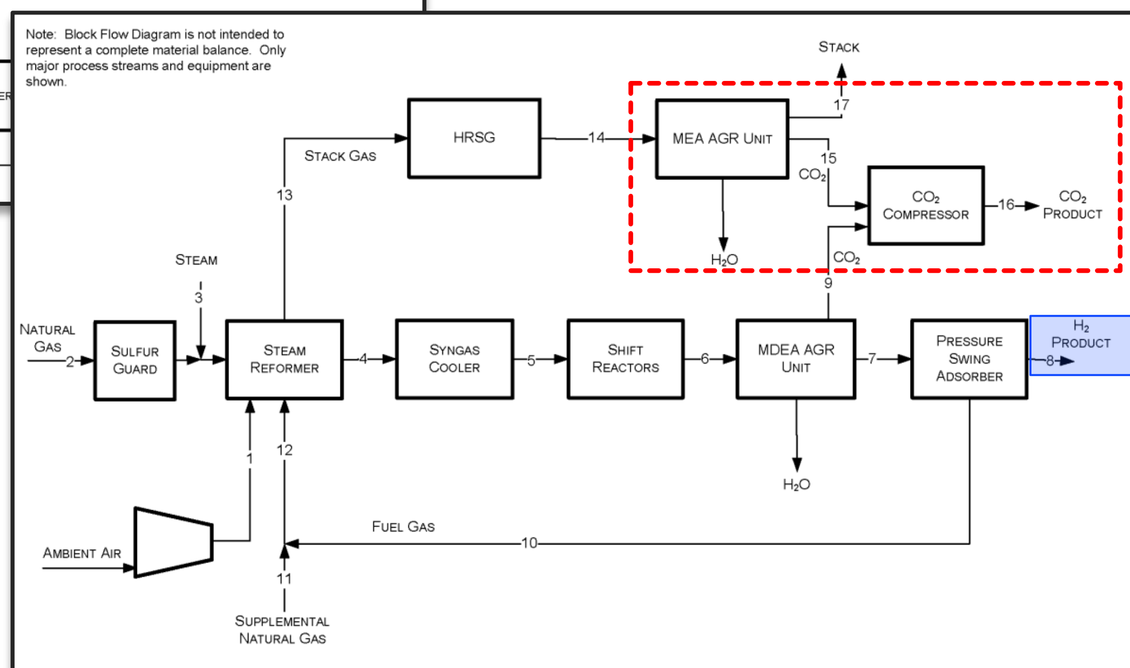
- 96% of hydrogen is produced from fossil fuel (Natural gas 48%, Oil 30%, Coal 18%)
- Air Product, Air Liquid, Linde AG, Praxair

Grey Hydrogen : from Coal



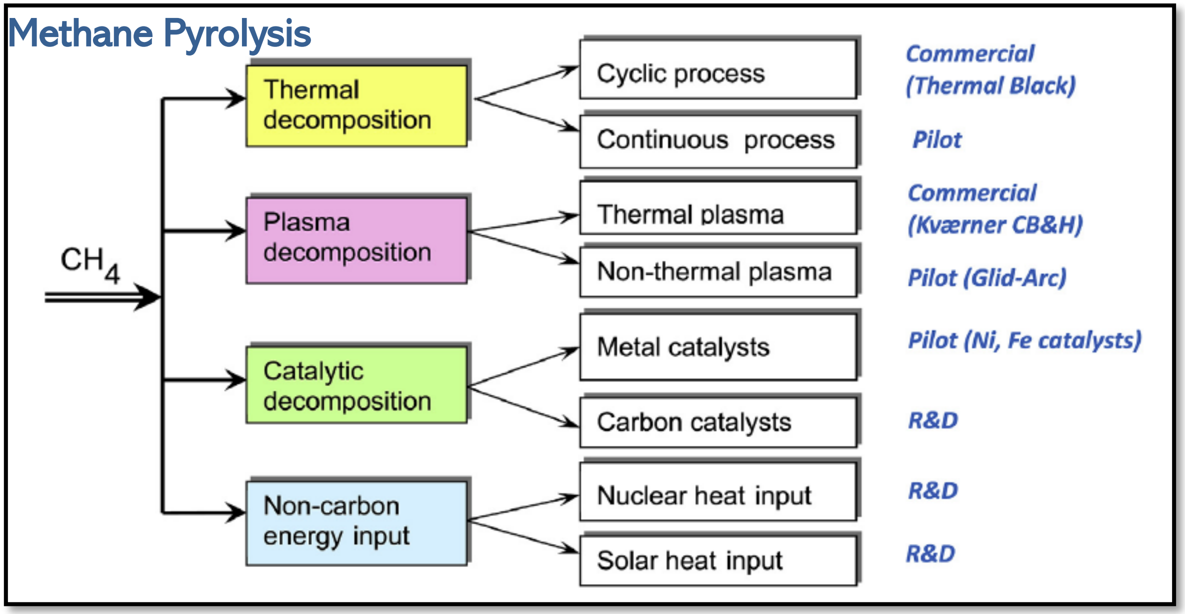
Blue Hydrogen (with CCS)

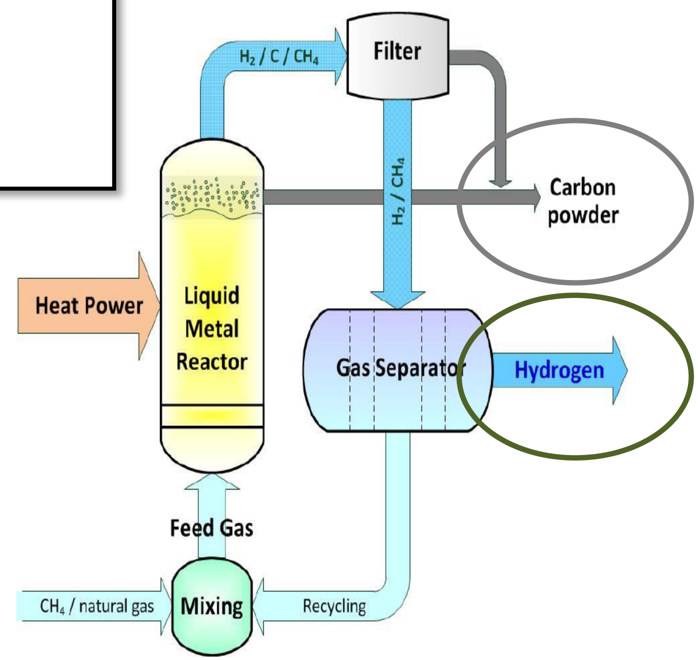




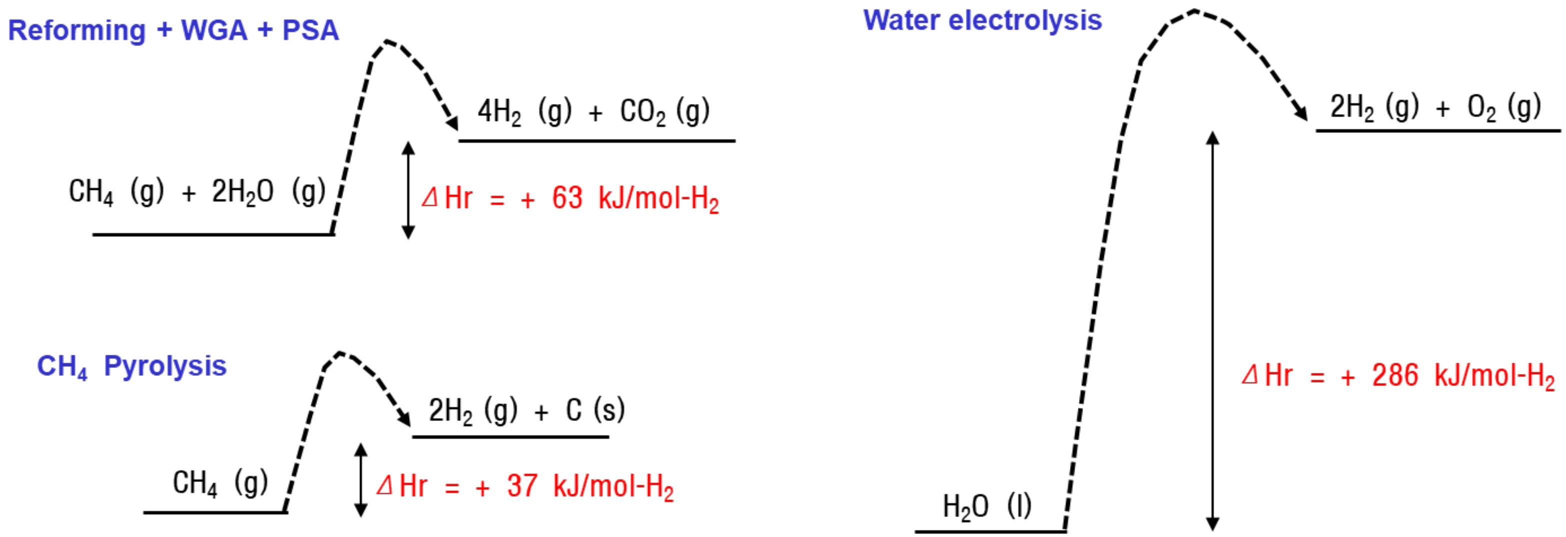
Turquoise Hydrogen

$$CH_4 \rightarrow 2H_2 + C$$



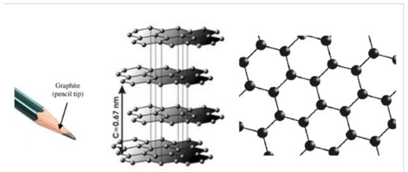


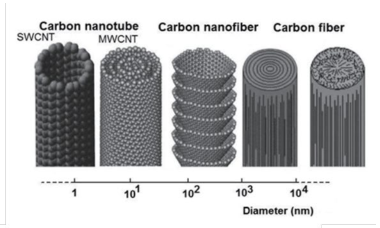
Turquoise Hydrogen

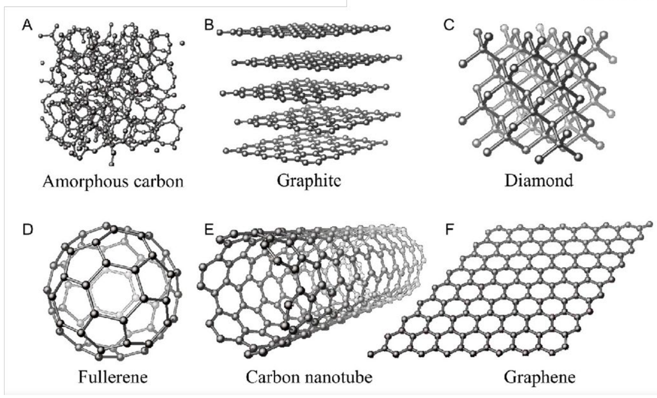


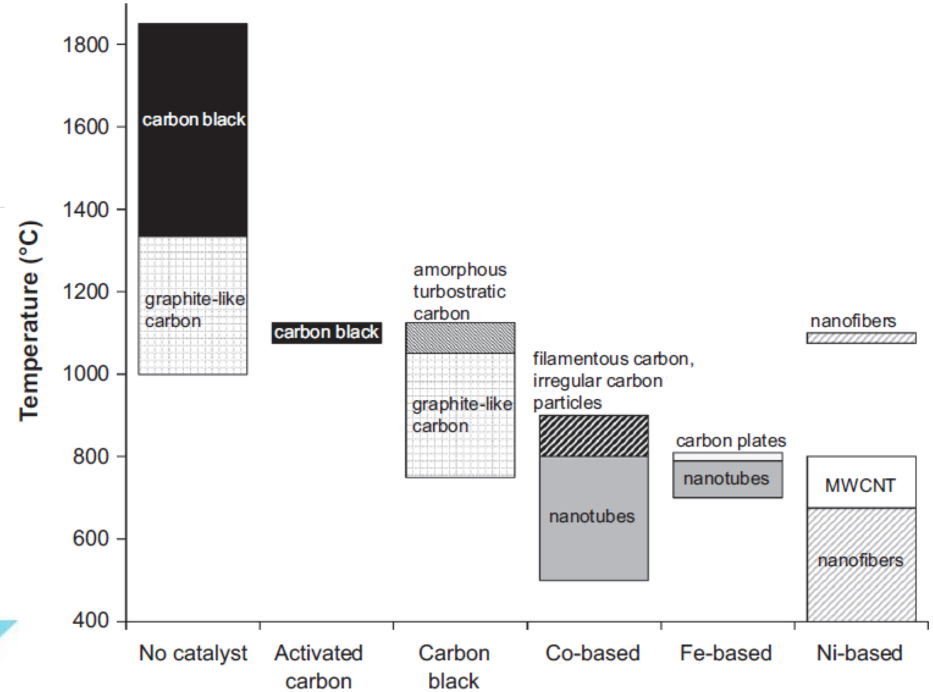
Technology	Reaction	Direct CO_2 emission ($kg\text{-}CO_2/kg\text{-}H_2$)	Minimum energy demand ($kJ/mol\text{-}H_2$)	Energy source	By-product
Steam reforming methane	$CH_4 + 2H_2O \rightarrow 4H_2 + CO_2$	8.85	63 (22%)	CH_4	CO_2
Water electrolysis	$2H_2O \rightarrow 2H_2 + O_2$	0	286 (100% basis)	Renewable electricity	O_2
Methane pyrolysis	$CH_4 \rightarrow 2H_2 + C$	0	37 (13%)	Renewable electricity or CO_2 free energy	Carbon

Turquoise Hydrogen

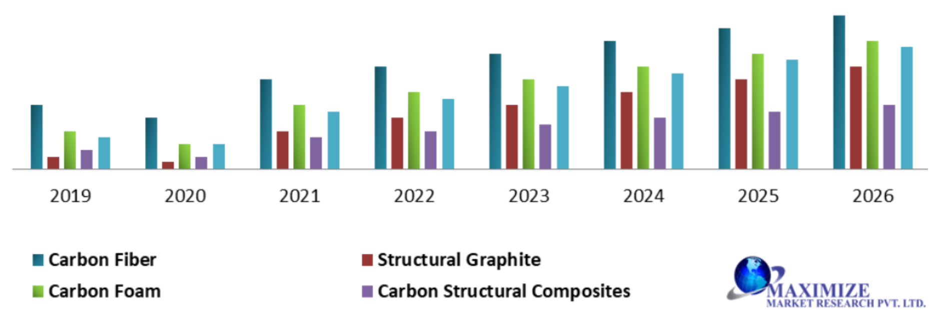




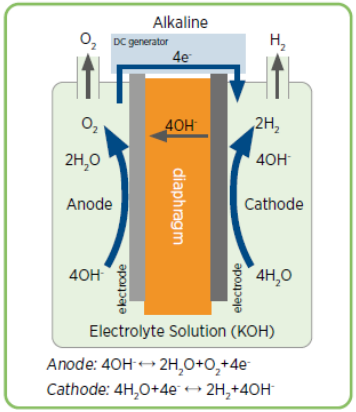


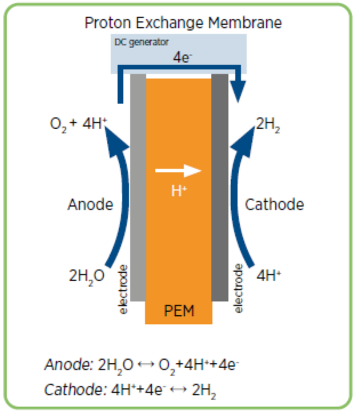


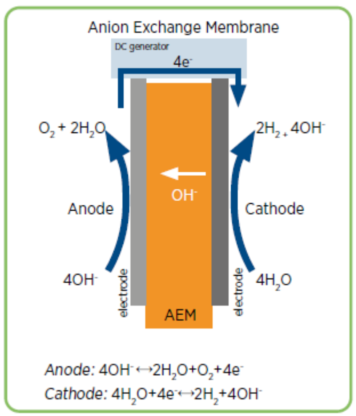
Global Advanced Structural Carbon Products Market, by Type (US$ Bn)

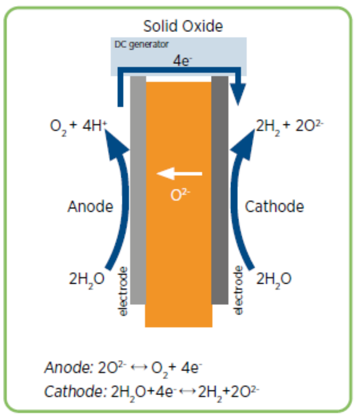


Green Hydrogen









	Alkaline	PEM	AEM	Solid Oxide
Operating temperature	70-90 °C	50-80 °C	40-60 °C	700-850 °C
Operating pressure	1-30 bar	< 70 bar	< 35 bar	1 bar
Electrolyte	Potassium hydroxide (KOH) 5-7 $molL^{-1}$	PFSA membranes	DVB polymer support with KOH or NaHCO3 1$molL^{-1}$	Yttria-stabilized Zirconia (YSZ)
Separator	ZrO_2 stabilized with PPS mesh	Solid electrolyte (above)	Solid electrolyte (above)	Solid electrolyte (above)
Electrode / catalyst (oxygen side)	Nickel coated perforated stainless steel	Iridium oxide	High surface area Nickel or NiFeCo alloys	Perovskite-type (*e.g.* LSCF, LSM)
Electrode / catalyst (hydrogen side)	Nickel coated perforated stainless steel	Platinum nanoparticles on carbon black	High surface area nickel	Ni/YSZ
Porous transport layer anode	Nickel mesh (not always present)	Platinum coated sintered porous titanium	Nickel foam	Coarse Nickel-mesh or foam
Porous transport layer cathode	Nickel mesh	Sintered porous titanium or carbon cloth	Nickel foam or carbon Cloth	None
Bipolar plate anode	Nickel-coated stainless steel	Platinum-coated titanium	Nickel-coated stainless steel	None
Bipolar plate cathode	Nickel-coated stainless steel	Gold-coated titanium	Nickel-coated Stainless steel	Cobalt-coated stainless steel
Frames and sealing	PSU, PTFE, EPDM	PTFE, PSU, ETFE	PTFE, Silicon	Ceramic glass

Source : Green hydrogen cost reduction, IRENA, 2020

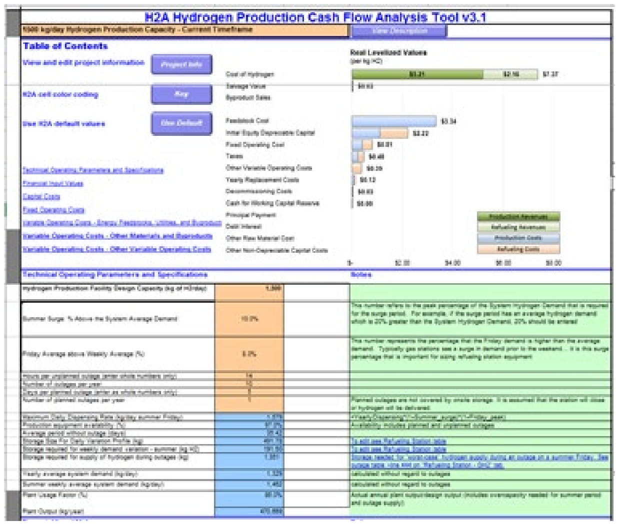
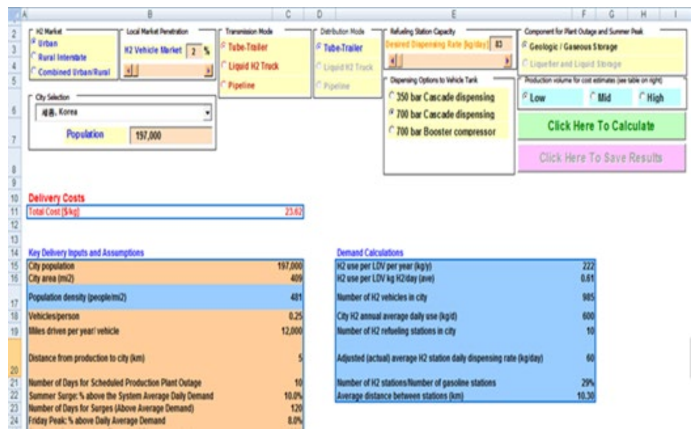
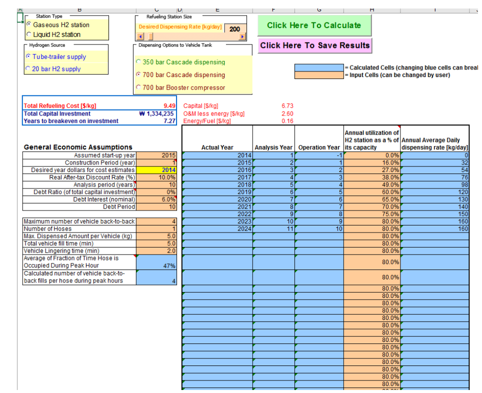
Green Hydrogen : State-of-the-art and future KPI for electrolysis

	2020			Target 2050		
	Alkaline	PEM	SOEC	Alkaline	PEM	SOEC
Nominal current density	0.2-0.8 A/cm^2	1-2 A/cm^2	0.3-1 A/cm^2	> 2 A/cm^2	4-6 A/cm^2	> 2 A/cm^2
Voltage range (limits)	1.4-3 V	1.4-2.5 V	1.0-1.5 V	< 1.7 V	< 1.7 V	< 1.48 V
Operating temperature	70-90°C	50-80°C	700-850°C	> 90°C	80°C	< 600°C
Cell pressure	< 30 bar	< 30 bar	1 bar	> 70 bar	> 70 bar	> 20 bar
Load range	15%-100%	5%-120%	30%-125%	5%-300%	5%-300%	0%-200%
H2 purity	99.9%-99.9998%	99.9%-99.9999%	99.90%	> 99.9999%	Same	100.00%
Voltage efficiency (LHV)	50%-68%	50%-68%	75%-85 %	> 70%	> 80%	> 85%
Electrical efficiency (stack)	47-66 kWh/Kg H_2	47-66 kWh/Kg H_2	35-50 kWh/Kg H_2	< 42 kWh/Kg H_2	< 42 kWh/Kg H_2	< 35 kWh/Kg H_2
Electrical efficiency (system)	50-78 kWh/Kg H_2	50-83 kWh/Kg H_2	40-50 kWh/Kg H_2	< 45 kWh/Kg H_2	< 45 kWh/Kg H_2	< 40 kWh/Kg H_2
Lifetime (stack)	60,000 hours	50,000-80,000 hours	< 20,000 hours	100,000 hours	100,000-120,00 hours	80,000 hours
Stack unit size	1 MW	1 MW	5 kW	10 MW	10 MW	200 kW
Electrode area	10 000-30 000 cm^2	1,500 cm^2	200 cm^2	30,000 cm^2	> 10,000 cm^2	500 cm^2
Cold start (to nominal load)	< 50 minutes	< 20 minutes	> 600 minutes	< 30 minutes	< 5 minutes	< 300 minutes
Capital costs(Stack) minimum 1MW	USD 270/kW	USD 400/kW	> USD 2 000/kW	USD 100/kW	USD 100/kW	< USD 200/kW
Capital costs(System) minimum 10MW	USD 500-1 000/kW	700-1400 USD/kW	Unknown	< 200 USD/kW	< 200 USD/kW	< USD 300/kW

Source : Green hydrogen cost reduction, IRENA, 2020

H2
H2
NEXO

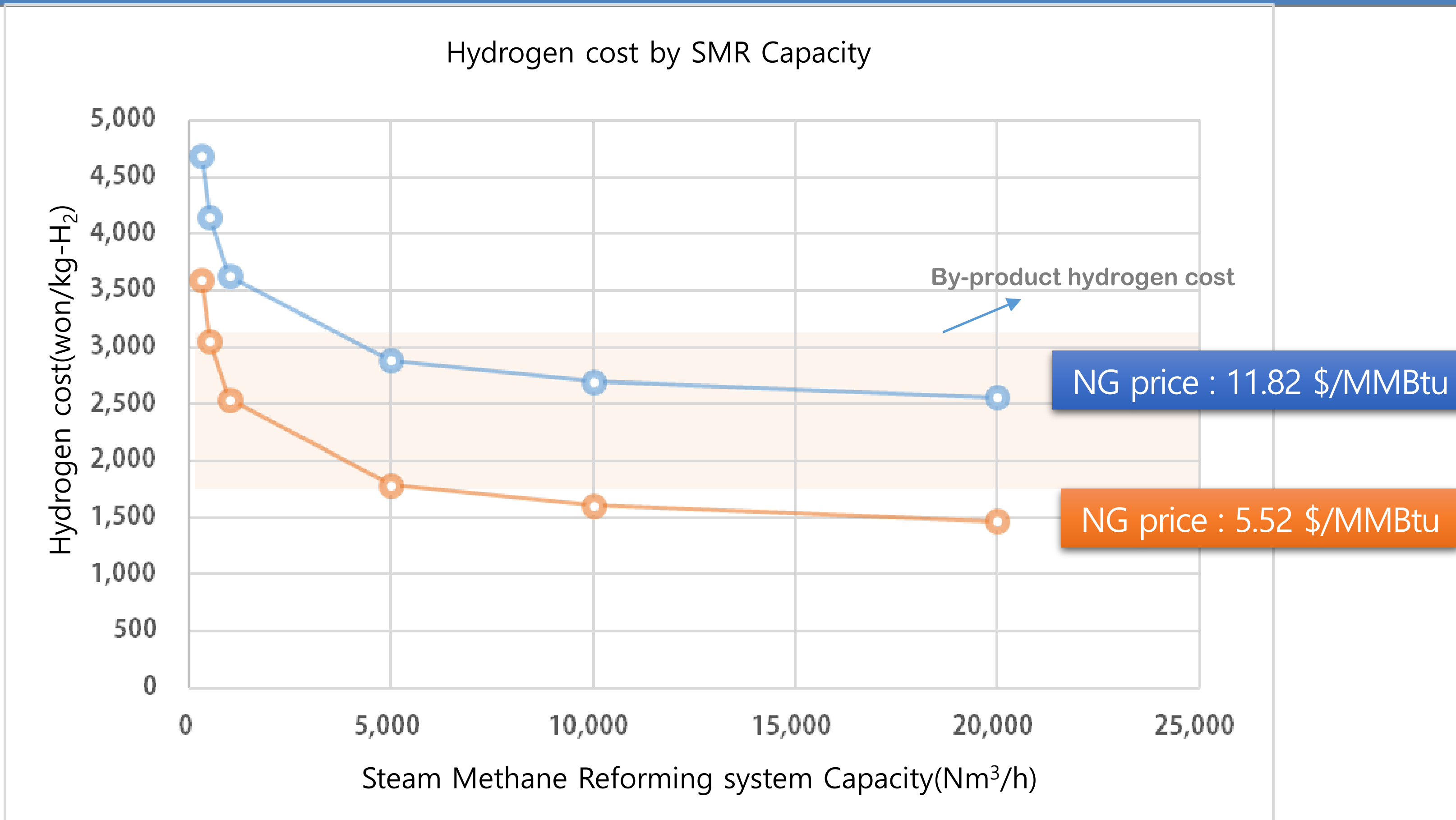
Analysis Program : H2A, HDSAM, HRSAM

H2A (H2A Production Model)	HDSAM (Hydrogen Delivery Scenario Analysis Model)	HRSAM (Hydrogen Refueling Station Analysis Mode)
		
• Levelized cost calculation of hydrogen production(SMR, Water electrolysis) (Since 2005, Ver. 3.2018)(NREL)	• Hydrogen delivery cost calculation : Compressed Gas, Liquid, Pipeline delivery (Since 2006, Ver. 3.1)	• Hydrogen refueling cost calculation(Since 2014, Ver. 2.0)

✓ Developed by DOE(Department of Energy)

Hydrogen production cost

Hydrogen cost by Steam Methane Reforming system

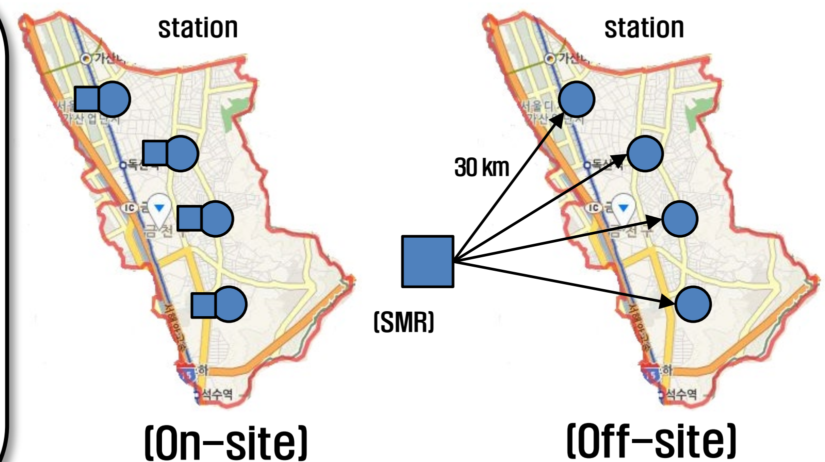


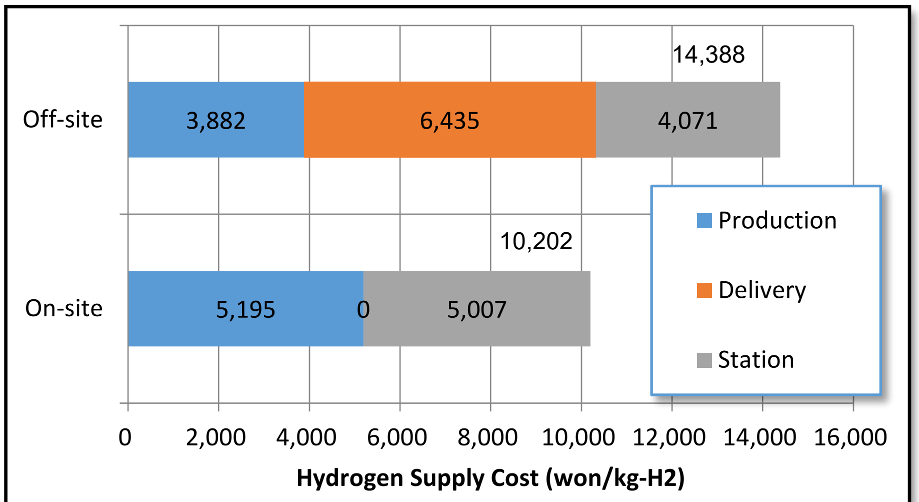
SMR Capacity(Nm^3/h)	500	1000	2000	5000	10000	20000
CAPEX(billion won)	4	6	9	16	24	36

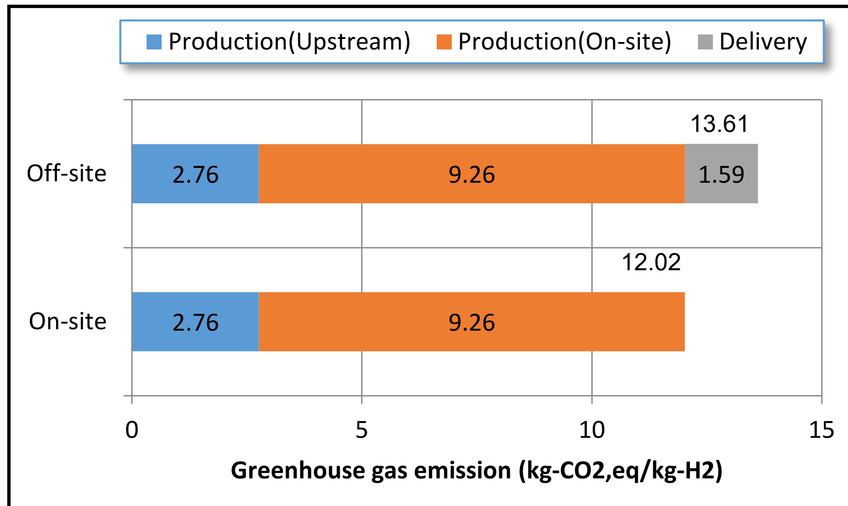
Hydrogen cost analysis example

Hydrogen supply cost & greenhouse gas emission

- S city K district
  - population 250,000, area 13 km^2,
  - fuel cell hydrogen vehicle market share : 4%(2,500 cars))
  - NG price : 513 won/Nm^3
- On-site
  - No. of station : 4 (500 kg/d)
  - SMR Capacity : 300 Nm^3/h
- Off-site
  - SMR Capacity : 1000 Nm^3/h,
  - Delivery : 30 km transportation by tube trailer
  - No. of station : 4 (500 kg/d)

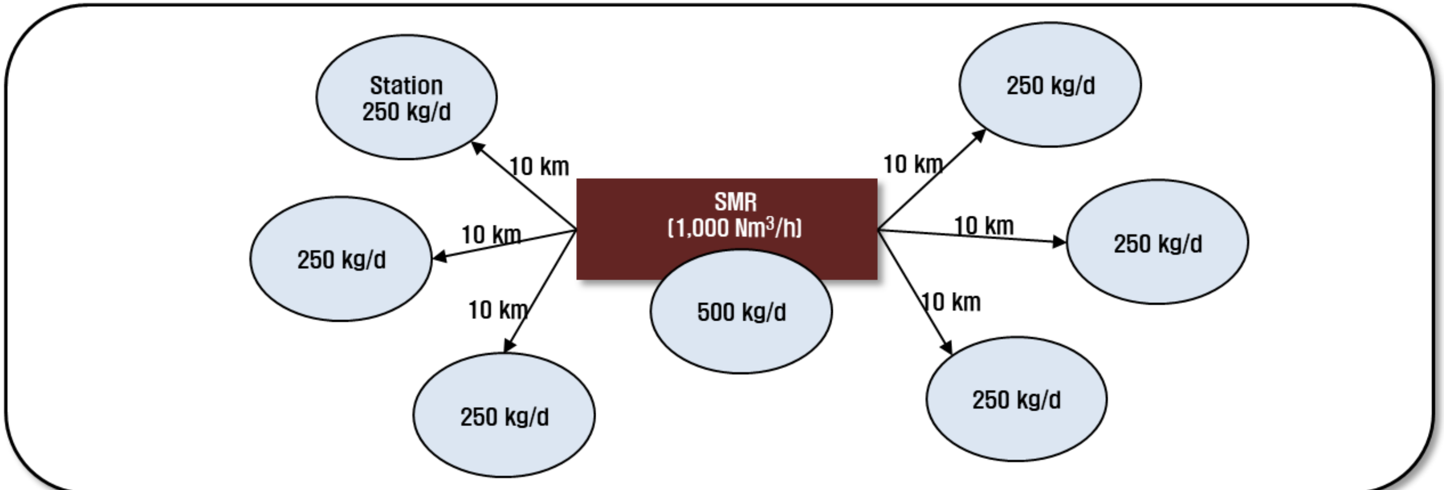


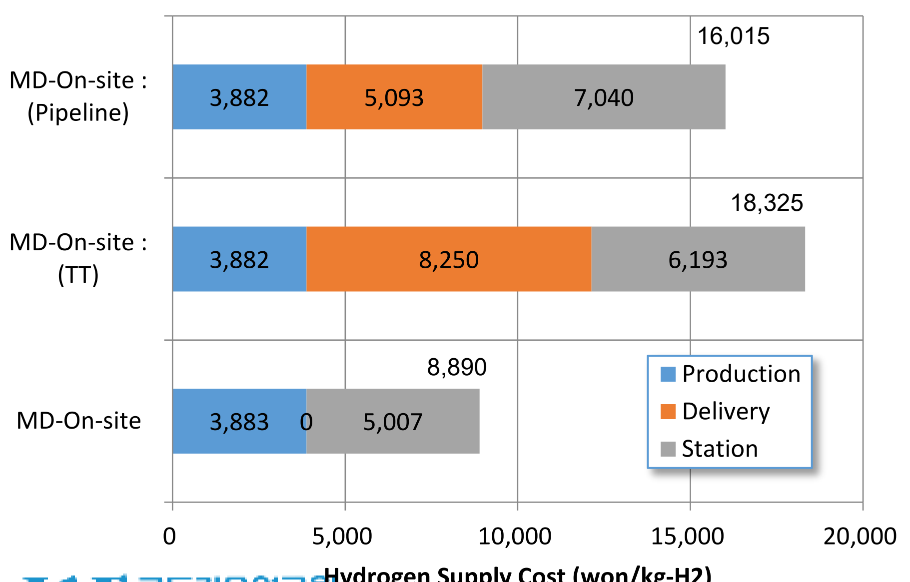


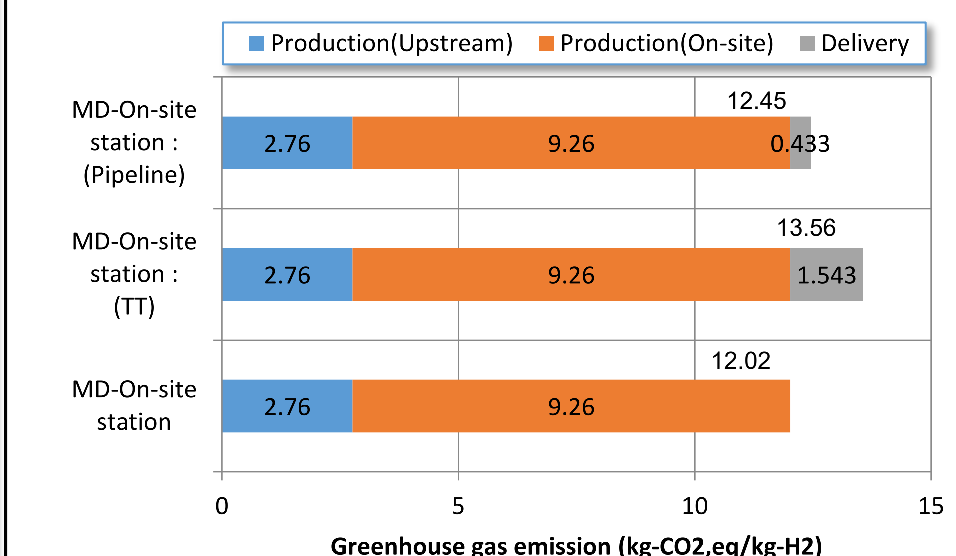


Hydrogen cost analysis example

Hydrogen supply cost & greenhouse gas emission







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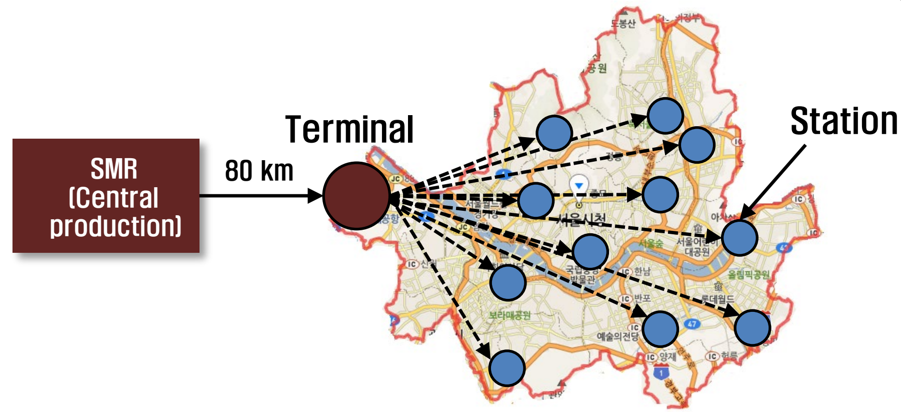
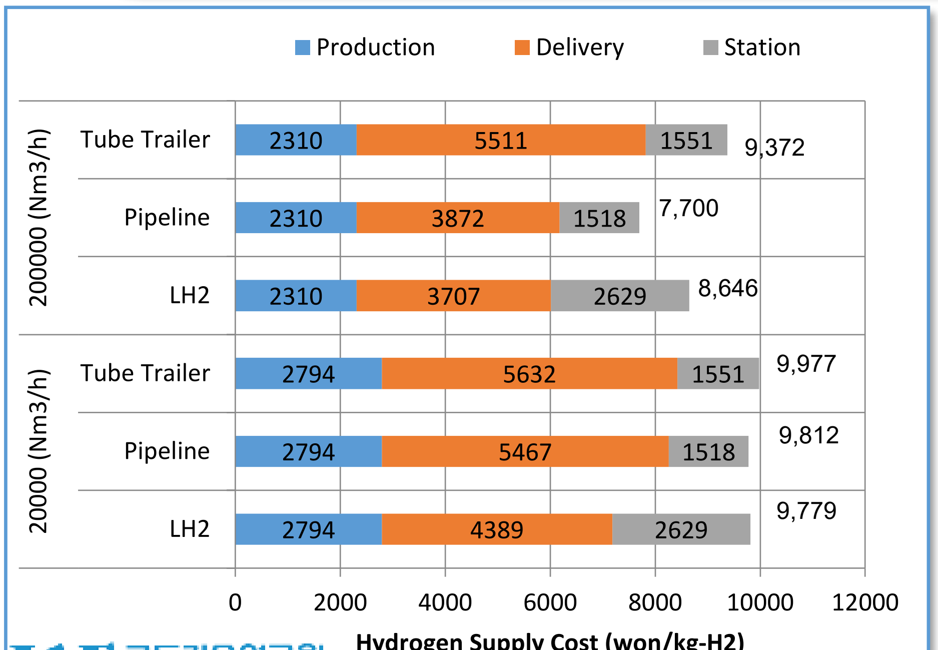
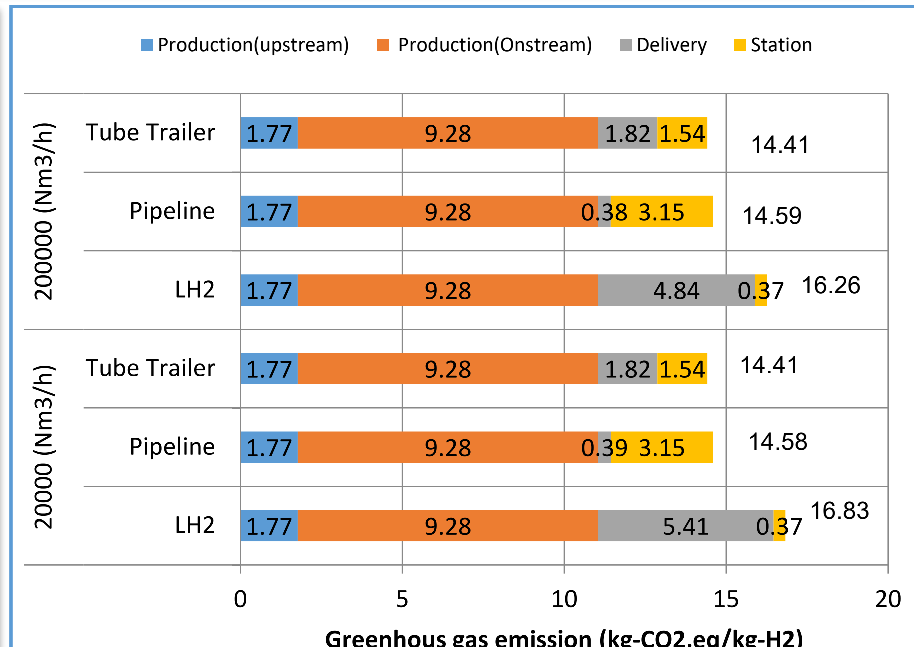
Hydrogen cost analysis example

Hydrogen supply cost & greenhouse gas emission

- S city : hydrogen supply by Off-site type
  - population 9.86 million, area 605 km^2
  - station capacity: 806 kg/d
- average distance between stations
  - 20,000 Nm^3/h supply case : 2.94km
  - 200,000 Nm^3/h supply case : 1.11km







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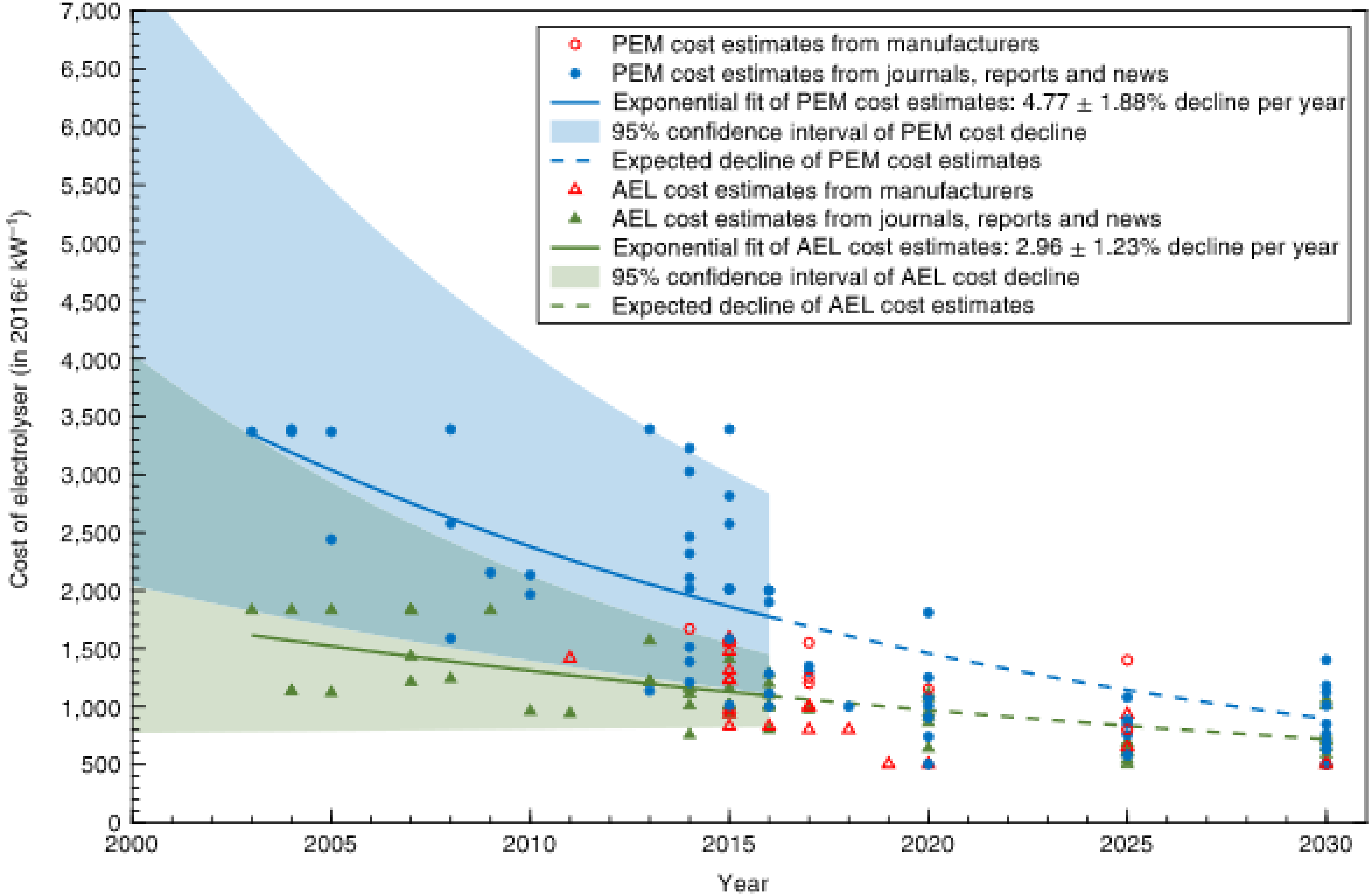
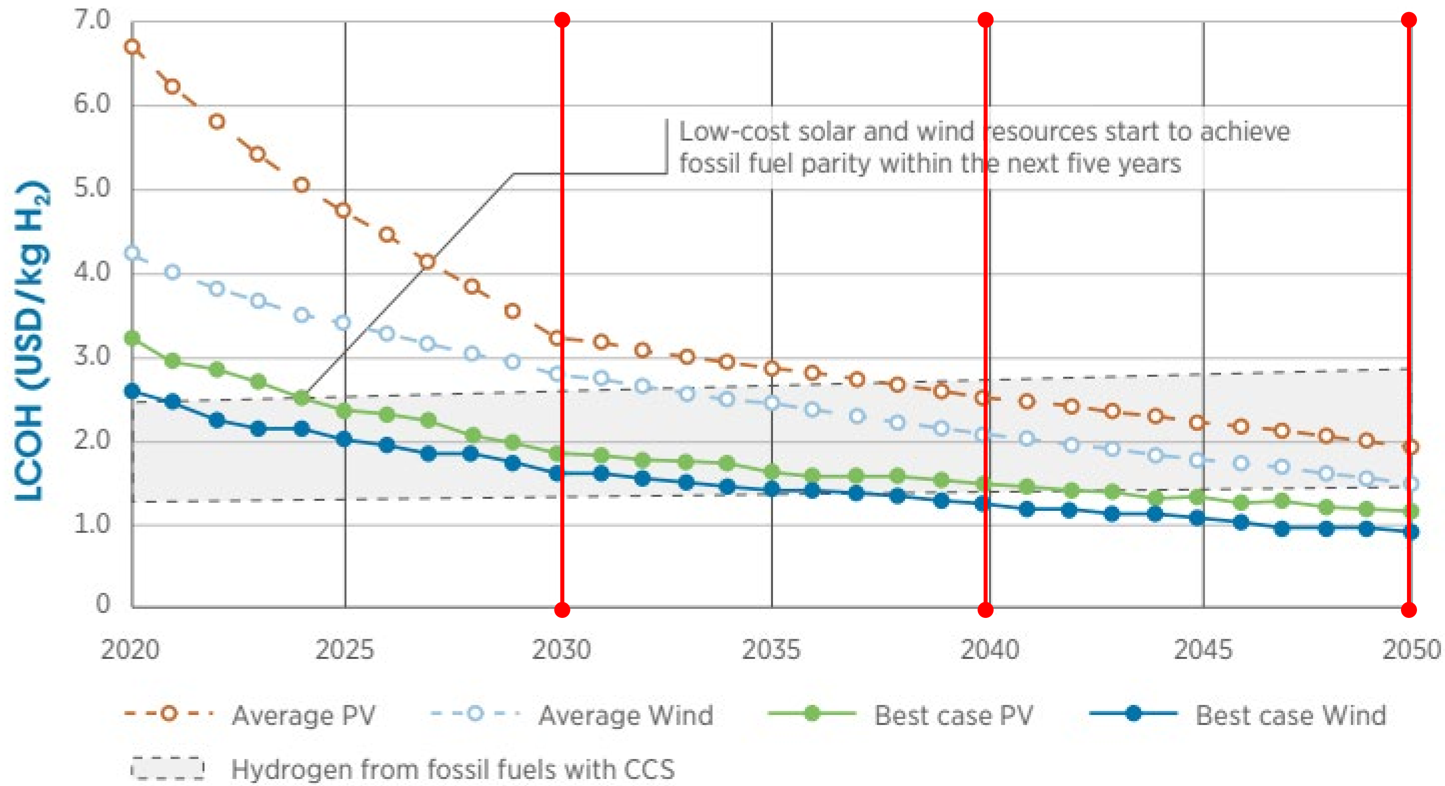
Electrolysis System CAPEX



Source : Economics of converting renewable power to hydrogen, Nature Energy, 2019

Green Hydrogen Cost(1)

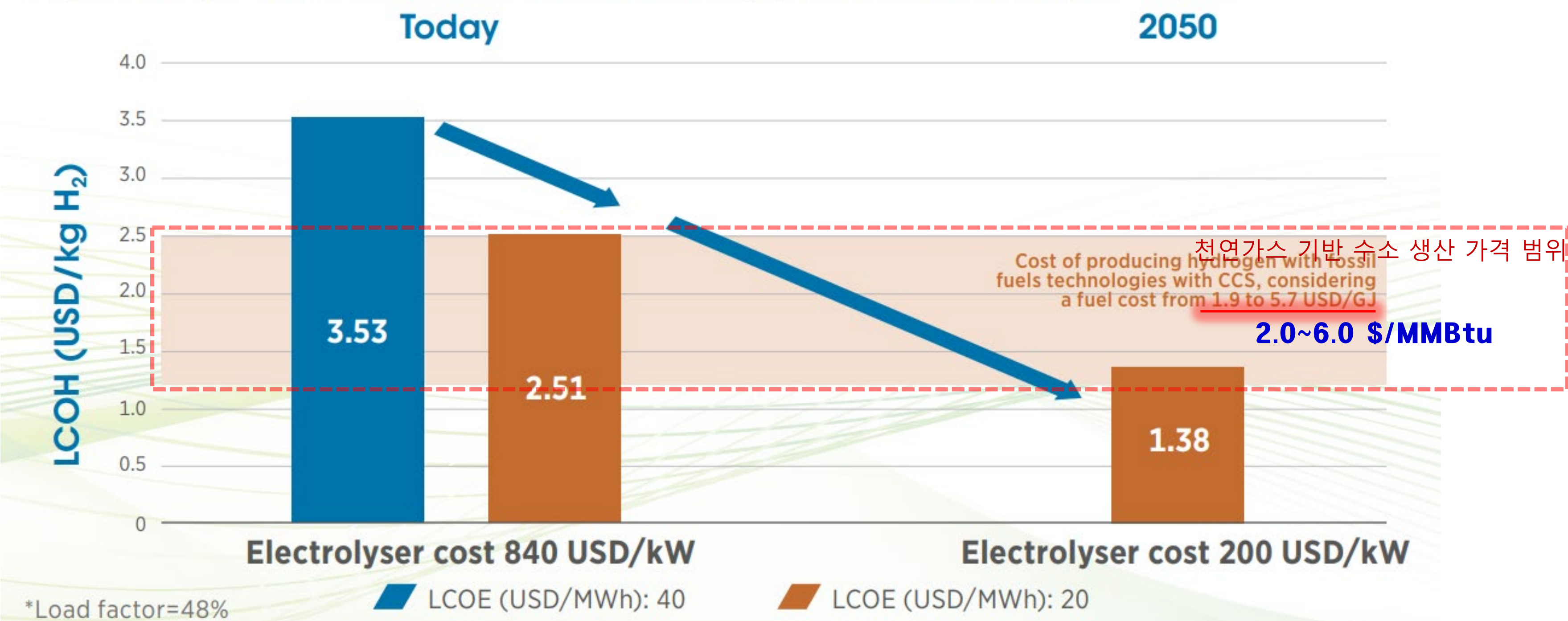


- Electroysis CAPEX : 770 USD/KW(2020), 540 USD/KW(2030), 435 USD/KW(2040), 370 USD/KW(2050)
- CO_2 price : 50 USD/ton(2030), 100 USD/ton(2040), 200 USD/ton(2050)

Source : IRENA, Hydrogen_A renewable energy perspective, 2019

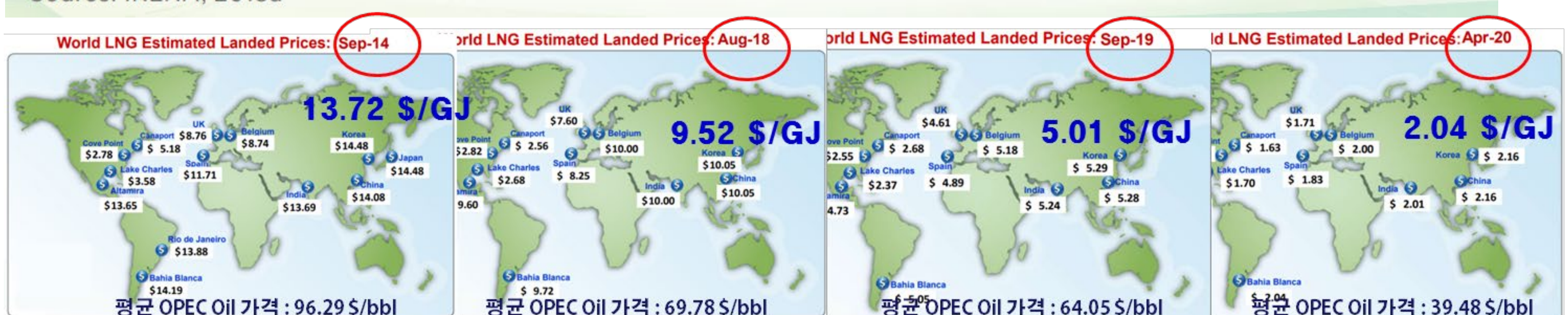
Green Hydrogen Cost(2)

Figure 9: Hydrogen costs at different electricity prices and electrolyser Capex*



*Load factor=48%

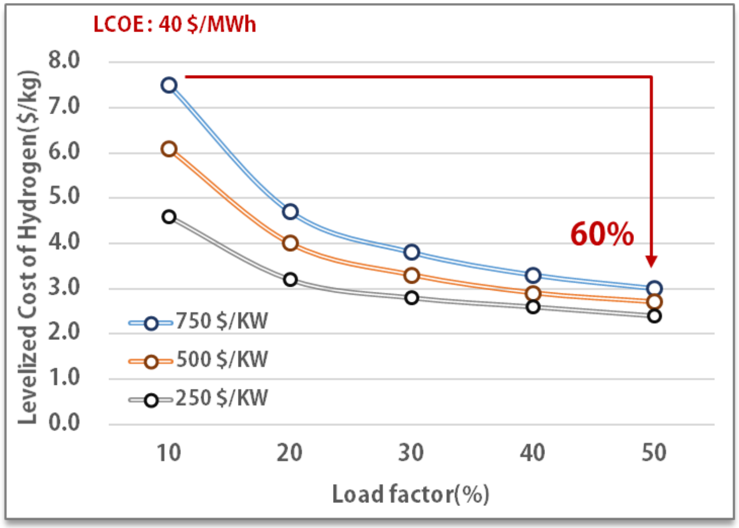
Source: IRENA, 2018a

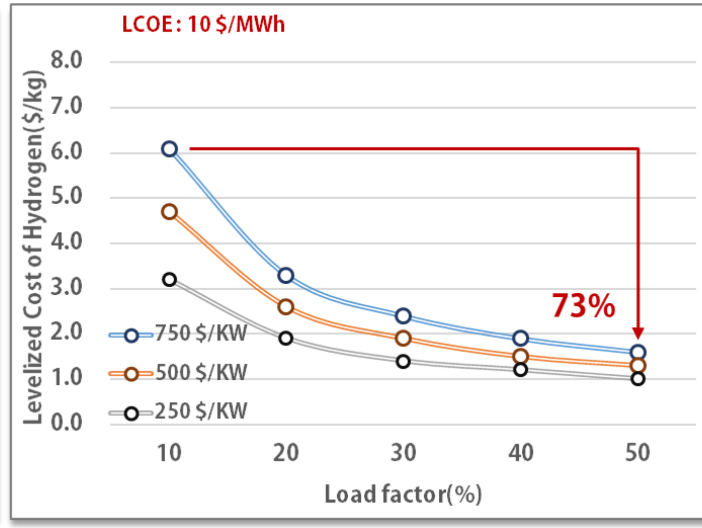


Source : IRENA, Hydrogen_A renewable energy perspective, 2019

Green Hydrogen Cost(3)

Hydrogen cost by load factor of electrolysis





Cost of renewable hydrogen with varying LCOE and load factors

USD/kg H_2

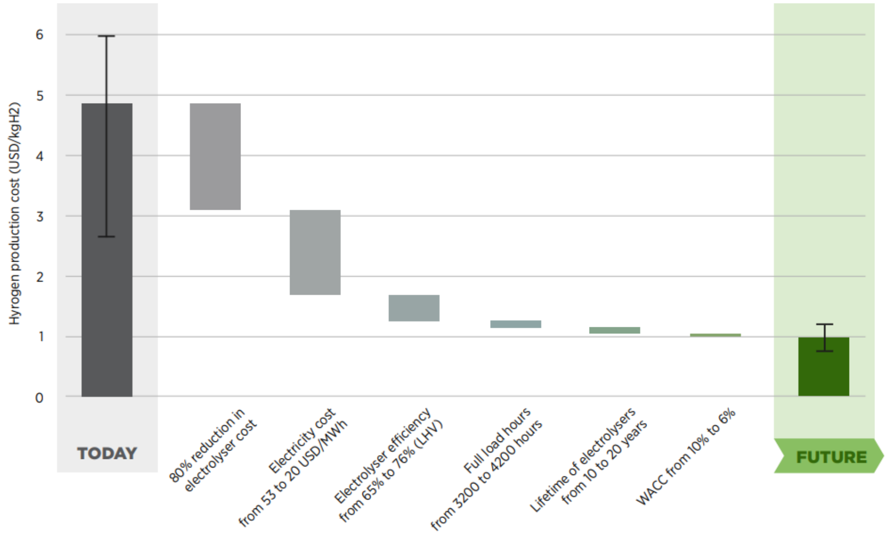
< USD 2/kg | USD 2-3/kg | USD 3-4/kg | > USD 4/kg | Viable medium-term (<2030)

LCOE \ Capex electrolyser	USD 750/kW					USD 500/kW					USD 250/kW				
UDD 0/MWh	5.7	2.8	1.9	1.4	1.1	4.2	2.1	1.4	1.1	0.9	2.8	1.4	0.9	0.7	0.6
USD 10/MWh	6.1	3.3	2.4	1.9	1.6	4.7	2.6	1.9	1.5	1.3	3.2	1.9	1.4	1.2	1.0
USD 20/MWh	6.6	3.8	2.8	2.4	2.1	5.2	3.0	2.3	2.0	1.8	3.7	2.3	1.9	1.6	1.5
USD 30/MWh	7.1	4.2	3.3	2.8	2.5	5.6	3.5	2.8	2.5	2.2	4.2	2.8	2.3	2.1	2.0
USD 40/MWh	7.5	4.7	3.8	3.3	3.0	6.1	4.0	3.3	2.9	2.7	4.6	3.2	2.8	2.6	2.4
USD 50/MWh	8.0	5.2	4.2	3.7	3.5	6.5	4.4	3.7	3.4	3.2	5.1	3.7	3.2	3.0	2.9
USD 100/MWh	10.3	7.5	6.5	6.1	5.8	8.9	6.7	6.0	5.7	5.5	7.4	6.0	5.6	5.3	5.2
Load factor	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%	10%	20%	30%	40%	50%

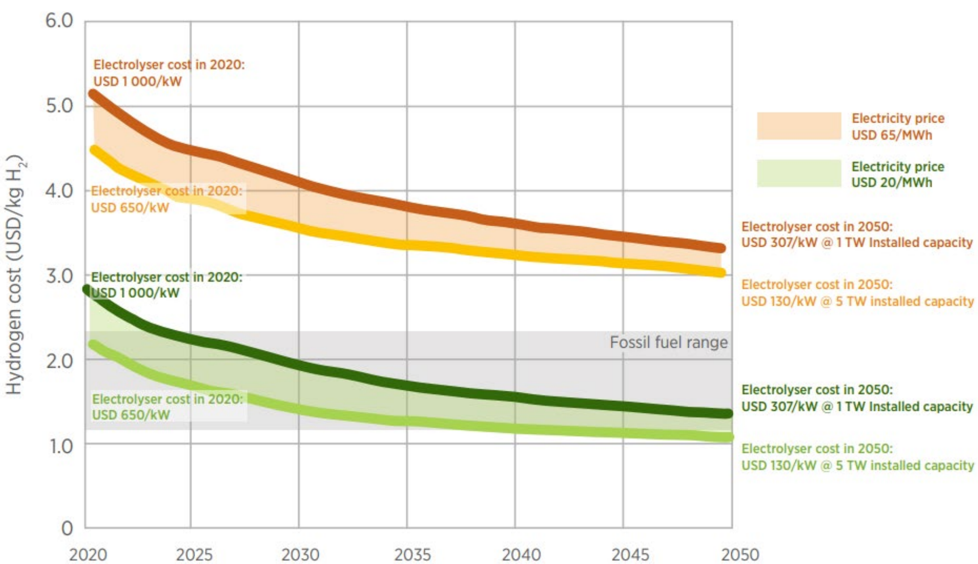
Source : Hydrogen Council, Path to hydrogen competitiveness, 2020

Green Hydrogen Cost(4)

- **Green hydrogen cost : determined by CAPEX of electrolysis, load factor, LCOE by renewable energy**

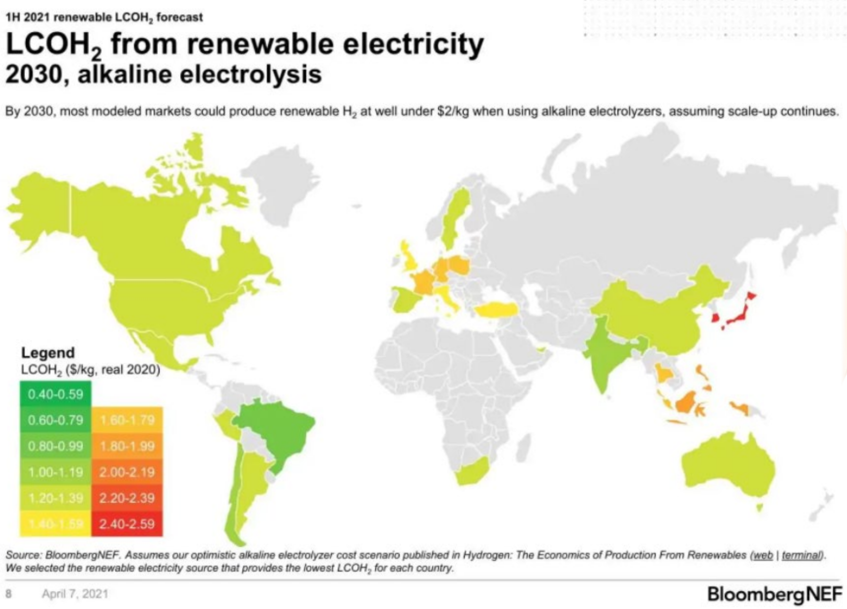


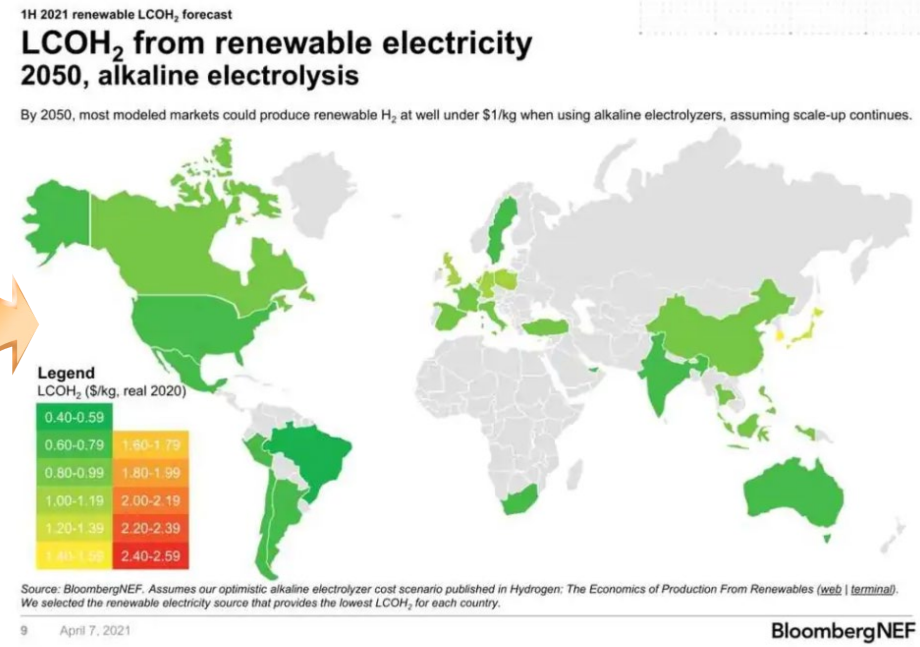
	2020				2050			
	Alkaline	PEM	AEM	SOEC	Alkaline	PEM	AEM	SOEC
Cell pressure [bara]	< 30	< 70	< 35	< 10	> 70	> 70	> 70	> 20
Efficiency (system) [kWh/KgH_2]	50-78	50-83	57-69	45-55	< 45	< 45	< 45	< 40
Lifetime [thousand hours]	60	50-80	> 5	< 20	100	100-120	100	80
Capital costs estimate for large stacks (stack-only, > 1 MW) [USD/kW_{el}]	270	400	-	> 2 000	< 100	< 100	< 100	< 200
Capital cost range estimate for the entire system, >10 MW [USD/kW_{el}]	500-1000	700-1400	-	-	< 200	< 200	< 200	< 300

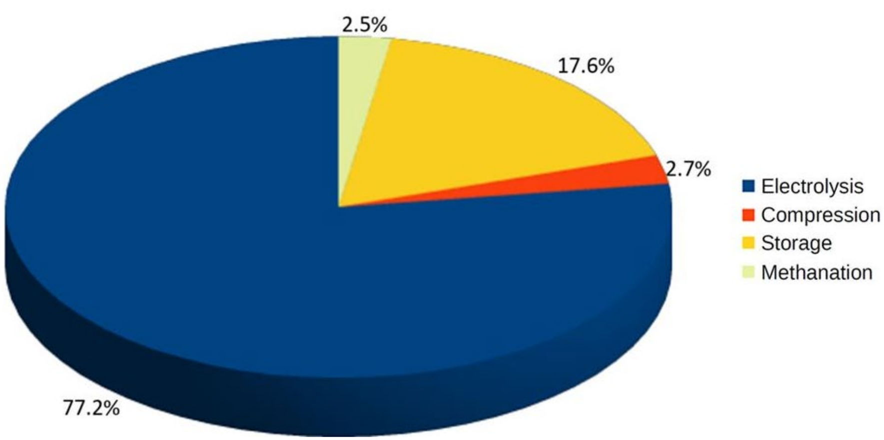


Source : Green hydrogen cost reduction, IRENA, 2020

Green Hydrogen Cost(3)







❖ $LCOCH_4$: determined by Carbon source, full load hours, electricity cost

Source : https://insideevs.com/news/499471/green-hydrogen-cheaper-2050-bnef/

Power-to-Fuel : How to speed up a hydrogen economy, 2021

Strategy for Green hydrogen

- Cost and capacity of electrolyzers
- Availability and affordability of renewable energy
- Transportation and storage of Hydrogen
- Effective use Carbon Capture Utilization and Storage(CCUS/CCS) technologies

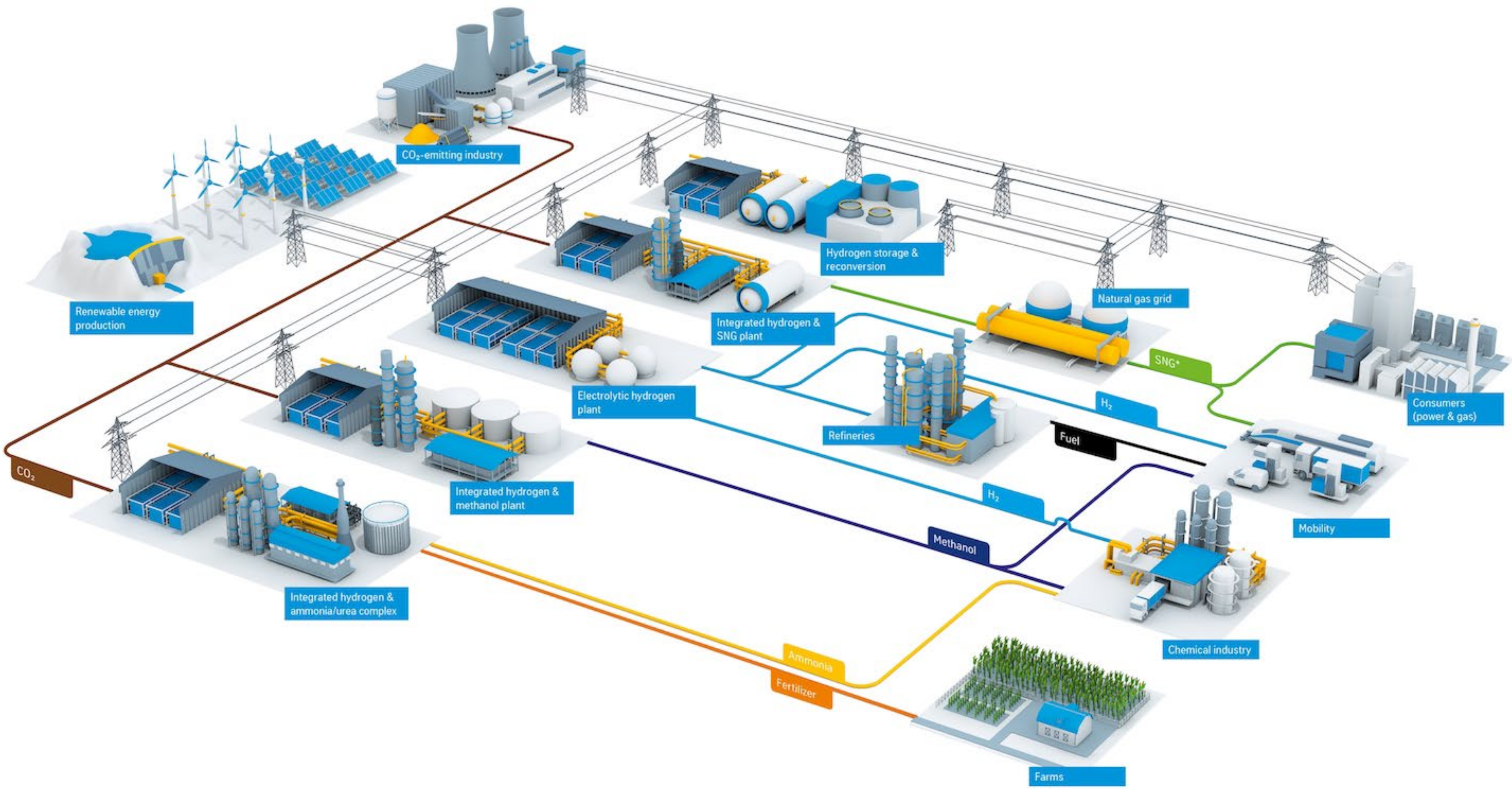
Public acceptance

Economic and reliable Technology

Sustainable policy Network

Effective integration with Renewable Power

BM Example based on green hydrogen



https://www.ammoniaenergy.org/articles/thyssenkrupps-green-hydrogen-and-renewable-ammonia-value-chain/

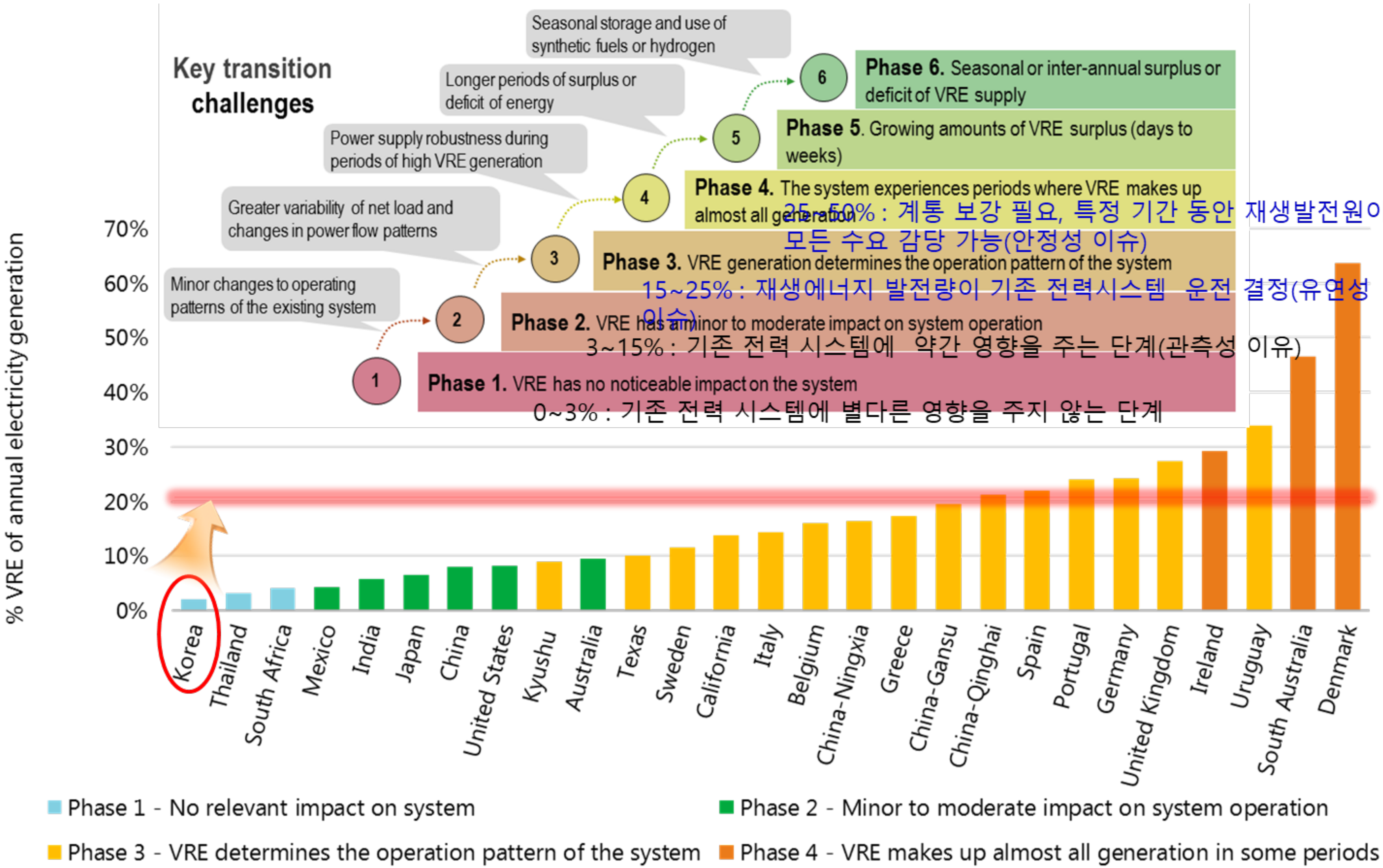
I. Hydrogen Supply Chain

II. Hydrogen Production Technology

III. Hydrogen Cost Analysis

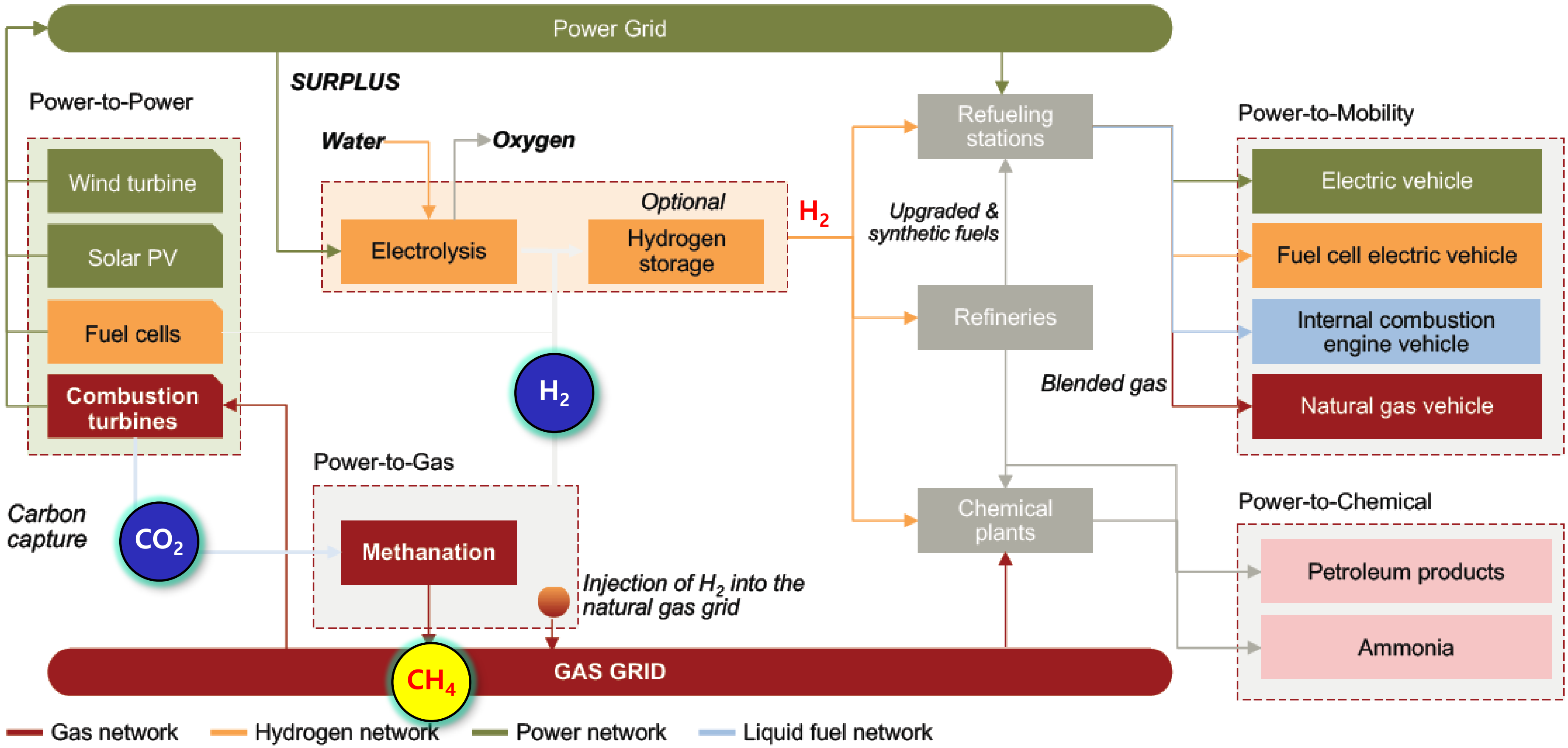
IV. Sector Coupling & P2G

Impact on power supply system by Renewable Energy



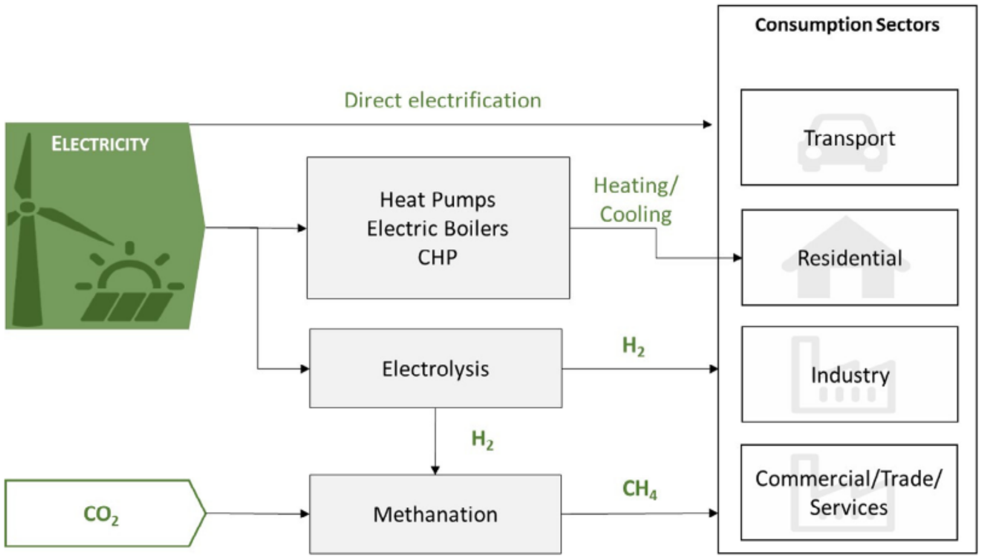
Source: IEA (2018a), World Energy Outlook 2018.

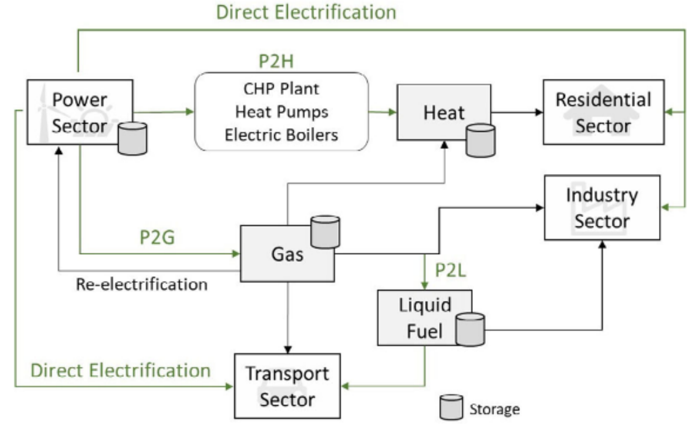
Green hydrogen : Power-to-Gas

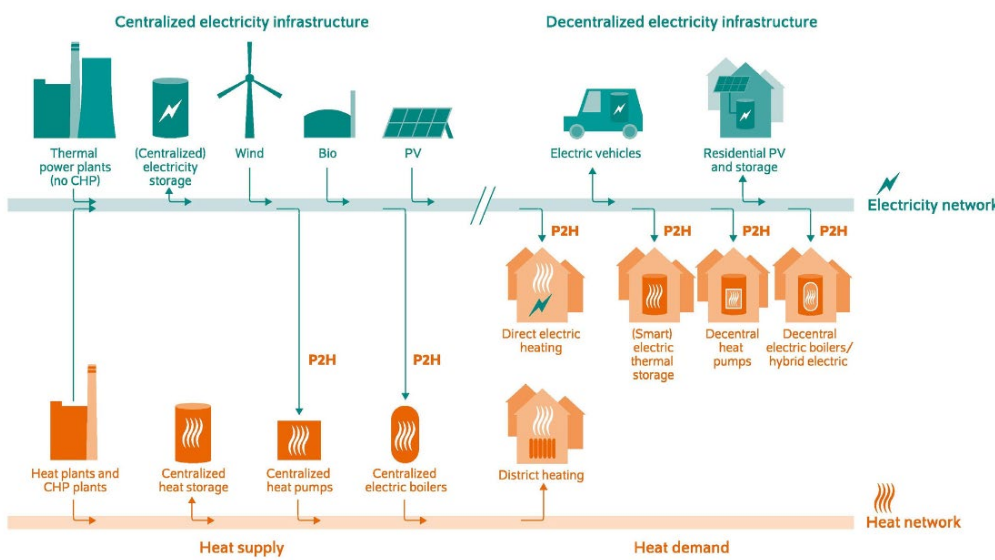


Source : Hydrogen-based energy conversion, A.T.Kearney Energy Transition Institute, 2014

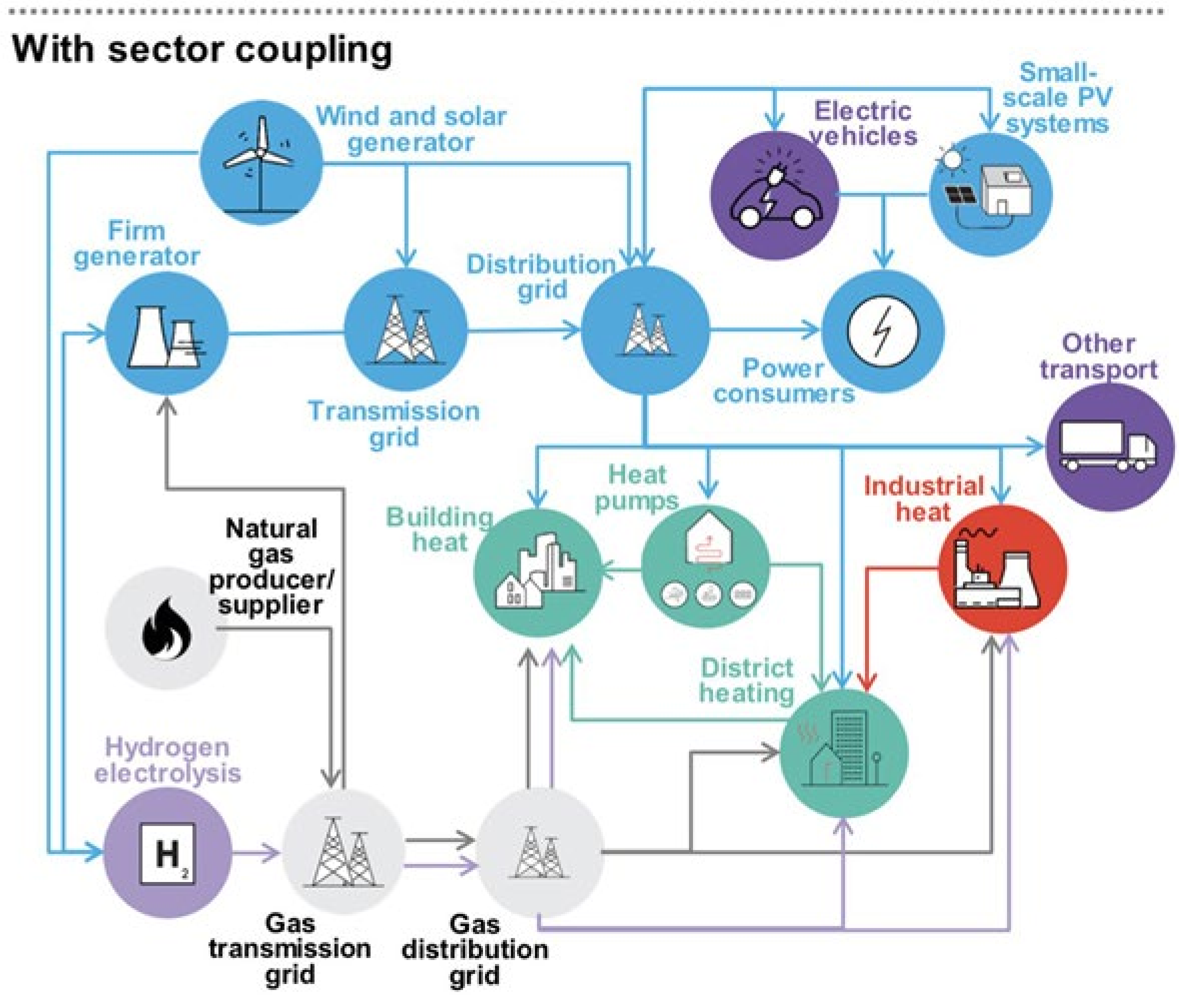
Energy Sector Coupling pathways(1)





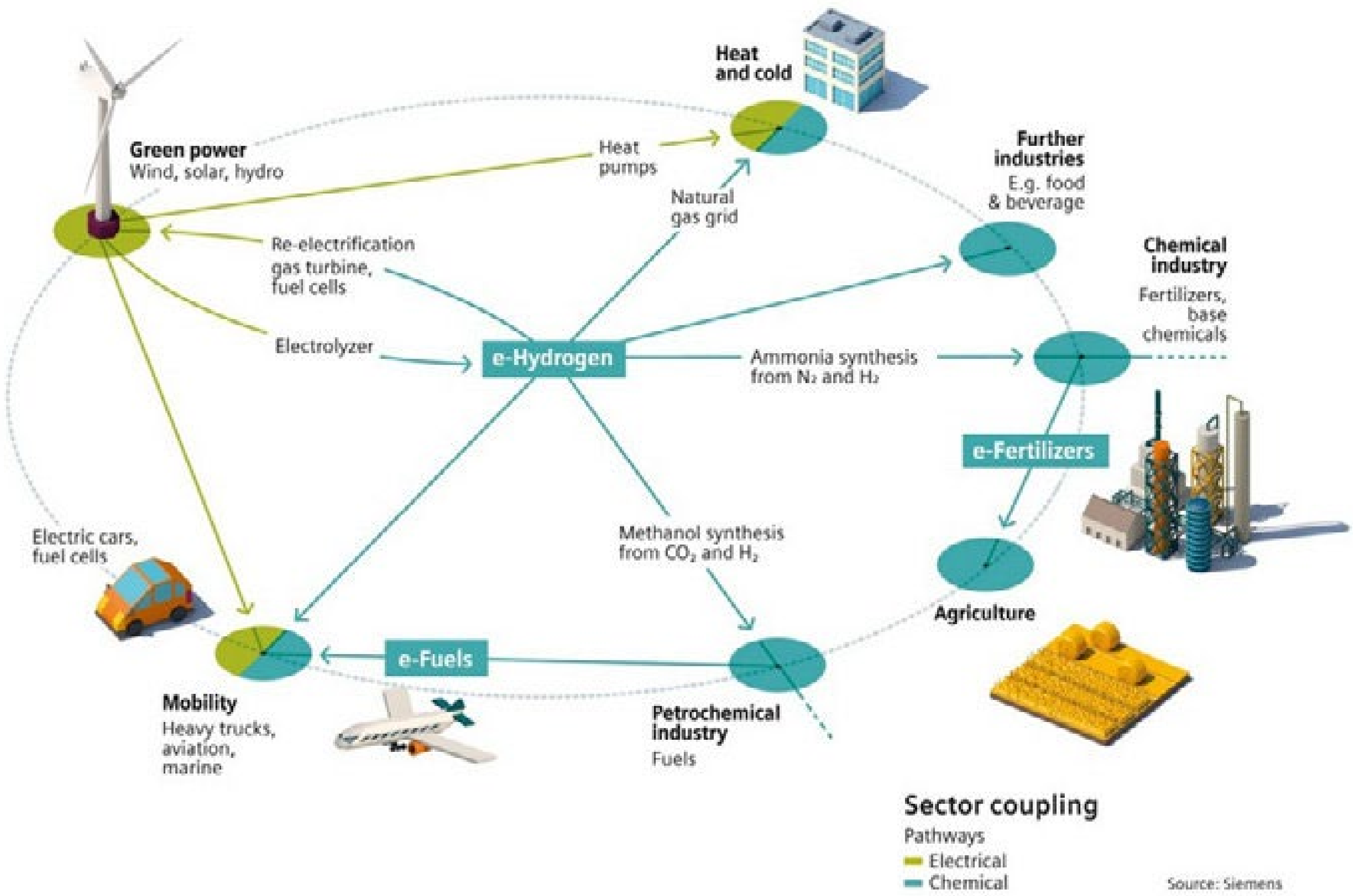


Energy Sector Coupling pathways(2)



Source: BloombergNEF.

Hydrogen role for Energy Sector Coupling




感謝你
Danke
Gracias
Grazie
Merci
Thanks!
THANK
YOU!