Lecture – 7

Hydrogen and Nuclear

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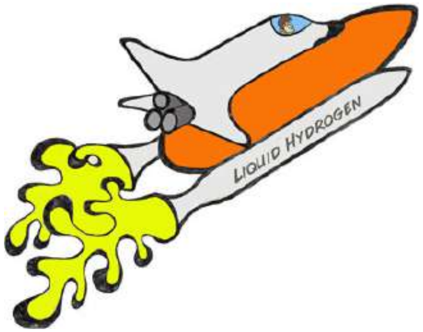
Outline

- ✓Hydrogen as energy
- ✓Fuel cell technologies
- ✓Nuclear energy

Hydrogen as new energy



Hydrogen economy

Electrolyser × Fuel cell

$H_2O \rightleftharpoons O_2 + H_2$

Grey : Fossil

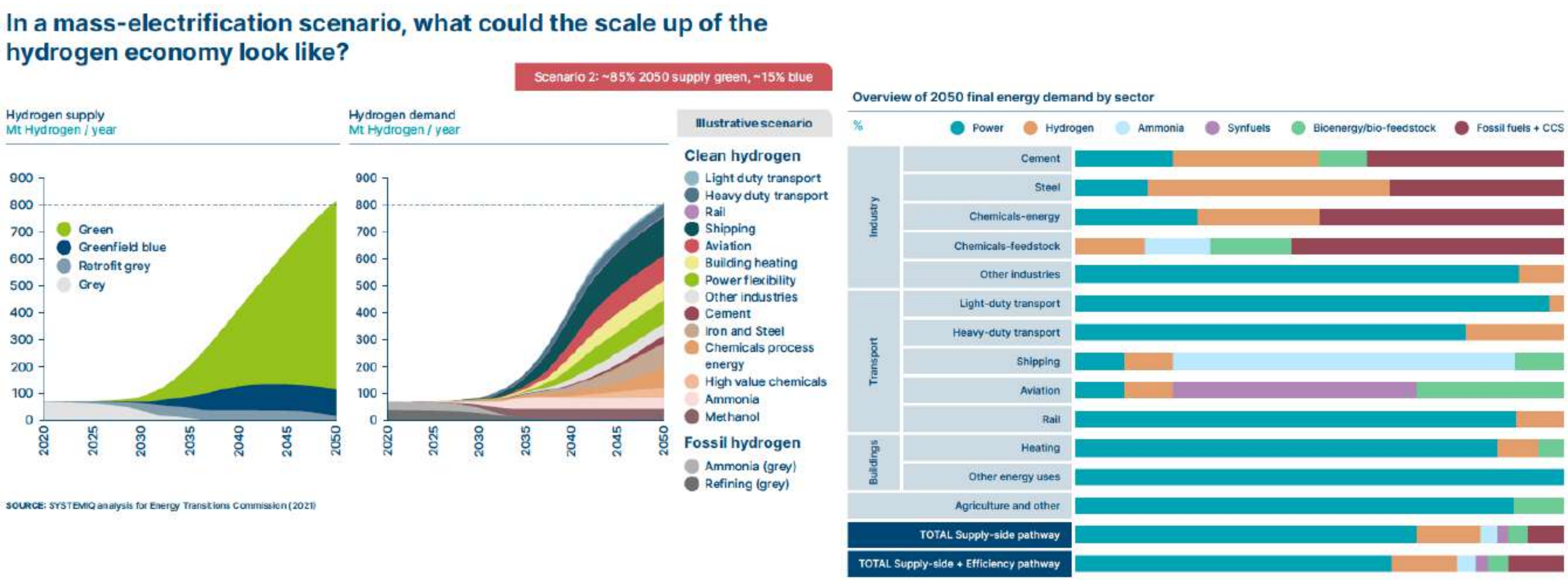
Green : Electrolysis

Reforming : Air → Syngas

Liq → Syngas

Gasification : Solid → Syngas

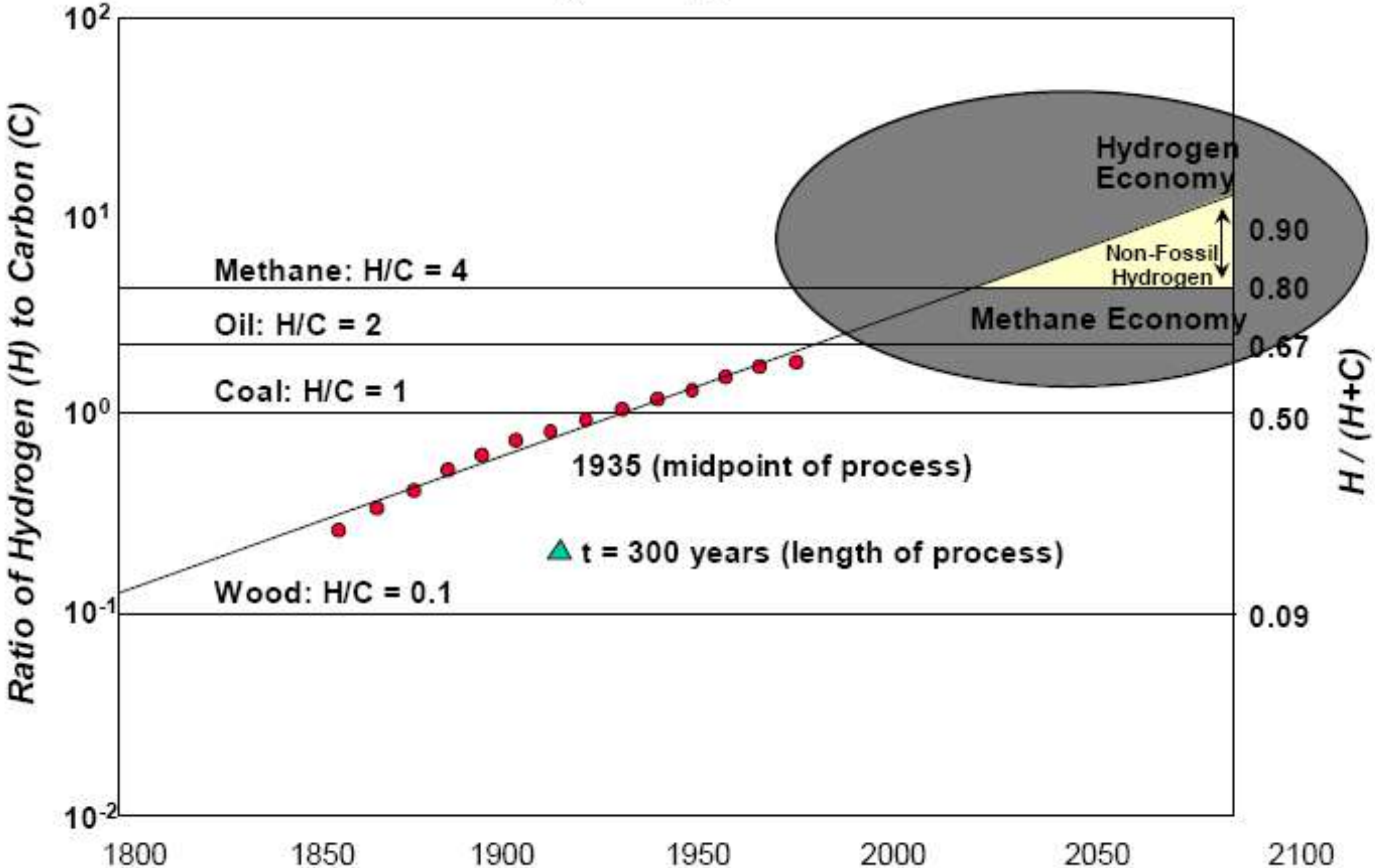
Decarbonisation strategies by hydrogen across value chains



"Hydrogen has long been seen as a potentially key component of a carbon-neutral future"

Source: ETC, 2022

Ratio of hydrogen to carbon



Source: IIASA, Nakicenovic

Why hydrogen for energy?

2.1 Hydrogen is the most abundant and lightest of the elements. It is odorless and nontoxic. It has the highest energy content of common fuels by weight -- nearly three times that of gasoline. Hydrogen is not found free in nature and must be "extracted" from diverse sources: fossil energy, renewable energy, nuclear energy and the electrolysis of water. A separate energy source (electricity, heat or light) is required to "produce" (extract or reform) the hydrogen. Today, most hydrogen is made from fossil energy using steam methane reforming (SMR) of natural gas, followed by partial oxidation (POX) and autothermal reforming (ATR), which combines SMR and POX processes.

2.2 Like electricity, hydrogen is an "energy carrier." It can be used in a full range of applications in all sectors of the economy: transportation, power, industry, and buildings.

2.3 Hydrogen can be converted to electricity by a fuel cell, an electrochemical device. Unlike batteries, fuel cells operate continuously in the presence of hydrogen and oxygen (in ambient air). Fuel cells are "scalable" and may be used in very small to very large sizes. The only byproducts of fuel cells are heat and water.

2.4 Hydrogen's relationship to renewables cannot be overemphasized. The 2015 IEA Technology Roadmap for Hydrogen and Fuel Cells recognizes that hydrogen with a low-carbon footprint has the potential to facilitate significant reductions in energy-related CO_2 emissions. Thus, use of renewable feedstocks for hydrogen production is very attractive from the environmental perspective.

2.5 Today, the world is witnessing significant growth in the installed capacity of renewables (primarily wind and solar). Onshore wind is the leader, accounting for over one-third of the renewable capacity and generation increase. Solar PV follows, accounting for another third of deployment. Hydropower is also growing and accounts for one-fifth of new renewable additions, and over a quarter of the growth in renewable energy electricity generation.[1]

2.6 As a result of this growth, the electricity grid must sometimes restrict uptake of renewable electricity when the grid is full (saturated) in order to balance electricity supply and demand. Consequently, renewable electricity production is curtailed. However, use of hydrogen for storage of renewable electricity (converted via water electrolysis) is a game changer. Hydrogen and

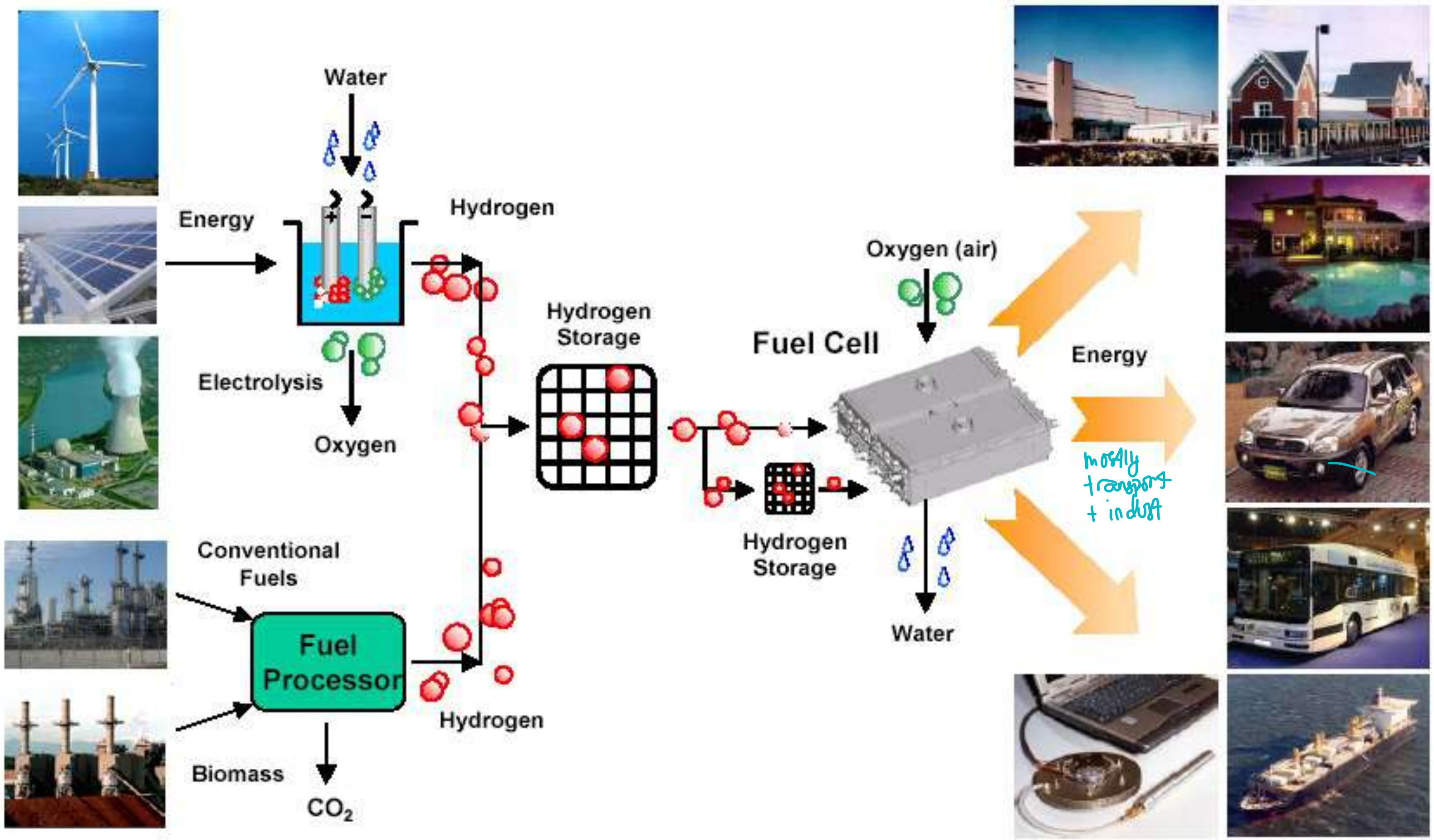
Source: IEA, 2017

The Hydrogen problem:

Fundamentally H_2 is the only feasible fuel in the foreseeable future

- Strictly, hydrogen is not a “fuel”, but an energy storage medium
  - Difficulty in hydrogen storage
  - Difficulty in hydrogen supply infra structure
- Hydrogen from fossil fuel is not an efficient energy option
- Environmental resistance for nuclear and hydroelectric options

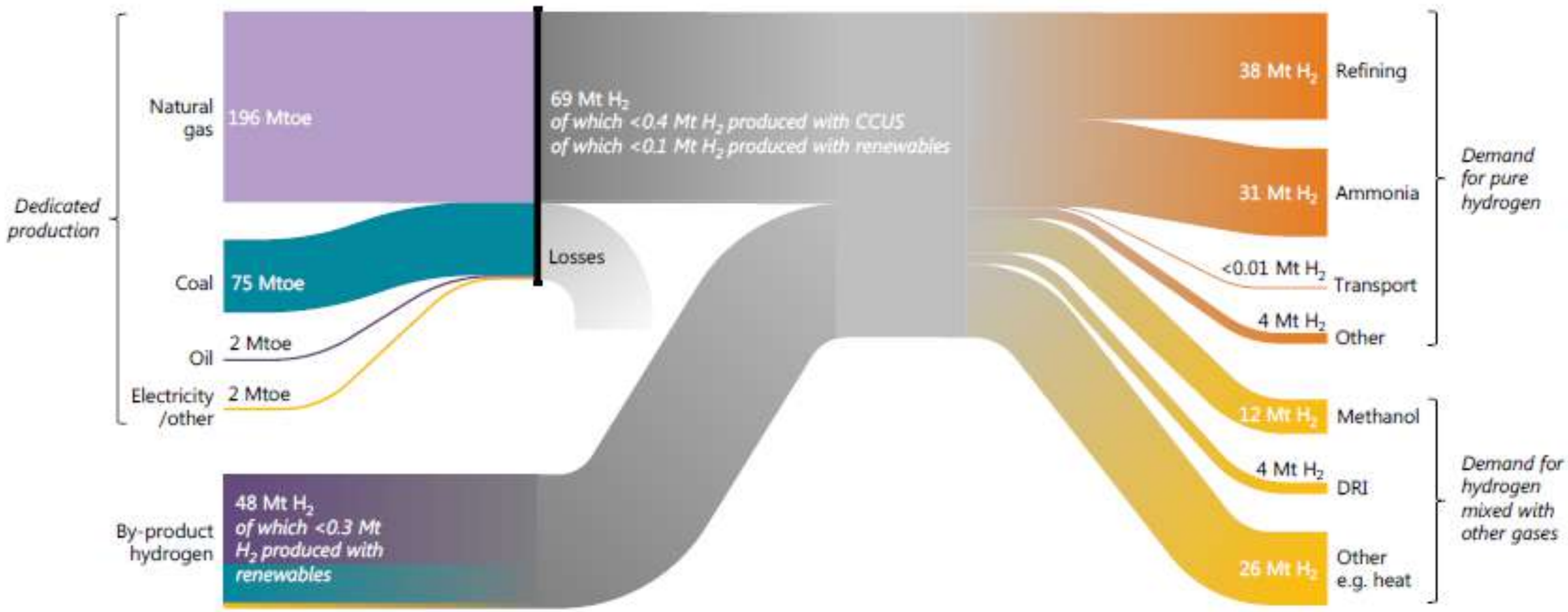
The Hydrogen Economy



Four key opportunities for scaling up hydrogen to 2030

Source: IEA, 2019

Hydrogen value chains

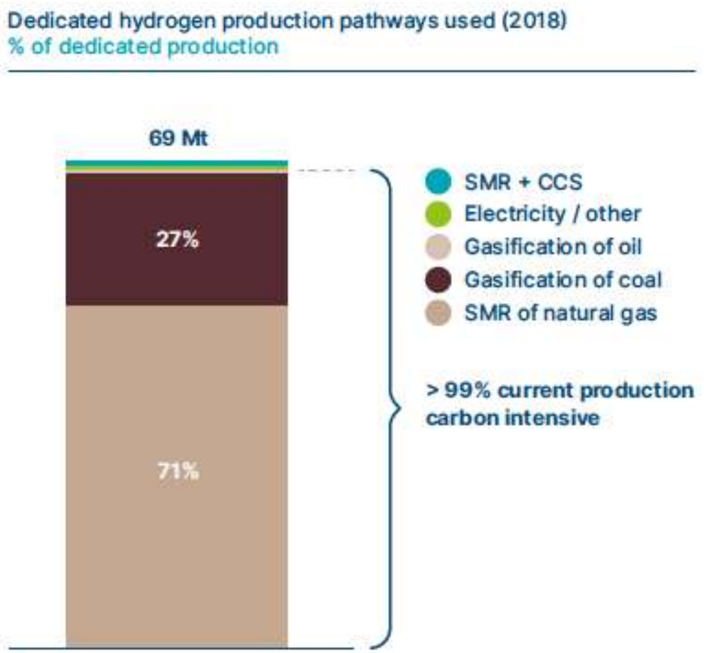


Notes: Other forms of pure hydrogen demand include the chemicals, metals, electronics and glass-making industries. Other forms of demand for hydrogen mixed with other gases (e.g. carbon monoxide) include the generation of heat from steel works arising gases and by-product gases from steam crackers. The shares of hydrogen production based on renewables are calculated using the share of renewable electricity in global electricity generation. The share of dedicated hydrogen produced with CCUS is estimated based on existing installations with permanent geological storage, assuming an 85% utilisation rate. Several estimates are made as to the shares of by-products and dedicated generation in various end uses, while input energy for by-product production is assumed equal to energy content of hydrogen produced without further allocation. All figures shown are estimates for 2018. The thickness of the lines in the Sankey diagram are sized according to energy contents of the flows depicted.

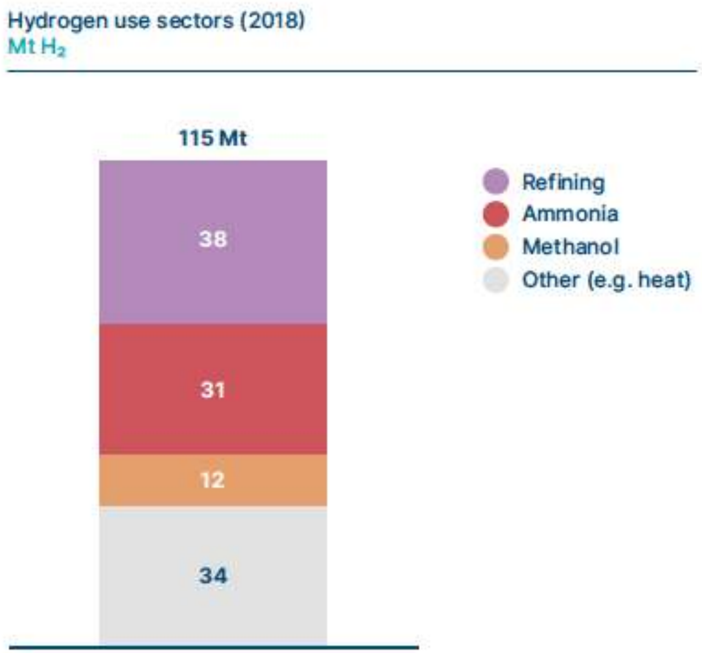
Source: IEA 2019.

Source: IEA, 2019

Current hydrogen production is via carbon-intensive processes and used sectors



SOURCE: IEA (2019), *The Future of Hydrogen*

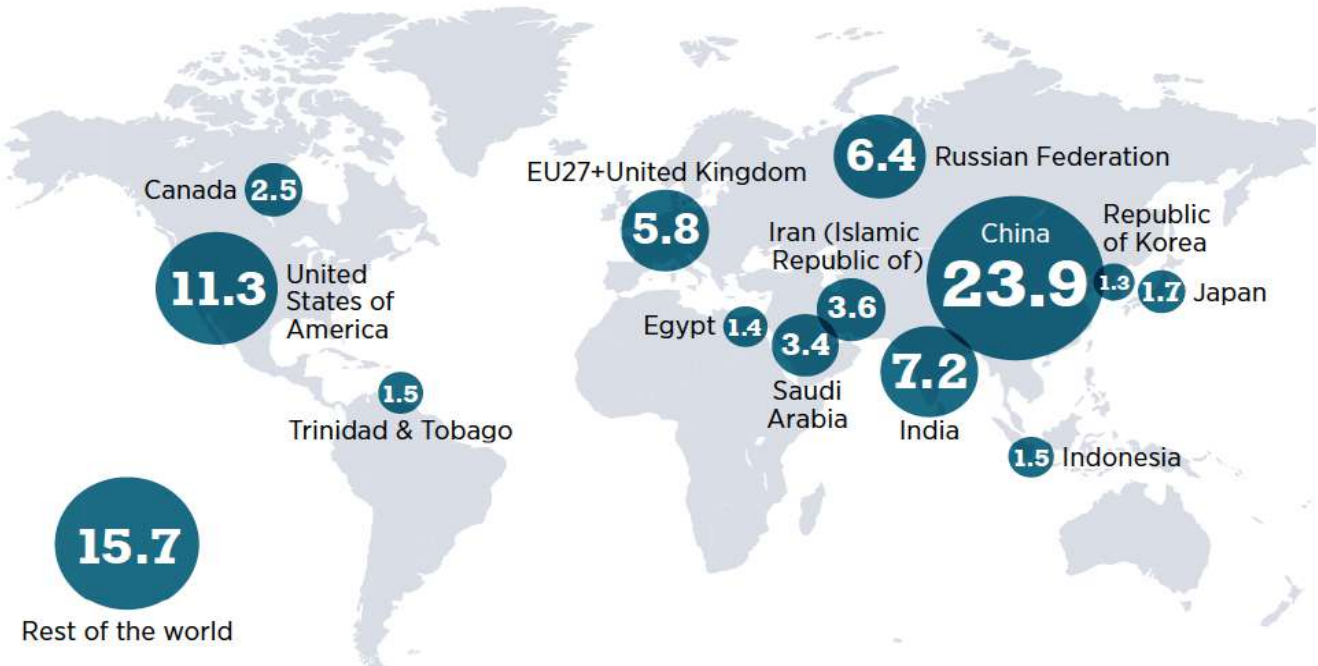


"Mostly for feedstock"

"Limited role in global energy mix"

Source: ETC, 2022

Hydrogen consumption in 2020 (million tonnes per year)



Map source: Natural Earth, 2021

Note: Values are derived from current production of ammonia, methanol, refining and direct reduced iron for steel.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Source: IRENA, 2022

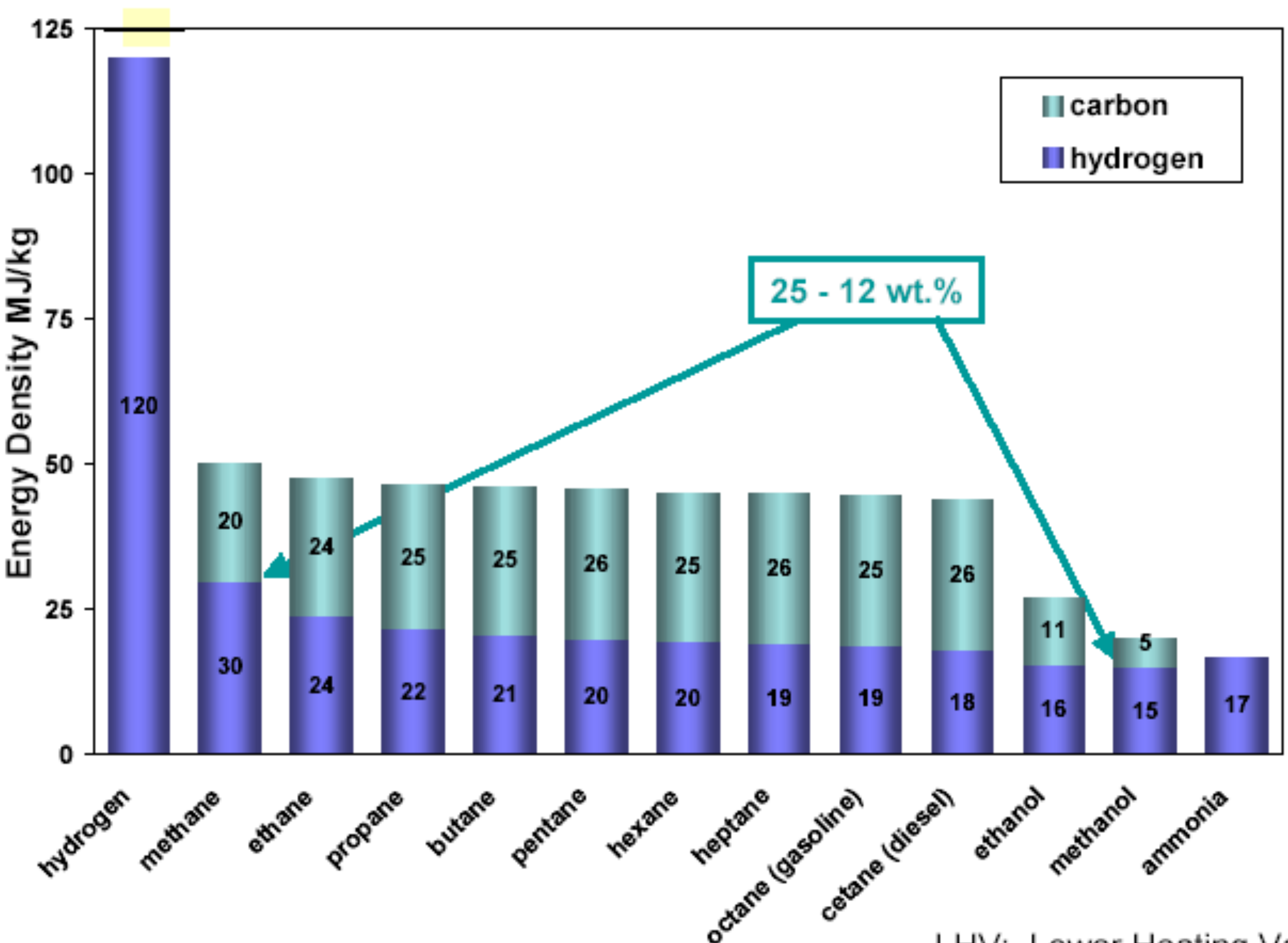
Physical properties of hydrogen

Property	Hydrogen	Comparison
Density (gaseous)	0.089 kg/m^3 (0°C, 1 bar)	1/10 of natural gas
Density (liquid)	70.79 kg/m^3 (-253°C, 1 bar)	1/6 of natural gas
Boiling point	-252.76°C (1 bar)	90°C below LNG
Energy per unit of mass (LHV)	120.1 MJ/kg	3x that of gasoline
Energy density (ambient cond., LHV)	0.01 MJ/L	1/3 of natural gas
Specific energy (liquefied, LHV)	8.5 MJ/L	1/3 of LNG
Flame velocity	346 cm/s	8x methane
Ignition range	4–77% in air by volume	6x wider than methane
Autoignition temperature	585°C	220°C for gasoline
Ignition energy	0.02 MJ	1/10 of methane

Notes: cm/s = centimetre per second; kg/m^3 = kilograms per cubic metre; LHV = lower heating value; MJ = megajoule; MJ/kg = megajoules per kilogram; MJ/L = megajoules per litre.

Source: IEA, 2019

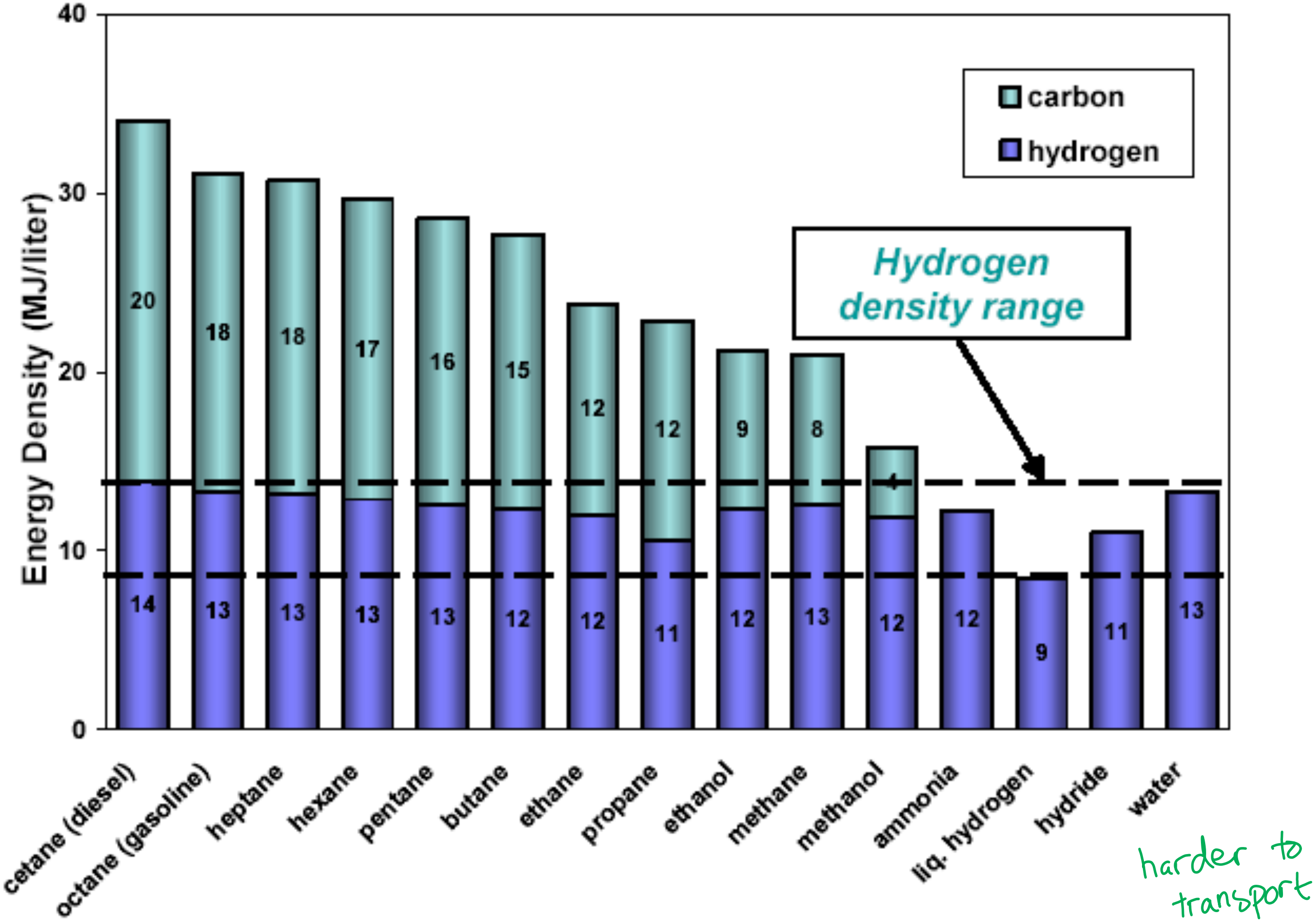
Specific energy of fuels (LHV)



LHV: Lower Heating Value

from George Thomas

Energy densities (LHV) for fuels in liquid state



from George Thomas

Hydrogen production

Colors of hydrogen production

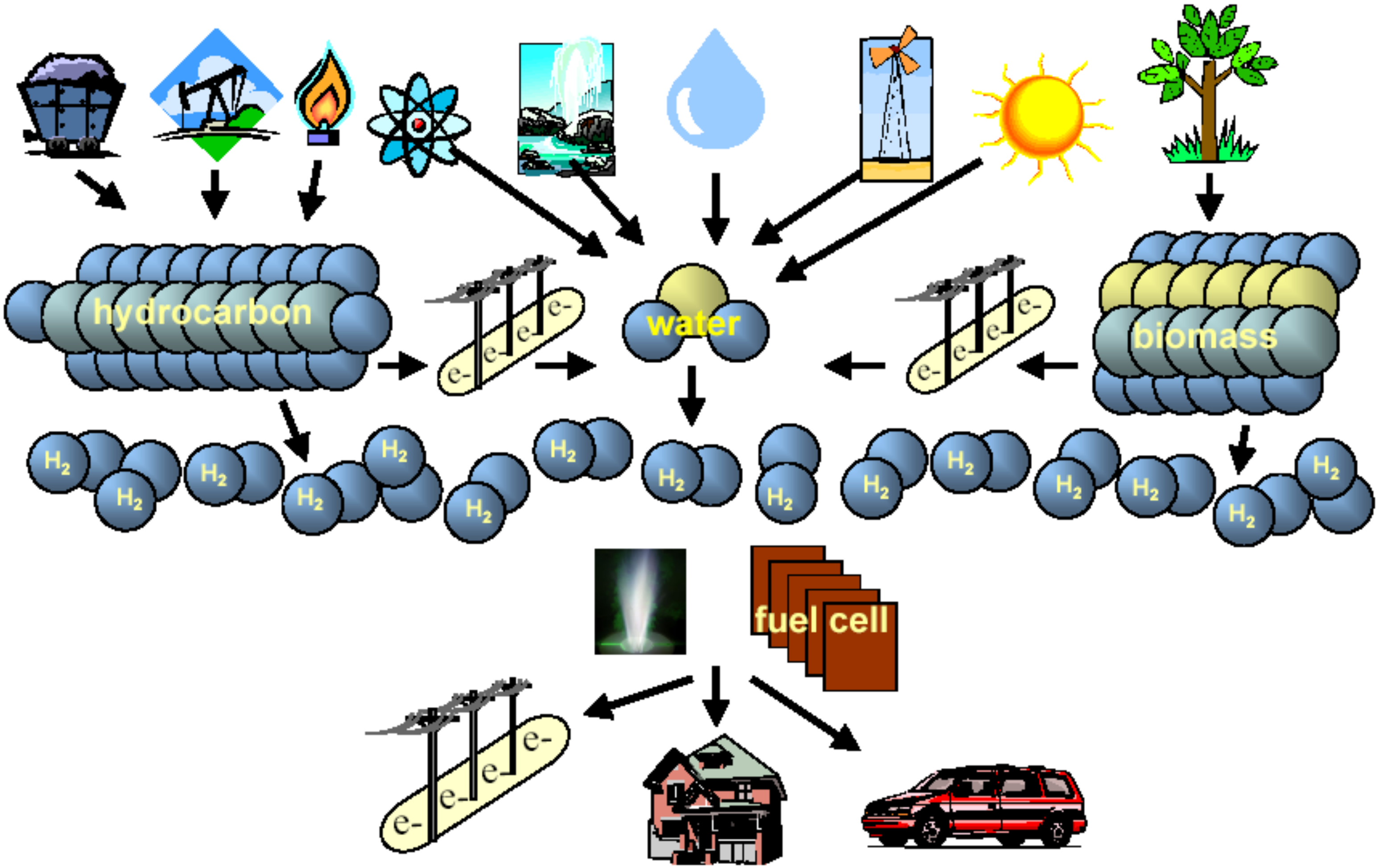
+ gold, pink

	GREY HYDROGEN	BLUE HYDROGEN	GREEN HYDROGEN
Process	Reforming or gasification	Reforming or gasification with carbon capture	Electrolysis
Energy source	Fossil fuels	Fossil fuels	Renewable electricity
Estimated emissions from the production process[a]	Reforming: 9 – 11[b] Gasification: 18 – 20	0.4-4.5[c]	0

Note: a) $CO_{2\text{-eq}}$/kg = carbon dioxide equivalent per kilogramme; b) For grey hydrogen, 2 kg $CO_{2\text{-eq}}$/kg assumed for methane leakage from the steam methane reforming process. c) Emissions for blue hydrogen assume a range of 98% and 68% carbon capture rate and 0.2% and 1.5% of methane leakage.

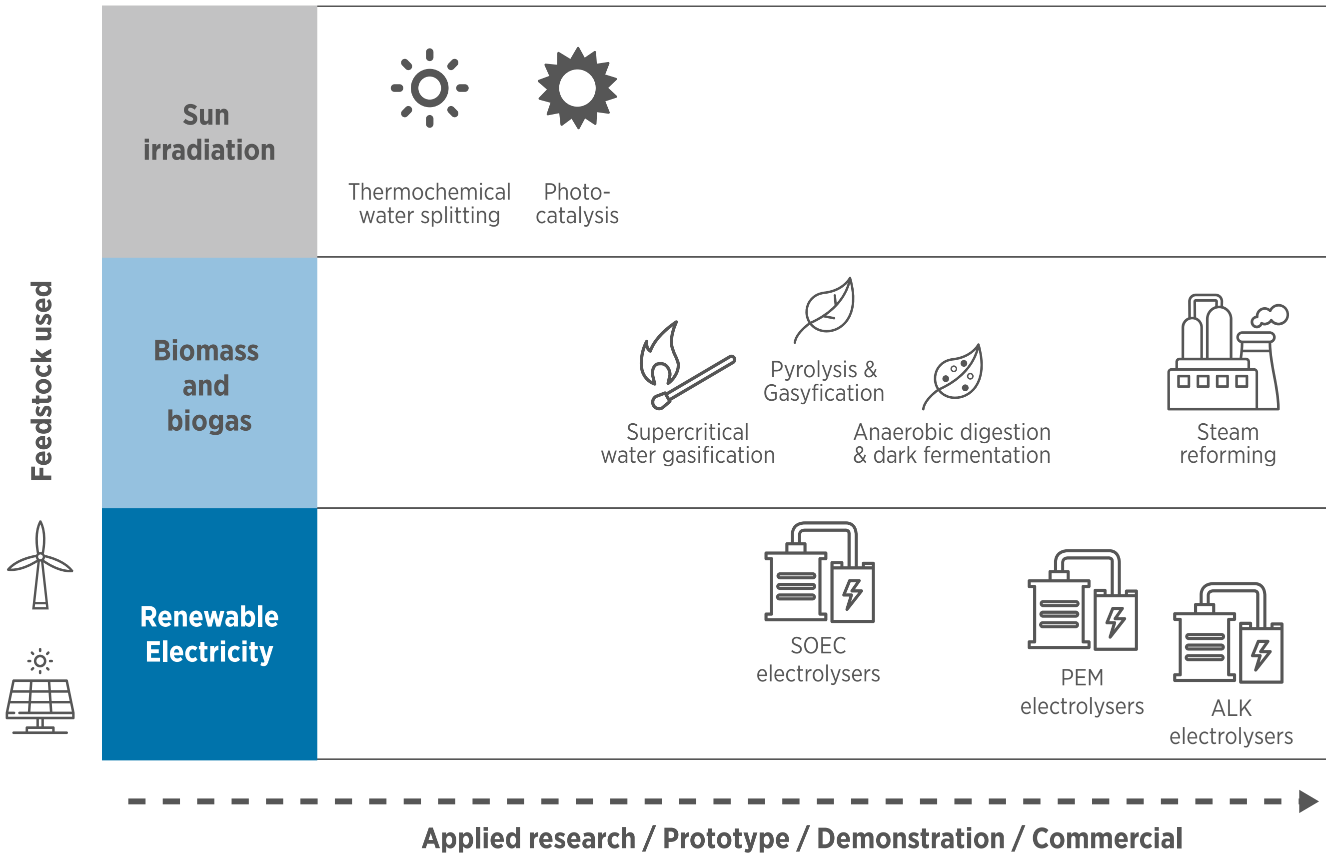
Source: IRENA, 2022

Hydrogen Pathways



Hydrogen is only an energy carrier – it is produced from other energy sources.

Renewable hydrogen production pathways and levels of maturity



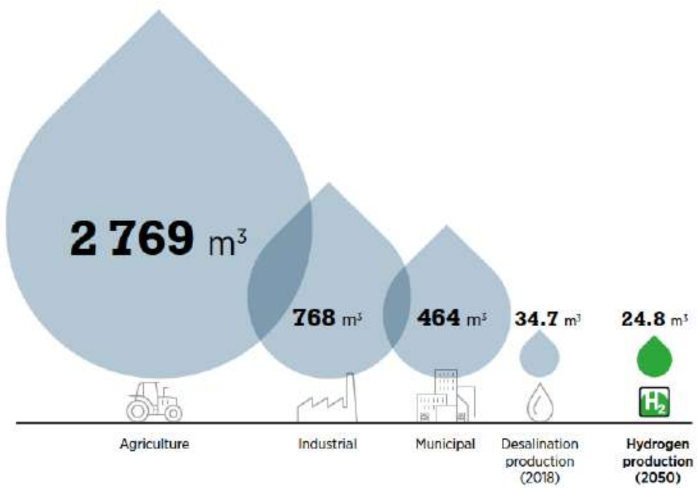
Notes: ALK = alkaline; PEM = proton exchange membrane; SOEC = solid oxide electrolyser cell.

Source: Based on FCH JU (2015), Study on Hydrogen from Renewable Resources in the EU.

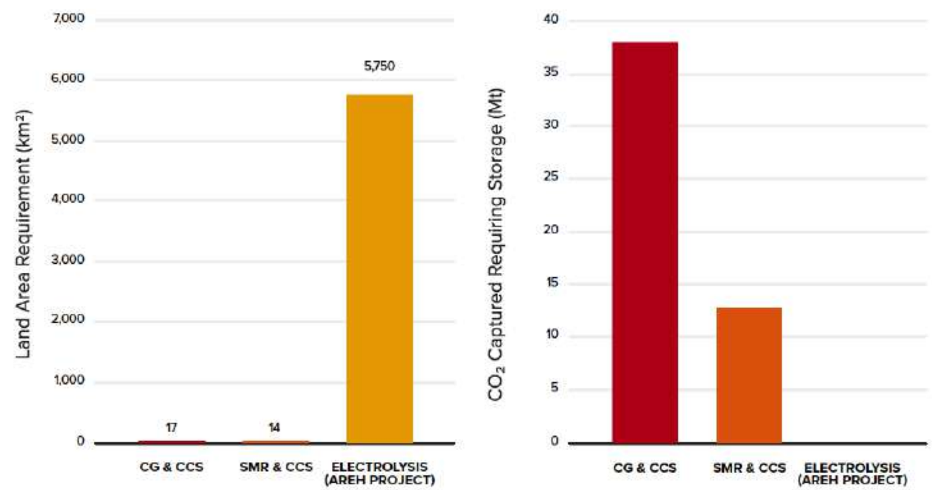
Source: IRENA, 2018

Water and land area required for blue and green hydrogen production

Figure 5.3 Water consumption of hydrogen in 2050 compared with selected sectors today (billion cubic metres)



Source: Blanco (2021).



“Barrriers of green hydrogen fron VRE is land area”

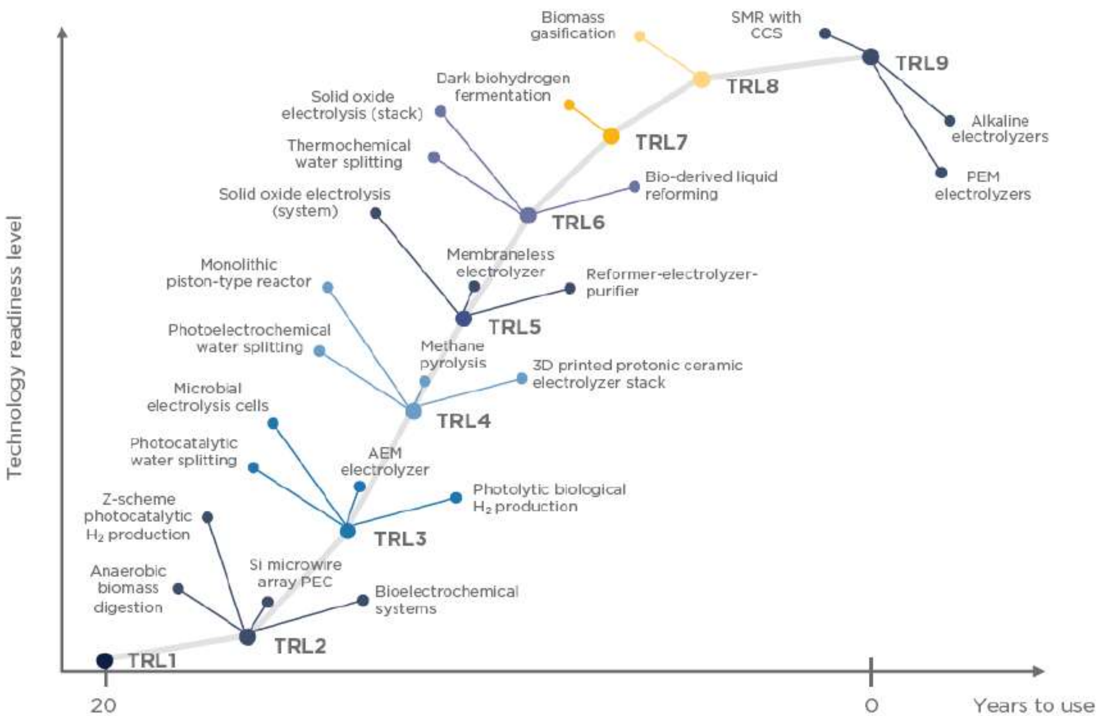
Source: IRENA, 2022

Source: Global CCS Institute, 2021

Technology readiness levels

"Several hydrogen technologies not yet commercially available"

Figure 1: Technology readiness level for hydrogen production

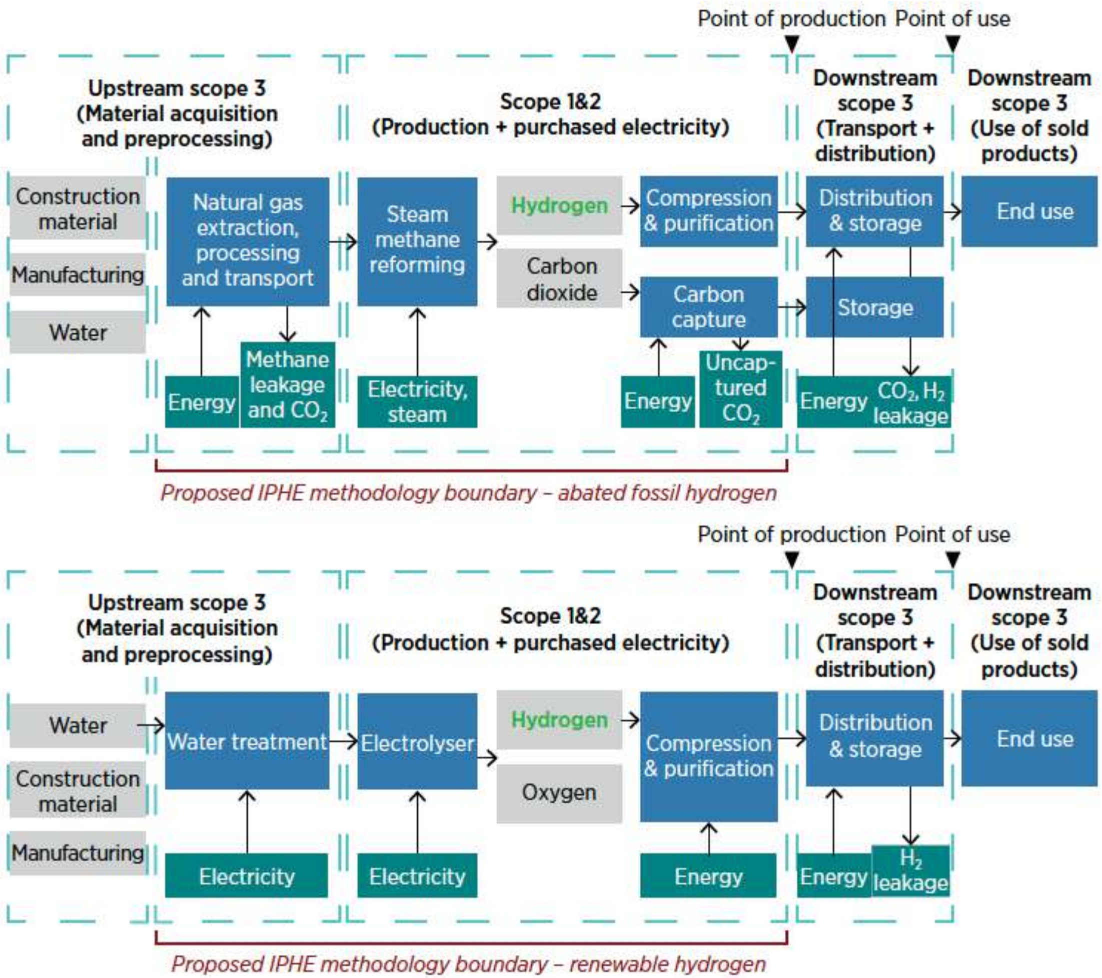


Note: TRL1 refers the lowest readiness (laboratory benchtop only), and TRL 9 refers to the highest readiness (commercially available)

Source: Authors' analysis based on Nadeem et al. (2021), Grimm et al. (2020), DOE (2020), Calise et al. (2019), Hallenbeck and Benemann (2018), and Miller et al. (2020).

Source: Columbia University CGEP

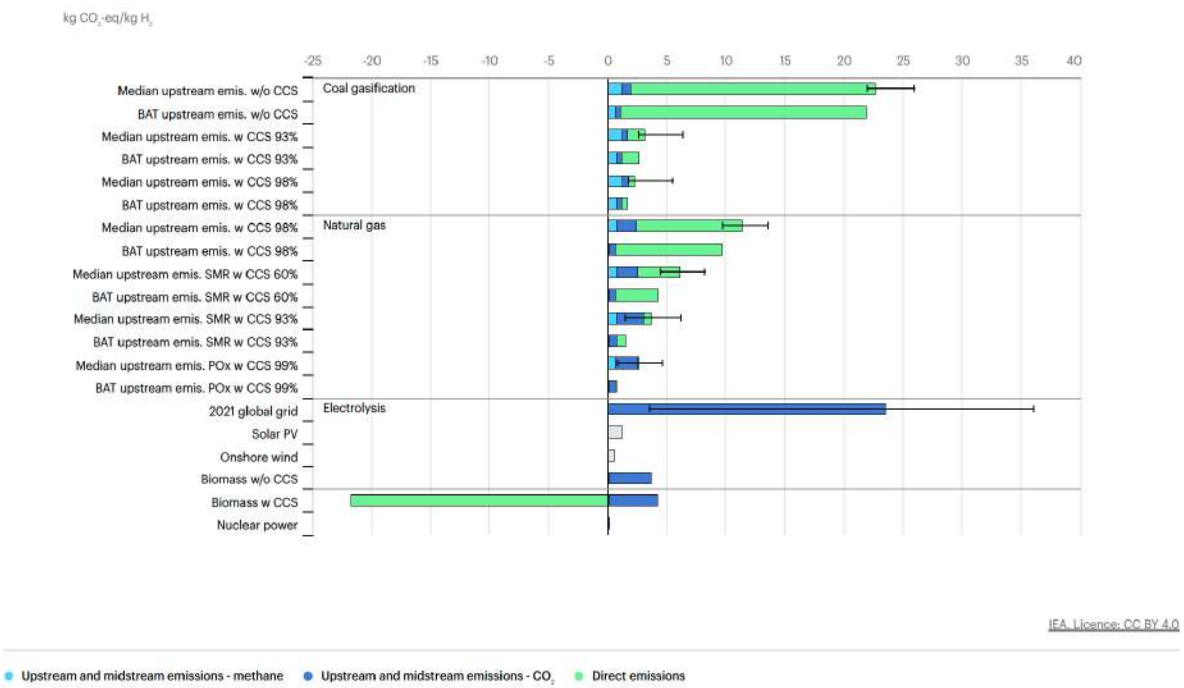
System boundary for blue (top) and green (bottom) hydrogen



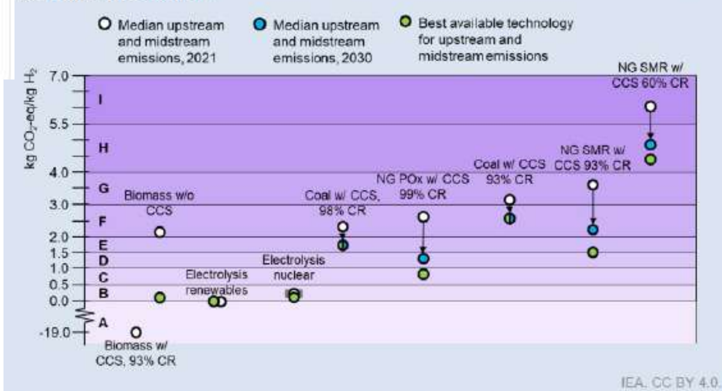
Notes: IPHE = International Partnership for Hydrogen and Fuel Cells in the Economy.

Source: IRENA, 2023

Comparison of the emissions intensity of different hydrogen production routes, 2021



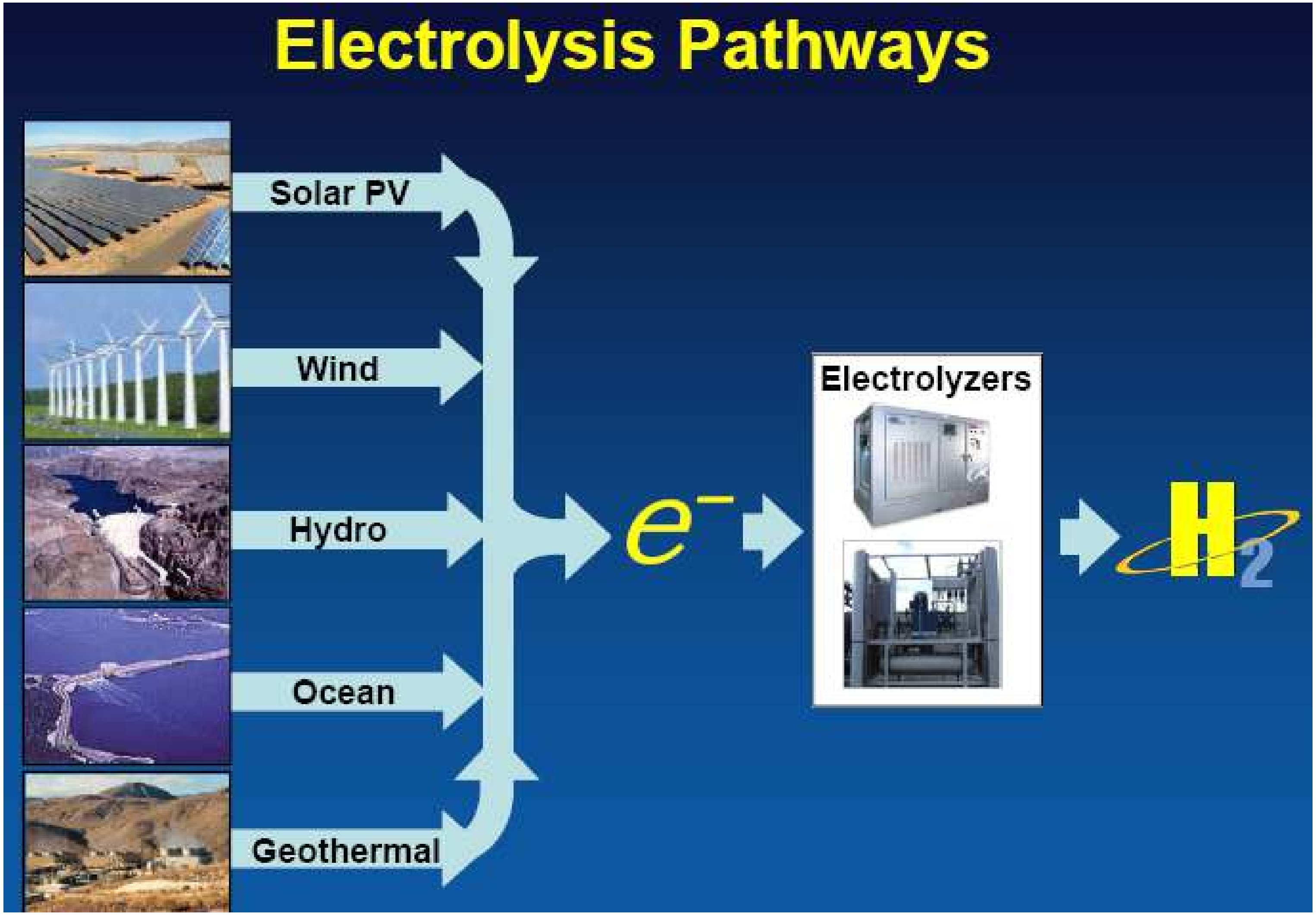
Example of a potential quantitative system for emissions intensity levels of hydrogen production



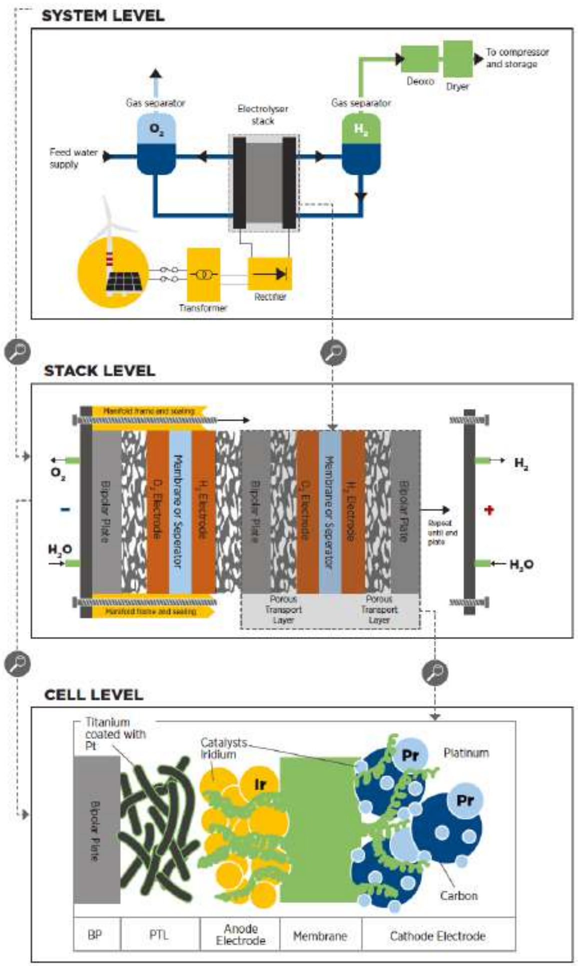
Notes: CCS = carbon capture and storage; CR= capture rate; NG = natural gas; POx = partial oxidation; SMR = steam methane reformer.

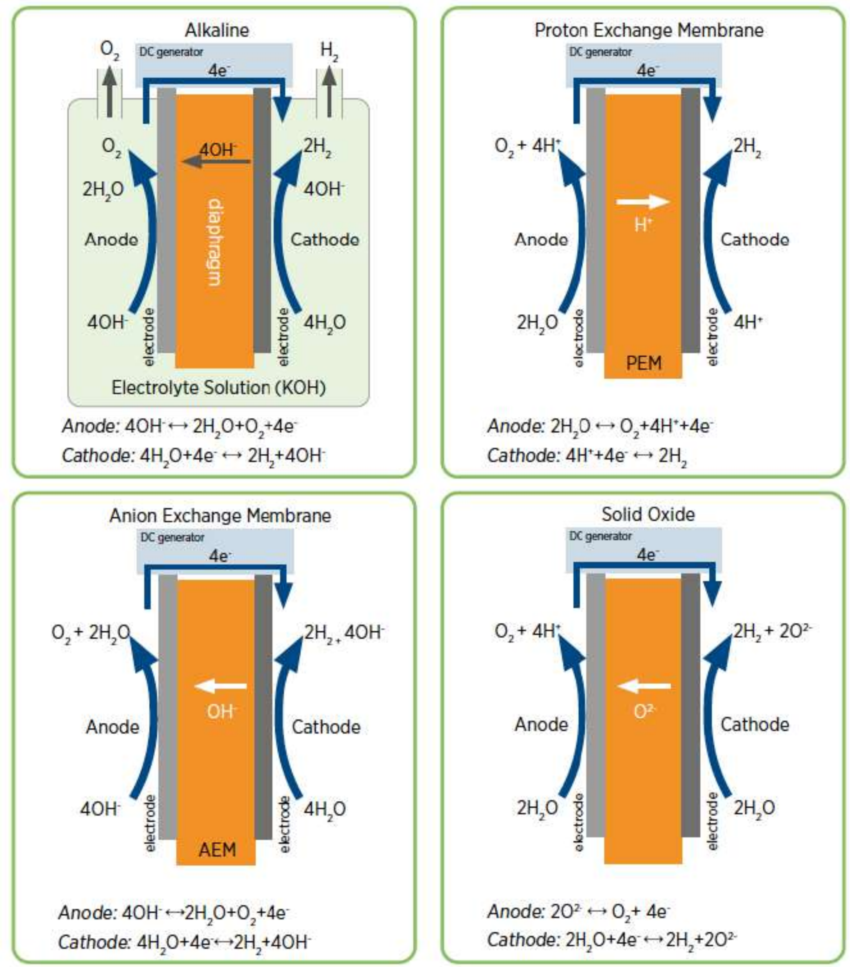
Source: IEA (2023), Towards hydrogen definitions based on their emissions intensity.

Source: IEA, 2023


Electrolysis Pathways
Solar PV
Wind
Hydro
Ocean
Geothermal
e⁻
Electrolyzers
H2

Basic components of water electrolysers and types of electrolysis technologies





Source: IREANA, 2020

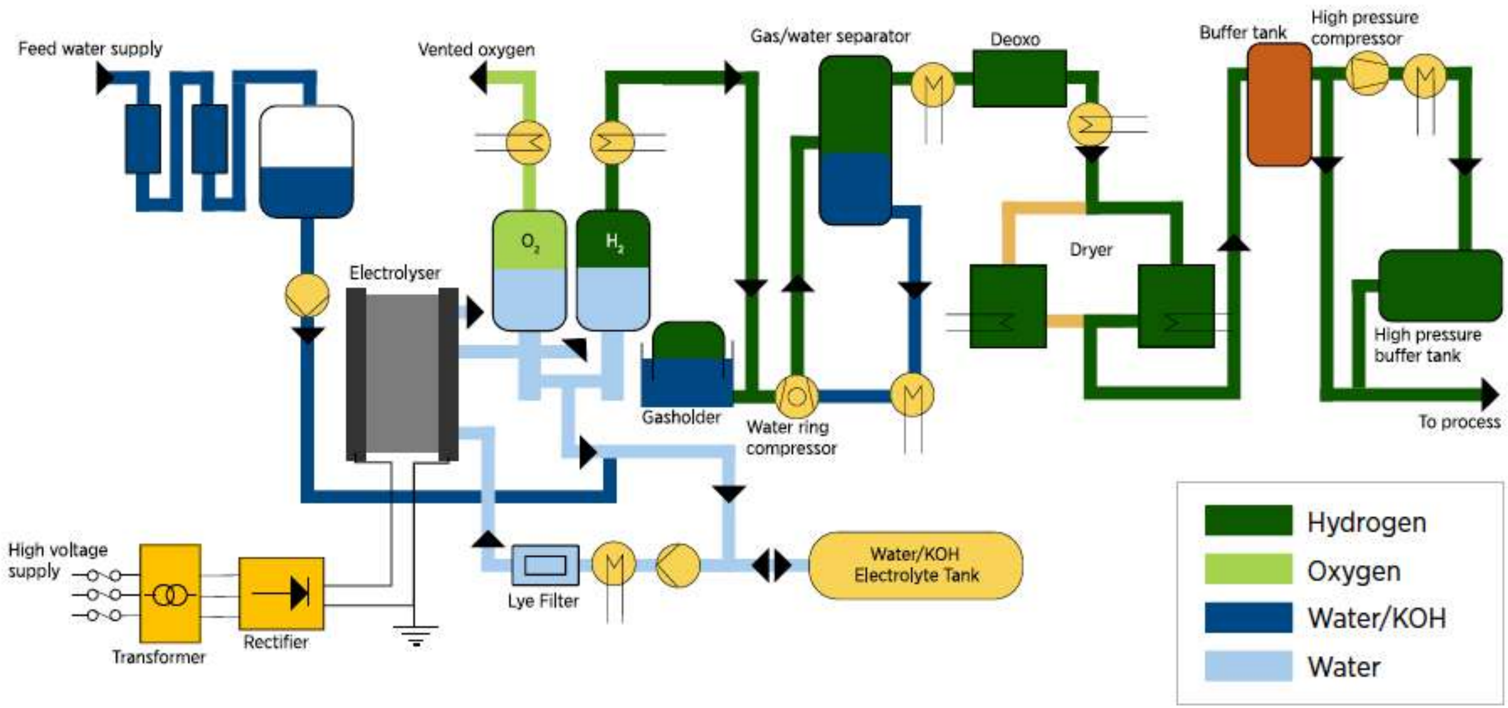
Characterisation of the four types of water electrolysers

	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

Note: Coloured cells represent conditions or components with significant variation among different companies.
PFSA = Perfluoroacidsulfonic; PTFE = Polytetrafluoroethylene; ETFE = Ethylene Tetrafluorethylene; PSF = poly (bisphenol-A sulfone); PSU = Polysulfone; YSZ = yttriastabilized zirconia; DVB = divinylbenzene; PPS = Polyphenylene sulphide; LSCF = $La_{0.58}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$-δ; LSM = $(La_{1-x}Sr_x)_{1-y}MnO_3$; § = Crofer22APU with co-containing protective coating.

Source: IRENA, 2020

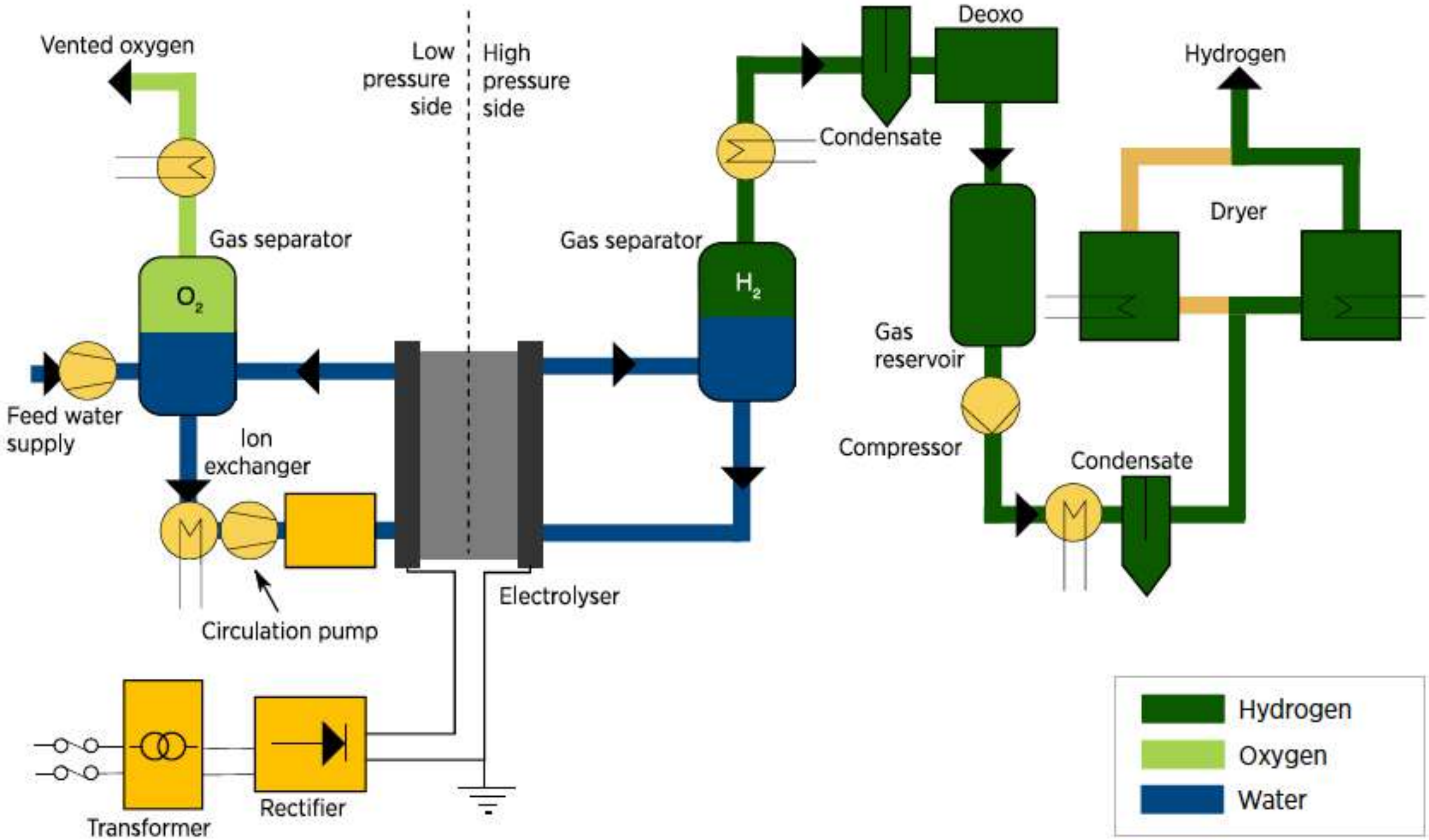
Typical system design and balance of plant for an alkaline electrolyser



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Source: 2020

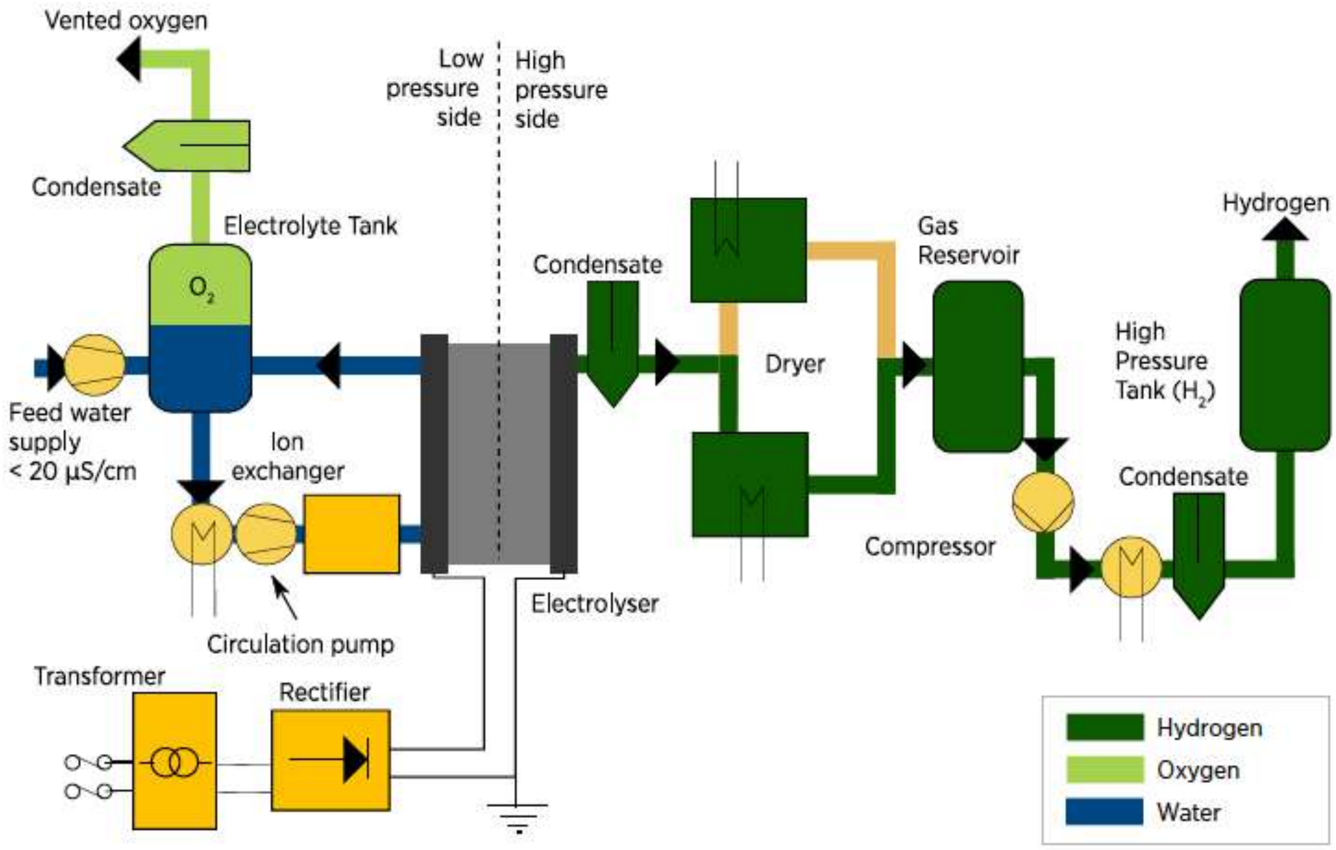
Typical system design and balance of plant for a PEM electrolyser



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Source: 2020

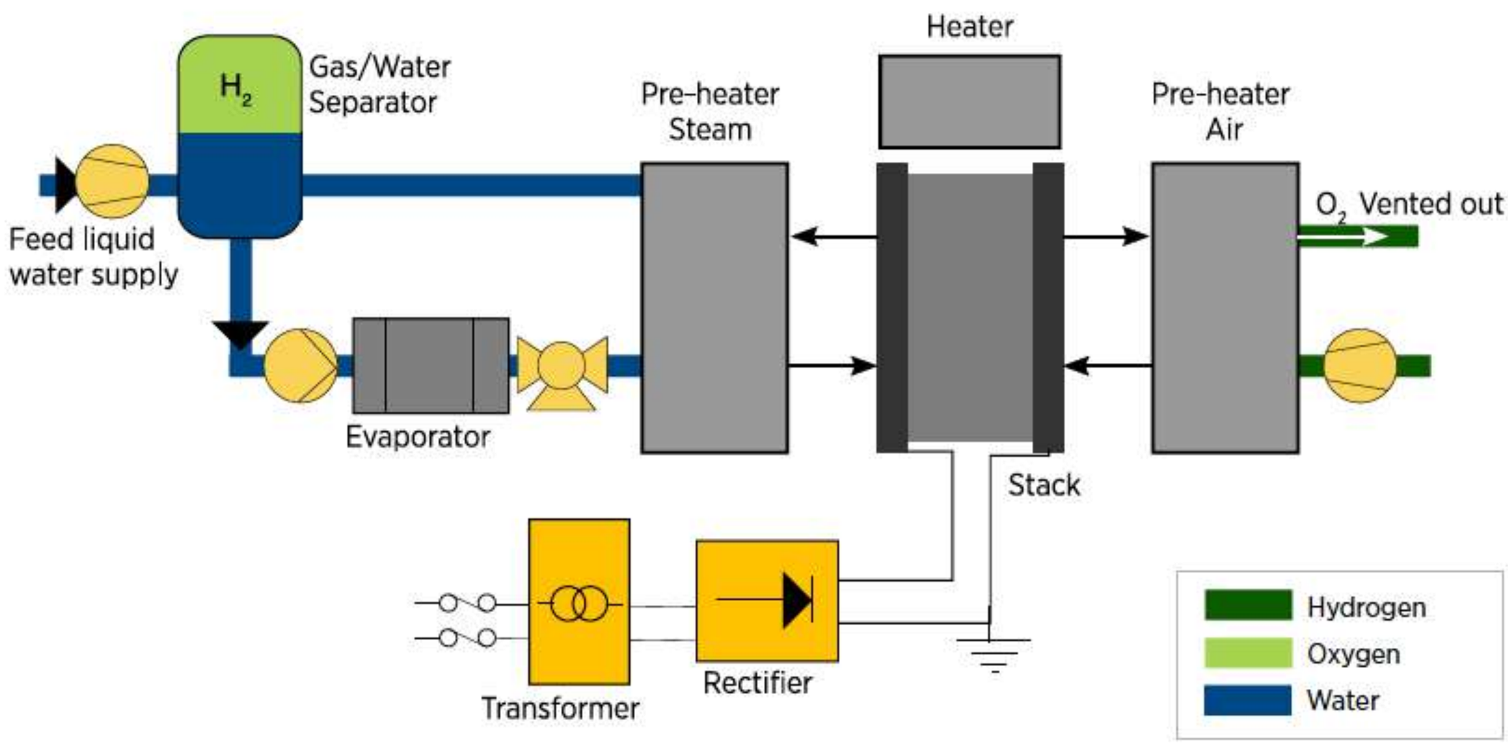
Typical system design and balance of plant for an AEM electrolyser



Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

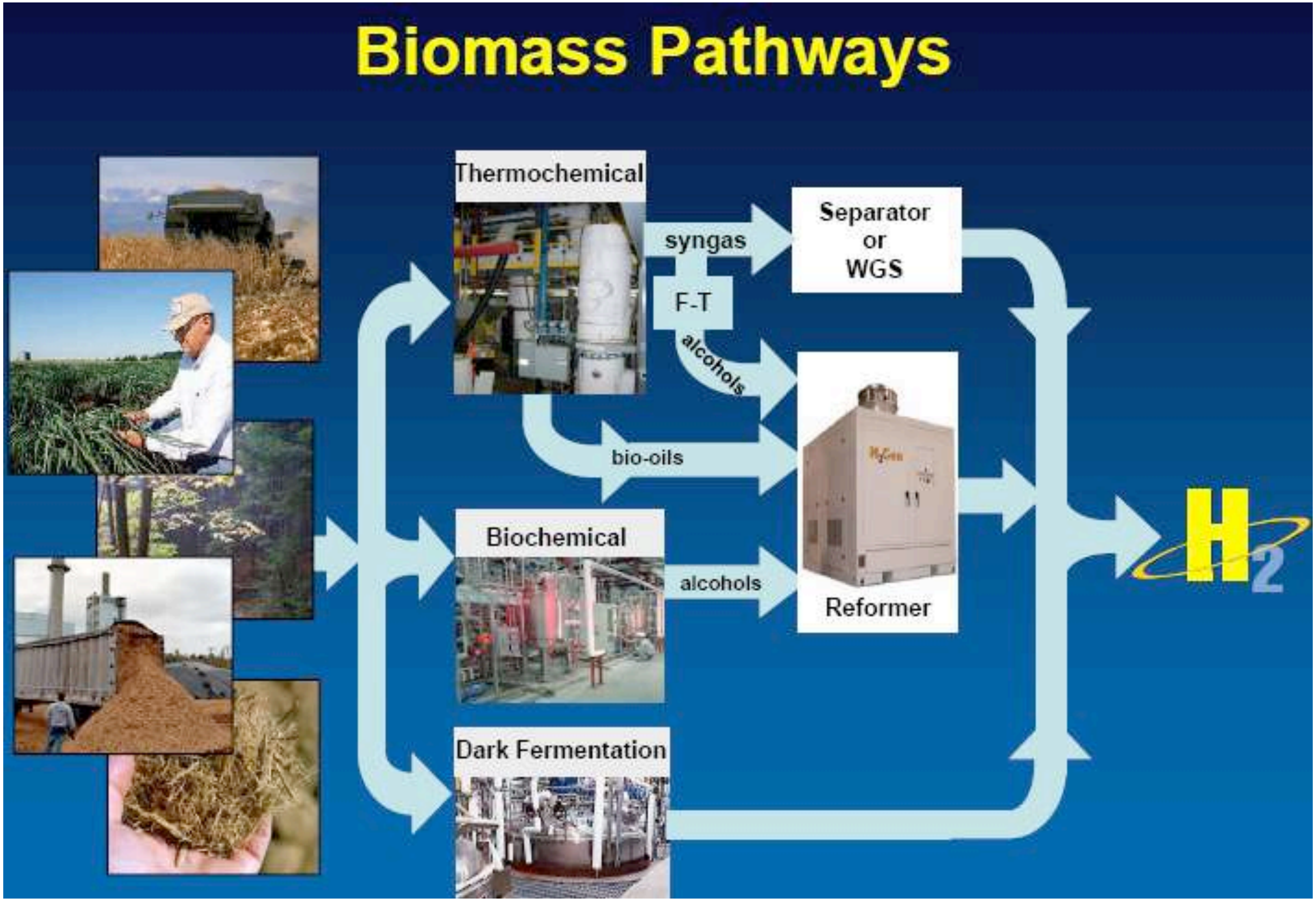
Source: 2020

Typical system design and balance of plant for a solid oxide electrolyser



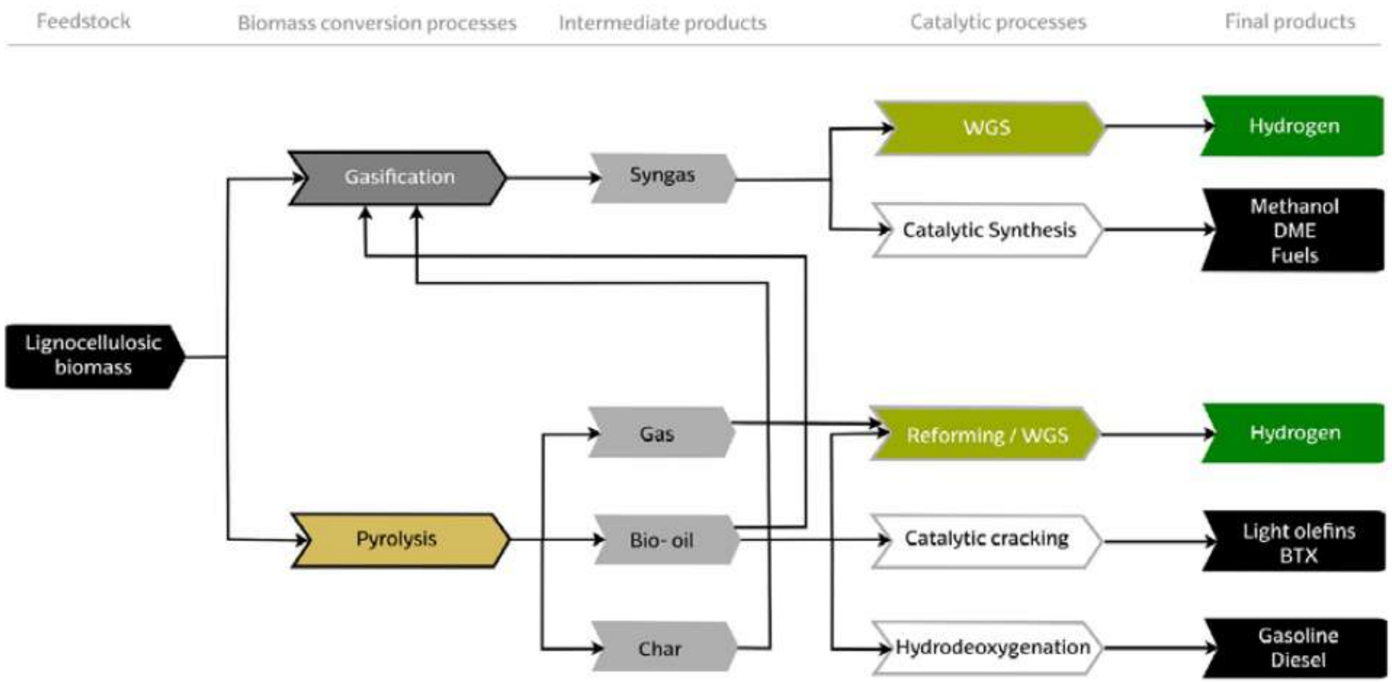
Note: This configuration is for a generic system and might not be representative of all existing manufacturers.

Source: 2020



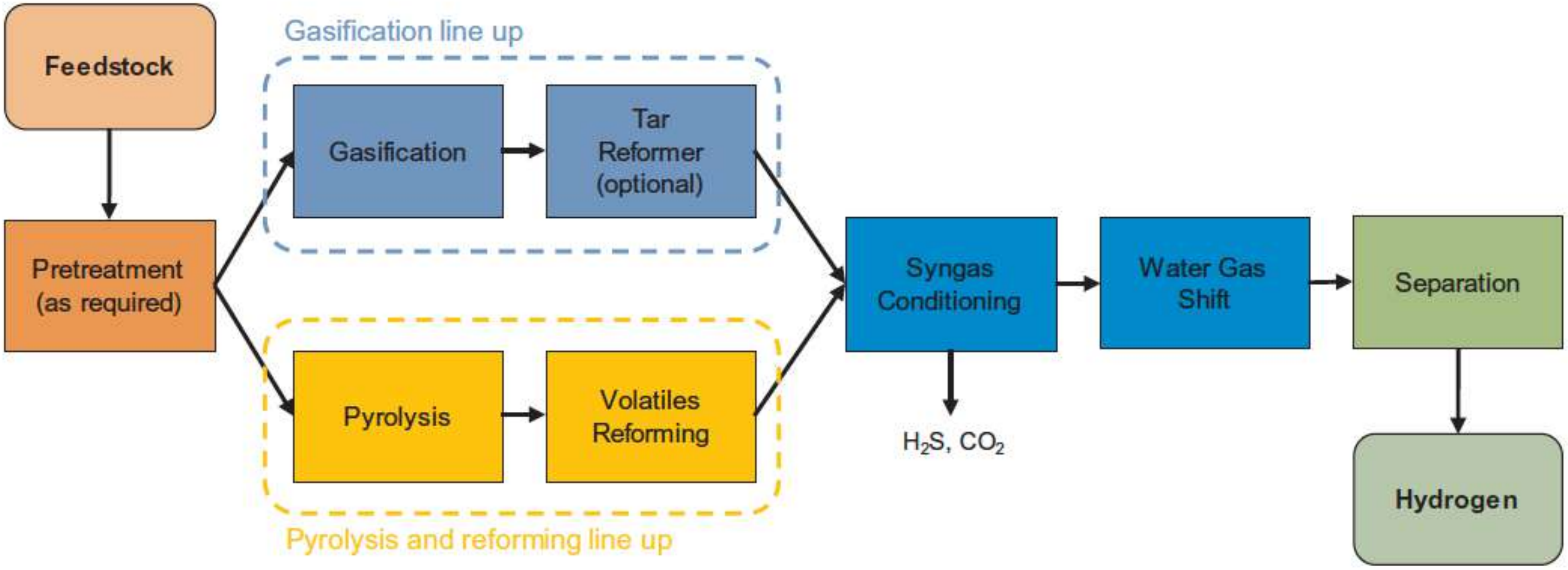
Biomass Pathways
Thermochemical
syngas
Separator
or
WGS
F-T
alcohols
bio-oils
Biochemical
alcohols
Reformer
Dark Fermentation
H2

Hydrogen production from biomass feedstock



Source: IEA, 2018

General scheme for producing hydrogen from biomass wastes using gasification and pyrolysis/reforming



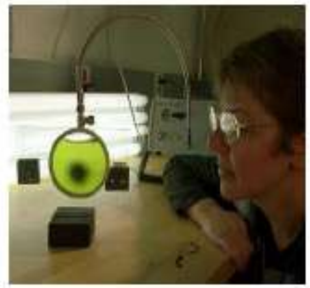
Source: M. Shahabuddin, et al., 2020

Table 1
Summary of characteristics of biological hydrogen production processes.

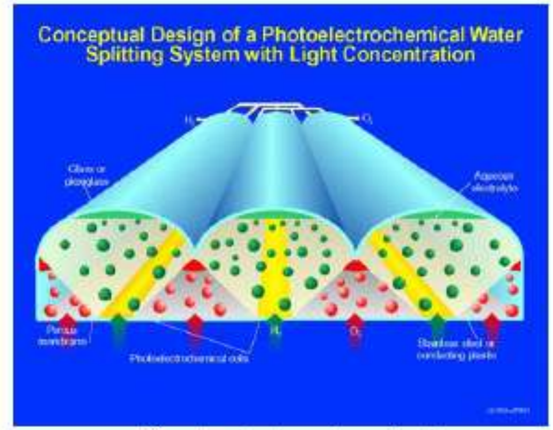
Bio-hydrogen system	H_2 production rate (mmol H_2)	Required inputs and broad classification of microorganism used	By-products	General reactions and advantages
Direct biophotolysis	0.07	Light energy, H_2O, CO_2, trace minerals • Micro-algae	O_2	$2H_2O + light = 2H_2 + O_2$ It can directly produce H_2 directly from water and sunlight.
Indirect biophotolysis	0.355	Light energy, H_2O, CO_2, trace minerals • Micro-algae, cyanobacteria	O_2	$12H_2O + light = 12H_2 + O_2$ It has the ability to fix N_2 from atmosphere.
Photo-fermentation	153.0	Light energy, H_2O, glucose • Purple-bacteria, microalgae	CO_2	$CH_3COOH + 2H_2O + light = 4H_2 + 2CO_2$ A wide spectral light energy can be used by these bacteria.
Dark fermentation (i) Mesophilic (ii) Thermophilic (iii) Extreme thermophilic	121.0 8.2 8.4	H_2O, carbohydrates, heat (ii and iii only) • Fermentative bacteria	CO_2, CH_4, CO, H_2S, acetate or other end products	$C_6H_{12}O_6 + 6H_2O = 12H_2 + 6CO_2$ It can produce H_2 all day long without light. A variety of carbon sources can be used as a substrate. It produces valuable metabolites such as butyric, lactic and acetic acid as a by-products. There is no O_2 limitation problem.
Hybrid reactor system		Light energy, H_2O, carbohydrates • Fermentative bacteria followed by anoxygenic phototrophic bacteria	CO_2	Stage-I: $C_6H_{12}O_6 + 2H_2O = 4H_2 + 2CH_3COOH + 2CO_2$ Stage-II: $CH_3COOH + 2H_2O + light = 4H_2 + 2CO_2$ Two stage fermentation can improve the overall yield of hydrogen

Bio-H_2 production

Wind Electrolysis



Photobiological Production



Photoelectrochemical Water Splitting

Biological Water-Gas Shift

Reforming Pyrolysis Streams

Solar Assisted Production

Courtesy of NREL.

Principal Approaches to H_2 Generation from Methane

Steam Reforming (SMR)

$CH_4 + H_2O = CO + H_2$ $\Delta H = +206$ kJ/mol

$CO + H_2O = CO_2 + H_2$ $\Delta H = -41$kJ/mol

Partial Oxidation (POX)

$CH_4 + ½ O_2 = CO + H_2$ $\Delta H = -38$ kJ/mol

$CO + H_2O = CO_2 + H_2$ $\Delta H = -41$ kJ/mol

Autothermal Reforming (ATR)

$CH_4 + 1.5\ O_2 = CO + 2\ H_2O$ $\Delta H = -520$ kJ/mol

$CH_4 + H_2O = CO + H_2$ $\Delta H = +206$ kJ/mol

$CO + H_2O = CO_2 + H_2$ $\Delta H = -41$ kJ/mol

Alexis T. Ball, LBL

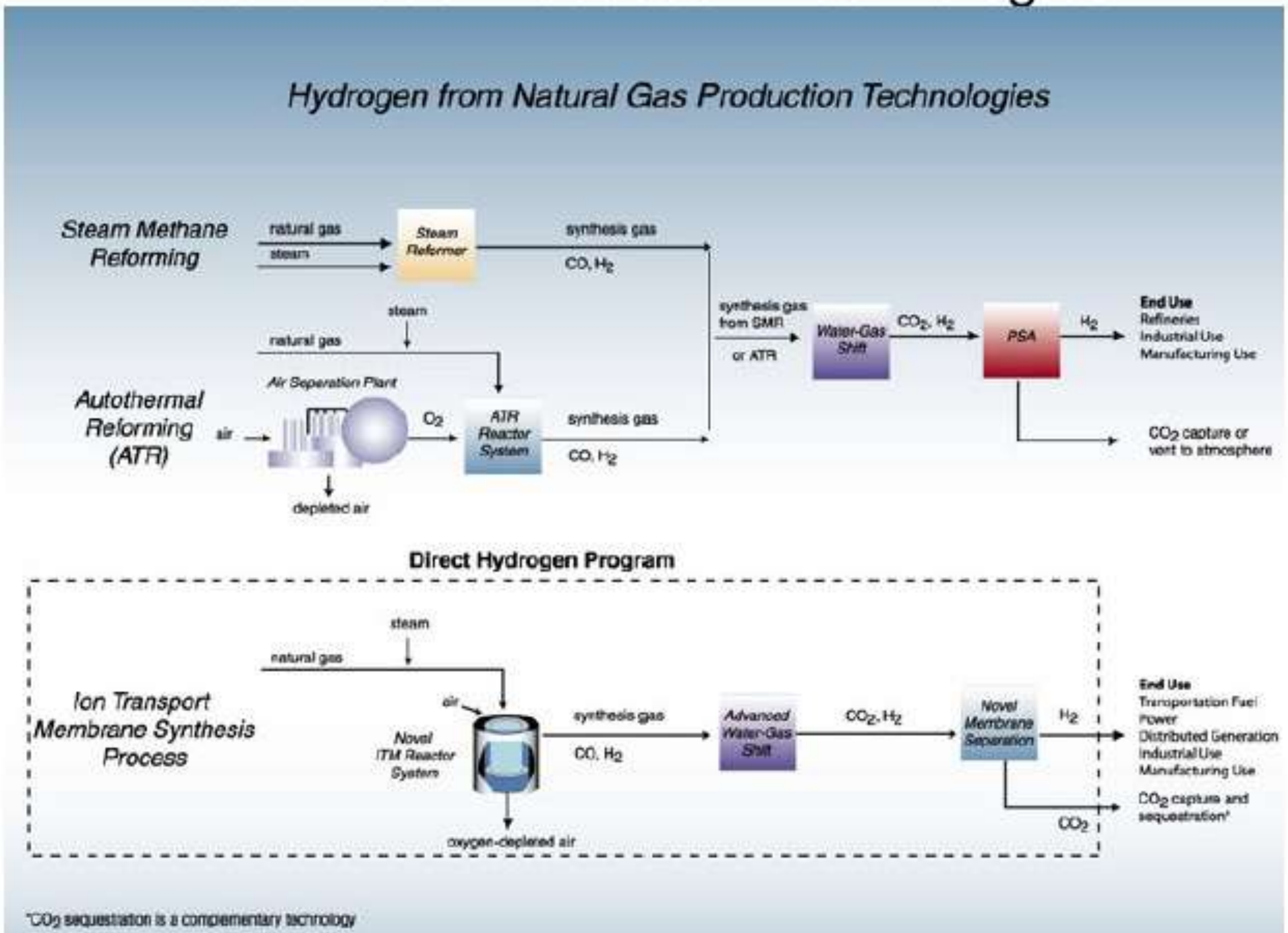
Steam Reforming Plant
39,000 Nm^3/h (0.93×10^6 Nm^3/day)

N denotes normal flow rate at 1 atm and 0°C

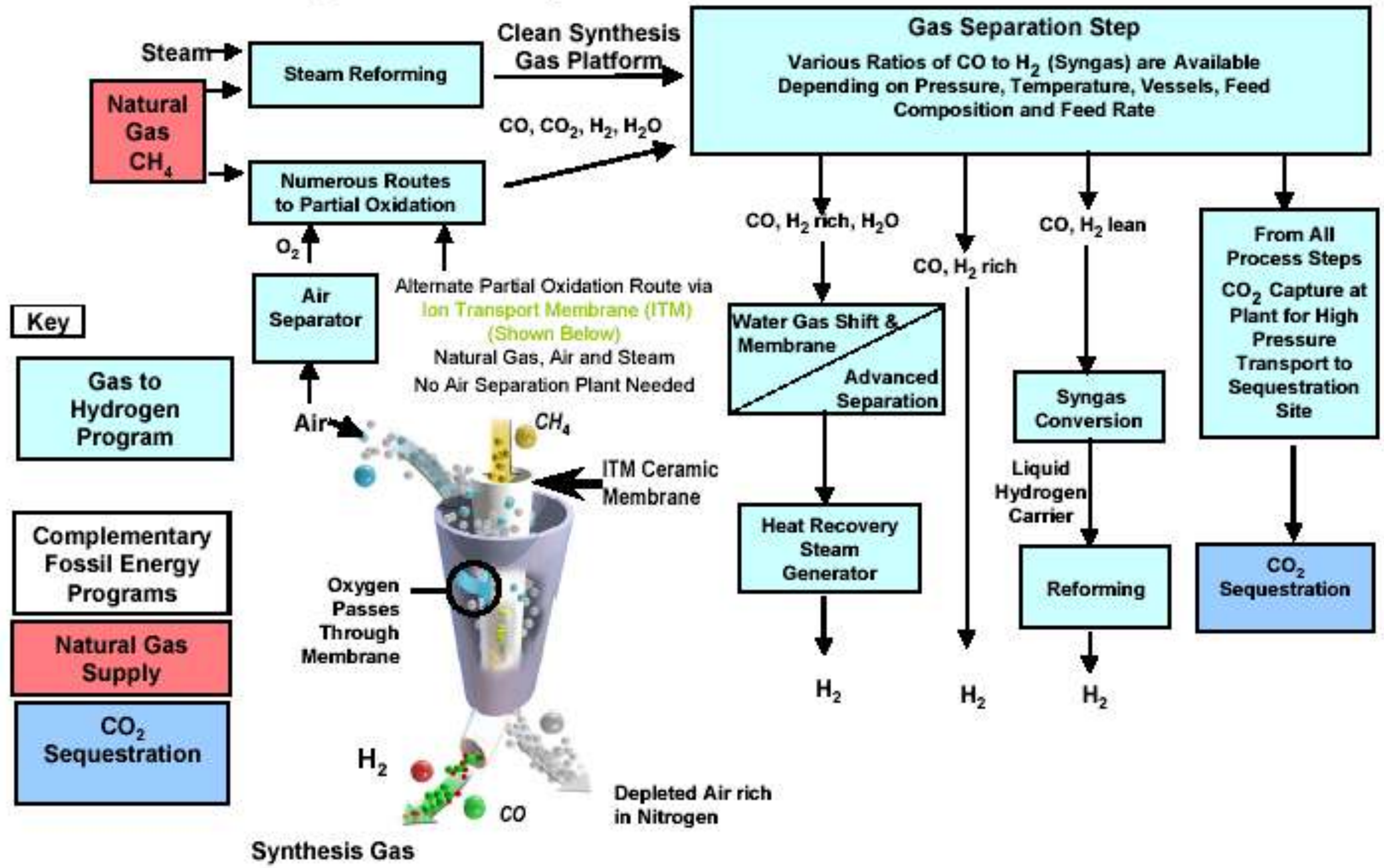
Steam reforming to produce H_2 is done in a large plant

www.mrw.interscience.wiley.com/encat/

Flow Diagrams of Various Hydrogen from Natural Gas Production Technologies

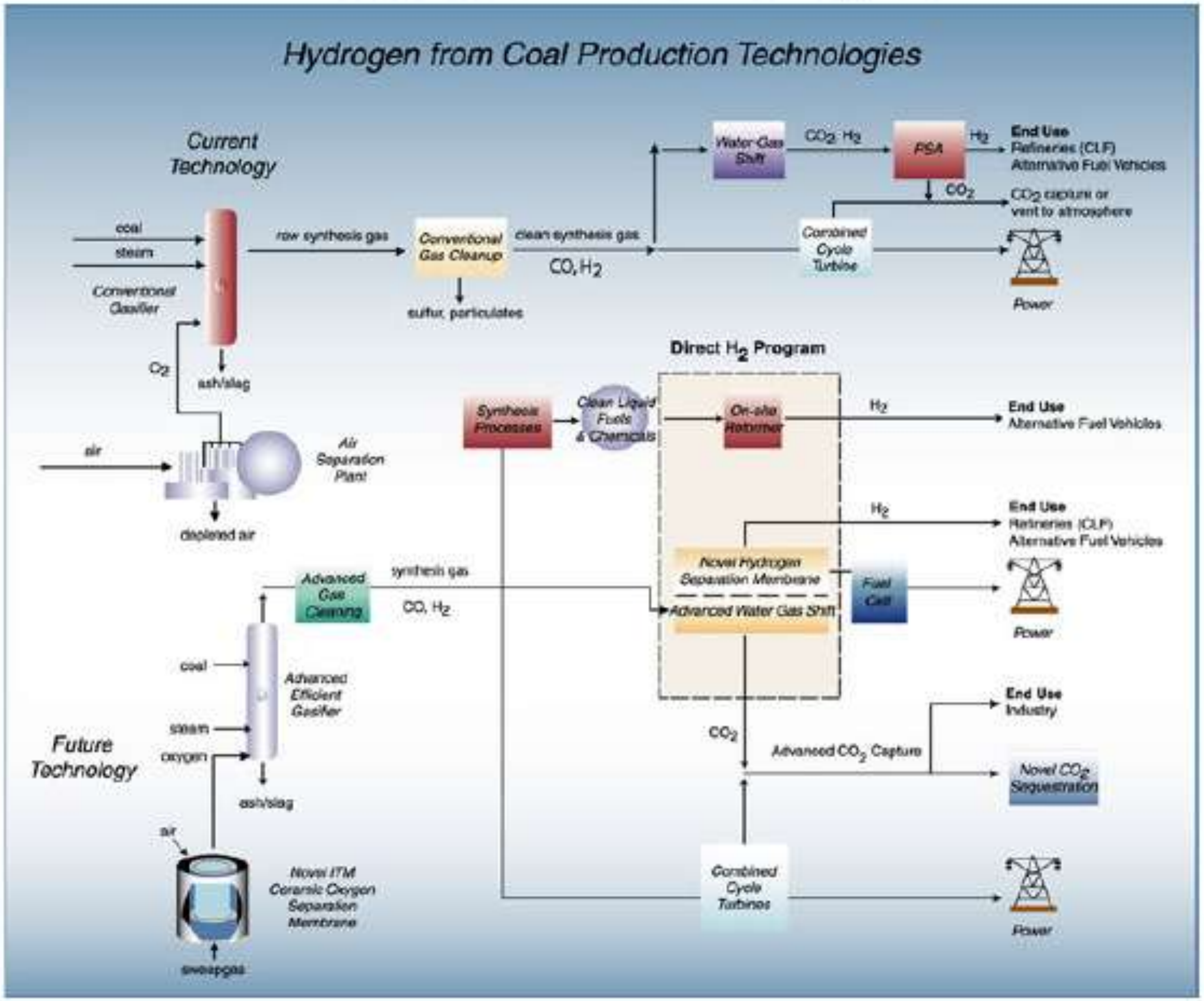


Hydrogen from Natural Gas
Program Components --- Product Areas

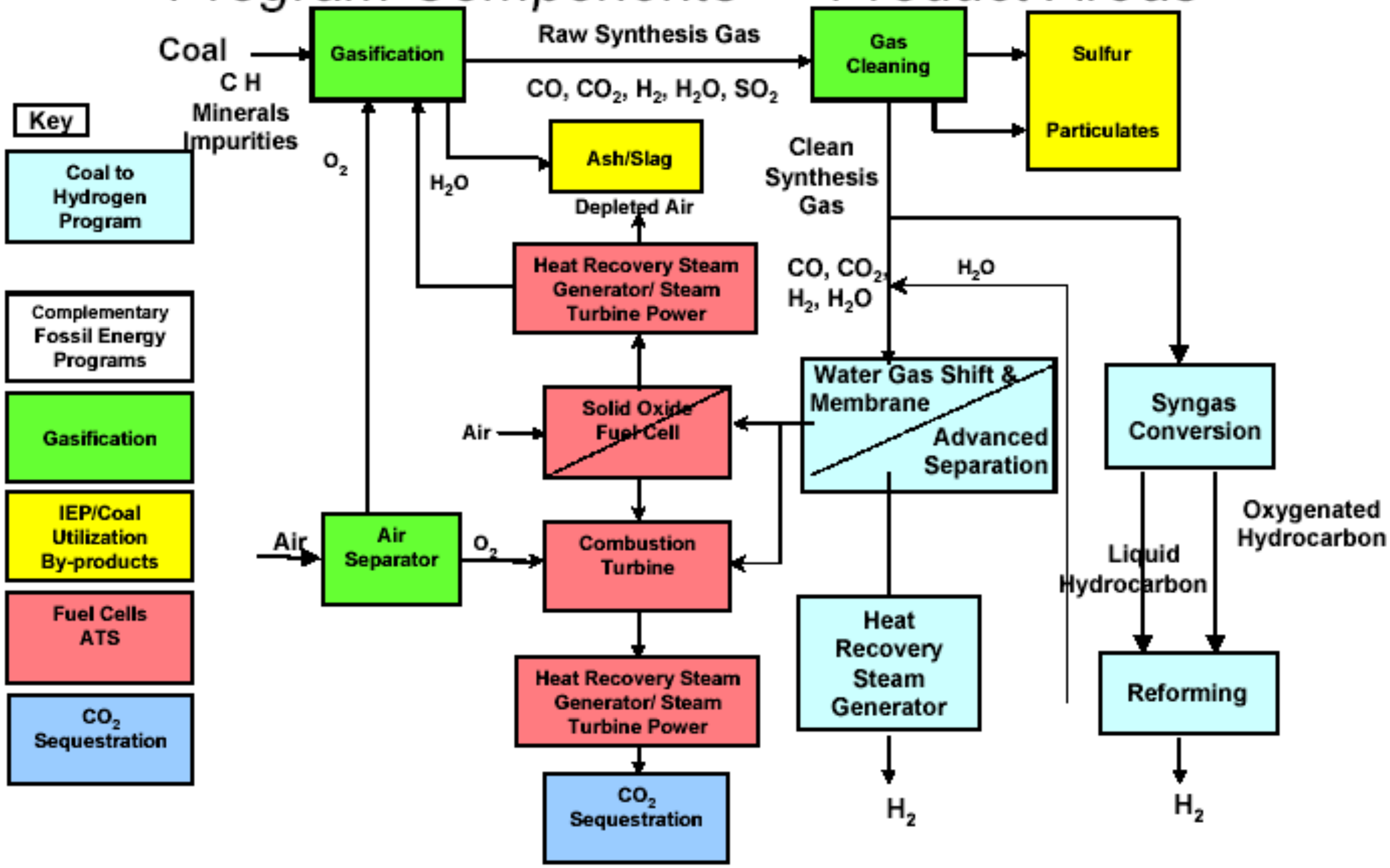


From APS POPA study

Current and Future Hydrogen from Coal Production Technologies

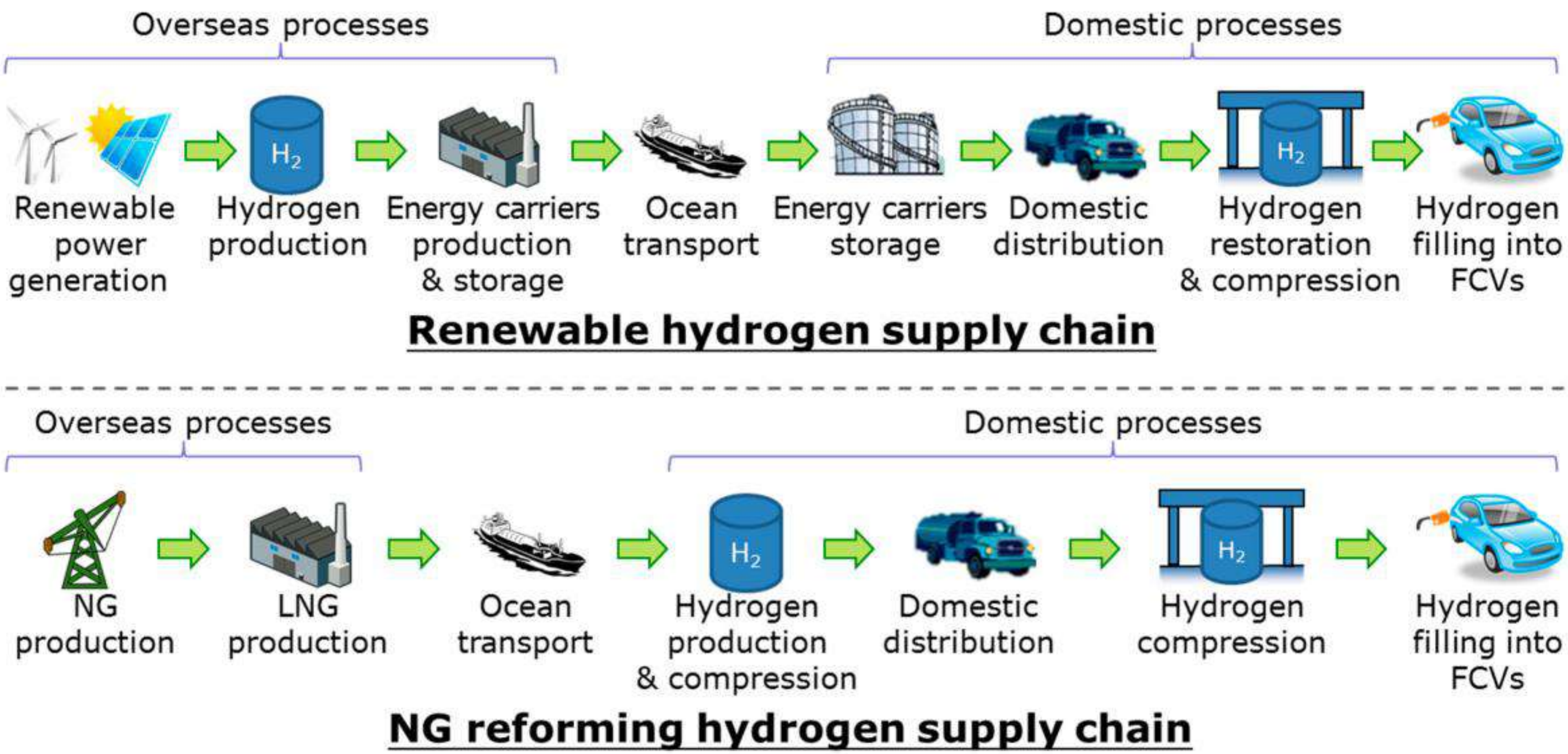


Hydrogen from Coal
Program Components --- Product Areas

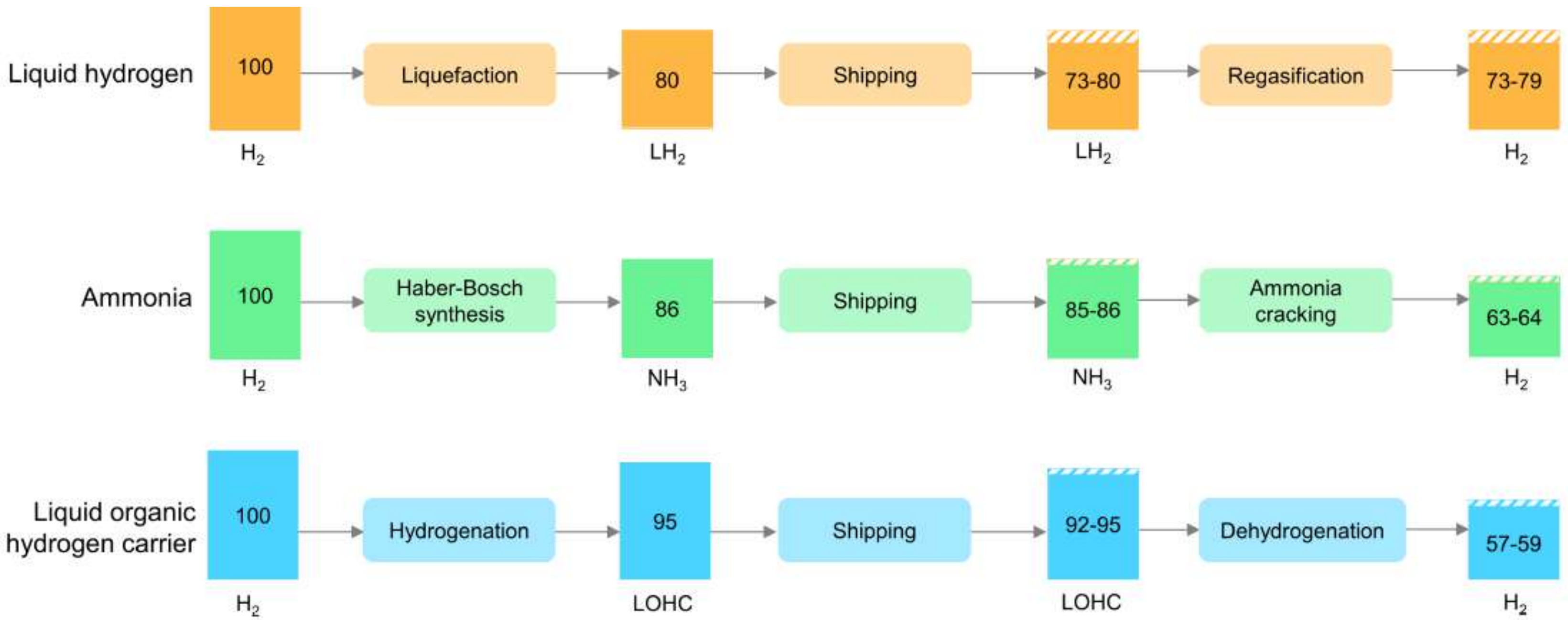


Hydrogen supply chain

Transport and distribution – renewable H2 supply chain



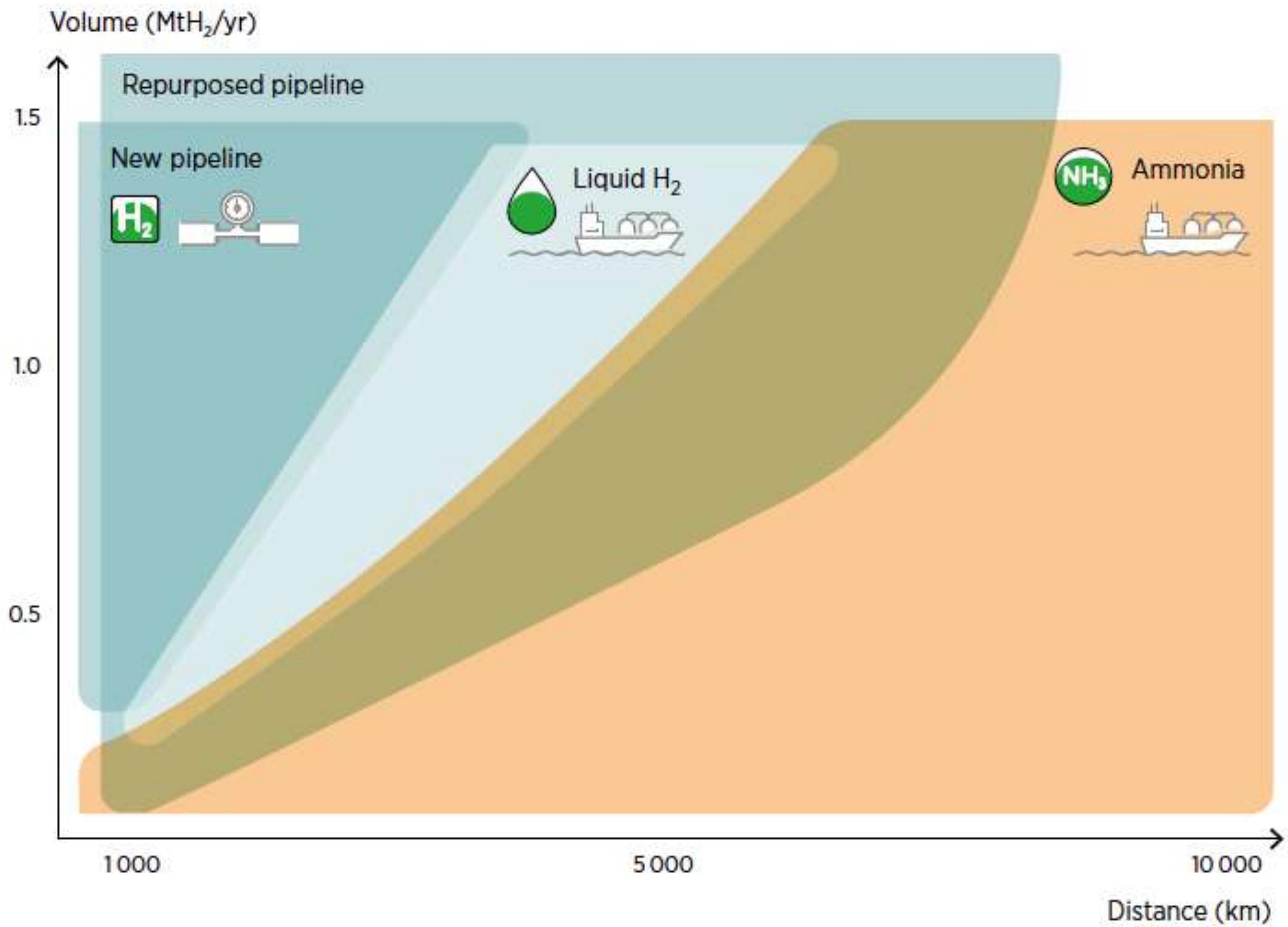
Energy available along the conversion and transport chain in hydrogen, 2030



Notes: LH_2 = liquefied hydrogen; NH_3 = ammonia; LOHC = liquid organic hydrogen carrier. Numbers show the remaining energy content of hydrogen along the supply chain relative to a starting value of 100, assuming that all energy needs of the steps would be covered by the hydrogen or hydrogen-derived fuel. The Haber-Bosch synthesis process includes energy consumption in the air separation unit. Boil-off losses from shipping are based on a distance of 8 000 km. For LH_2, dashed areas represent energy being recovered by using the boil-off gases as shipping fuel, corresponding to the upper range numbers. For NH_3 and LOHC, the dashed area represents the energy requirements for one-way shipping, which are included in the lower range numbers.

Source: IEA, 2022

Cost efficiency of transport options when considering volume and distance

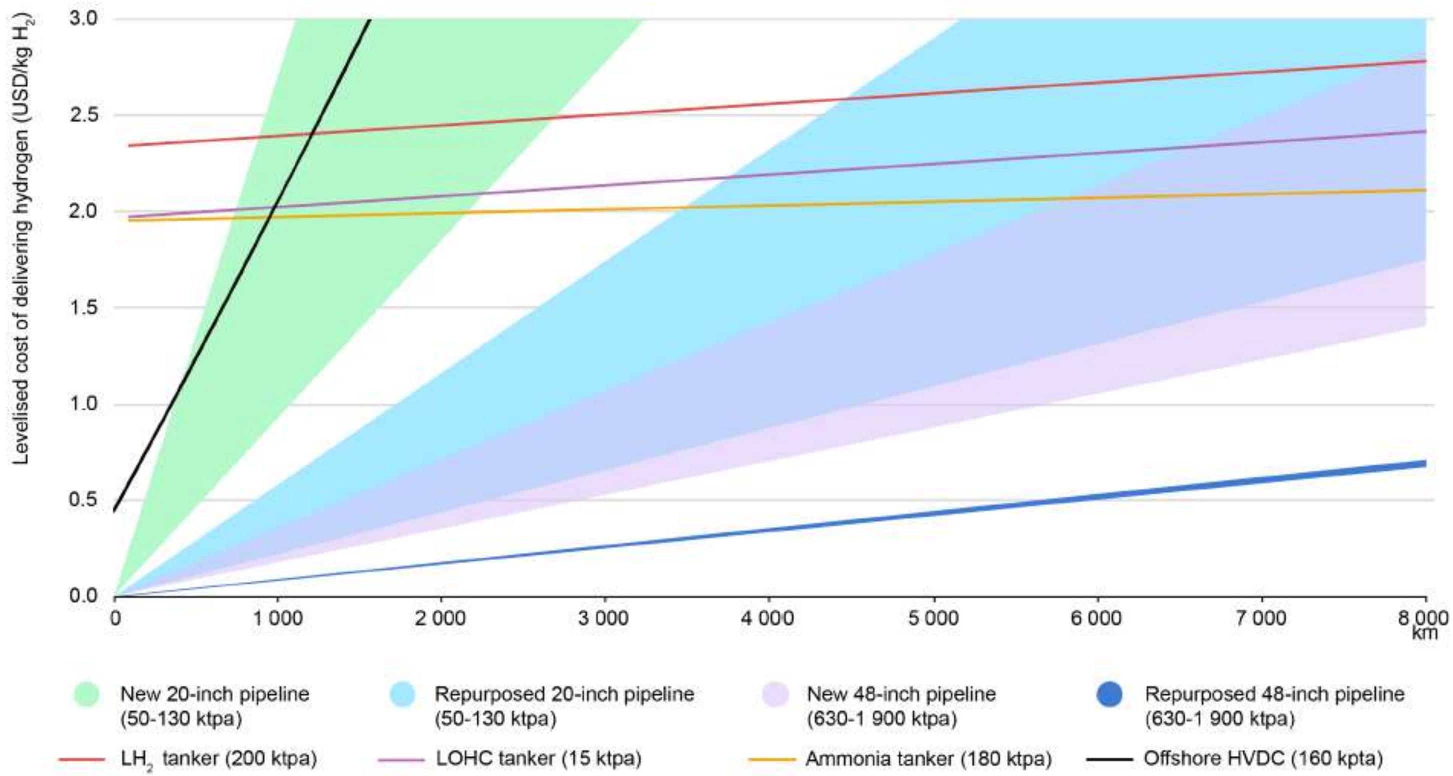


Source: IRENA (forthcoming-a)

Note: H_2 = hydrogen gas; km = kilometre. MtH_2/yr = million tonnes of hydrogen per year.

Source: IRENA, 2022

Levelised costs of delivering hydrogen by pipeline and by ship as LH2, LOHC and ammonia carriers, and electricity transmission, 2030



Notes: ktpa = kilotonnes per year; LH_2 = liquefied hydrogen; LOHC = liquid organic hydrogen carrier. Includes conversion, export terminal, shipping, import terminal and reconversion costs for each carrier system (LH_2, LOHC and ammonia). The import and export terminals include storage costs at the port. Pipelines refer to onshore transmission pipelines operating at ranges between 25% and 75% of their design capacity during 5 000 full load hours. Electricity transmission reflects the transmission of the electricity required to obtain 1 kg H_2 in an electrolyser with a 69% efficiency located at the distance represented by the x-axis.

Source: IEA analysis based on data from Guidehouse (2021) and IAE (2016).

Source: IEA, 2022

Comparison of various energy storage technologies and their storage capability

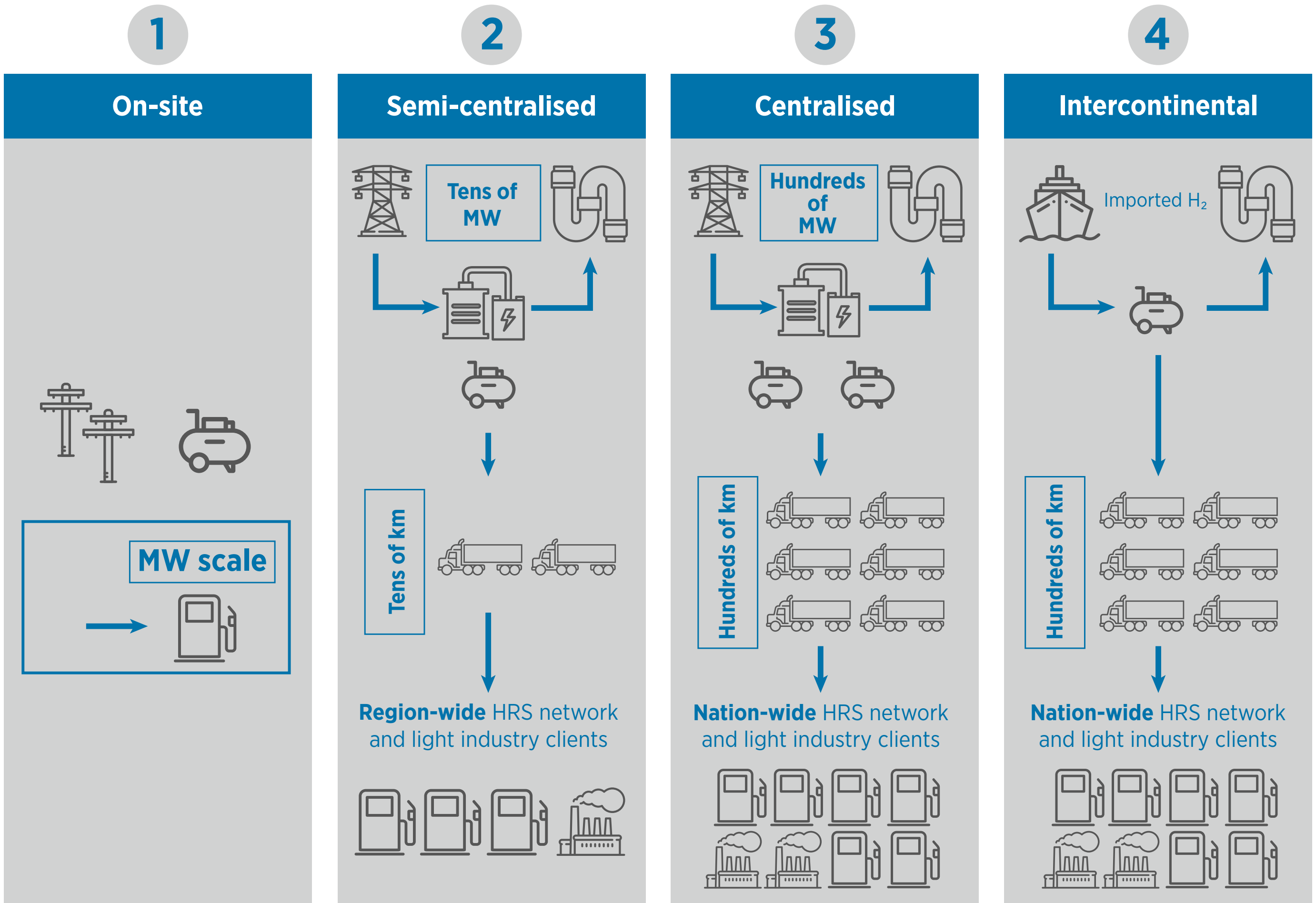
Storage technology	Efficiency (%)	Typical storage capacity	Typical discharge time	Maturity of technology
Hydrogen energy storage	**30–45%**	**< 1 GW**	**< 1 h–1 000+h**	**Under RD&D**
Batteries	70–85%	< 100 MW	< 5 h	Under R&D in some regions and commercialised in United States, United Kingdom and Australia
Compressed air energy storage (CAES)	45–70%	< 10 MW	5–100 h	RD&D
Flywheels	85–100%	< 1 MW	< 30 min	R&D
Pumped hydro storage (PHS)	70–85%	0.1–1 GW	10–500 h	Commercialised

Note: GW = gigawatt; h = hour; min = minute; MW = megawatt; R&D = research and demonstration; RD&D = research, development and demonstration.

Source: Adapted from California Hydrogen Council, 2015; NREL, 2014; IEA, 2014

Source: IRENA, 2019

Potential future ramp up pattern of the hydrogen supply chain



Note: The numbers 1, 2, 3 and 4 refer to the different potential future development stages in chronological order.
Based on: HINICIO (2016) .

Source: IRENA, 2019

Techno-economic characteristics of ALK and PEM electrolysers (2017, 2025)

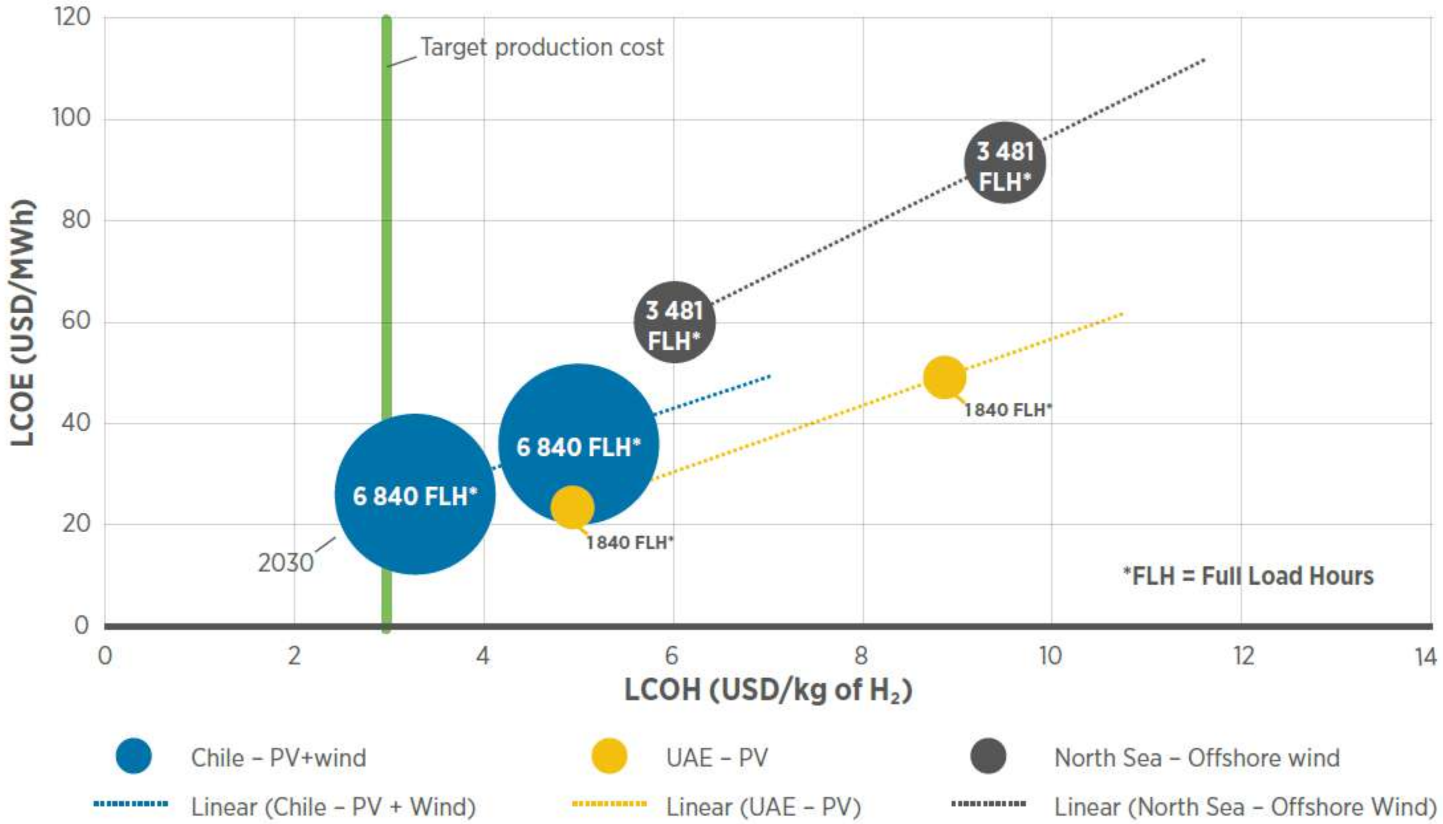
Technology		ALK		PEM	
	Unit	2017	2025	2017	2025
Efficiency	kWh of electricity/ kg of H_2	51	49	58	52
Efficiency (LHV)	%	65	68	57	64
Lifetime stack	Operating hours	80 000 h	90 000 h	40 000 h	50 000 h
CAPEX – total system cost (incl. power supply and installation costs)	EUR/kW	750	480	1 200	700
OPEX	% of initial CAPEX/year	2%	2%	2%	2%
CAPEX – stack replacement	EUR/kW	340	215	420	210
Typical output pressure*	Bar	Atmospheric	15	30	60
System lifetime	Years	20		20	

* Higher output pressure leads to lower downstream cost to pressurise the hydrogen for end use.

Notes: H_2 = hydrogen; h = hour; kg = kilogram; kW = kilowatt; kWh = kilowatt hour; LHV = lower heating value; OPEX = operating expenditure; CAPEX and OPEX are based on a 20 MW system.
Sources: FCH JU (2017a), Program Review Days Report; FCH JU (2014), Development of Water Electrolysis in the European Union.

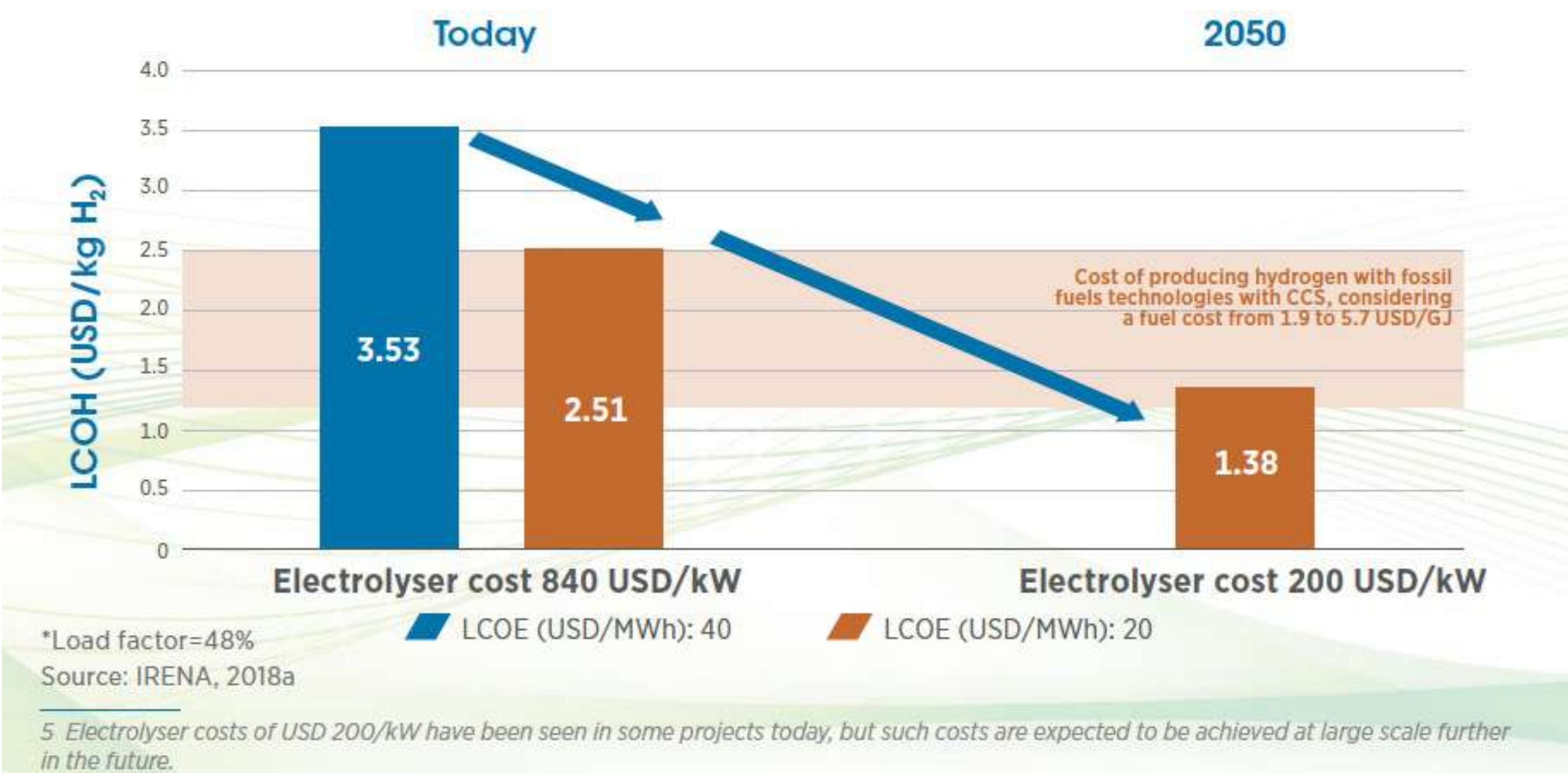
Source: IRENA, 2018

Cost of hydrogen as a function of cost of electricity and utilisation rate of PEM electrolyser



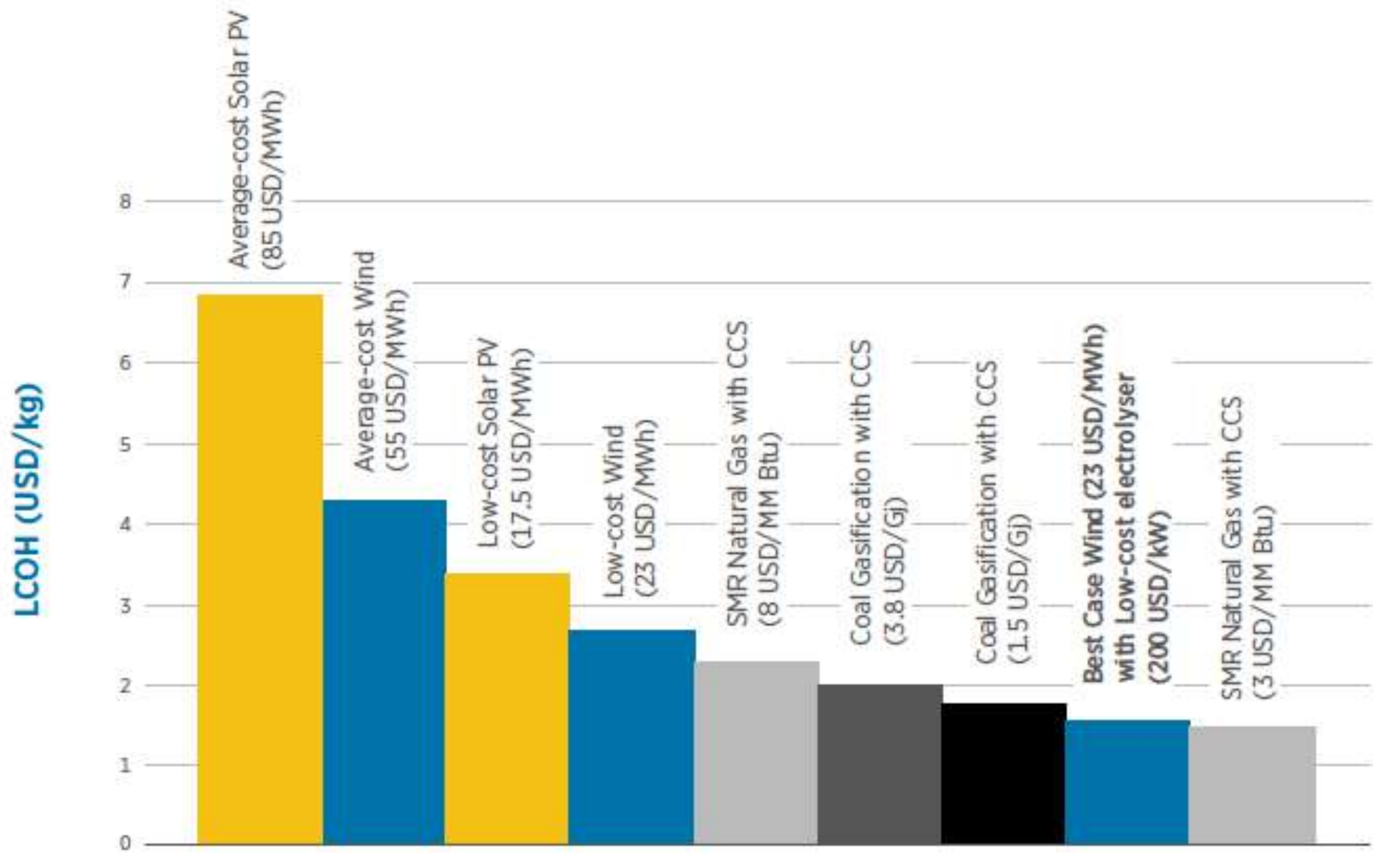
Source: IRENA, 2019

Hydrogen costs at different electricity prices and electrolyser Capex*



Source: IRENA, 2019

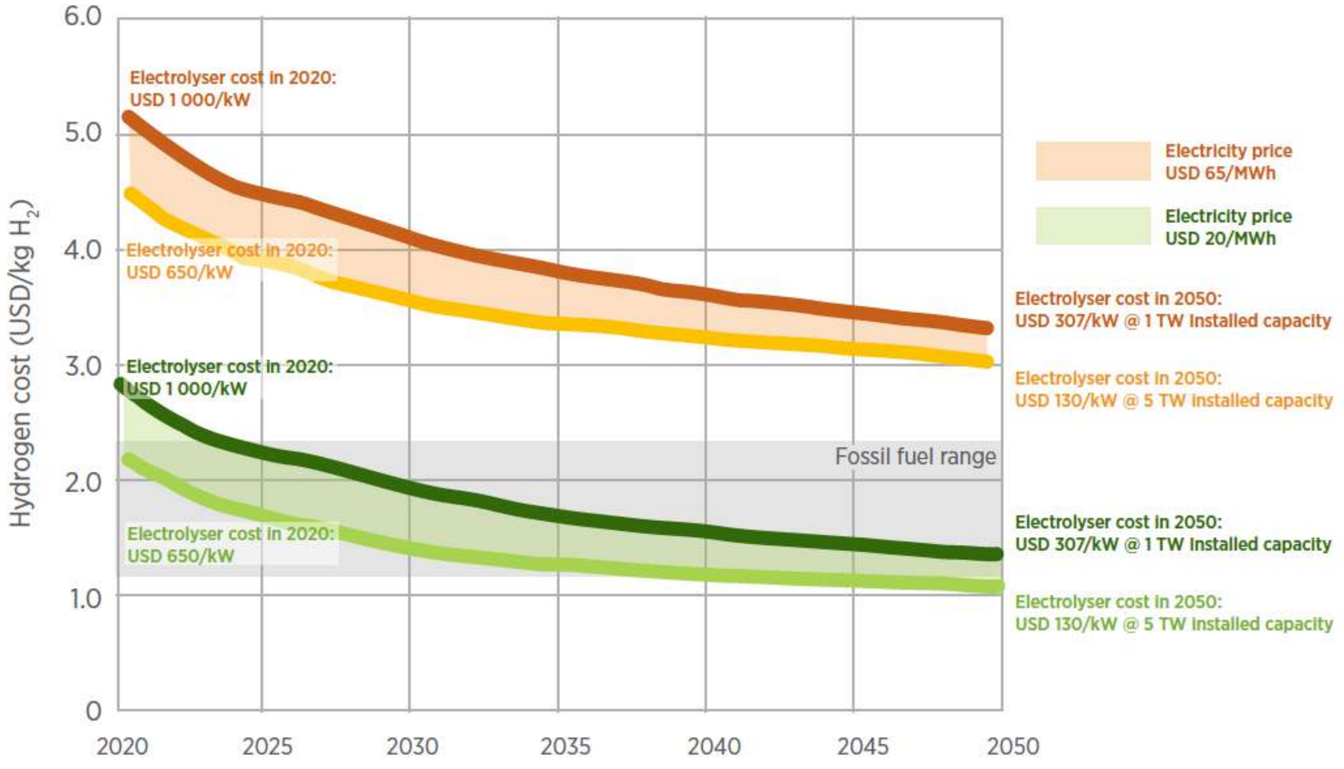
Costs of producing hydrogen from renewables and fossil fuels today



Notes: Electrolyser capex: USD 840/kW; Efficiency: 65%; Electrolyser load factor equals to either solar or wind reference capacity factors. For sake of simplicity, all reference capacity factors are set at 48% for wind farms and 26% for solar PV systems.
Source: IRENA analysis

Source: IRENA, 2019

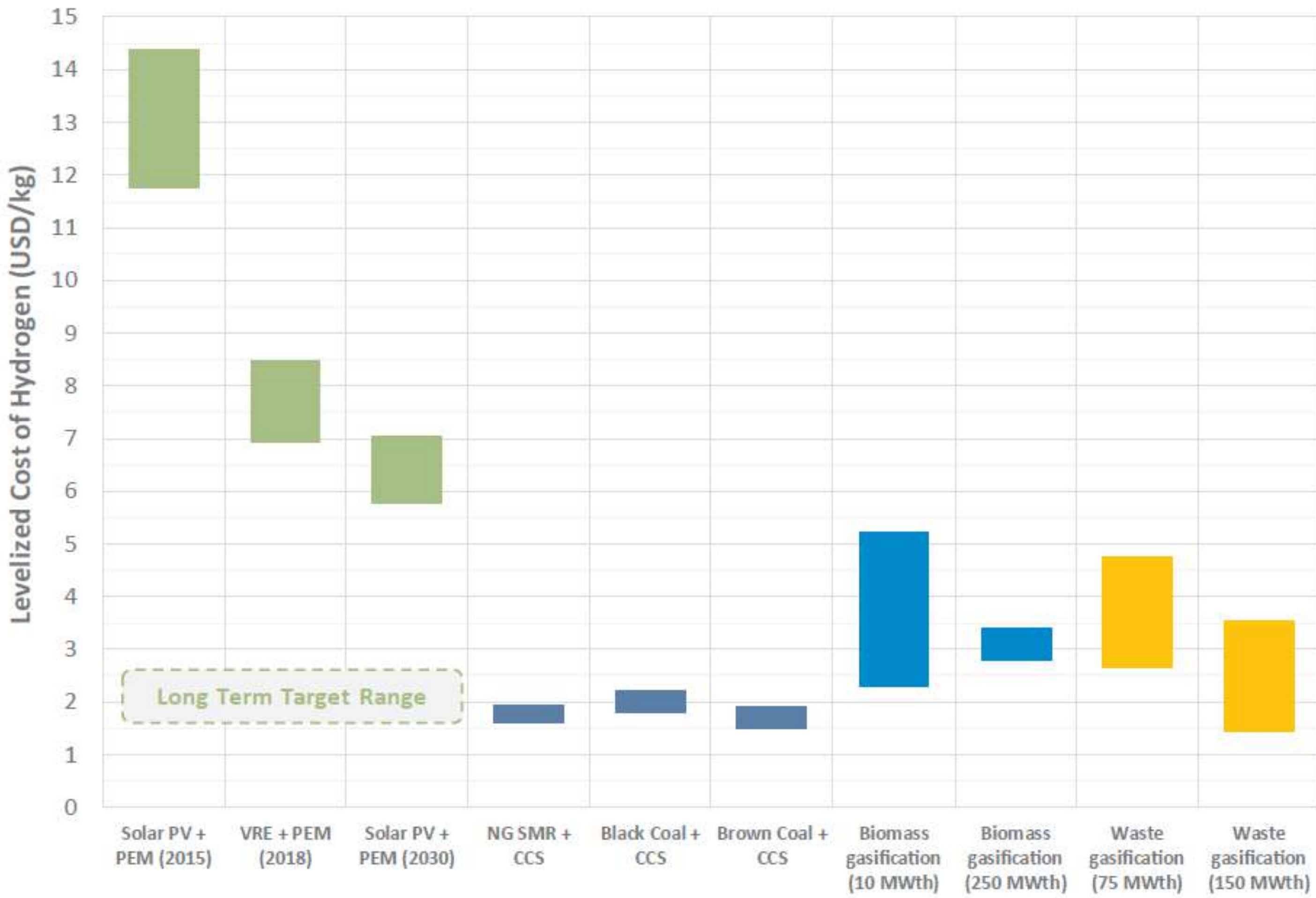
Cost of producing hydrogen vis electrolyzer



Note: Efficiency at nominal capacity is 65%, with a LHV of 51.2 kilowatt hour/kilogramme of hydrogen (kWh/kg H2) in 2020 and 76% (at an LHV of 43.8 kWh/kg H2) in 2050, a discount rate of 8% and a stack lifetime of 80 000 hours. The electrolyser investment cost for 2020 is USD 650-1000/kW. Electrolyser costs reach USD 130-307/kW as a result of 1-5 TW of capacity deployed by 2050.

Source: IRENA, 2020

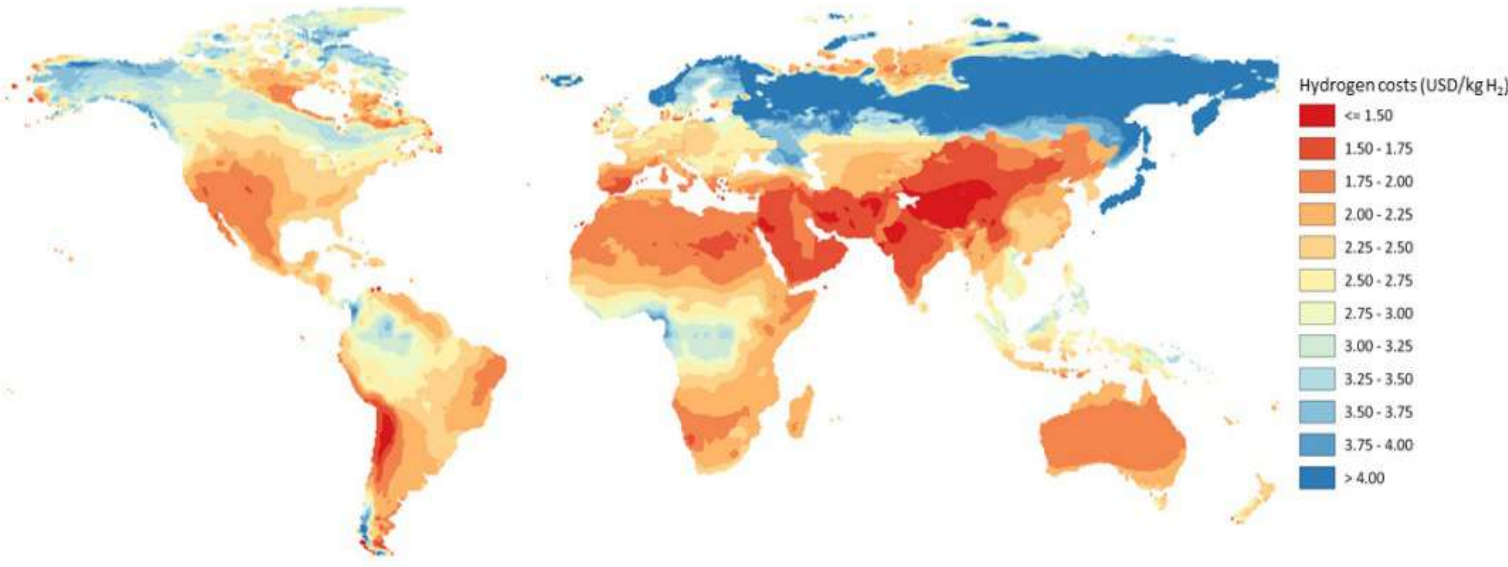
Levelized costs of clean hydrogen production (USD/kg) from a variety of production pathways



Source: M. Shahabuddin, et al., 2020

Hydrogen from electrolysis can compete with hydrogen from gas in several regions

Hydrogen production cost from hybrid solar PV and wind systems in 2030

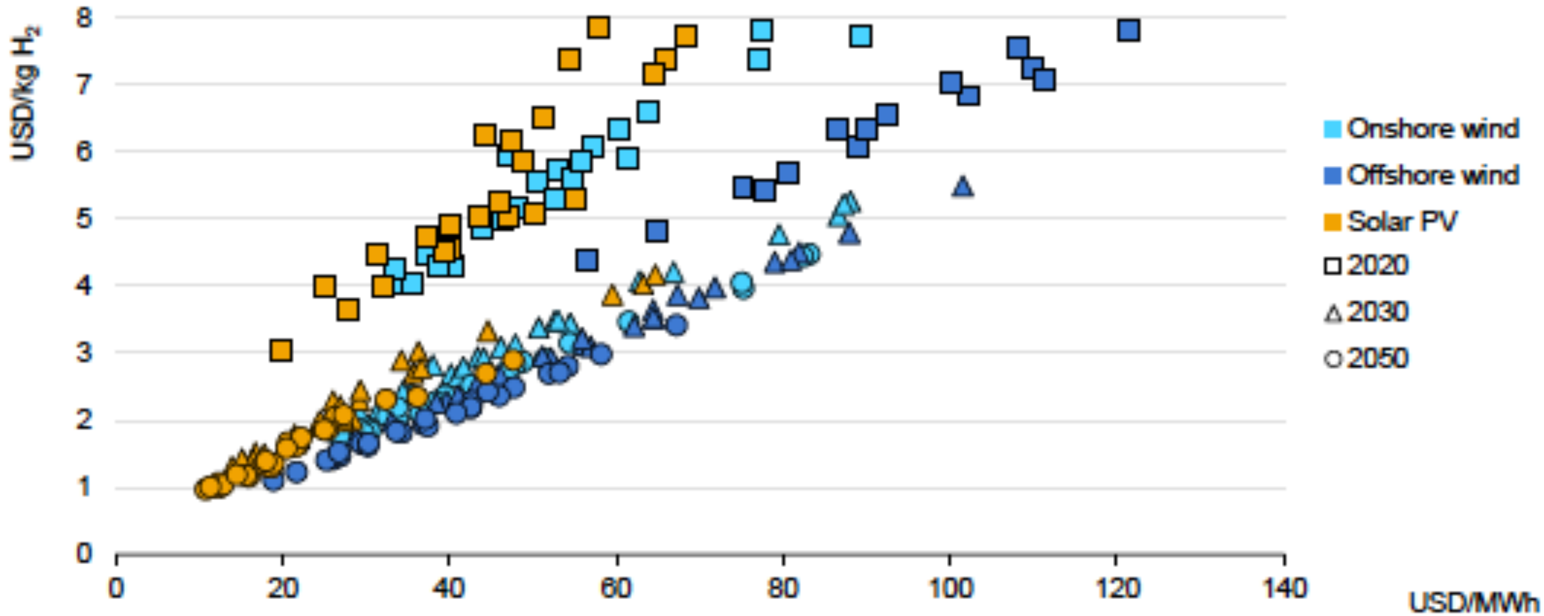


Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. For each location, production were derived by optimising the mix of solar PV, onshore wind and electrolyser capacities, resulting in the lowest costs and including the option to curtail electricity generation.

Sources: Based on hourly wind data from Copernicus Climate Change Service and hourly solar data from Renewables.ninja.

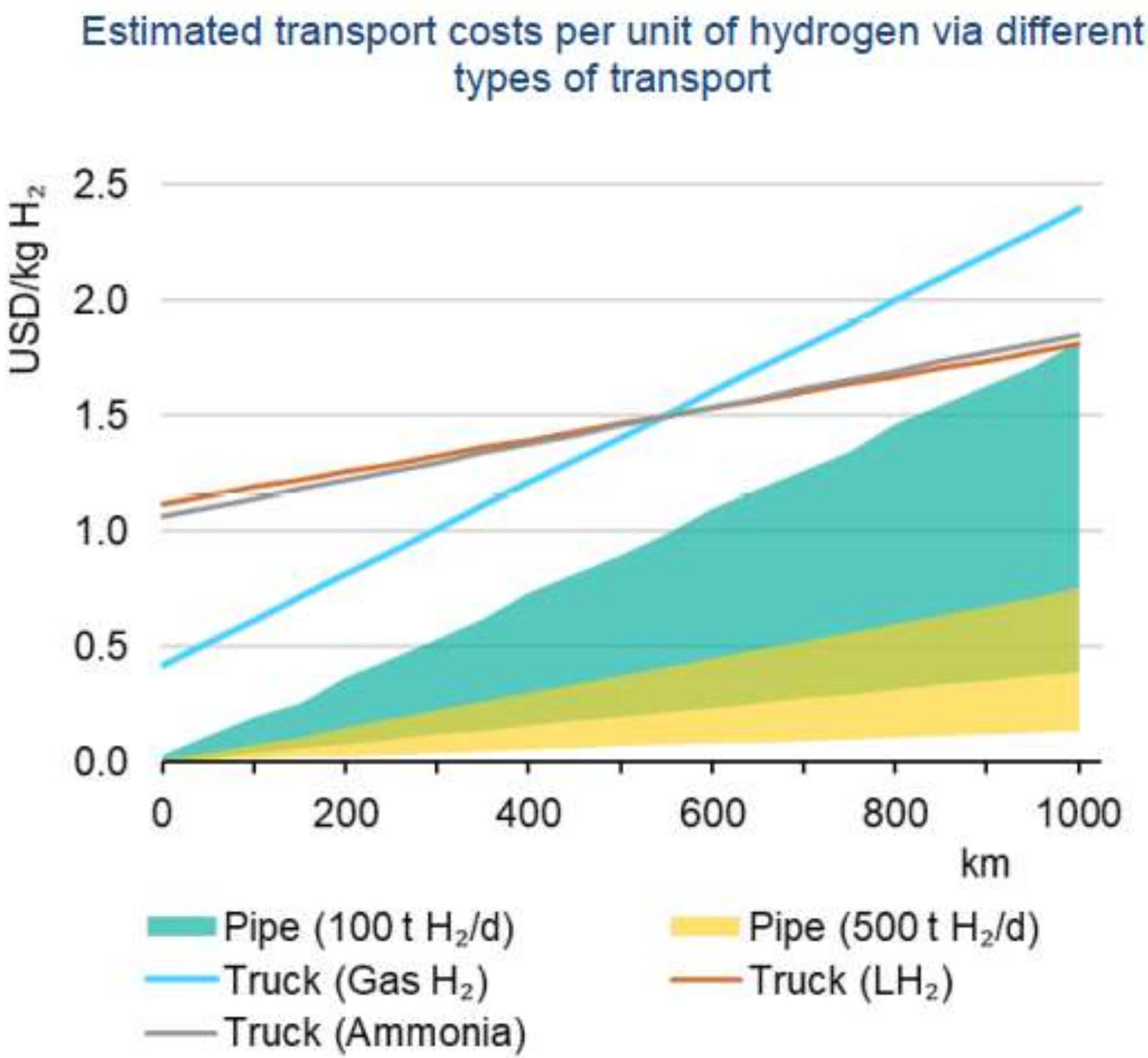
Source: IEA, 2021

Hydrogen production costs in the Net zero Emissions Scenario as a function of renewable electricity costs for solar PV and onshore and offshore wind, 2020, 2030 and 2050



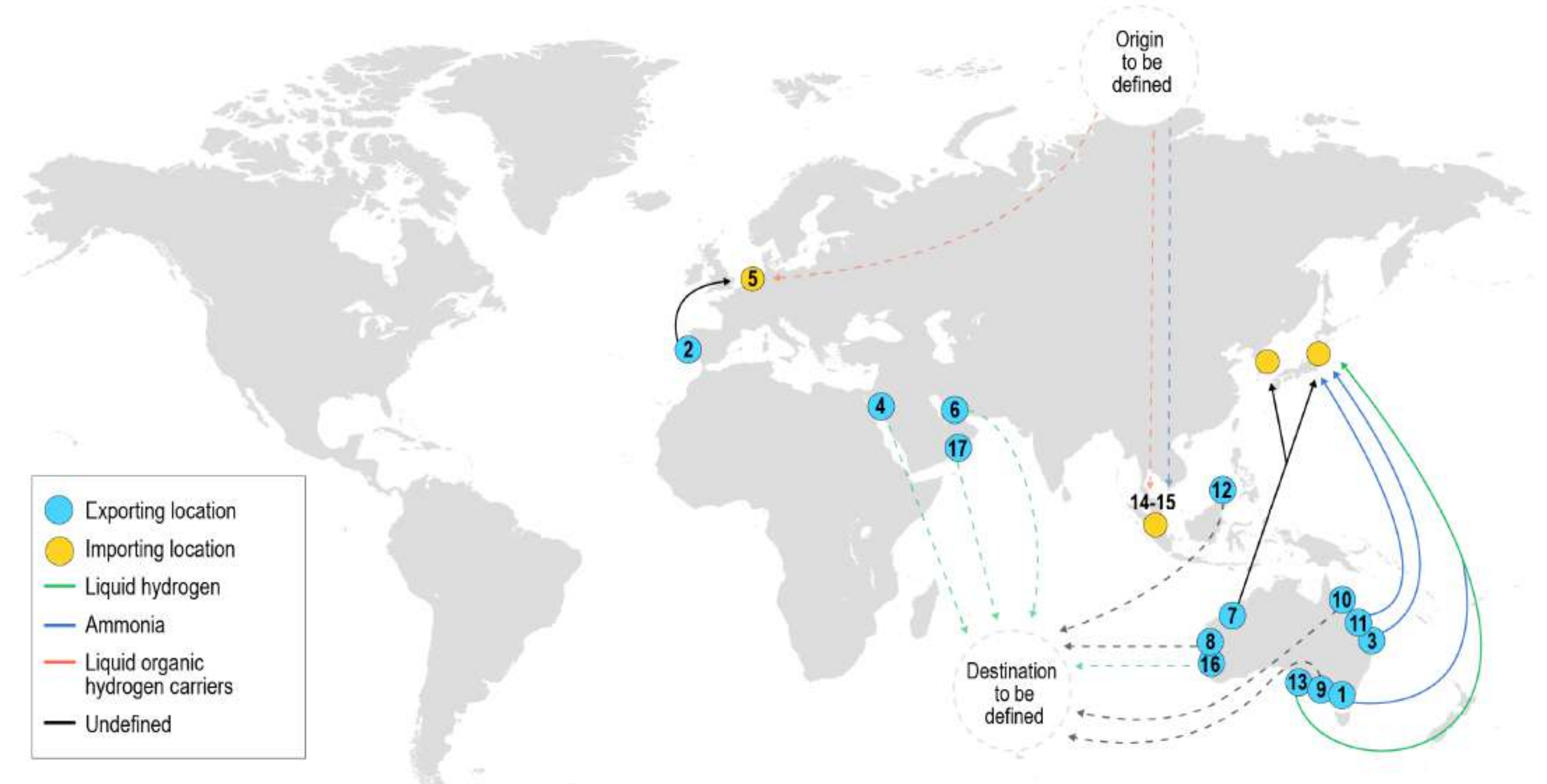
Notes: Points represent electricity and hydrogen production costs for different regions around the world, taking local renewable resource conditions into account.
Sources: Based on data from McKinsey & Company and the Hydrogen Council; IRENA (2020).

Source: IEA, 2021



Source: IEA, 2021

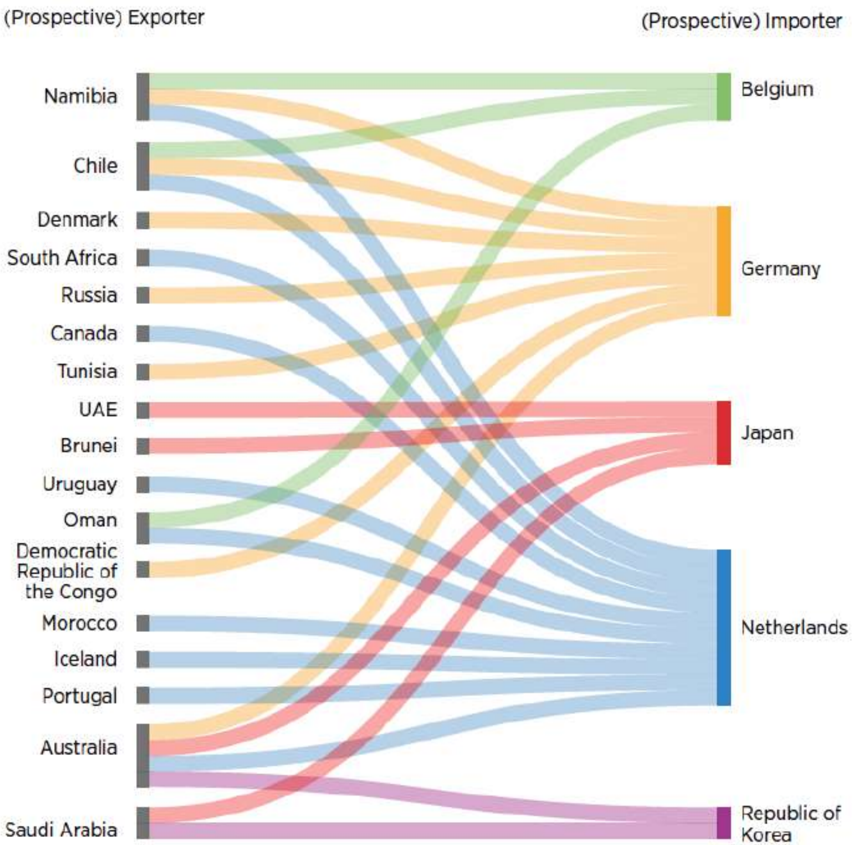
Most hydrogen trade projects under development are in Asia-Pacific



Notes: This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area. LH_2 = liquid hydrogen. NH_3 = ammonia. LOHC = liquid organic hydrogen carrier. TBD = to be determined.

Source: IEA, 2021

Potential hydrogen trade and 20 largest announced green hydrogen projects



Note: Figure covers hydrogen trade related agreements only, based on public announcements and is not exhaustive. Private agreements and those that focus exclusively on technology co-operation are not included. MOU = Memorandum of Understanding.

1. HyDeal Ambition (67GW) .... Western Europe
2. Unnamed (30GW) .... Kazakhstan
3. Western Green Energy Hub (28GW) .... Australia
4. AMAN (16GW)[a] .... Mauritania
5. Asian Renewable Energy Hub (14GW) .... Australia
6. Oman Green Energy Hub (14GW)[a] .... Oman
7. AquaVentus (10GW) .... Germany
8. NorthH2 (10GW) .... Netherlands
9. H2 Magallanes (8GW) .... Chile
10. Beijing Jingneng (5GW) .... China
11. Project Nour (5GW)[a] .... Mauritania
12. HyEnergy Zero Carbon Hydrogen (4GW)[a]. Australia
13. Pacific solar Hydrogen (3.6GW) .... Australia
14. Green Marlin (3.2GW).......... Ireland
15. H2-Hub Gladstone (3GW) .... Australia
16. Moolawatana Renewable Hydrogen Project (3GW)[a] – Australia
17. Murchison Renewable Hydrogen Project (3GW) – Australia
18. Unnamed (3GW).......... Namibia
19. Base One (2GW)[a].......... Brazil
20. Helios green Fuels Project (2GW) .... Saudi Arabia

Note: Size refers to electrolyser capacity. Information based on announced plans.

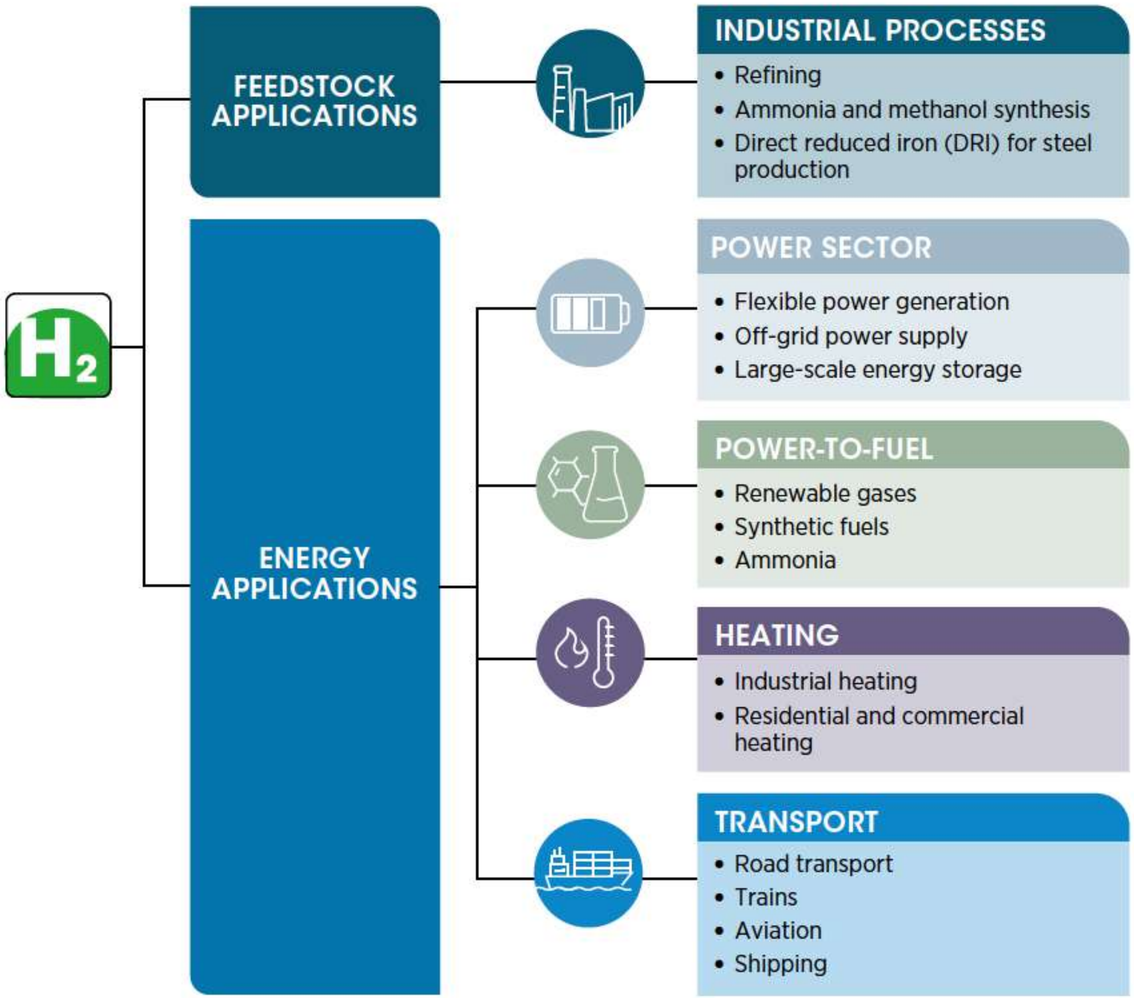
a. Estimated electrolyser capacity based on a comparison with similar-sized schemes.

Disclaimer: This map is provided for illustration purposes only. Boundaries shown on this map do not imply any endorsement or acceptance by IRENA. Map source: Natural Earth, 2021

Source: IRENA, 2022

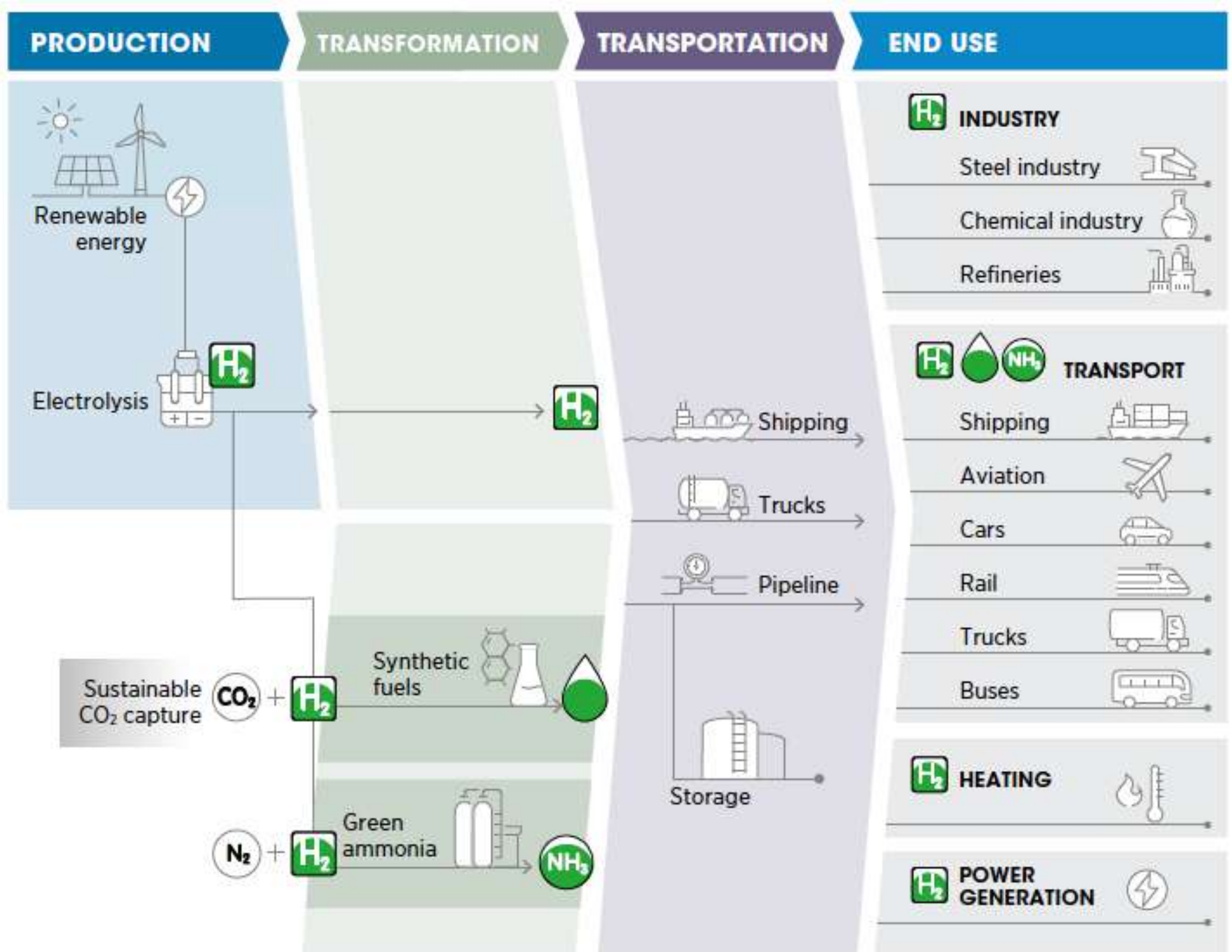
Potential hydrogen uses

Potential uses for clean hydrogen



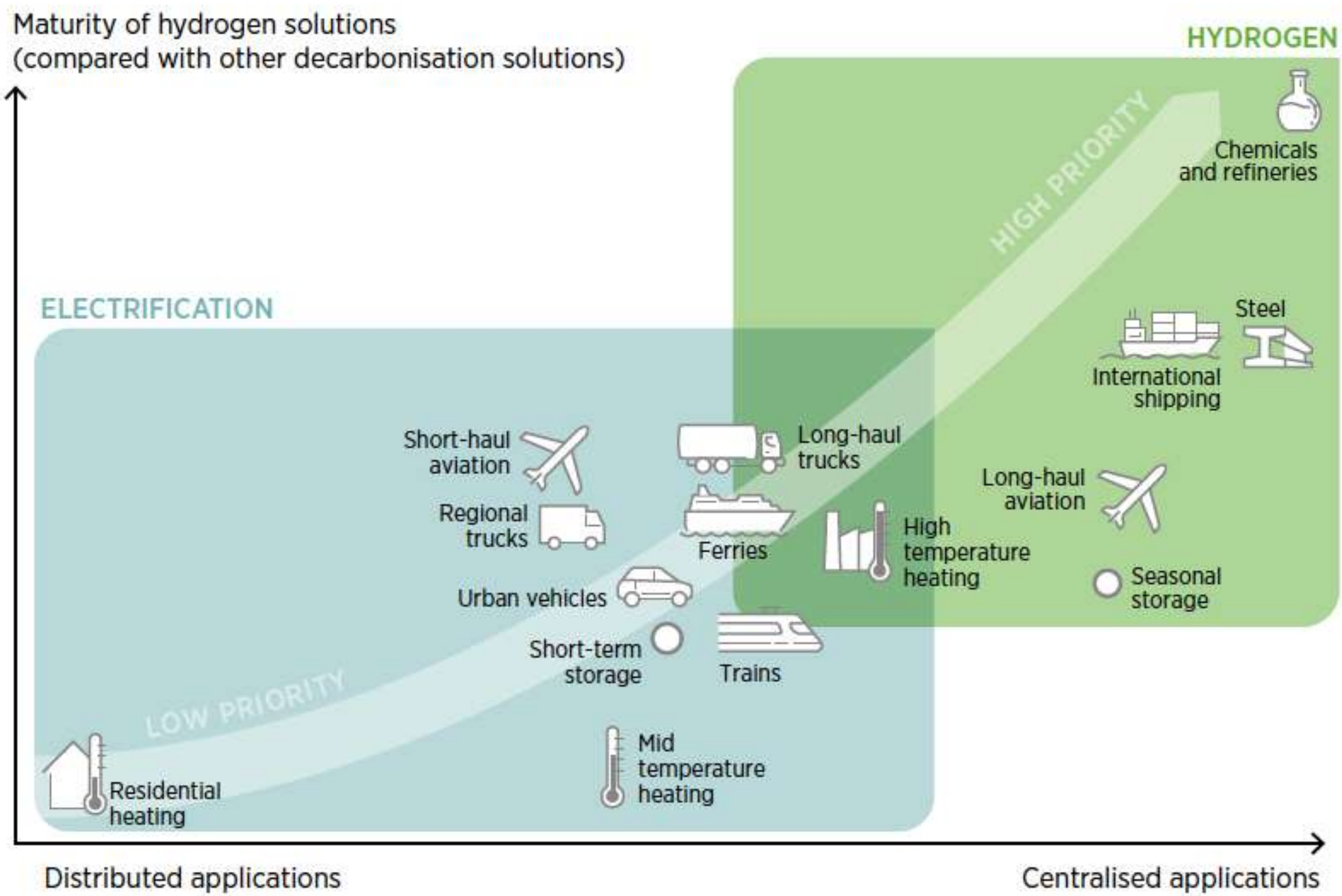
Source: IRENA (2020b).

Technology leadership opportunities in green hydrogen value chains



Source: IRENA, 2022

Clean hydrogen policy priorities



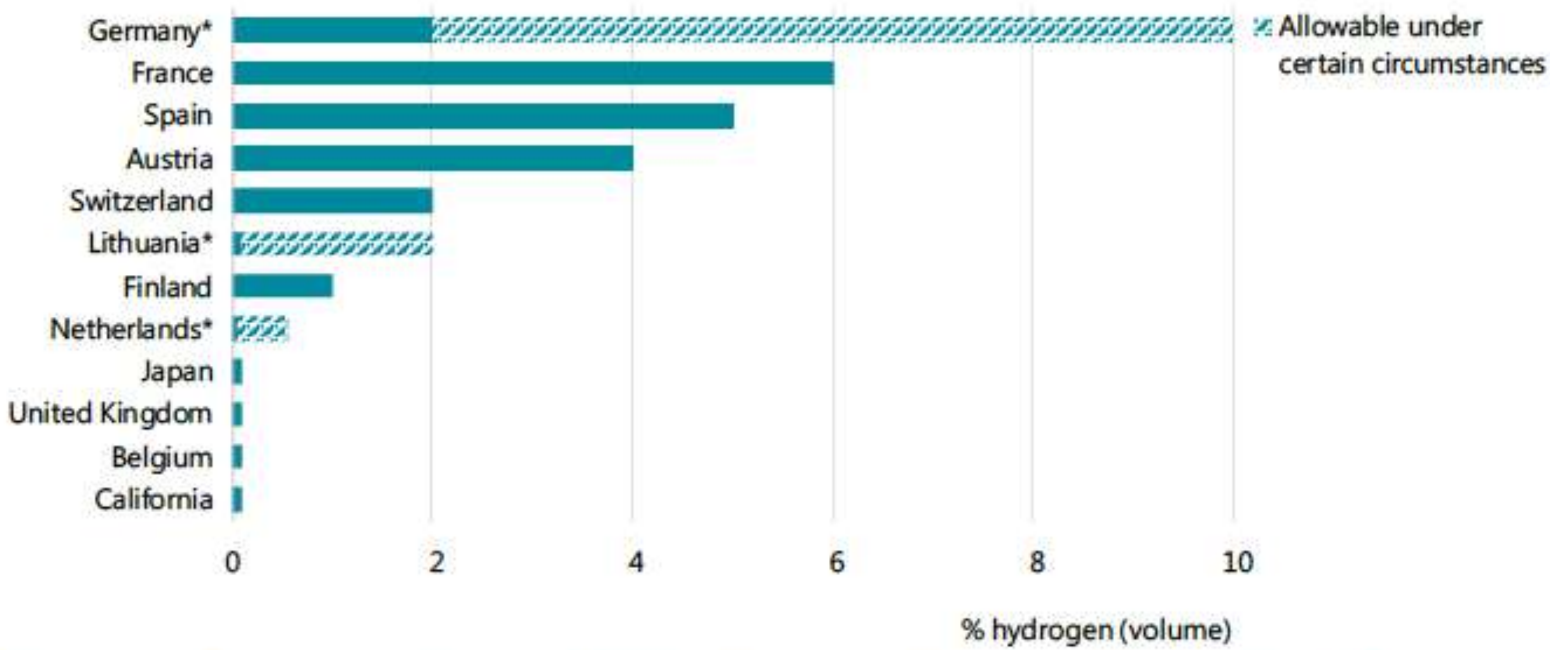
Source: IRENA, 2022

Selected operational and planned hydrogen blending projects in distribution networks

Project name	Country	City	Start year	End year	Blending volume	Project size as announced
HyP SA	Australia	Tonsley	2021	-	<5%	700 homes
Western Sydney Green Gas	Australia	Sydney	2021	2026	2%	23 500 residential, 100 commercial and 7 industrial customers
Clean Energy Innovation Park	Australia	Perth	2023	-	<10%	1 500 t H_2/year
HyP Murray Valley	Australia	Albury and Wodonga	2024	-	<10%	800 homes
HyP Gladstone	Australia	Gladstone	Mid-2020s	-	<10%	66 kg H_2/day, 770 homes
Enbridge Gas and Cummins Ontario	Canada	Markham	2022	-	2%	3 600 customers
ATCO - Alberta	Canada	Fort Saskatchewan	2022	-	5%	2 100 customers
Gasvalpo Energas-Coquimbo	Chile	La Serena	2022	-	5-20%	1 800 customers
Promigas, Surtigas - Heroica	Colombia	Cartagena	2022	-	NA	1.6 t H_2/year (15 t H_2/year in next pilot phase)
GRHYD	France	Dunkerque	2017	2019	0-20%	100 homes
Jupiter 1000	France	Fos-sur-Mer	2020	-	1-2%	430 kg H_2/day
ITM Power Thüga Plant	Germany	Frankfurt	2013	2017	NA	325 kW electrolyser
WindGas Haßfurt	Germany	Haßfurt	2016	-	4-5%	14 000 customers
Freiburg Municipal Energy Network	Germany	Freiburg	2017	-	2%	300 kW electrolyser
Wind2Gas Energy	Germany	Brunsbüttel	2019	-	2%	2.4 MW electrolyser
GAIL- Madhya Pradesh	India	Indore	2022	-	2%	NA
NTPC-Gujarat Gas Limited	India	Hazira	Mid-2020s	-	5%	200 homes
H_2 in natural gas in Ameland	Netherlands	Ameland	2007	2011	<20%	14 homes
Green Pipeline Project -Setubal	Portugal	Seixal	2022	-	2-20%	80 customers
HyDeploy	United Kingdom	Staffodshire	2019	2021	<20%	130 homes (Keele University campus)

Source: IEA, 2022

Current limits on hydrogen blending in natural gas networks



* Higher limit for Germany applies if there are no CNG filling stations connected to the network; higher limit for the Netherlands applies to high-calorific gas; higher limit for Lithuania applies when pipeline pressure is greater than 16 bar pressure.

Sources: Dolci et al. (2019), "Incentives and legal barriers for Power-to-Hydrogen pathways: An international snapshot", *International Journal of Hydrogen*; HyLaw (n.d.), *Online Database*; Staffell et al. (2019) "The role of hydrogen and fuel cells in the global energy system", *Energy and Environmental Science*.

Soure: IEA, 2019

Expansion of hydrogen and fuel cells for road vehicles

Industry announcements

Industry announcements indicate that the market for hydrogen-powered vehicles is poised to expand over the next decade in all road segments.

Cars

- In June 2021, Jaguar Land Rover announced testing of a prototype passenger fuel cell vehicle, as part of a project partially funded by the UK government.
- Changan launched a fuel cell version of their large sedan model in July 2022, the first mass-produced hydrogen fuel cell car in China.
- BMW aims to produce a small series of the iX5 Hydrogen fuel cell vehicle by end-2022, after successfully completing winter weather testing.
- Great Wall Motors is expected to launch a luxury brand focussing on hydrogen fuel cell passenger cars by end-2022.
- Riversimple unveiled a prototype hydrogen fuel cell car in February 2022.
- Renault announced an electric concept car with a hydrogen fuel cell range extender, which is expected to debut in 2024.

Vans and other light commercial vehicles

- Hyundai continue to increase its range of available FCEV models and plans to introduce a fuel cell multi-purpose vehicle.
- Several Stellantis brands including Citroën, Peugeot and Opel are introducing hydrogen light commercial vehicles, which are expected to be available in 2023.
- Hino Motors, Isuzu, Toyota and Commercial Japan Partnership Technologies Corportation have announced a plan to jointly develop light-duty commercial trucks.

Buses

- Kansai Airport (Japan) launched a hydrogen fuel cell shuttle bus service in 2022.
- In September 2022, Solaris announced plans to unveil an 18-metre fuel cell bus with the first deliveries scheduled for the second quarter of 2023. Since 2019, Solaris has delivered nearly 100 of their 12-metre fuel cell buses to European customers.
- Wrightbus will supply up to 60 fuel cell buses to the City of Cologne (Germany), and Solaris will provide up to a further 20 fuel cell buses with deliveries beginning in 2023.
- The United Kingdom's West Midlands will deploy 124 new fuel cell buses, adding to the existing fleet of 20 buses.

Trucks

- Nikola delivered two Tre heavy-duty hydrogen fuel cell trucks to Anheuser-Busch in the United States in February 2022 for daily service for a three-month pilot test.
- SINOTRUK and Weichai unveiled China's first heavy-duty truck powered by a hydrogen internal combustion engine in June 2022.

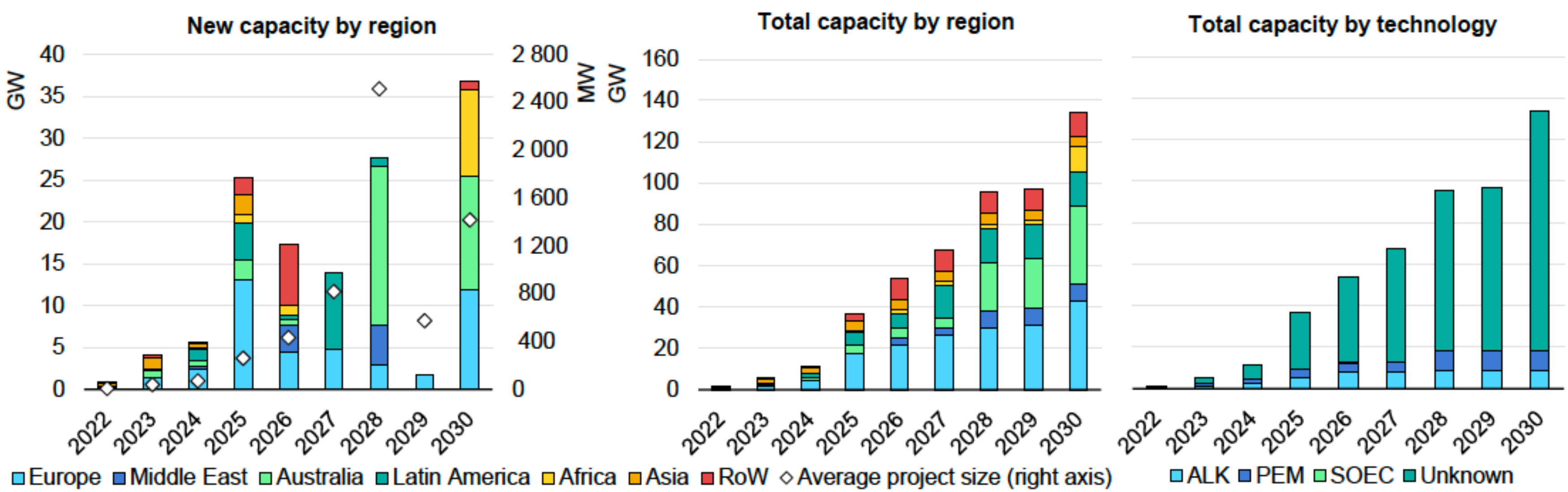
Heavy-duty fuel cell electric truck models, 2022

Make	Model	Range (km)	Year available
Hyundai	XCIENT	400	2019
Hyzon	Hymax	400-680*	2021
Hyzon	FCET 8	800	2021
Dayun	E8	310	2021
Dayun	E9	430	2021
Skywell	TP11	500	2021
FAW	J7	700	2022
Feichi	FSQ4250	500	2022
King Long	KLQ4250FCEV3	510	2022
SAIC	CQ1180FCEVEQ		2022
Shaanxi	X5000		2022
Dongfeng	LZ5180	460	2022
Hyundai	HDC-6	1 280	2023
Kenworth	T680	480	2023
Nikola	Tre	800	2023
Nikola	Two	1 450	2024

* Ranges given for the 24-, 46-, and 70-tonne configurations.
Source: CALSTART (2022), Drive to Zero's Zero-emission Technology Inventory (ZETI) Tool Version 7.0

Source: IEA, 2022

Electrolyser capacity by region and type based on project pipeline to 2030



Notes: RoW = rest of world; ALK = alkaline electrolyser; PEM = proton exchange membrane electrolyser; SOEC = solid oxide electrolyser. Only projects with a disclosed start year for operation are included. Projects at very early stages of development, such as those in which only a co-operation agreement among stakeholders has been announced, are not included
Source: IEA Hydrogen Projects Database (2022).

Source: IEA, 2022

Areas of activity for hydrogen in the Port of Rotterdam

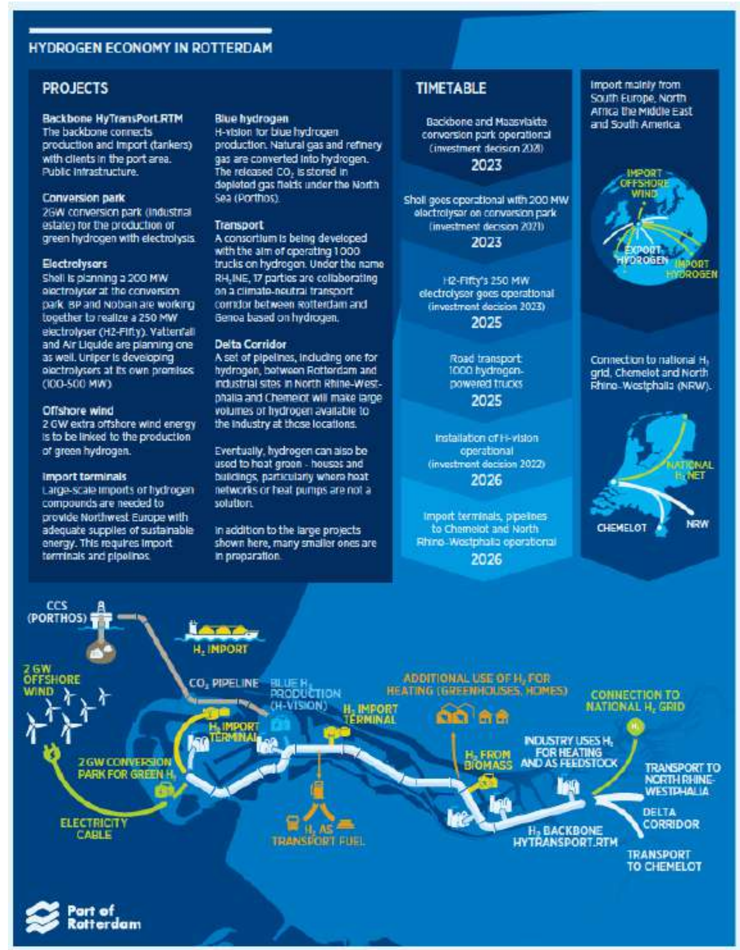
Box 1.2. Hydrogen Imports to Europe through the Port of Rotterdam

The Port of Rotterdam trades 8 800 petajoules (PJ) of energy annually, which is equivalent to three times the Netherland's energy demand or about 13% of the European Union energy demand. About 40% of the total throughput of the port in 2020 consisted of fossil fuels. It is the largest port in Europe, with almost a third of the total throughput in Europe. Several conditions make the port attractive as a leading hub for future hydrogen trade: large industrial use of hydrogen (about 1 MtH_2 in 2019 [Notermans *et al.*, 2020]), access to offshore wind and underground carbon dioxide storage reservoirs in the North Sea, an existing 1600 km hydrogen pipeline network, 9 million tonnes per year of liquefied natural gas regasification capacity and an existing natural gas network.

Like other locations, the port is pursuing efforts with multiple hydrogen carriers to develop experience and reduce risk. For ammonia, new dedicated green ammonia terminals will be available by 2025. For liquid organic hydrogen carriers, the first pilot with dibenzyltoluene (DBT) at the existing Botlek terminal is planned for 2023, and other pilot projects are planned before 2030. Koole Terminals, Chiyoda and Mitsubishi also started a feasibility study in August 2021 to import 0.2-0.3 MtH_2/year by 2025 and 0.3-0.4 MtH_2/year by 2030 using methylcyclohexane (a liquid organic hydrogen carrier), which is expected to be completed in a year. For liquid hydrogen, a feasibility study with Kawasaki Heavy Industries is targeted to start by 2030.

By 2050, the port targets a hydrogen flow of 20 MtH_2/year (2 400 PJ), requiring about 200 GW of renewable generation capacity and 100 GW of electrolysis. About one-third (7 MtH_2/year) of this demand would be for domestic use, with the rest being exported to the rest of Europe. The intermediate target by 2030 is 6% of this flow, or 1.2 MtH_2/year (144 PJ/year), with a larger contribution of blue hydrogen in this closer time horizon of 0.8 MtH_2/year. The port is planning to have a hydrogen backbone connecting the industrial facilities inside the port complex by 2025. This will be connected to other industrial hubs in the region through two main efforts: (1) HyWay27, which aims to connect industrial clusters in the Netherlands by 2026 and with the rest of the European network by 2028-2030 and (2) the Delta Corridor, connecting Rotterdam to North-Rhine Westphalia (Germany).

To achieve these targets, various pillars are being tackled, including an import terminal, a conversion park for hydrogen production, offshore wind (2 GW), blue hydrogen (Porthos and H-vision projects), and hydrogen transport (see Figure 1.7).



Source: IRENA, 2022

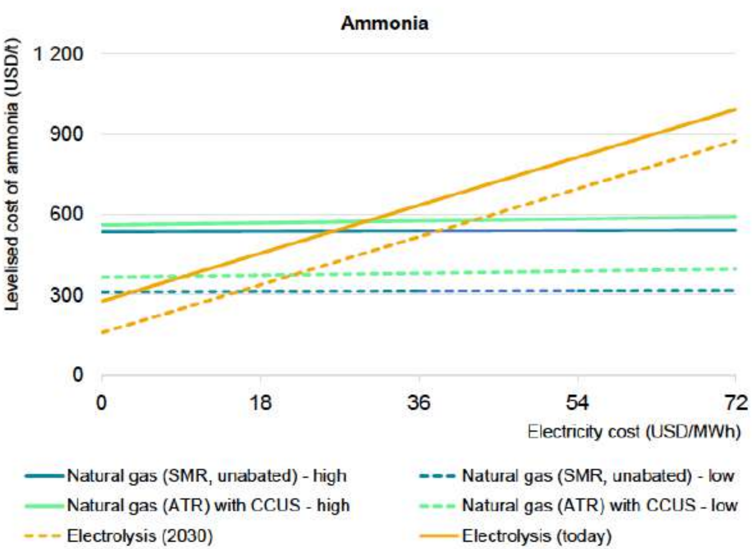
Flexibility capability of electrolysers

	Alkaline electrolyser	PEM electrolyser
Load range	15–100% of nominal load	0–160% of nominal load
Start-up	1–10 minutes	1 second–5 minutes
Ramp-up	0.2–20% per second	100% per second
Ramp-down	0.2–20% per second	100% per second
Shutdown	1–10 minutes	Seconds

Note: The ramp-up and ramp-down figures are percentage of nominal load.

Note: Hz = hertz.
Source: Gardiner, 2014

Levelized cost of green ammonia

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DOI: 10.1002/ese3.281

MODELING AND ANALYSIS

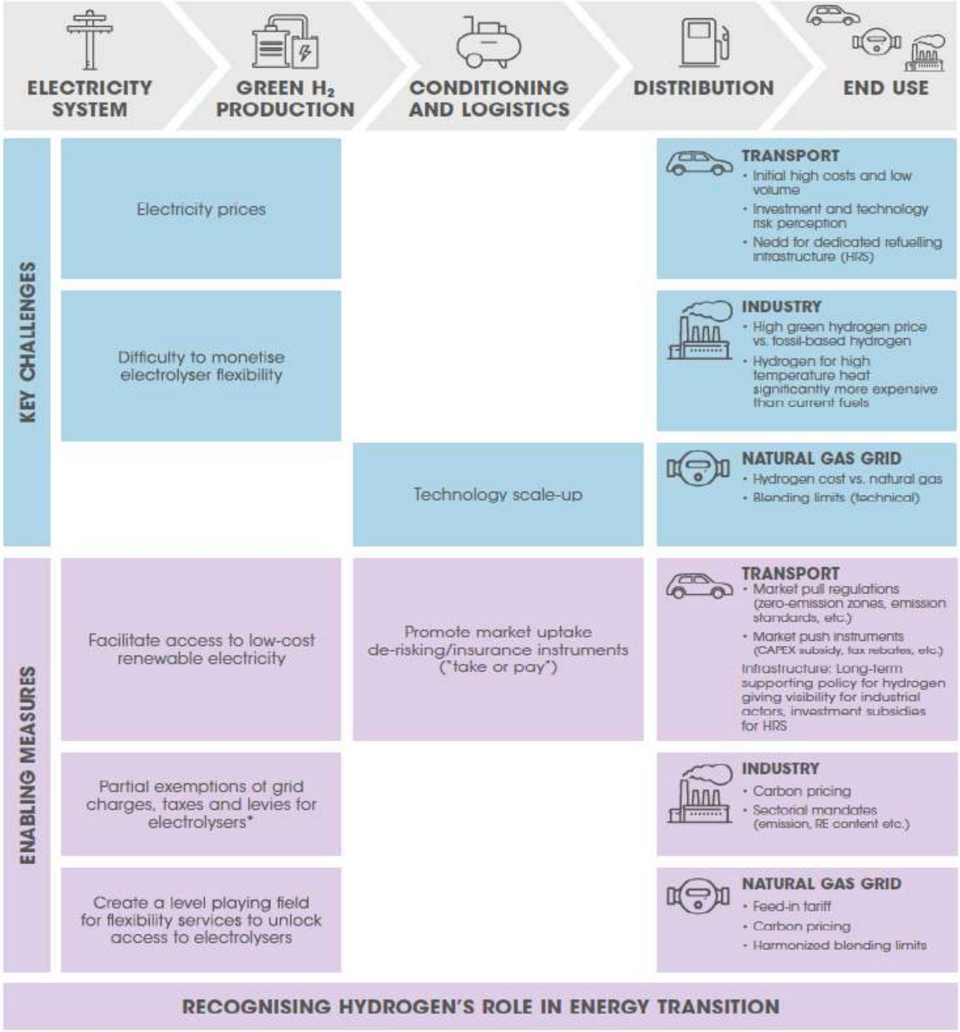
Multi-objective optimization of green urea production

Mohammad Alfian | Widodo W. Purwanto

Soure: IEA, 2021

Source: Hydrogen council, 20

Key challenges and overview of possible enabling measures for power-to-hydrogen



Source: IRENA, 2019

Implementation requirements

TECHNICAL REQUIREMENTS	**Hardware:** • Electrolyser technology to produce hydrogen from renewable electricity • Hydrogen fuel cells to convert hydrogen into electricity when required • Conversion units to use renewable hydrogen and convert into other substitutes such as methane • Hydrogen transport vessels such as ships and trucks • Transport infrastructure (*e.g.* existing natural gas infrastructure) • Storage facilities for hydrogen (in form of high-pressure or liquid hydrogen storage)
POLICIES NEEDED	• Recognise hydrogen's role in energy transition • Promote use of hydrogen produced via electrolysis from renewable energy sources for the decarbonisation of the economy • Adopt policies that encourage the use of renewable hydrogen in end-use sectors (for example, implement market pull regulations in transport sector, such as zero emission zones, emission standards etc) • Allow hydrogen mixed with natural gas to be used in existing natural gas infrastructure by defining a remuneration mechanism to encourage renewable hydrogen injection into gas networks • Develop appropriate mechanisms to price the emissions of greenhouse gases, which would encourage decarbonisation of the economy
REGULATORY REQUIREMENTS	• Allow use of existing gas networks for transporting renewable hydrogen and set relevant standards, including safety standards (*e.g.* encourage blending of hydrogen with natural gas in appropriate proportions, harmonise blending limits) • Provide the necessary incentives for hydrogen to offer flexibility services (*e.g.* exemption from taxes, levies and grid fees for electrolysers providing flexibility to the grid) • Allow electrolysers to participate across the power sector (*e.g.* in some countries, only generators can access frequency containment reserves and frequency restoration reserves)
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Public sector:** • Adopt clear policies to decarbonise economies • Encourage and fund pilot programmes to work as a test bed and for dissemination of results • Promote innovations in reducing the cost of electrolysis **Private sector:** • Work together with the public sector on innovative projects • Disseminate information about the contribution of renewable hydrogen to power sector transformation and VRE integration • Develop new business models for the power sector and VRE integration

Source: IRENA, 2019

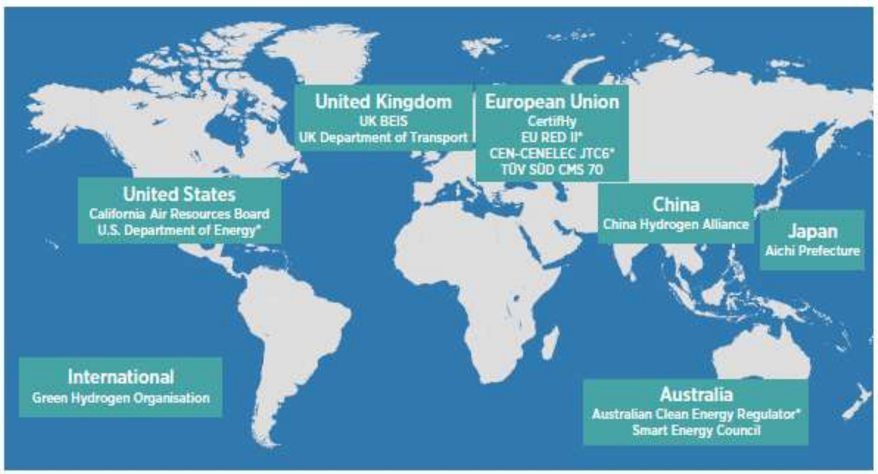
Figure 4 Overview of hydrogen certification

VOLUNTARY MARKET		MANDATORY MARKET
Aichi Prefecture Low Carbon Hydrogen Certification	**China Hydrogen Alliance** Standard and Assessment for Low Carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen Energy	**California Air Resources Board** Low Carbon Fuel Standard
Australian Clean Energy Regulator* Hydrogen Guarantee of Origin	**Green Hydrogen Organisation** Green Hydrogen Standard	**European Commission*** Renewable Energy Directive (RED II)
CertifHy Green and Low-Carbon Hydrogen Certification	**Smart Energy Council** Zero Carbon Certification Scheme	**UK Department for Business, Energy & Industrial Strategy** Low Carbon Hydrogen Standard
CEN-CENELEC* Joint Technical Committee 6	**TÜV SÜD** CMS 70	**UK Department for Transport** Renewable Transport Fuel Obligation
		US Department of Energy** Clean Hydrogen Production Standard

*in development.
**in development for specific program eligibility.

Notes: CEN = European Committee for Standardization; CENELEC = European Committee for Electrotechnical Standardization.

Figure 5 Map of organisations working on hydrogen certification



Notes: * in development. BEIS = Department for Business, Energy and Industrial Strategy; CEN = European Committee for Standardization; CENELEC = European Committee for Electrotechnical Standardization; JTC = Joint Technical Committee; RED II = Renewable Energy Directive II.
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply the expression of any opinion on the part of IRENA concerning the status of any region, country, territory, city or area or of its authorities, or concerning the delimitation of frontiers or boundaries.

Table 1 Summary of voluntary market mechanisms with published technical criteria

TITLE	LABEL	EMISSIONS THRESHOLD ($kgCO_2eq/kgH_2$)	BOUNDARY	POWER SUPPLY REQUIREMENT FOR ELECTROLYSIS	HYDROGEN PRODUCTION PATHWAY	CHAIN OF CUSTODY MODEL
Australia **Smart Energy Council** Zero Carbon Certification Scheme	Renewable H_2	No threshold				Unclear
China **China Hydrogen Alliance** Standard and Assessment for Low-carbon Hydrogen, Clean Hydrogen, and Renewable Hydrogen Energy	Renewable H_2	4.9				Not specified
	Clean H_2	4.9				Not specified
	Low-carbon H_2	14.5		n/a		Not specified
European Union **CertifHy** Green and Low-Carbon Hydrogen Certification	Green H_2	4.4		*		B&C
	Low-carbon H_2	4.4				B&C
Germany **TÜV SÜD** CMS 70	Green H_2 (non-transport)	2.7				B&C
	Green H_2 (transport)	2.8				Mass
Japan **Aichi Prefecture** Low-Carbon Hydrogen Certification	Low-carbon H_2	No threshold				B&C
International **Green Hydrogen Organisation** Green Hydrogen Standard	Green H_2	1.0				Not specified

*Aligned with REDII methodology and may be updated once EU delegated act is finalised.

Indicates threshold value; Includes upstream methane; To point of production; To point of use

Power supply requirements: GO + additionality; GO required; No GO/additionality specified; Solar, wind or hydro; Nuclear; Grid (or unspecified)

Hydrogen production pathway specified: Electrolysis; Fossil SMR/ATR with carbon capture; Biogas SMR

Notes: ATR = autothermal reforming; B&C = book and claim; GO = guarantee of origin; SMR = steam methane reforming.

Table 2 Summary of mandatory markets with published technical criteria

COUNTRY/ REGION	NATIONAL HYDROGEN STRATEGY	BOUNDARY AND SCOPE (SECTORS)	EMISSIONS THRESHOLD ($kgCO_2eq/kgH_2$)	POWER SUPPLY REQUIREMENT FOR ELECTROLYSIS	HYDROGEN PRODUCTION PATHWAY	REGULATORY MECHANISM	STATUS OF REGULATORY MECHANISM
United Kingdom	**Government of the United Kingdom** UK Hydrogen Strategy	(Energy)	2.4			**BEIS** Low Carbon Hydrogen Standard	To be implemented in 2022 Certification scheme **to be developed by 2025**
		(Transport)	3.9			**UK Dept. for Transport** Renewable Transport Fuel Obligation	**Active**
European Union (Proposed)	**European Commission** A hydrogen strategy for a climate-neutral Europe	(Transport, energy)	3.4	*		**European Commission** RED II	**Active** New Delegated Act of RED II **proposed in May 2022**
		Boundary not specified	3.0			**European Commission** EU Taxonomy	**Active**
United States (Proposed)	**US Department of Energy** National Clean Hydrogen Strategy and Roadmap	(Transport, energy)	4.0	**		**US Department of Energy** H2Hubs draft *(may be adopted by standard for clean H_2 production)*	CHPS not yet finalised H2Hubs criteria requires 2 $kgCO_2/kgH_2$ at point of production to qualify
		(Transport)	No threshold (Certificate issued based on reduction from annual target)			**California Air Resources Board** Low Carbon Fuel Standard - California only	**Active**

*refers to delegated act criteria, grid connected conditions in delegated act undergoing revision and are subject to change.
**denotes no detail of additionality in draft, but is yet to be finalized.

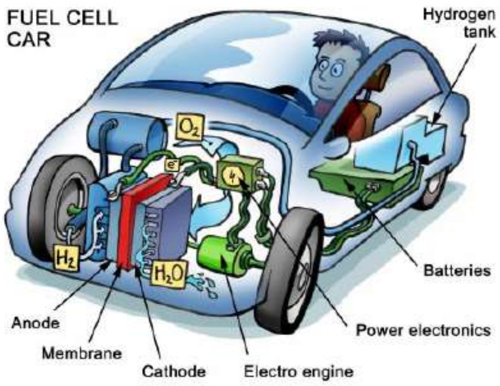
Indicates threshold value; Includes upstream methane; To point of production; To point of use

Power supply requirements: GO + additionality; GO required; No GO/additionality specified; Solar, wind or hydro; Nuclear; Grid (or unspecified)

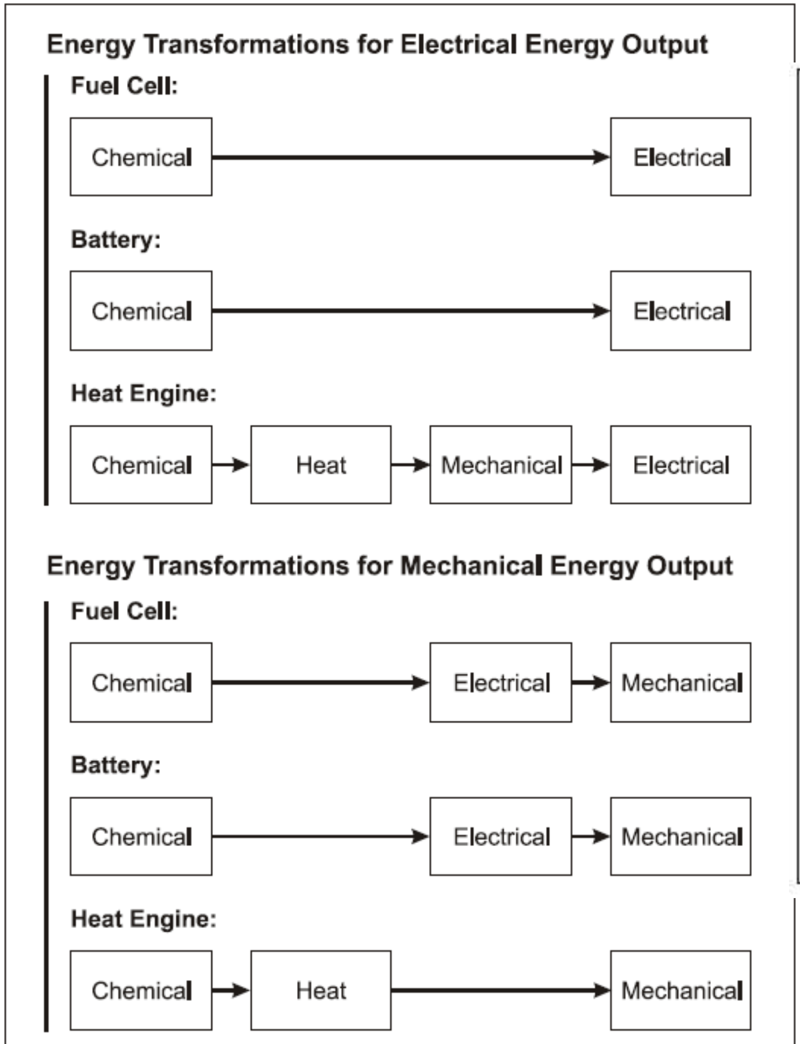
Hydrogen production pathway specified: Electrolysis; Fossil SMR/ATR with carbon capture; Biogas SMR

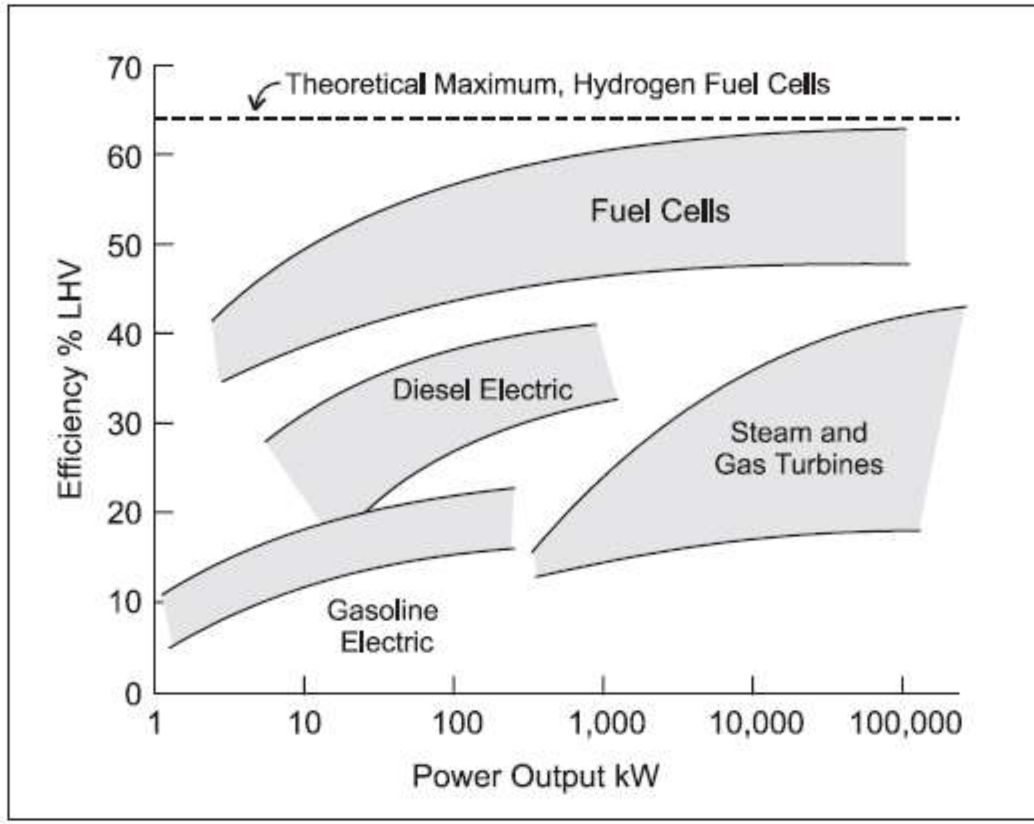
Notes: ATR = autothermal reforming; B&C = book and claim; GO = guarantee of origin; SMR = steam methane reforming.

Fuel Cell Technology



Energy transformations





Source: Fuel cell technology, 2001

Pros-Cons FC

+

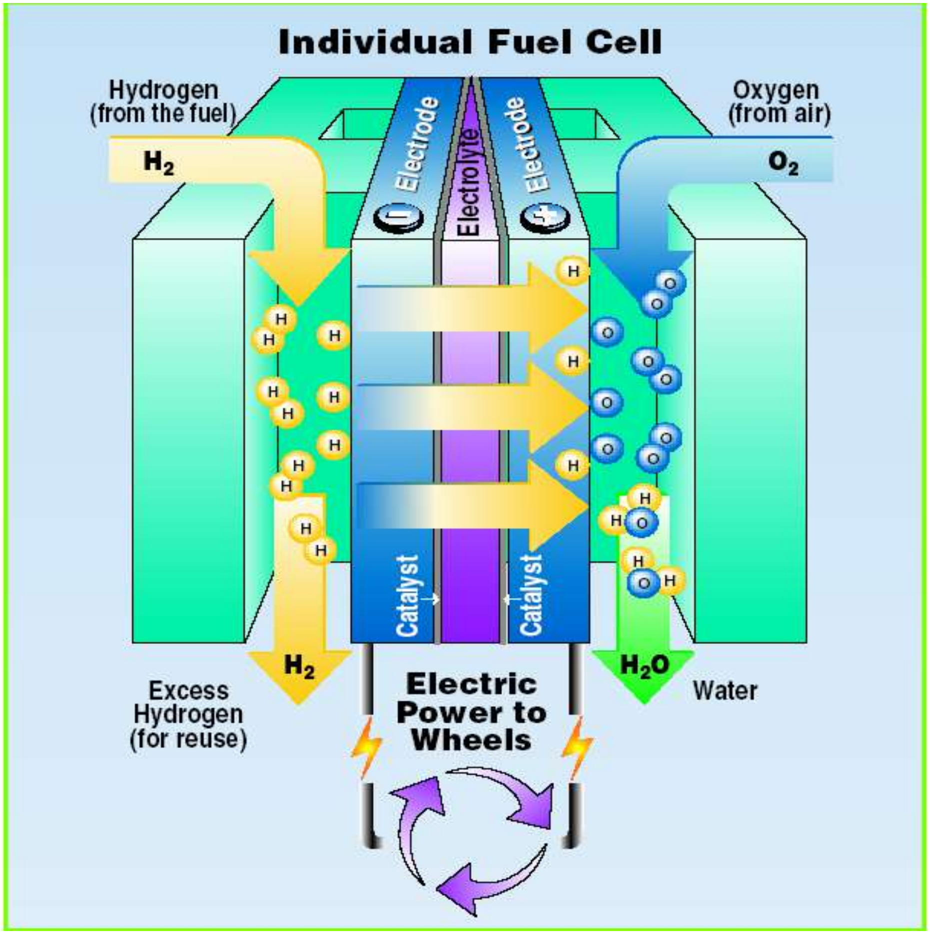
- Direct energy conversion (no combustion)
- Low emissions
- No moving part in the energy converter
- Quiet
- High availability of lower temperature units
- Siting ability
- Fuel flexibility
- Remote/unattended operation
- Small size

—

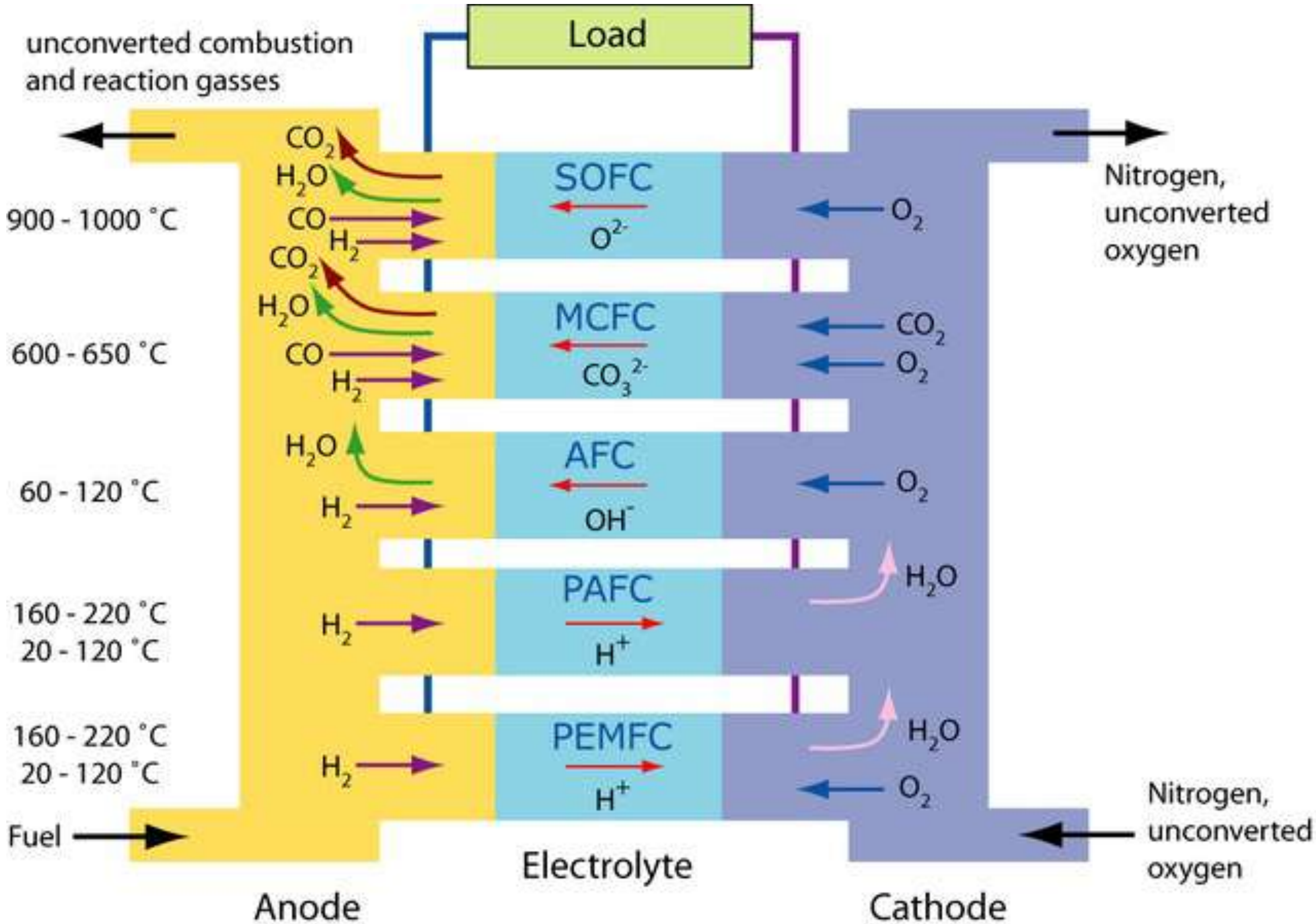
- High market entry cost, production cost
- Unfamiliar technology to the power industry
- Almost no infrastructure
- Still at level of development

Source: T. Jacob, 2004

How Does a Fuel Cell Work?



Fuel Cell Types



FC applications

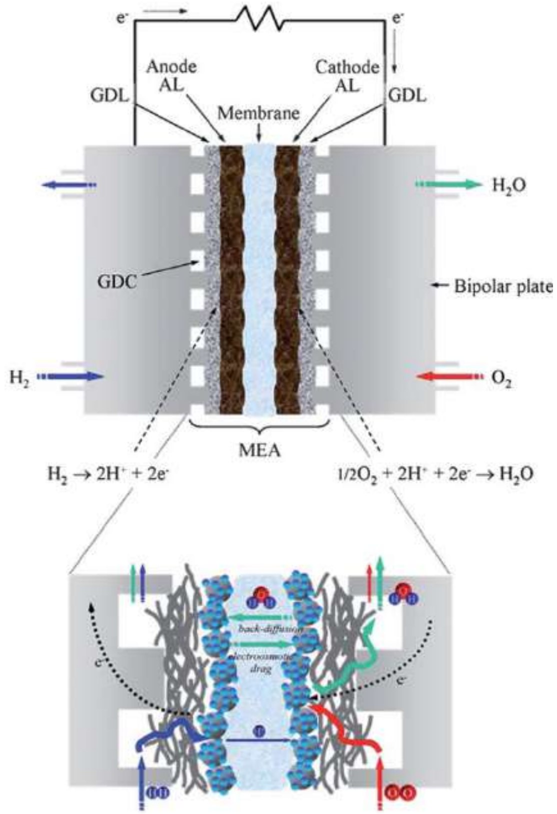
Application type	Portable	Stationary	Transport
Definition	Units that are built into, or charge up, products that are designed to be moved, including small auxiliary power units (APUs)	Units that provide electricity (and sometimes heat) but are not designed to be moved	Units that provide propulsive power or range extension to a vehicle
Typical power range	1 W to 20 kW	0.5 kW to 2 MW	1 kW to 300 kW
Typical technology	PEMFC DMFC SOFC	PEMFC MCFC AFC SOFC PAFC	PEMFC DMFC
Example	• Small 'movable' APUs (campervans, boats, lighting) • Military applications (portable soldier-borne power, skid-mounted generators) • Portable products (torches, battery chargers), small personal electronics (mp3 player, cameras)	• Large stationary prime power and combined heat and power (CHP) • Small stationary micro-CHP • Uninterruptible power supplies (UPS) • Larger 'permanent' APUs (e.g. trucks and ships)	• Materials handling vehicles • Fuel cell electric vehicles (FCEV) • Trucks and buses • Rail vehicles • Autonomous vehicles (air, land or water)

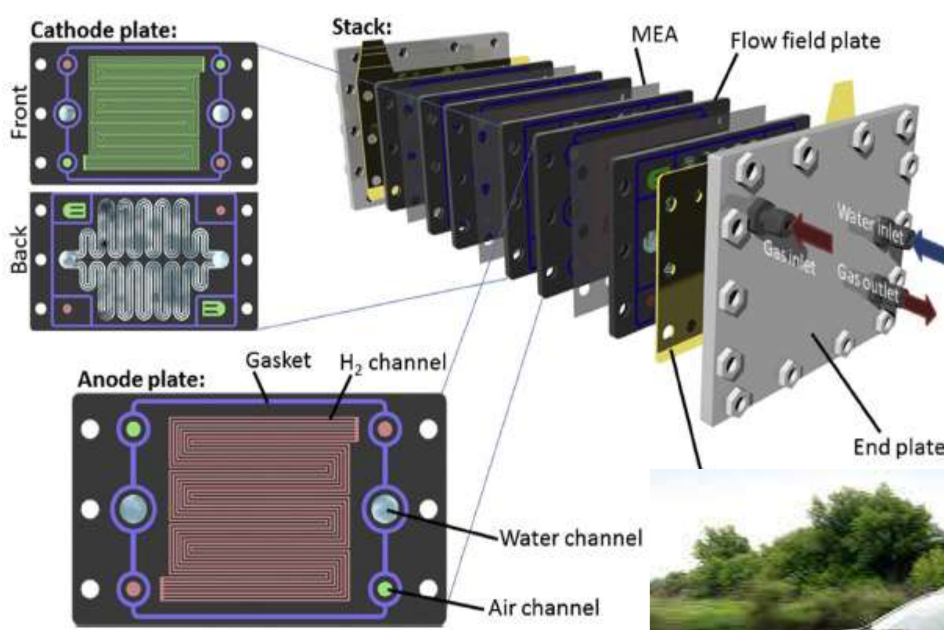
Source: E4tech

Proton exchange membrane FC -H2

Issue:

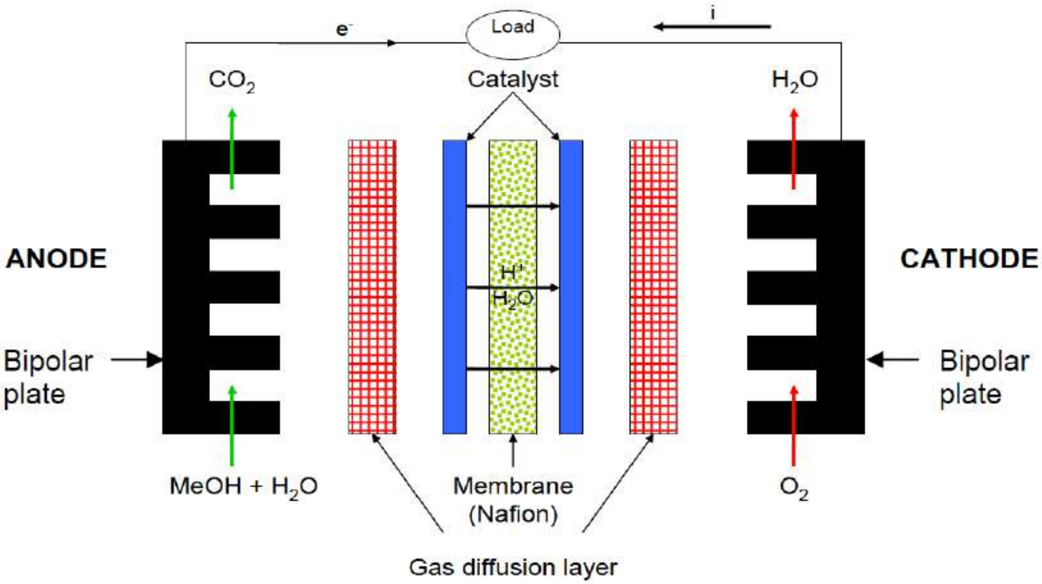
- Durability & degradation
- Water management





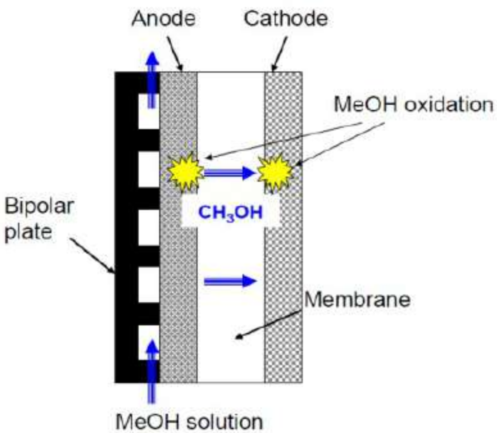
Source: Millichamp, 2015

Direct Methanol FC



Issue:

- Slow electro-oxidation kinetics
- Methanol crossover



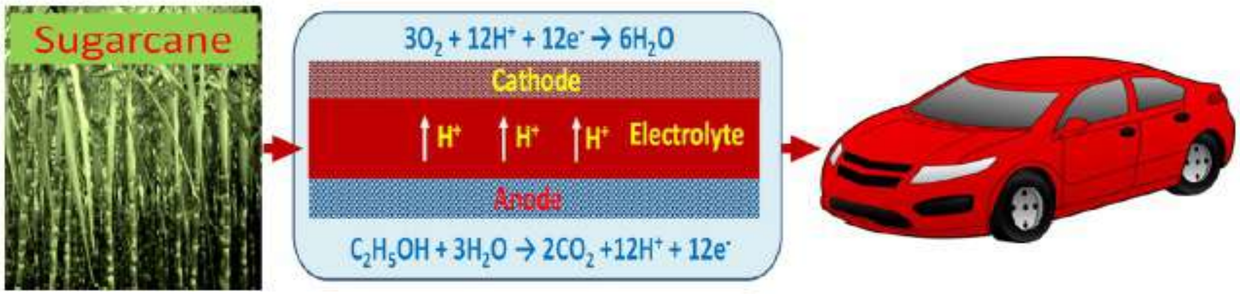
Anode reaction: $CH_3OH + 7H_2O \leftrightarrows CO_2 + 6H_3O^+ + 6e^-$ $E^0=0.02V$

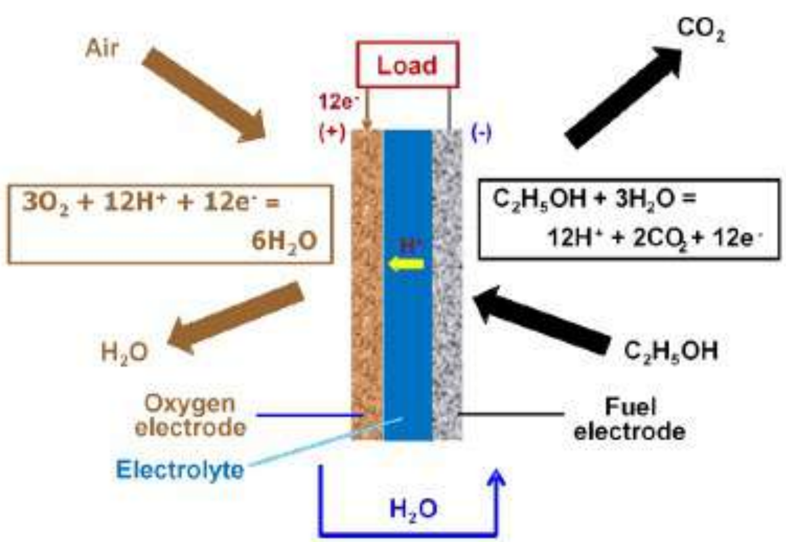
Cathode reaction: $^3/_2O_2 + 6H_3O^+ + 6e^- \leftrightarrows 9H_2O$ $E^0=1.23V$

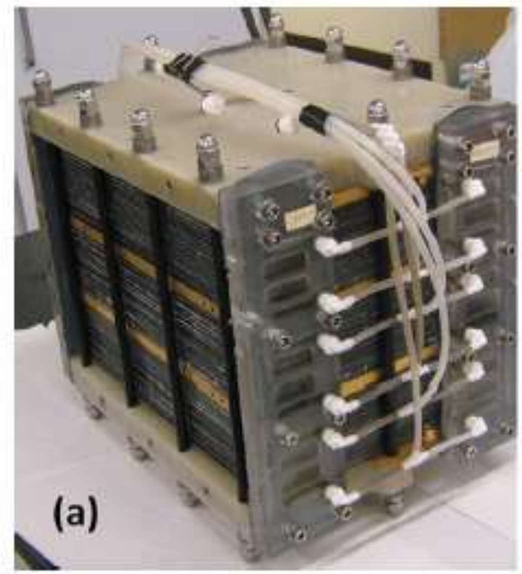
Overall reaction: $CH_3OH + ^3/_2O_2 \leftrightarrows CO_2 + 2H_2O$ $E^0=1.21V$

Source: Hacquard, 2005

Direct Ethanol FC







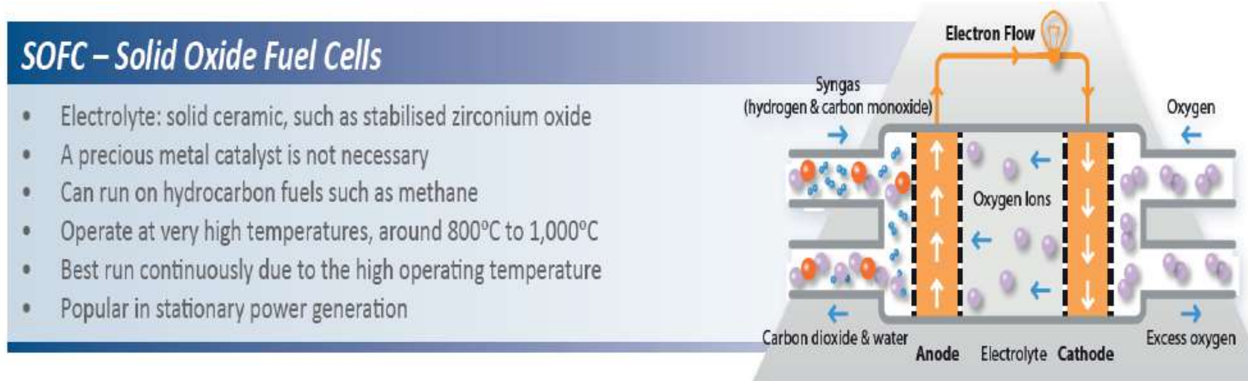
1 kW

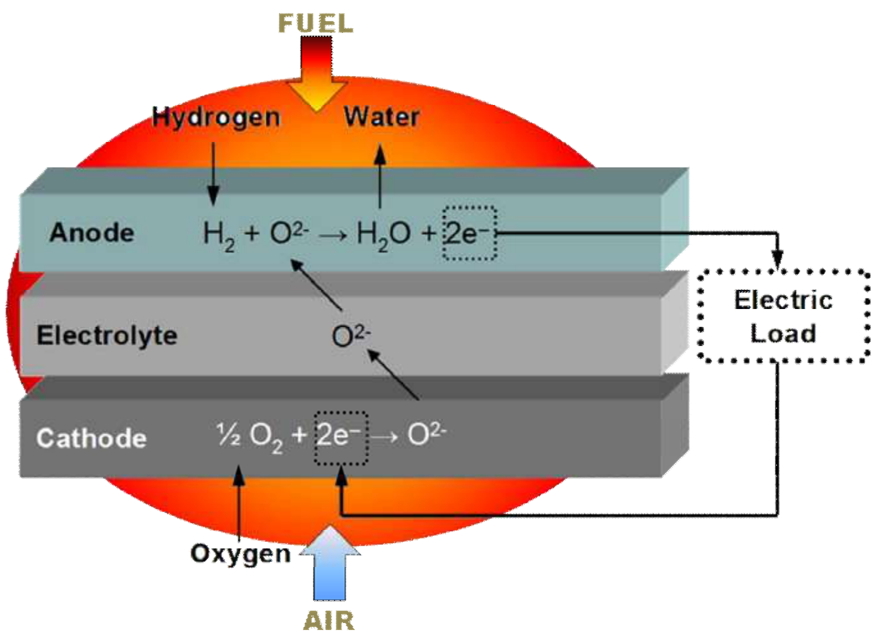
Issue:

- Slow electro-oxidation kinetics
- Ethanol crossover

Source: Badwal et al, 2015

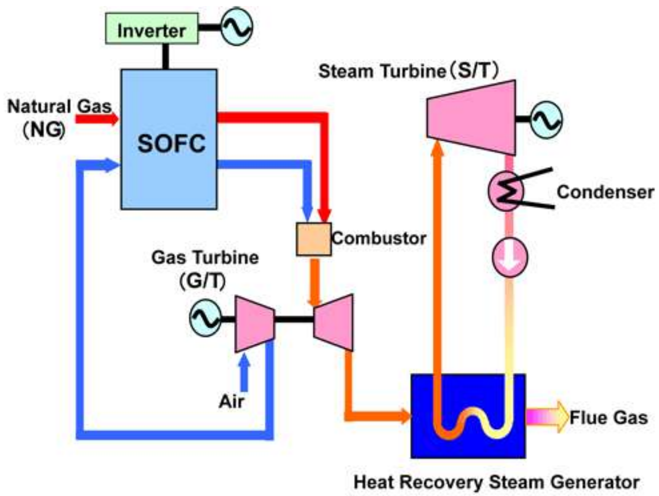
Solid Oxide FCs

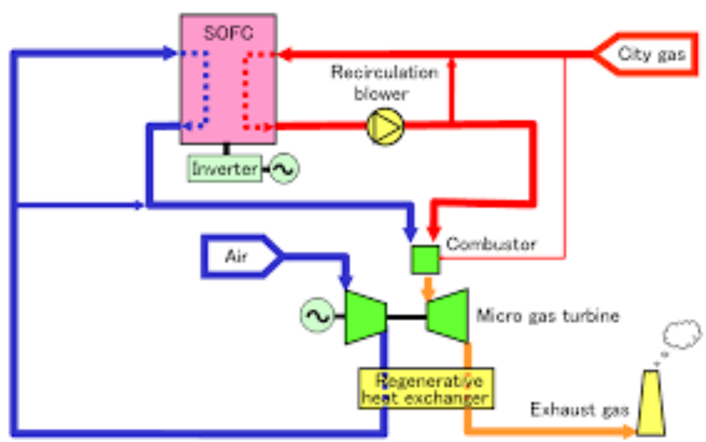




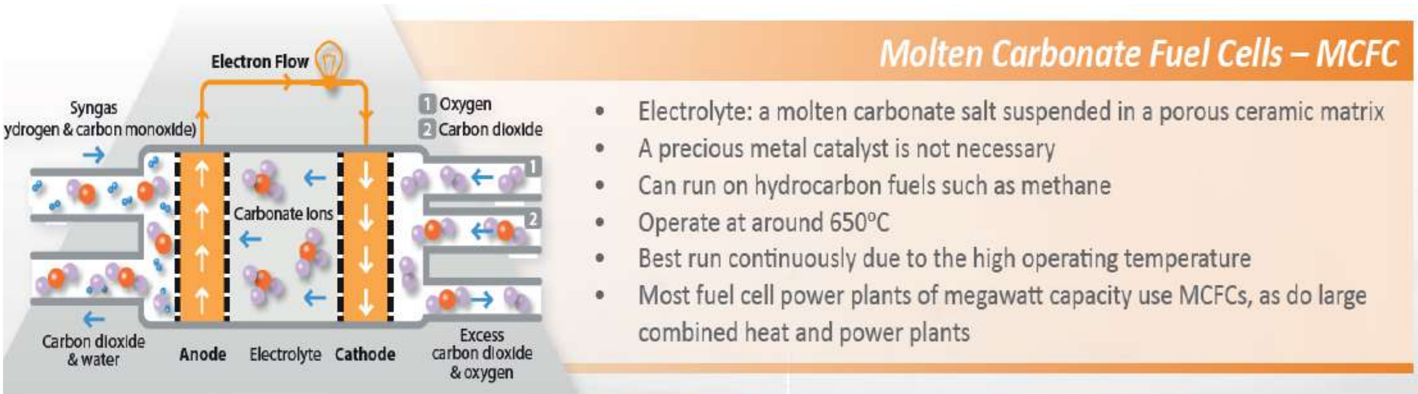
Source: Fuelcelltoday

Integrated SOFC & Other Cycle





Molten Carbonate FCs

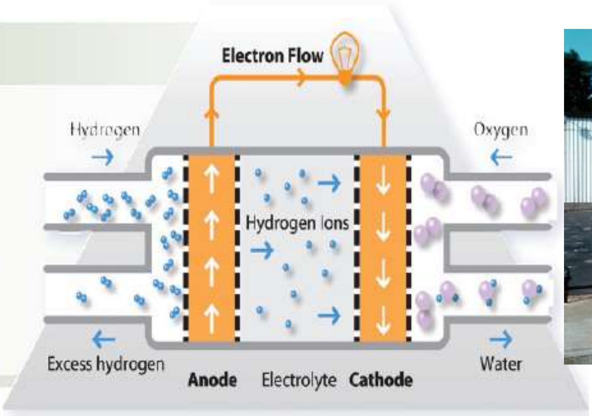


Source: Fuelcelltoday

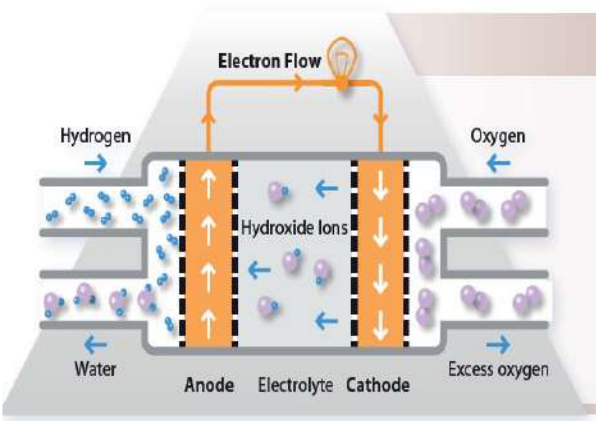
Phosphoric acid and alkaline FC

PAFC – Phosphoric Acid Fuel Cells

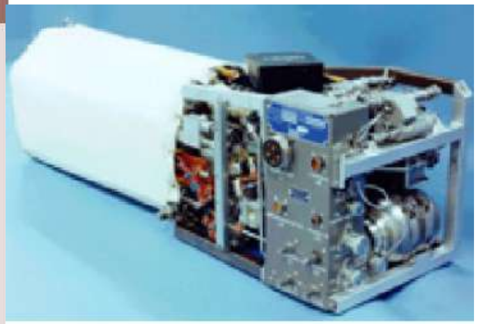
- Electrolyte: liquid phosphoric acid in a bonded silicon carbide matrix
- Use a finely dispersed platinum catalyst on carbon
- Quite resistant to poisoning by carbon monoxide
- Operate at around 180°C
- Electrical efficiency is relatively low, but overall efficiency can be over 80% if the heat is used
- Used in stationary power generators (100 kW to 400 kW)



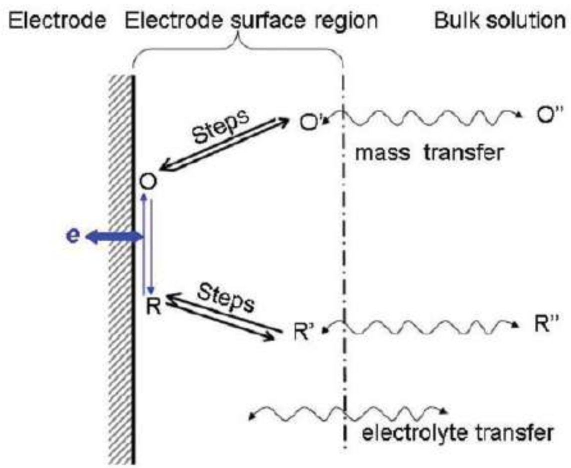
Alkaline Fuel Cells – AFC



- Electrolyte: alkaline solution such as potassium hydroxide in water
- Commonly use a nickel catalyst
- Generally fuelled with pure hydrogen and oxygen as they are very sensitive to poisoning
- Typical operating temperatures are around 70°C
- Can offer high electrical efficiencies
- Tend to have relatively large footprints
- Used on NASA shuttles throughout the space programme

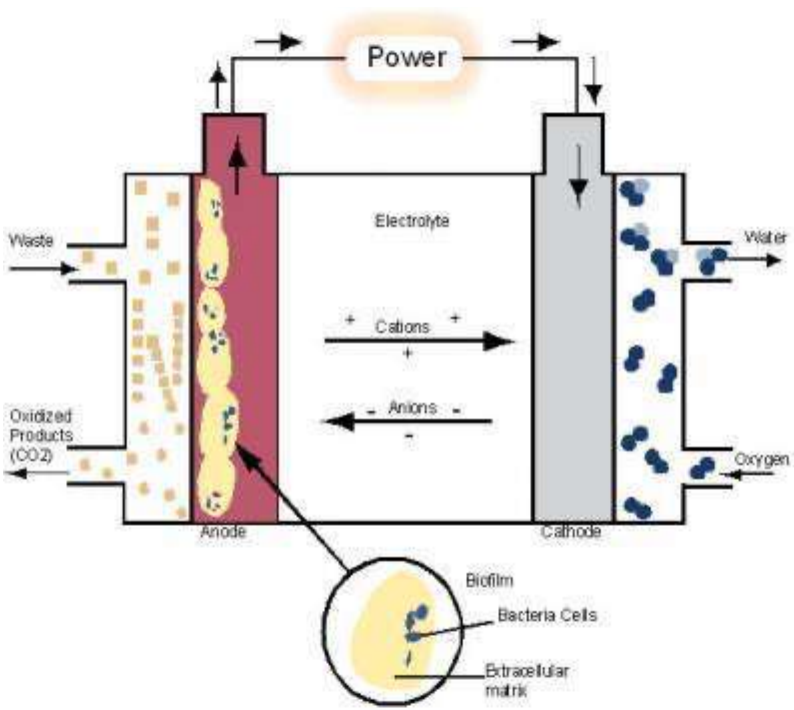


Microbial Fuel Cell



$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O;\ \Delta G^0 = -2895\ \mathrm{KJ\ mol^{-1}}$$

$$C_{12}H_{22}O_{11} + 13H_2O \rightarrow 12CO_2 + 48H^+ + 48e^-$$



- The biofilm is attached to the anode
- Anaerobic conditions force bacteria to respire anaerobically

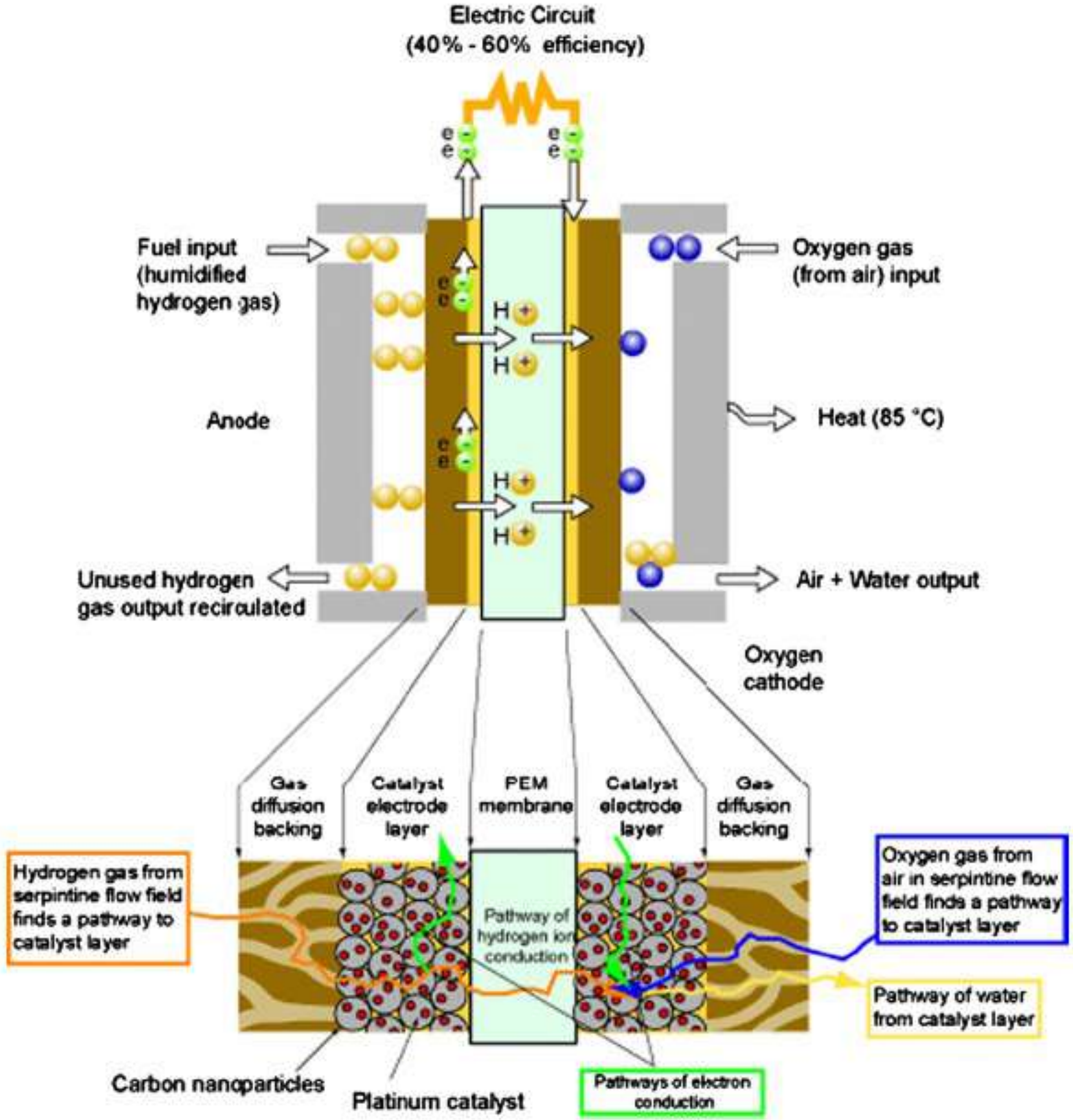


Fig. 15. Phenomena in a PEM fuel cell: two-dimensional sectional view [272].

Basic Fuel Cell Operation
(PEM FC example)

Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

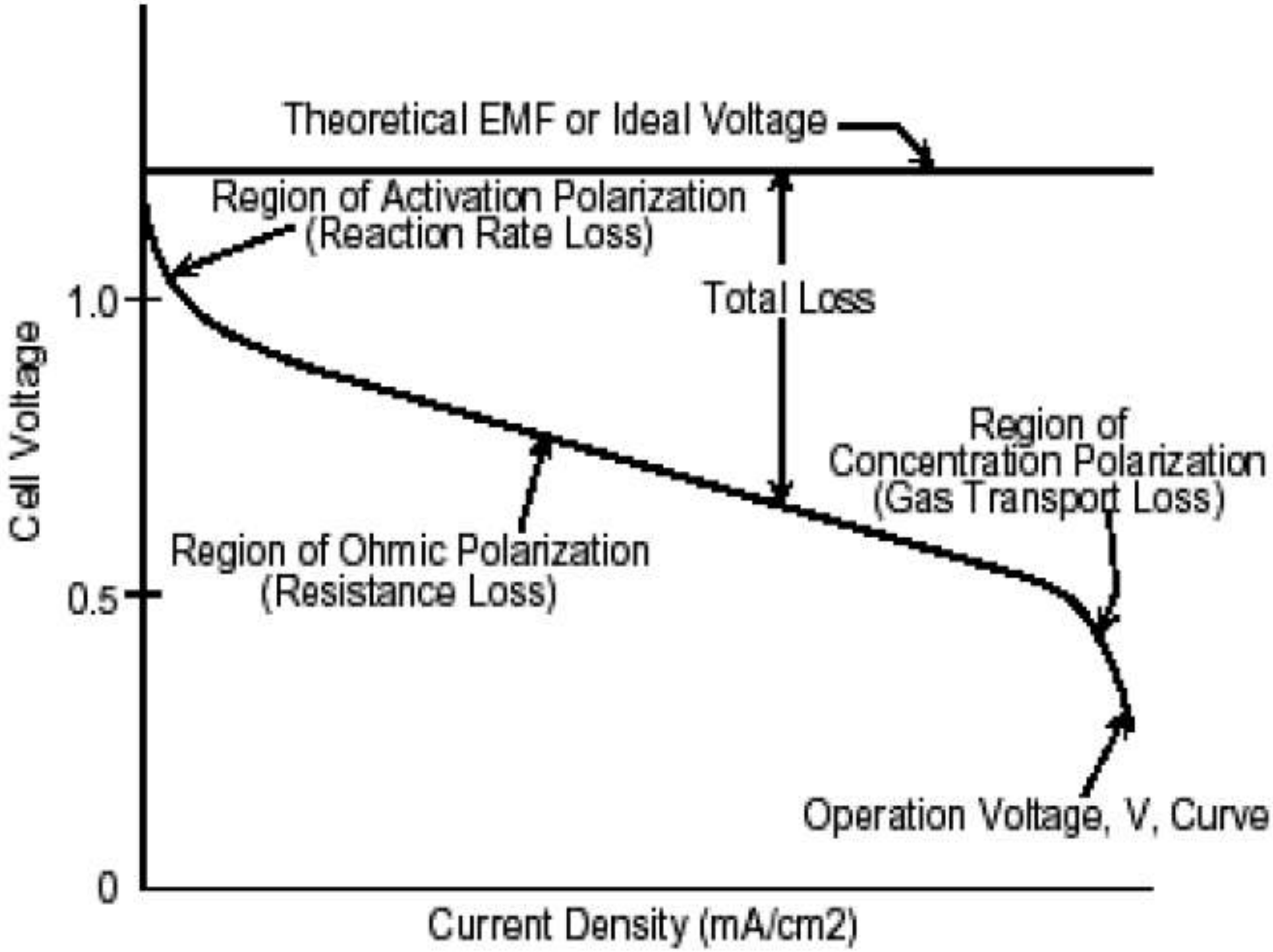
Cathode: $4e^- + 4H^+ + O_2 \rightarrow 2H_2O$

Overall: $2H_2 + O_2 \rightarrow 2H_2O$

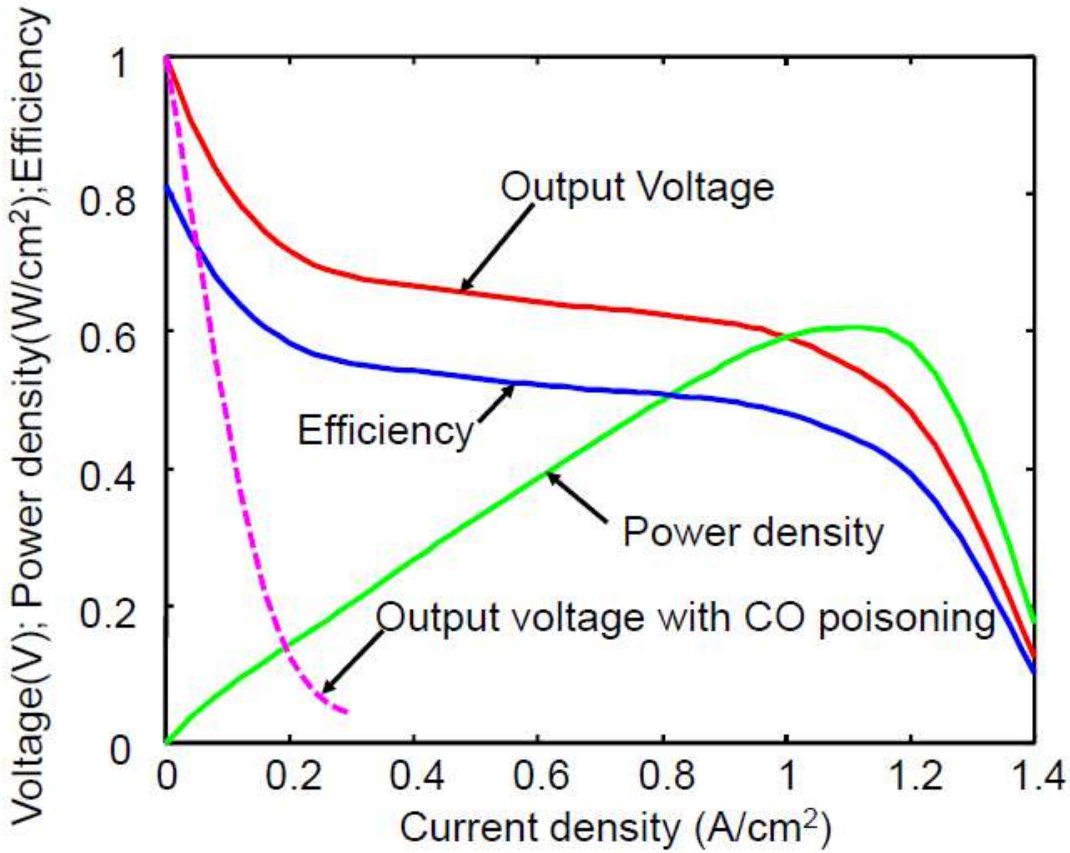
The overall reaction is the same as hydrogen combustion…

This reaction is *exothermic*, so it will occur spontaneously

Current-Voltage Curves

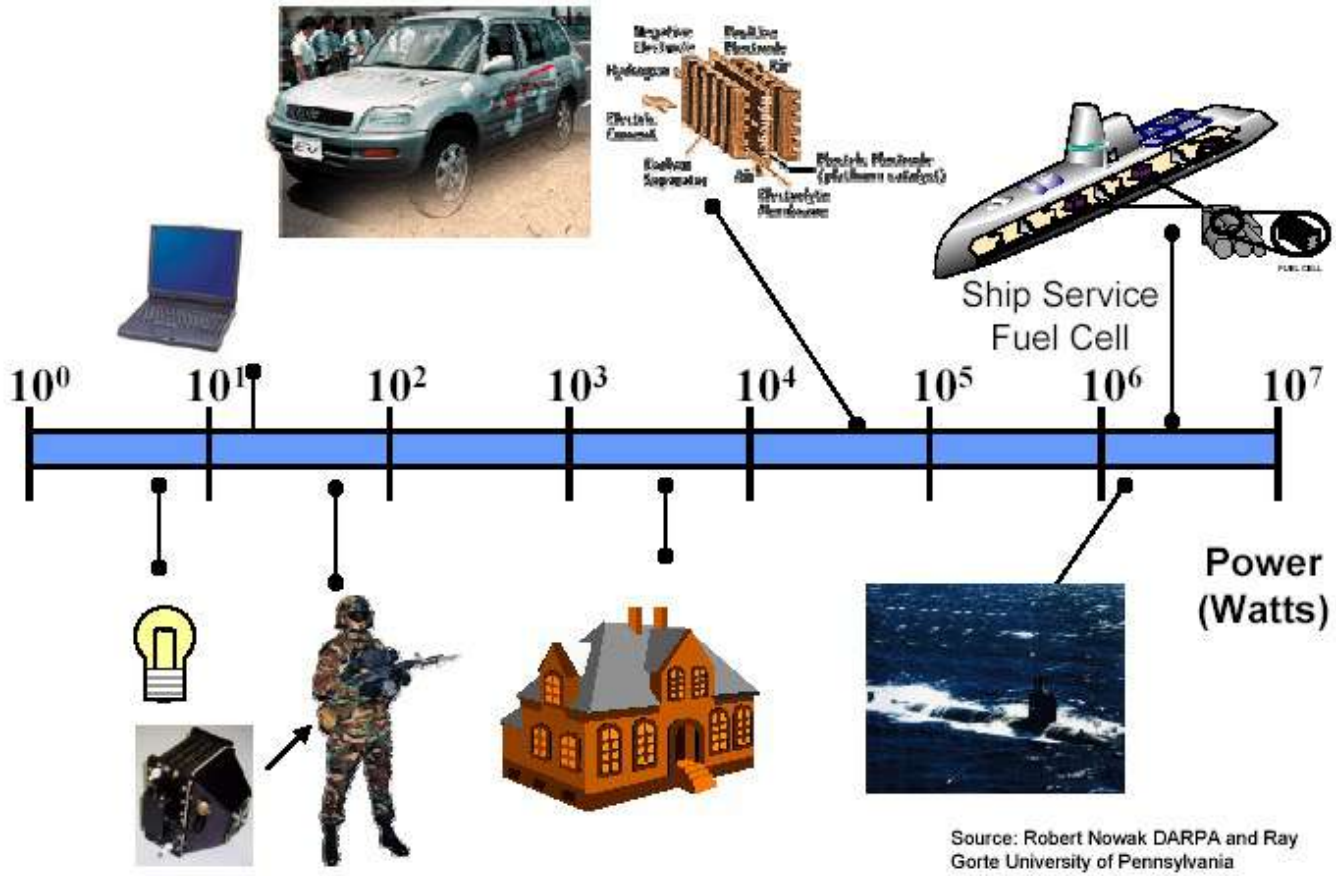


Current PEM H_2/O_2 Fuel Cell Performance



Note: Efficiency does not include power required to run supporting system

Fuel Cells Applications & Power Ranges



R. Gorte, U. Penn

Light Duty- Passenger Cars & Captive Fleets; Heavy Transport on Land - buses, heavy duty trucks, light rail trains, logistics/utility vehicles; Maritime and Air; Portables

Passenger Cars & Captive Fleets

Toyota Mirai | Honda Clarity | Hyundai Tucson | Hyundai Genesis

- Japanese vehicle production increases dramatically.
- FCEV registration is now being tracked in California.
- Norway anticipates application of FCEVs incentives similar to BEVs.

Buses

- **UC Transit in Oakland**, CA, USA - largest fleet in North America, with 12 fuel cell buses.
- Foshan and Yunfu – $17 million order for 300 fuel cell buses.
- EU Coordination a national Call for order in progress for a 1000 FC Buses
- French project for BEV/Range extender:300 vehicles with 20 HRS
- South Korea - planning to replace 27,000 CNG buses with FC buses by 2030.

Heavy Duty Trucks

Nikola Motor Company H2 powered **long range tractor trailer**

Logistics Vehicles

UPS - first hydrogen fuel cell electric class 6 delivery van. 17 vans in the U.S. by year end 2018.

Toyota a heavy duty drayage vehicle (class 8), **Amazon** buying $70 million of **fuel-cell forklifts.**

Light Rail Trains

In 2017, **Alstom** unveiled its **Coradia iLint**, which will **replace diesel trains** in the extensive, **un-electrified sections** of rail in Germany.

Airplanes & Drones

Hydrogen-powered Drone
Fuel cell technologies power drones varied applications from lightweight Hycopter to larger military based applications like the Boeing Insitu's ScanEagle drone.

HY4 Hydrogen Fuel Cell Electric Aircraft, World's first 4 seater H2 plane.

Maritime

90% of all trade is by ship. Maritime tourism is huge global industry.

The **Red and White Ferry Company** and **Sandia National Laboratory** have teamed up on a feasibility study for designing, building and operating a high-speed hydrogen fuel cell powered passenger ferry and refueling station.

Portables

Source: IEA, 2017

Ene-farm Residential CHP Fuel Cells, Japan

2010 World Expo, China

Air Liquide, Canada

TOTAL Deutschland GmbH, Germany

Box 13. Policy opportunities for promoting the use of hydrogen in road transport

Policy options to promote the uptake of FCEVs include fuel economy standards, zero-emission vehicle (ZEV) mandates, feebates (which tax the worst performing vehicles to subsidise those that perform best in terms of CO_2 or air pollutant emissions) and purchase subsidies. The first two put the onus on private industry to provide technological solutions to climate and air quality externalities and give them the freedom to find the solutions that work best for them. Fuel economy standards and feebates can be technology-neutral, while ZEV mandates are more specific and could help to secure the demand that hydrogen refuelling stations need to bring down the costs of delivering hydrogen during an initial deployment phase.

Focusing initially on building refuelling infrastructure for captive fleets would provide a way to address the barrier of underutilisation. Examples of captive fleets include truck and handling vehicles at industrial sites and clusters and at ports; buses; and taxi fleets. Refuelling stations originally built for captive fleets could be opened for public use, thereby offering refuelling points to early adopters of FCEVs at a low marginal cost. An alternative approach would be to give credits to refuelling stations (under fuel standards) based on the gap between actual and targeted utilisation rates, as in California where a range of policy instruments combine to support private investment in refuelling infrastructure (CEC and CARB, 2018).

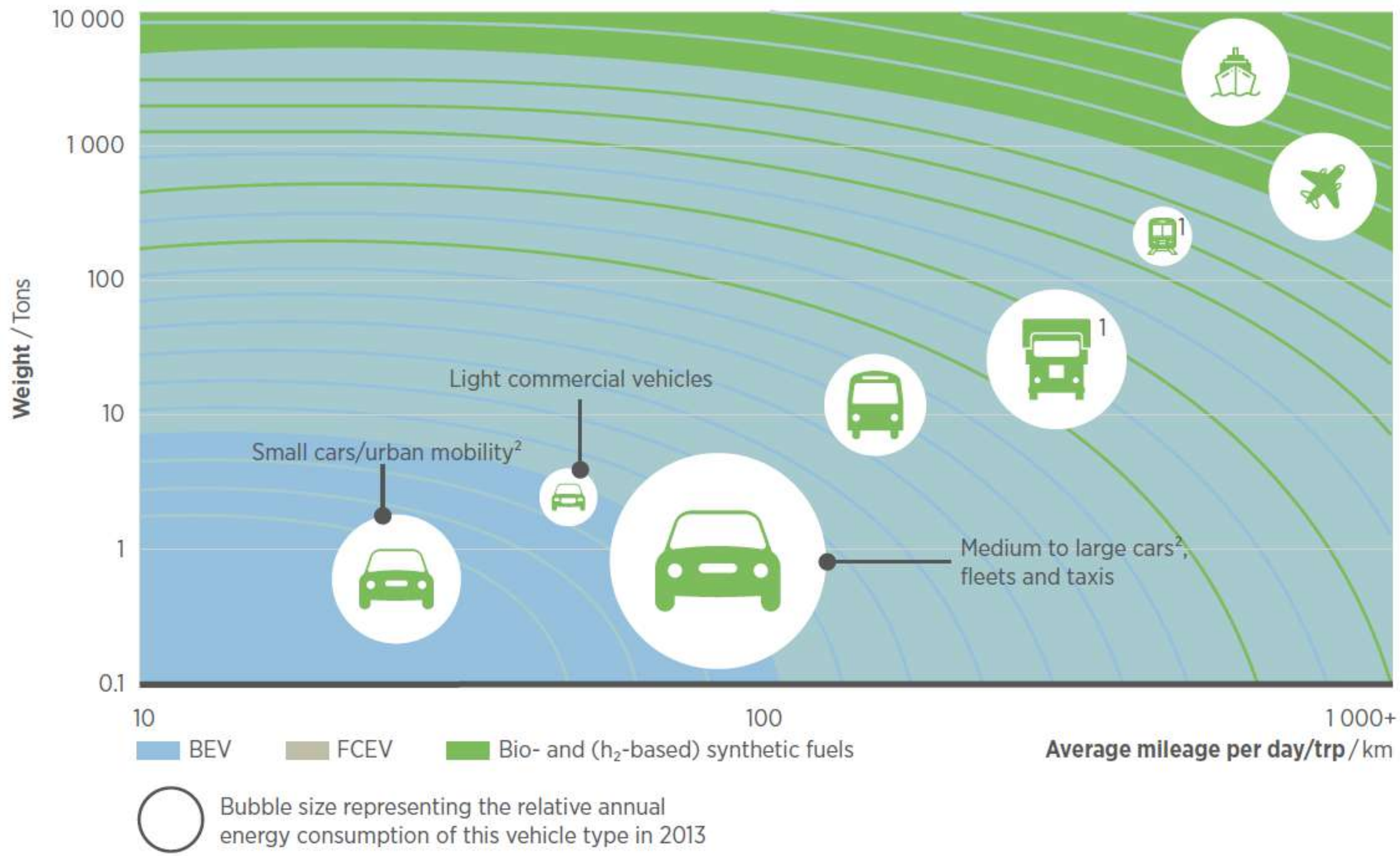
Public policy can also play a supportive role in the initial stages by:

- Easing regulatory burdens associated with the transport of hydrogen (e.g. in vehicles on bridges and tunnels) and with the permitting and construction of necessary infrastructure.
- Engaging with industry stakeholders that are able to make the required investments, brokering commitments among industry partners to support credible and well-structured business plans, and offering a critical assessment (e.g. based on audits) of areas for improvement of such plans at regular intervals.
- Temporarily repurposing funds from vehicle or fuel taxes to decrease the investment risk of nascent hydrogen refuelling station networks.

Source: CEC and CARB (2018).

Source: IEA, 2019

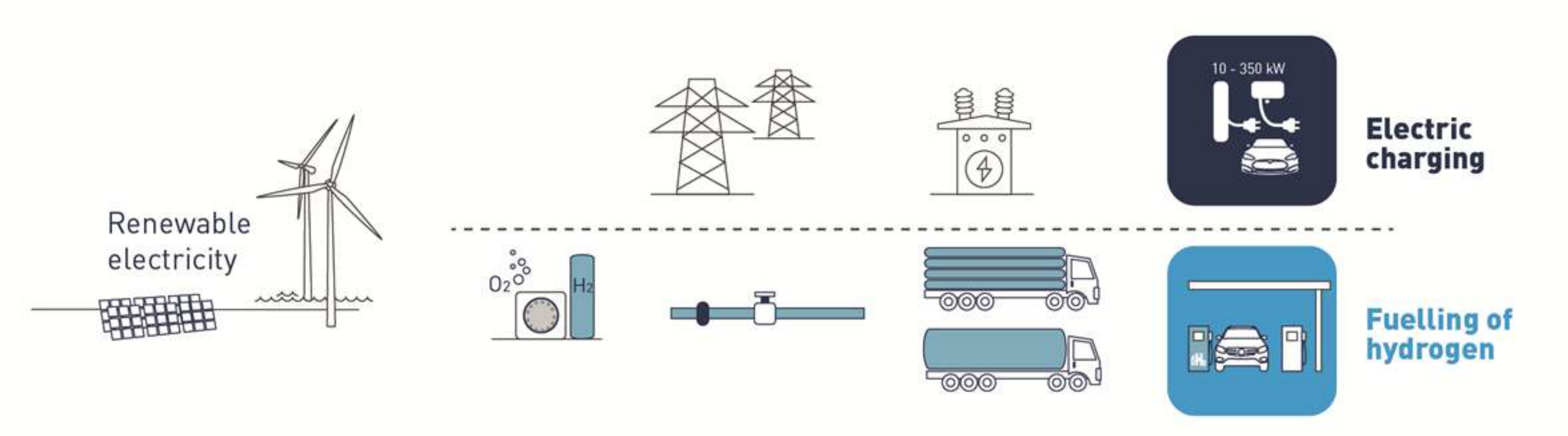
Segmentation of the transport market

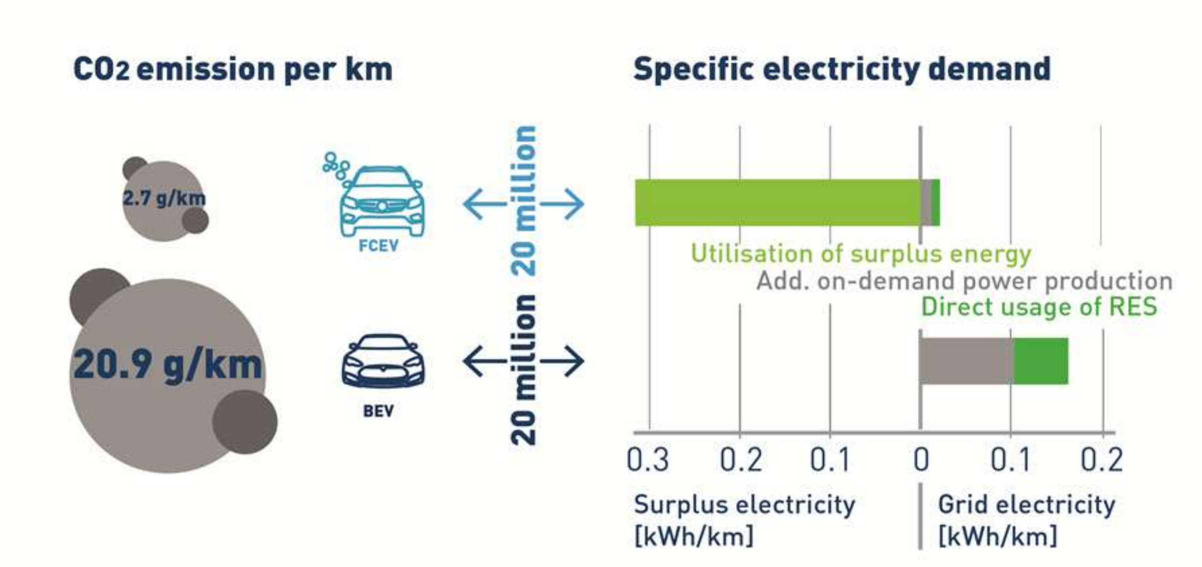


1 Battery-hydrogen hybrid to ensure sufficient power
2 Split in A- and B-segment LDVs (small cars) and C+segment LDVs (medium to large cars) based on a 30 % market share of A/B-segment cars and a 50 % less energy demand

Source: IRENA, 2018

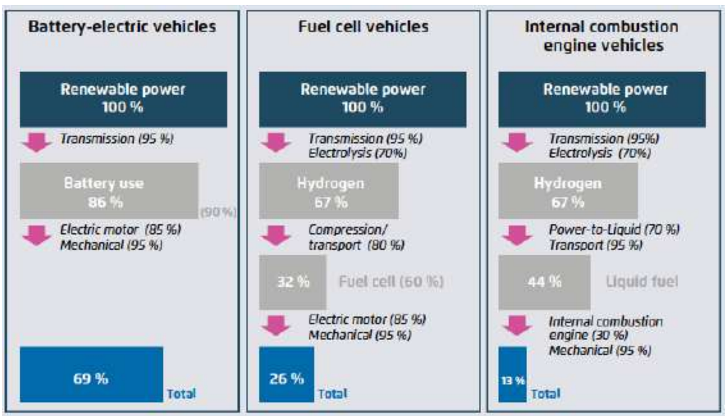
BEV vs FCEV

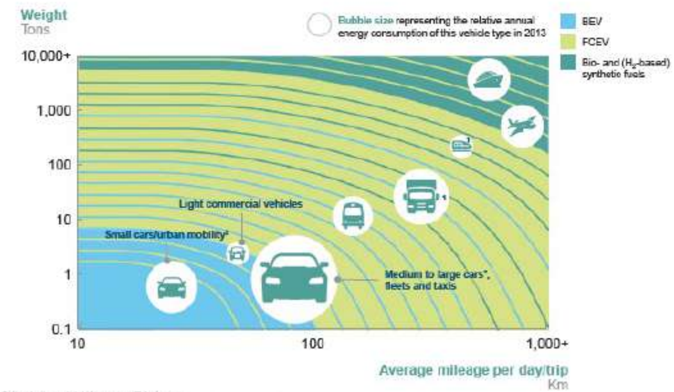


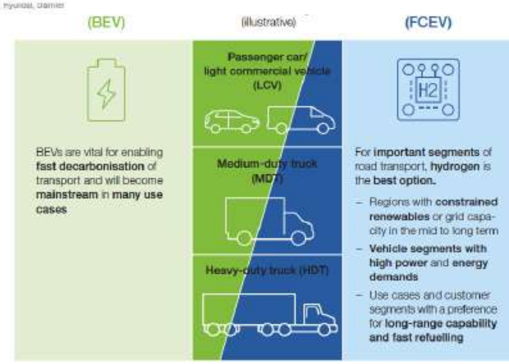


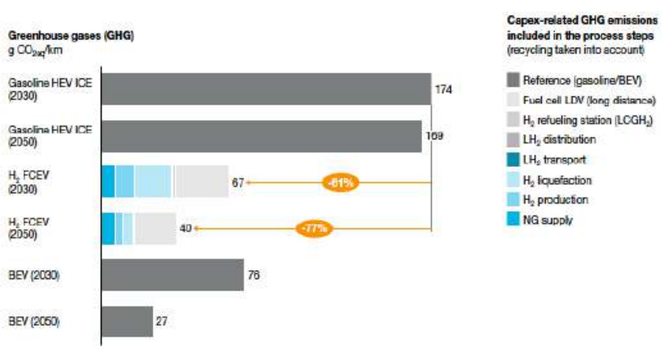
Source: Julich, 2018

Decarbonize transport - BEV, FCEV, ICE





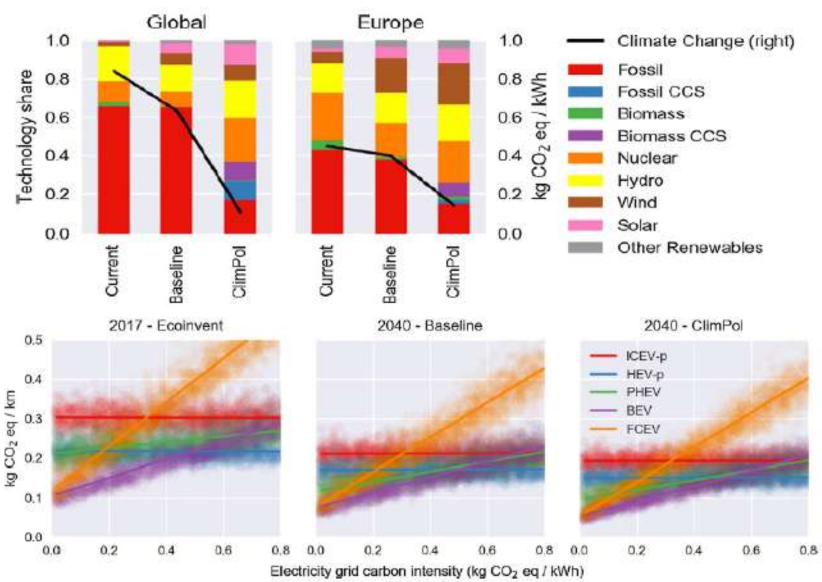


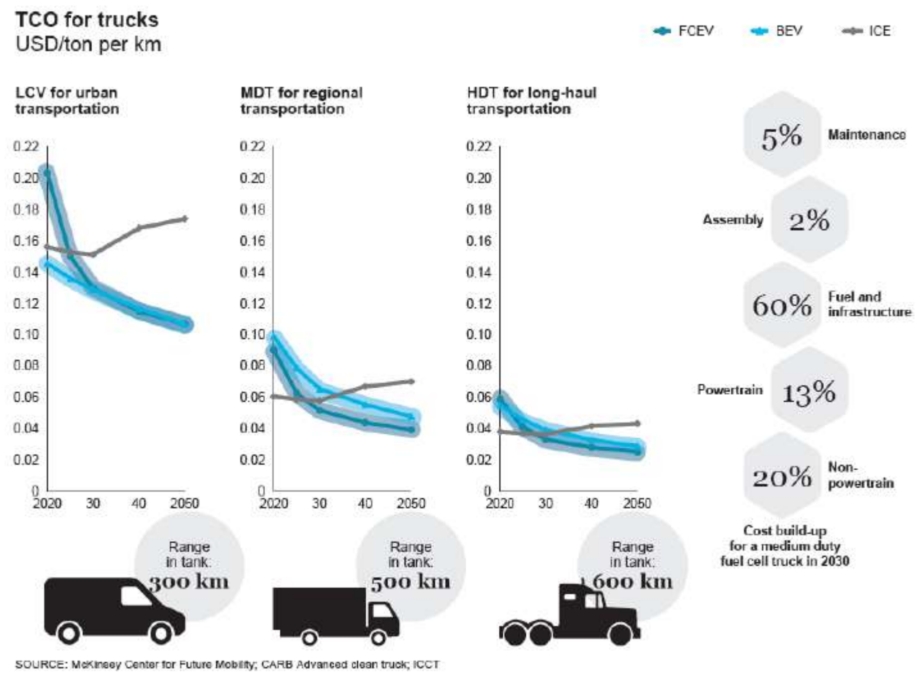


Source: Hydrogen Council

Source: Agora Energiewende

GHG emissions and Total Cost of Ownership





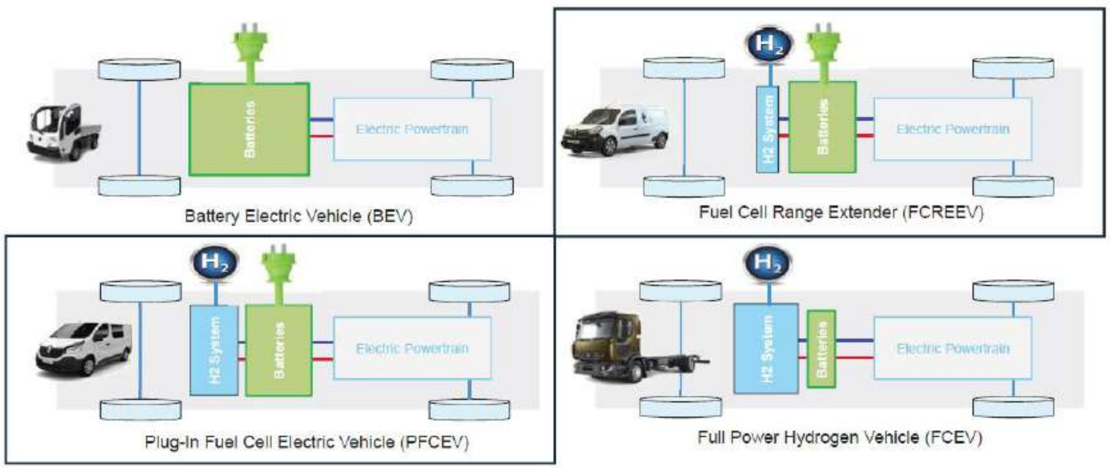
Source: Cox et al, 2020

Source: Hydrogen council, 2020

FCEVs

Hydrogen as a gas like others electrofuels has unique advantage to uncouple power to energy due to storage capacity
New fuels/electricity Infrastructure design
will be key for massive deployment

Different design for power train architecture



FC vehicles

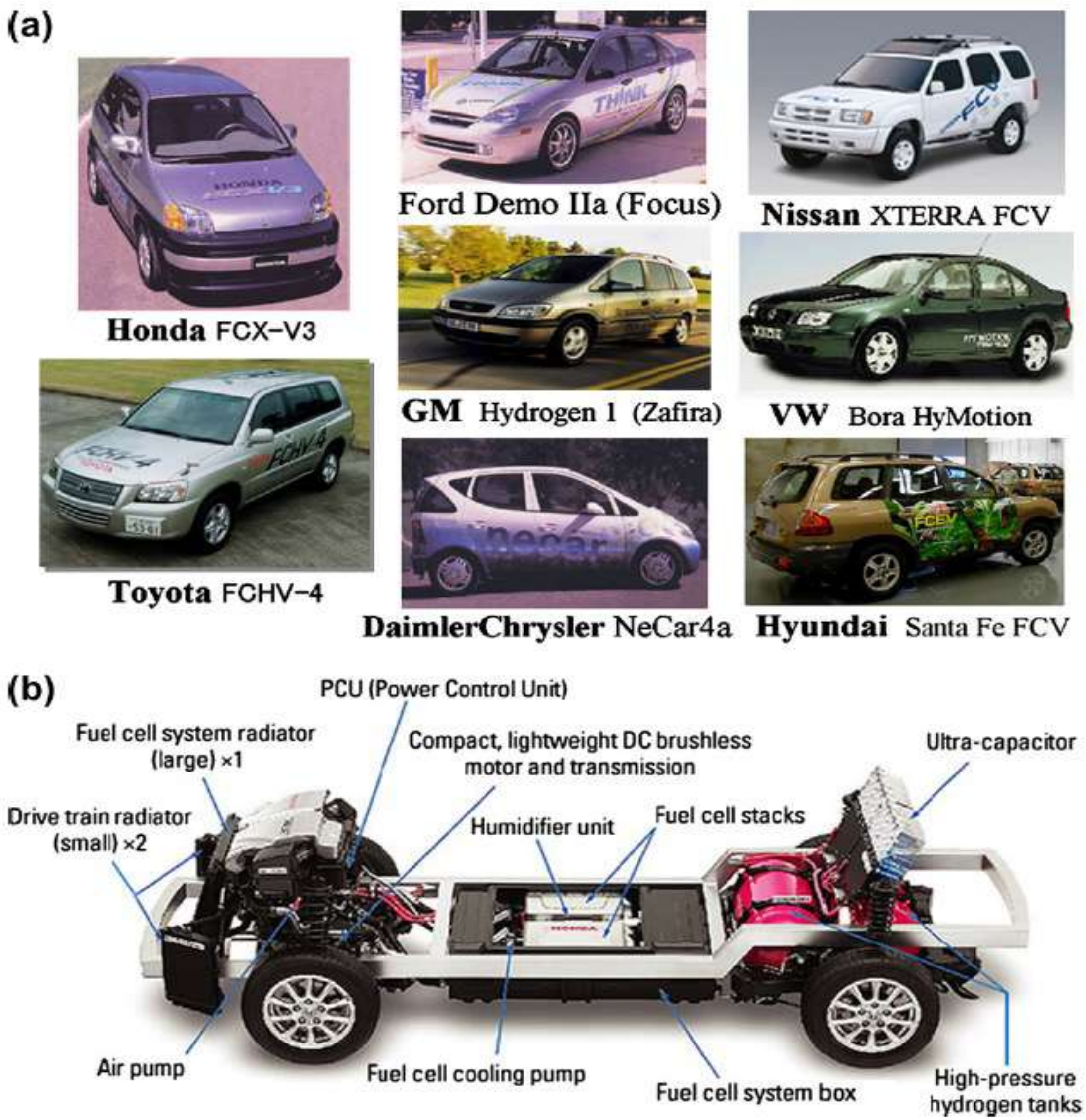


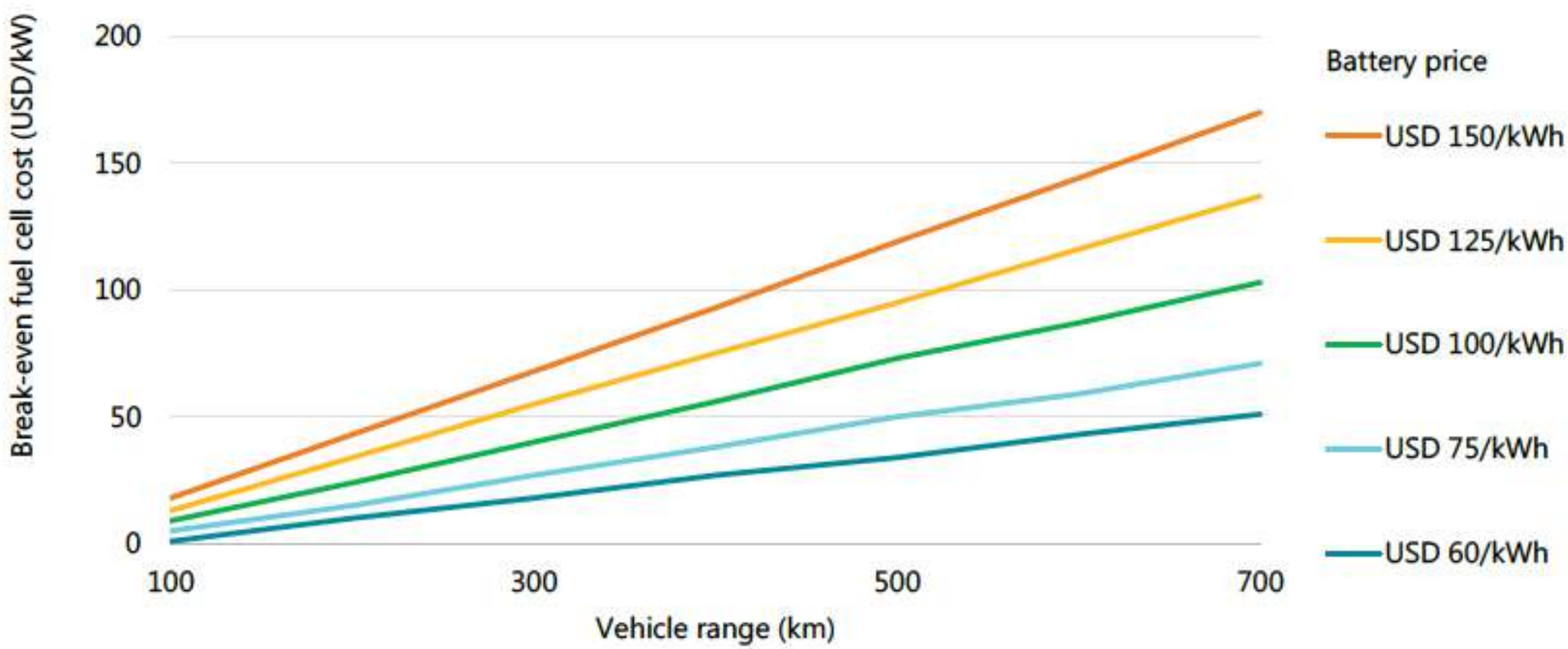
Fig. 5. Fuel cell vehicles by various automakers [264] (a) and layout of the Honda FCX Powertrain [265] (b).

Comparative performance of primary drivetrains

		ICE	FCEV	BEV
Lower is better	Current capital cost	$	$ $ $	$ $
	Fuel cost	$ $	$ $ $	$
	Maintenance costs	$ $ $	$	$
	Infrastructure needs	$	$ $ $	$ $
	Emissions	🌢 🌢 🌢	🌢	🌢
Higher is better	Efficiency	*	* *	* * *
	Range	* * *	* * *	*
	Refuelling speed	* * *	* * *	*
	Lifetime	* * *	* * *	* *
	Acceleration	* *	* * *	* * *

Source: Staffell et.al, 2019

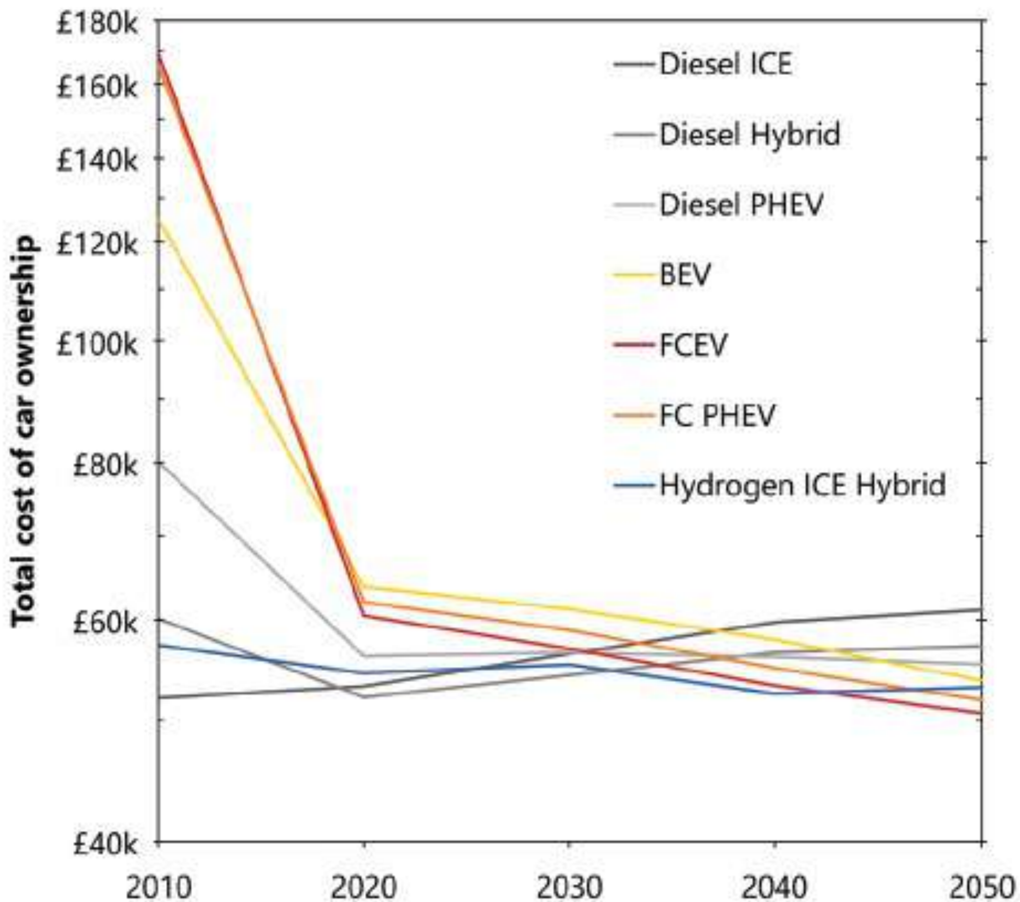
Break-even fuel cell cost to be competitive with BEV in the long term



Note: More information on the assumptions is available at www.iea.org/hydrogen2019.

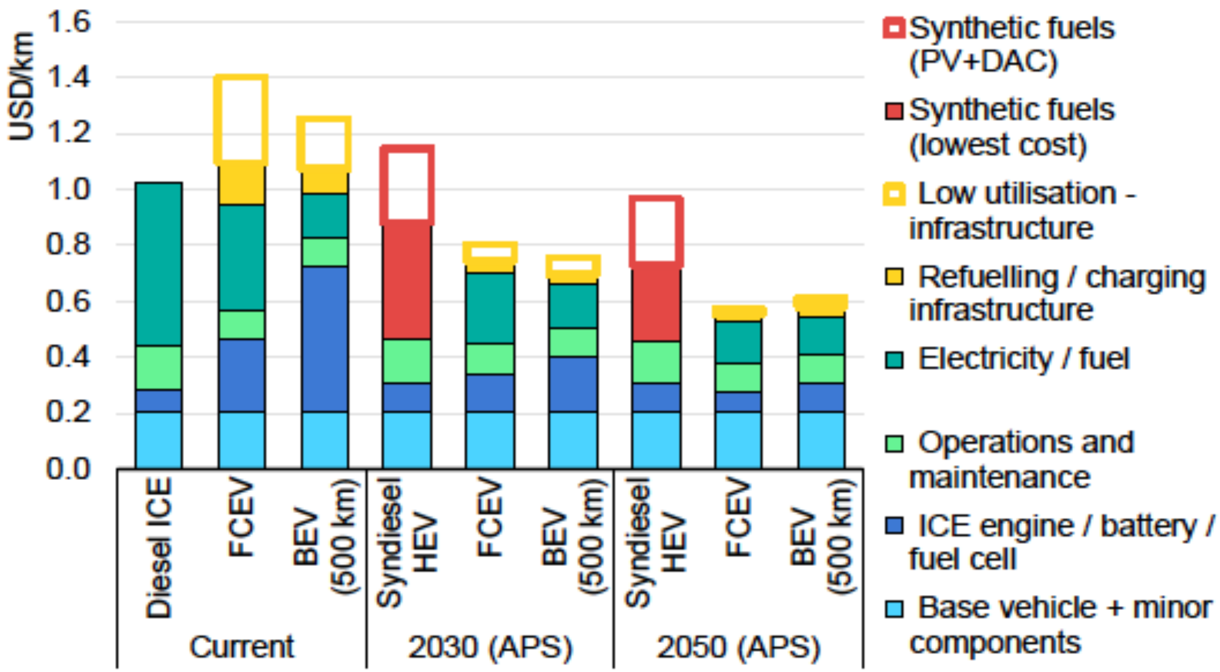
Source: IEA 2019.

Projection of total cost of ownership for major powertrains



Source: Staffell et.al, 2019

Current and future total cost of ownership of fuel/powertrain alternatives for heavy-duty trucks.

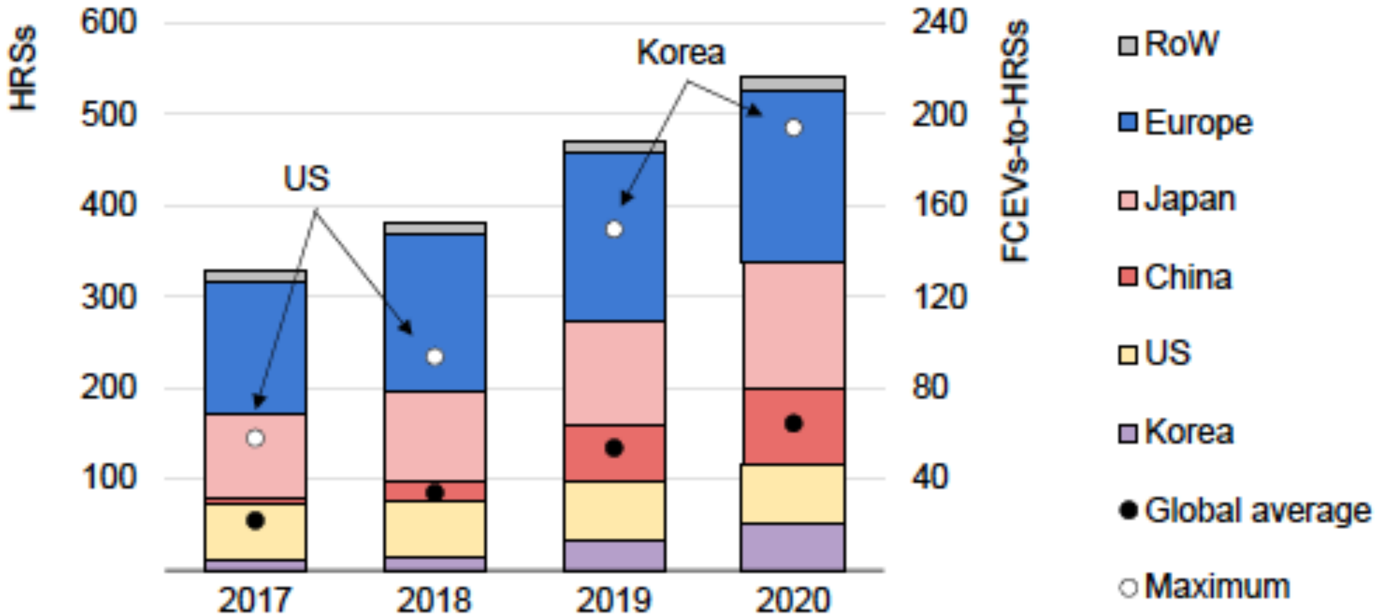


Notes: APS = Announced Pledges Scenario. ICE = internal combustion engine. FCEV = fuel cell electric vehicle. BEV = battery electric vehicle. HEV = hybrid electric vehicle. PV = photovoltaic (solar electricity for synthetic fuel production). DAC = direct air capture. Techno-economic assumptions available in the Annex.

Source: Based on input from McKinsey & Company and the Hydrogen Council.

Source: IEA, 2021

Hydrogen refuelling stations by region and ratio of hydrogen refuelling stations to fuel cell electric vehicles, 2017-2020

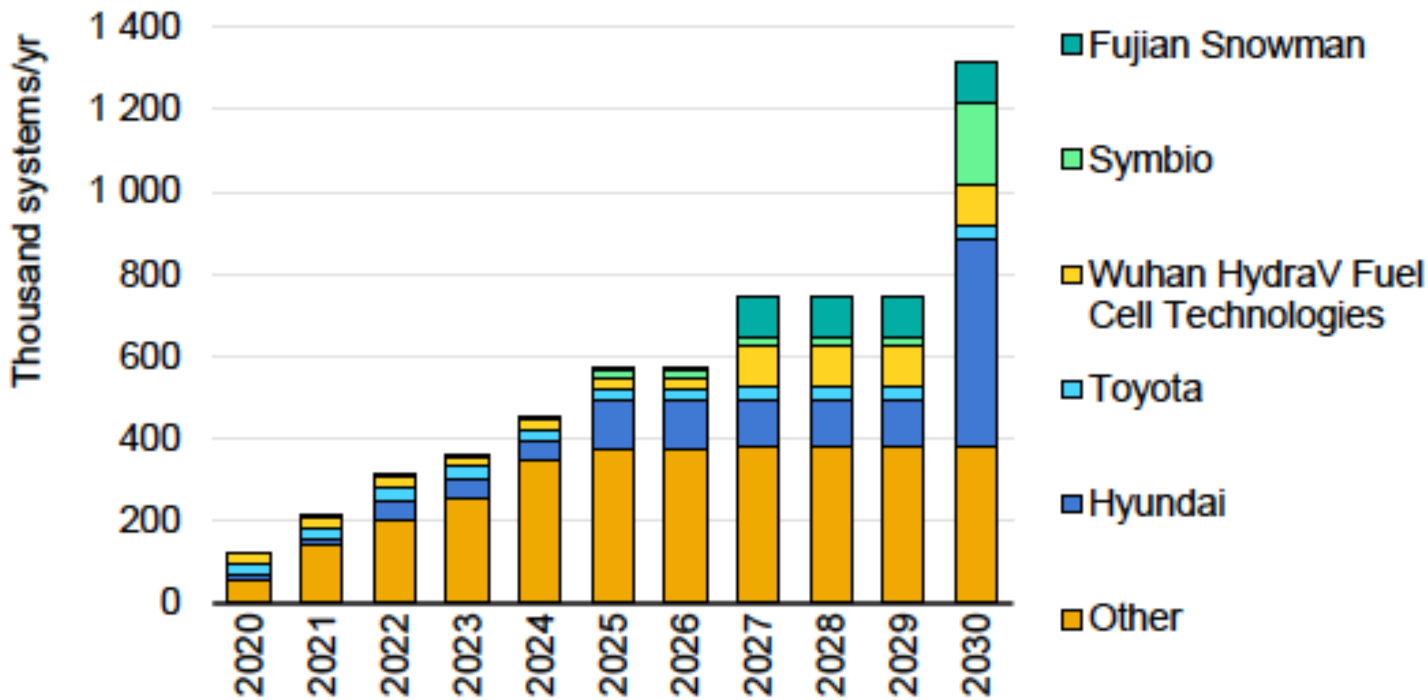


Notes: HRS = hydrogen refuelling station. FCEV = fuel cell electric vehicle. RoW = rest of world.

Source: AFC TCP Deployment Status of Fuel Cells in Road Transport: 2021 Update.

Source: IEA, 2021

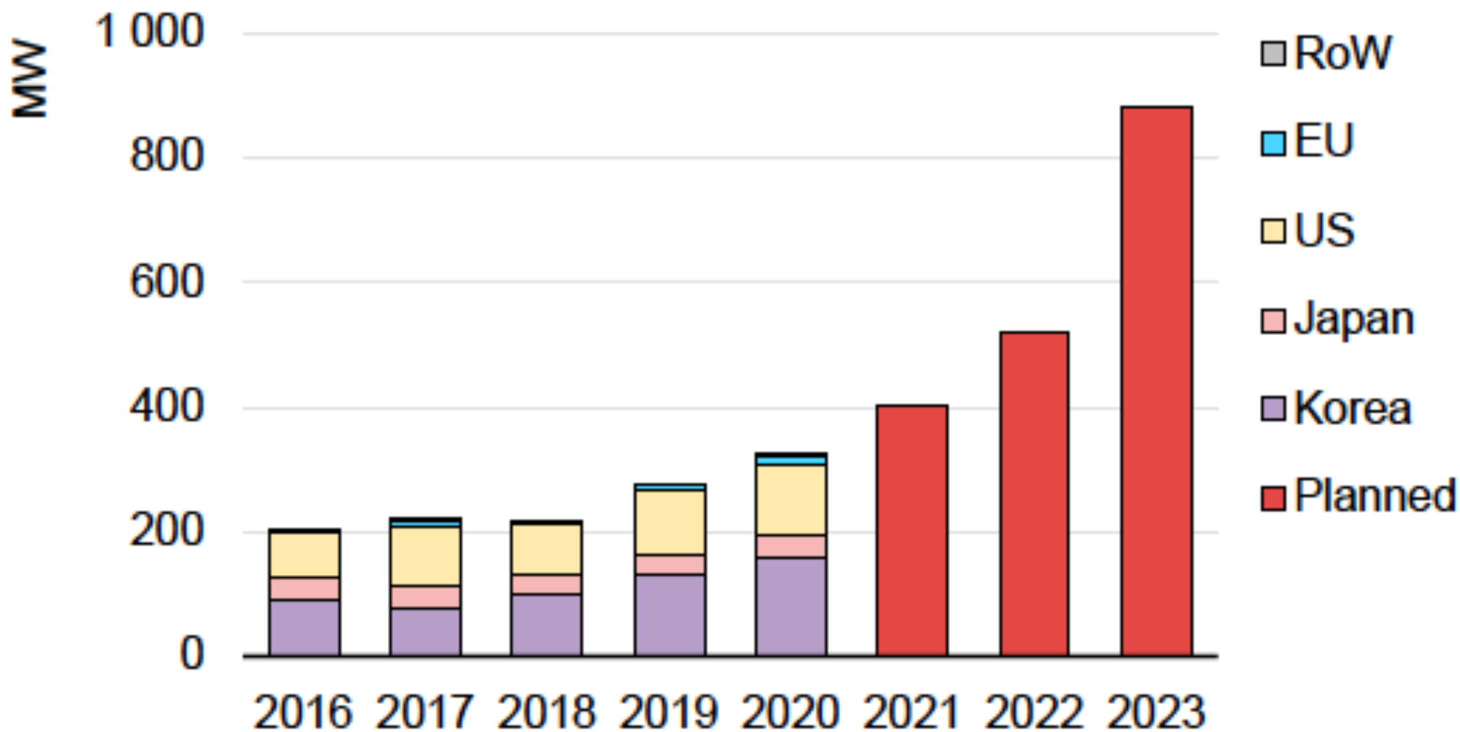
Announced annual automotive fuel cell manufacturing capacity, 2020-2030



Source: E4tech.

Source: IEA, 2021

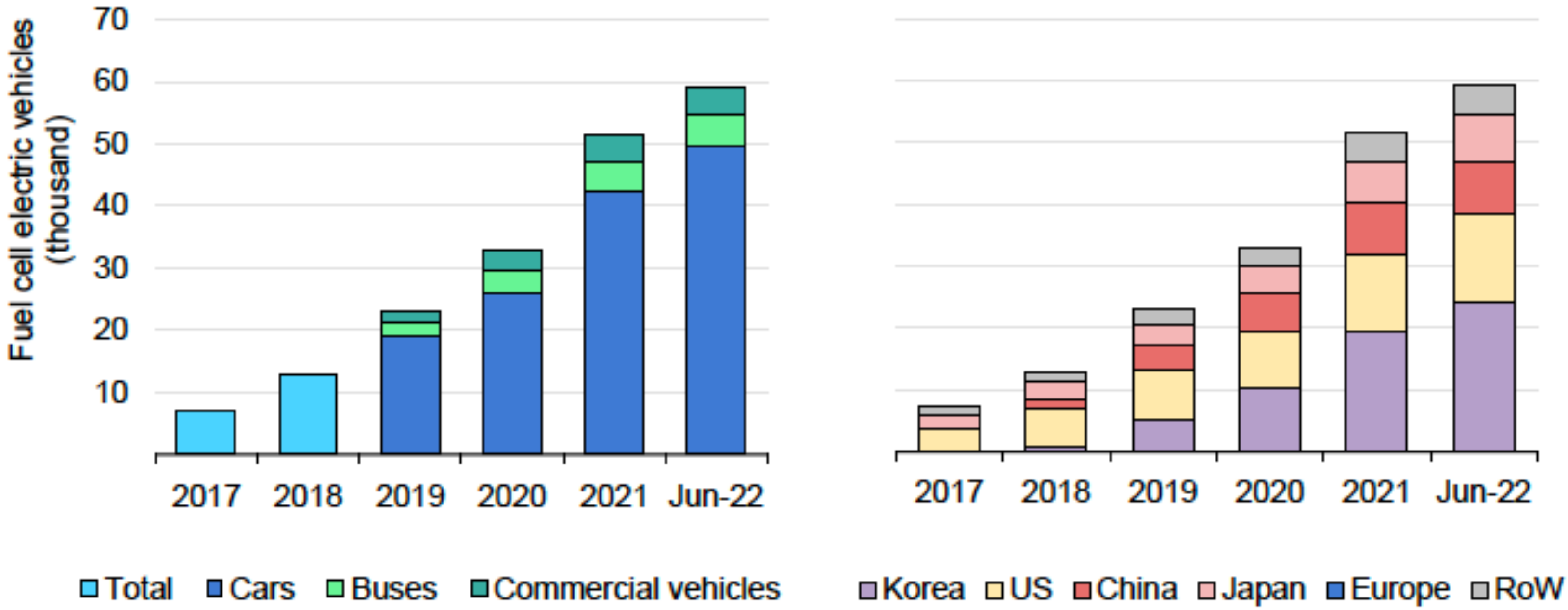
Stationary fuel cell capacity deployment, 2016-2023



Notes: RoW = rest of world. Data for 2020 estimated based on Q1-Q3 information. Planned capacity (2021-23) based on capacity increases and historic trends.
Source: E4tech.

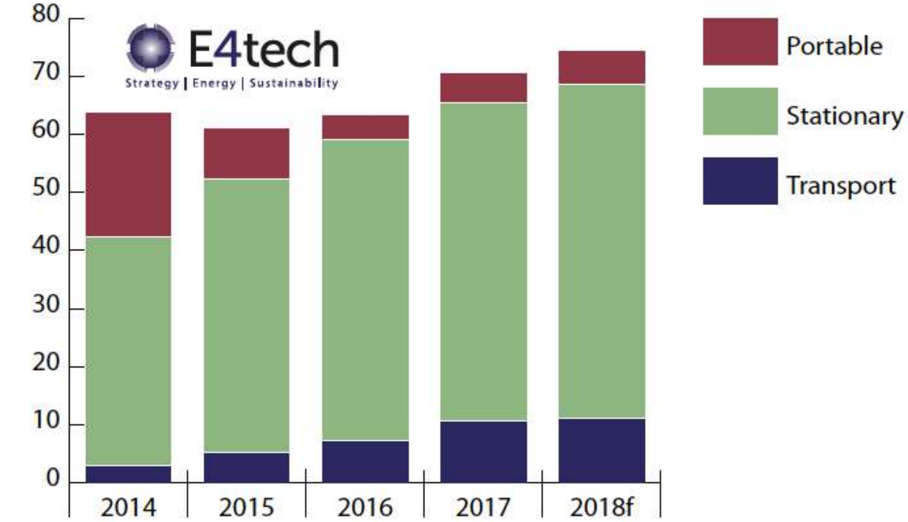
Source: IEA, 2021

Fuel cell electric vehicle stock by segment and region, 2017-June 2022

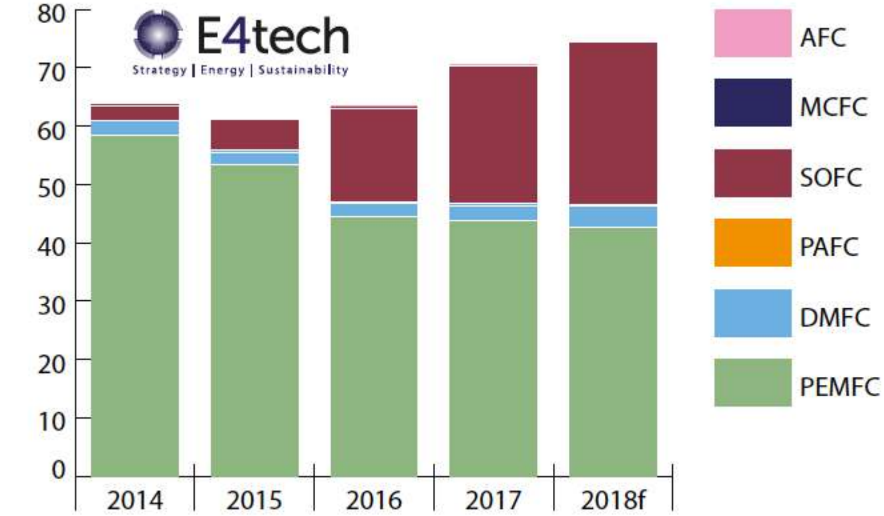


Source: IEA, 2022

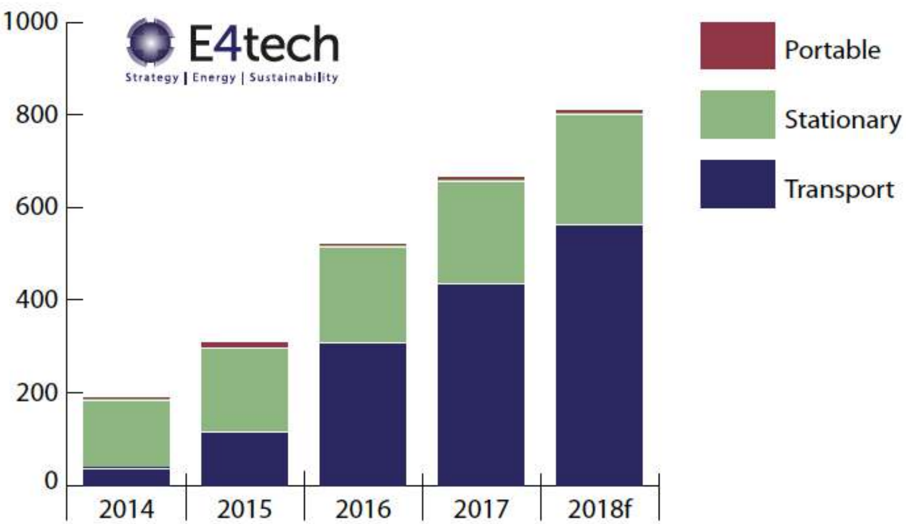
Shipments by application 2014 - 2018 (1,000 units)



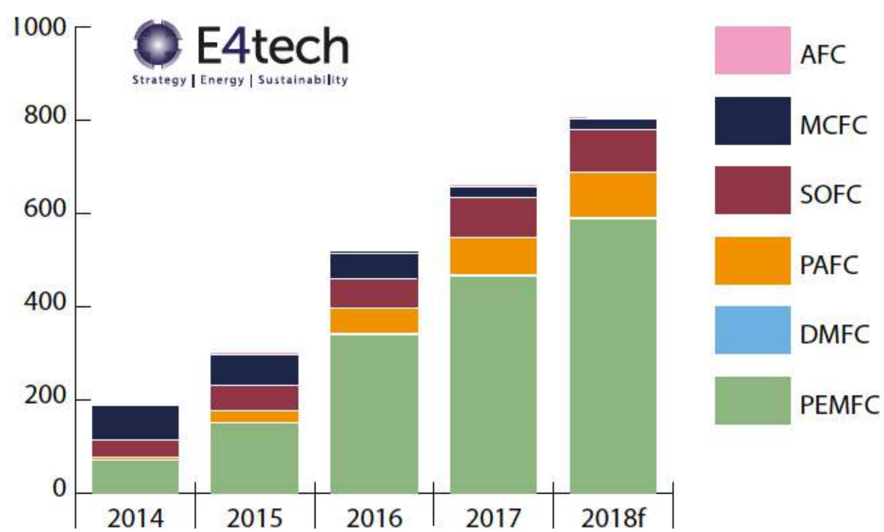
Shipments by fuel cell type 2014 - 2018 (1,000 units)



Megawatts by application 2014 - 2018



Megawatts by fuel cell type 2014 - 2018



Source: E4tech

Table 1
Specifications of several fuel-cell vehicles [265,286–293] (for a more complete listing of fuel-cell vehicles, see Ref. [294]).

Vehicle name	Type	Year	Power (kW)	Hydrogen storage and capacity	Driving range
Honda FCX-V3	Compact Car	2000	60	100 L at 250 atm	180 km
Honda FCX-V4	Compact Car	2002	60	137 L at 350 atm	315 km
Honda FCX 2nd Generation	Compact Car	2004	80	156.6 L at 350 atm	430 km
Honda FCX Clarity FCEV	Compact Car	2007	100	3.92 kg at 5000 psi	240 miles
Chevrolet HydroGen3	Minivan	2001	60	3.1 kg at 700 bar/4.6 kg at −253 °C	270 km/400 km
Chevrolet Sequel	Cross-over SUV	2005	73	8 kg at 700 bar	300 miles
Chevrolet Equinox FCV	Sport utility vehicle	2008	93	4.2 kg at 700 bar	200 miles
Toyota FCHV	Sport utility vehicle	2001	90	350 bar	180 miles
Toyota FCHV	Sport utility vehicle	2005	90	350 bar	200 miles
Toyota FCHV-adv	Sport utility vehicle	2009	90	156 L at 700 bar	430 miles
Kia Borrego	Sport utility vehicle	2009	109	–	426 miles
Daimler B-Class	Compact car	2009	100	700 bar	400 km
Passat LingYu	Sedan	2008	55	–	186 miles

Transport industry announcements for FCEVs

Company	Target	Target year	Vehicle category
BMW	Limited-series fuel cell SUV release	2022	PLDV
Jaguar Land Rover	Prototype testing of fuel cell SUV	End of 2021	PLDV
Great Wall Motor	Fuel cell SUV release	2021	PLDV
Toyota Motor Corp.	Deployment of 600 FCEV taxis in greater Paris region	End of 2024	PLDV
Riversimple	Production target of 5 000 fuel cell coupes/yr	2023	PLDV
Riversimple	Light goods vehicle model release	2023	LCV
Stellantis	Fuel cell van models release	2021	LCV
Renault and Plug Power	Light commercial vehicle models release	2021	LCV
Symbio and Safra	Availability of 1 500 buses	2021	Bus
Symbio and Safra	Construction of largest EU fuel cell plant (60 000 units/yr)	Unspecified*	Bus
H2Bus Consortium	Deployment of 600 fuel cell buses	2023	Bus
Daimler	Testing of GenH2 truck with liquid hydrogen onboard storage	2021	Truck
Air Products and Cummins	Conversion of ~2 000-truck fleet to hydrogen fuel cells	2022+	Truck
Nikola	Purchase order of up to 800 fuel cell trucks to US Anheauser-Busch	2023+	Truck
MAN	Deployment of hydrogen fuel cell demonstration fleet	2024	Truck
Hyzon	Purchase orders for 1 500 fuel cell trucks to Hiringa Energy in New Zealand; 20 to Jan Baaker and Millenaar & van Schaik in the Netherlands; and 70 to JuVE/MPREIS in Austria	2024	Truck
Hyundai	Purchase order of 1 600 fuel cell trucks to Switzerland	By 2025	Truck
Daimler and Volvo	Large-scale series production of fuel cell trucks	2025+	Truck
Industry Coalition	Deployment of 100 000 heavy-duty fuel cell trucks in Europe	From 2030	Truck

* Although plant construction has already begun, the target date for operations is unspecified.
Notes: PLDV = passenger light-duty vehicle. LCV = light commercial vehicle.

Source: IEA, 2021

FC Cost & companies

CHART 5.15: FUEL CELL COST OUT FOR SELECTED ELECTROLYTES, WIND AND SOLAR

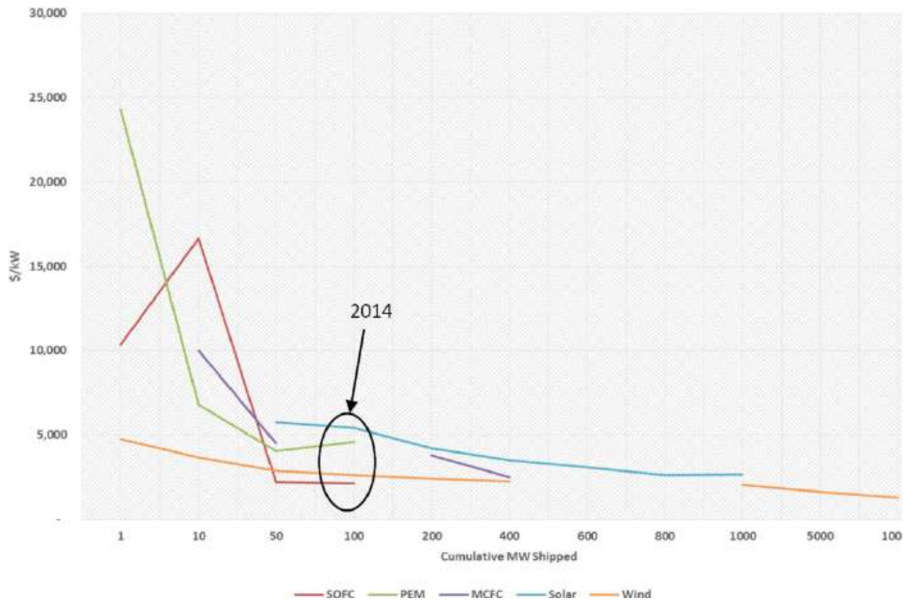


CHART 5.12: FUEL CELL PLATINUM THRIFTING OVER TIME, 2005 – 2030 (F)

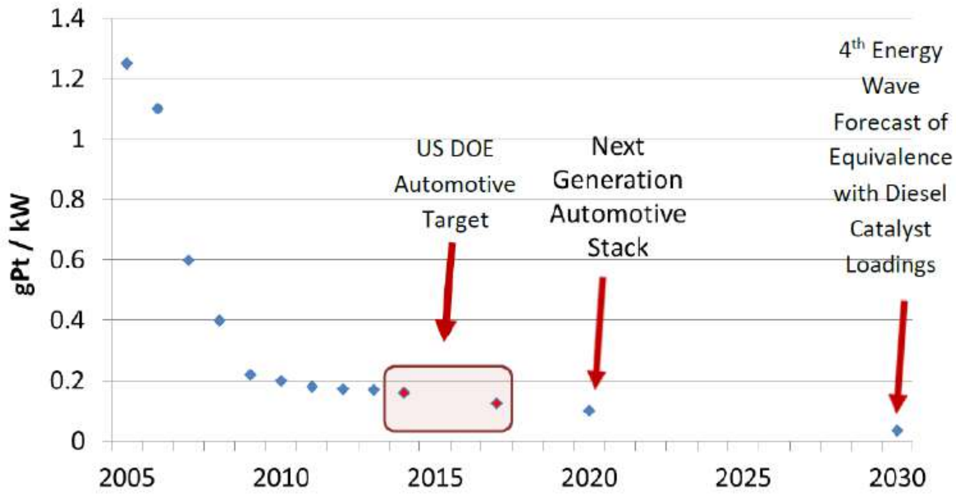
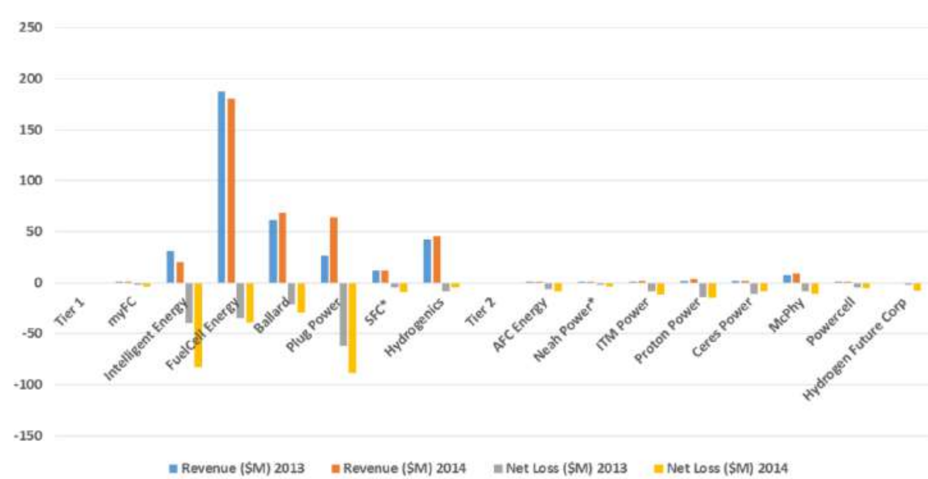


CHART 8.1: FINANCIALS FROM LISTED FUEL CELL AND HYDROGEN COMPANIES



- The industry has very few big companies; only five may have shipped 80% of the MW:
  - FuelCell Energy, Bloom, Panasonic, Toshiba, Plug Power
- Boom and bust continue:
  - Big names went under the wave: Topsoe Fuel Cells, ClearEdge Power, Lilliputian (and now BIC and CFCL)
  - Others rode it: Plug Power, FuelCell Energy, Intelligent Energy
- Cars are finally launching: Hyundai and Toyota are the earliest
  - Hydrogen refuelling station deployment in Japan and California is getting serious

1. Bloom Energy (Stationary, USA)
2. eZelleron (Portable, Germany)
3. Fuji Electric (Stationary, Japan)
4. GE (Stationary, USA)
5. Hydrogenics (Stationary / Transport / Hydrogen, Canada)
6. Intelligent Energy (Portable / Stationary / Transport, UK)
7. ITM Power (Hydrogen, UK)
8. myFC (Portable, Sweden)
9. NEL (Hydrogen, Sweden)
10. Riversimple (Transport, UK)

Source: E4tech

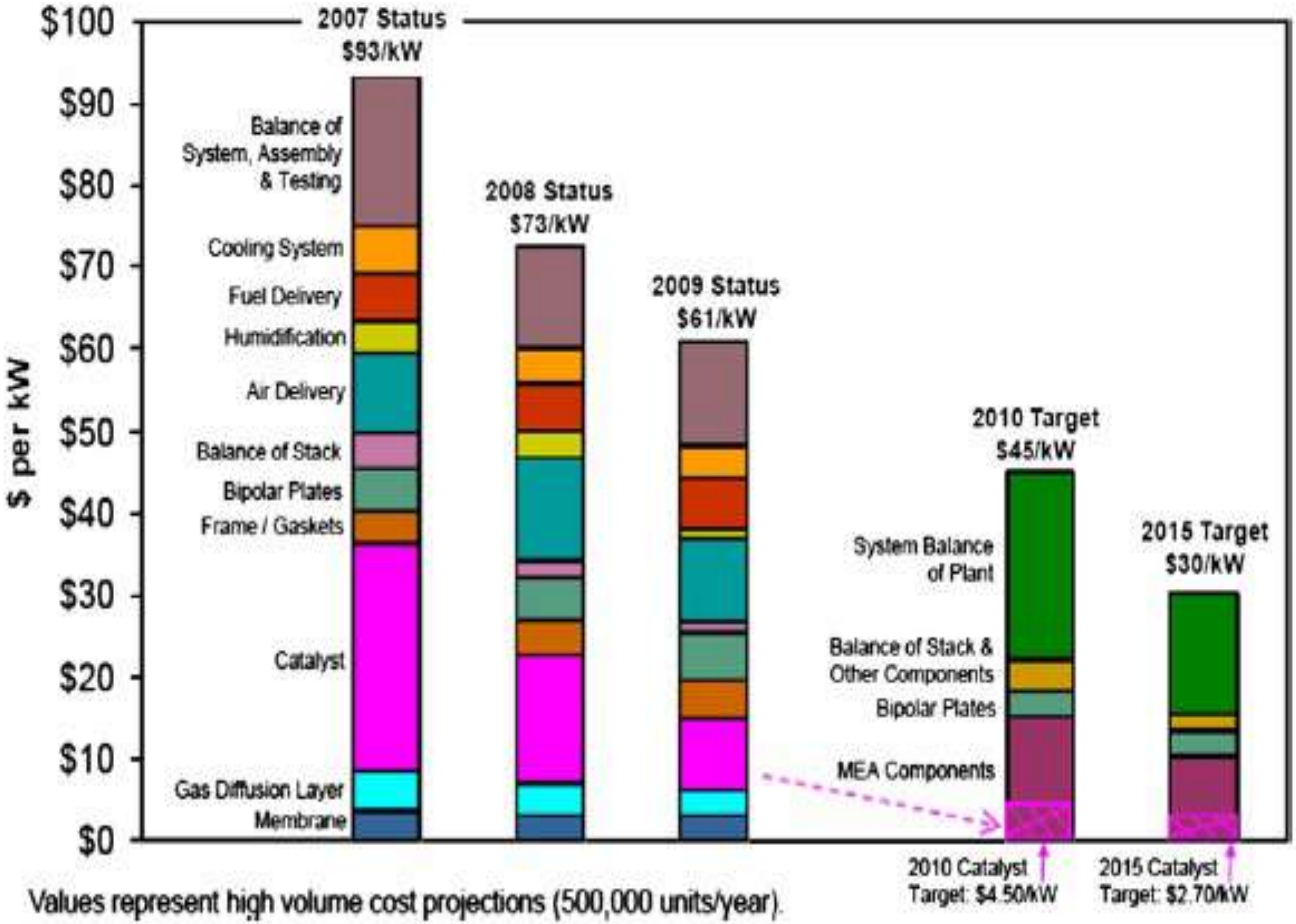
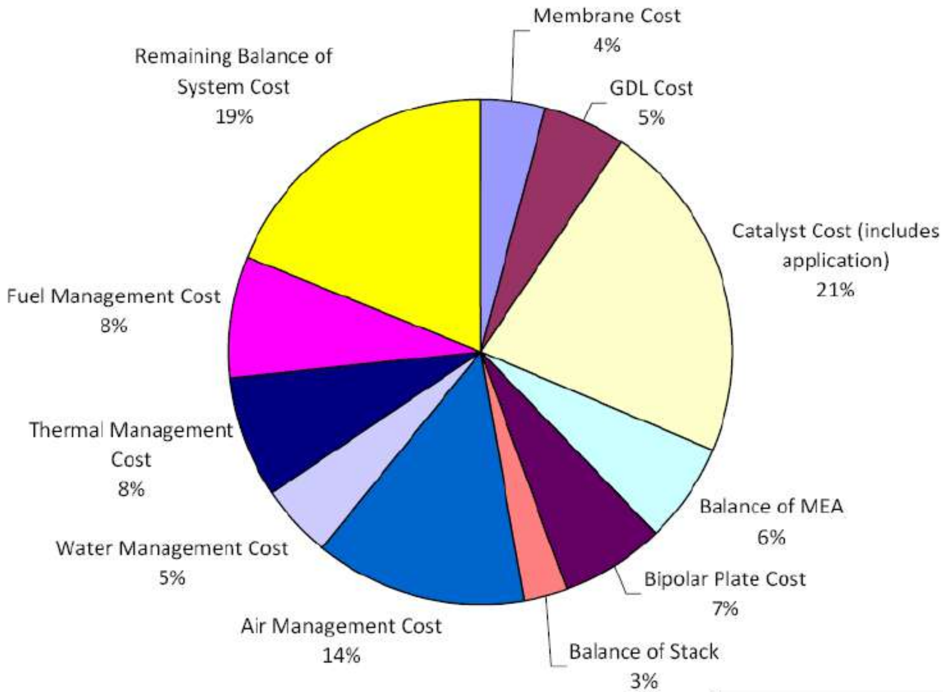


Fig. 2. Fuel cell cost breakdown [1].



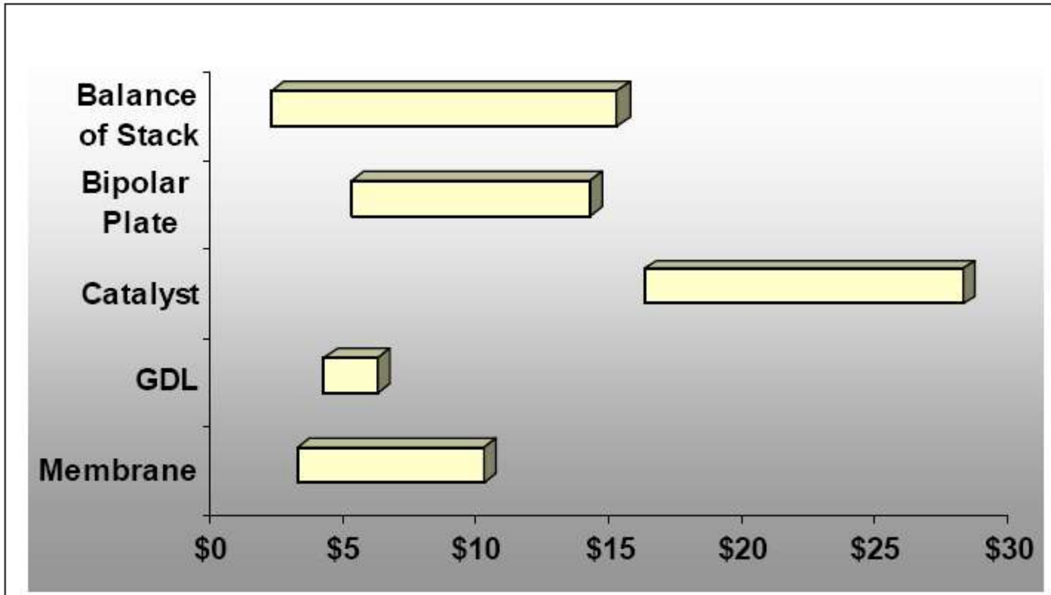
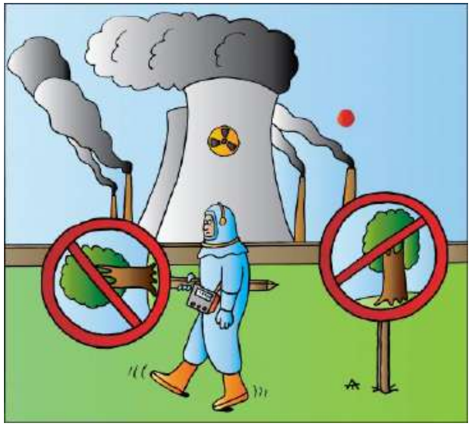


Figure 3. Cost range for 500,000 units/year: stack status

Nuclear Energy

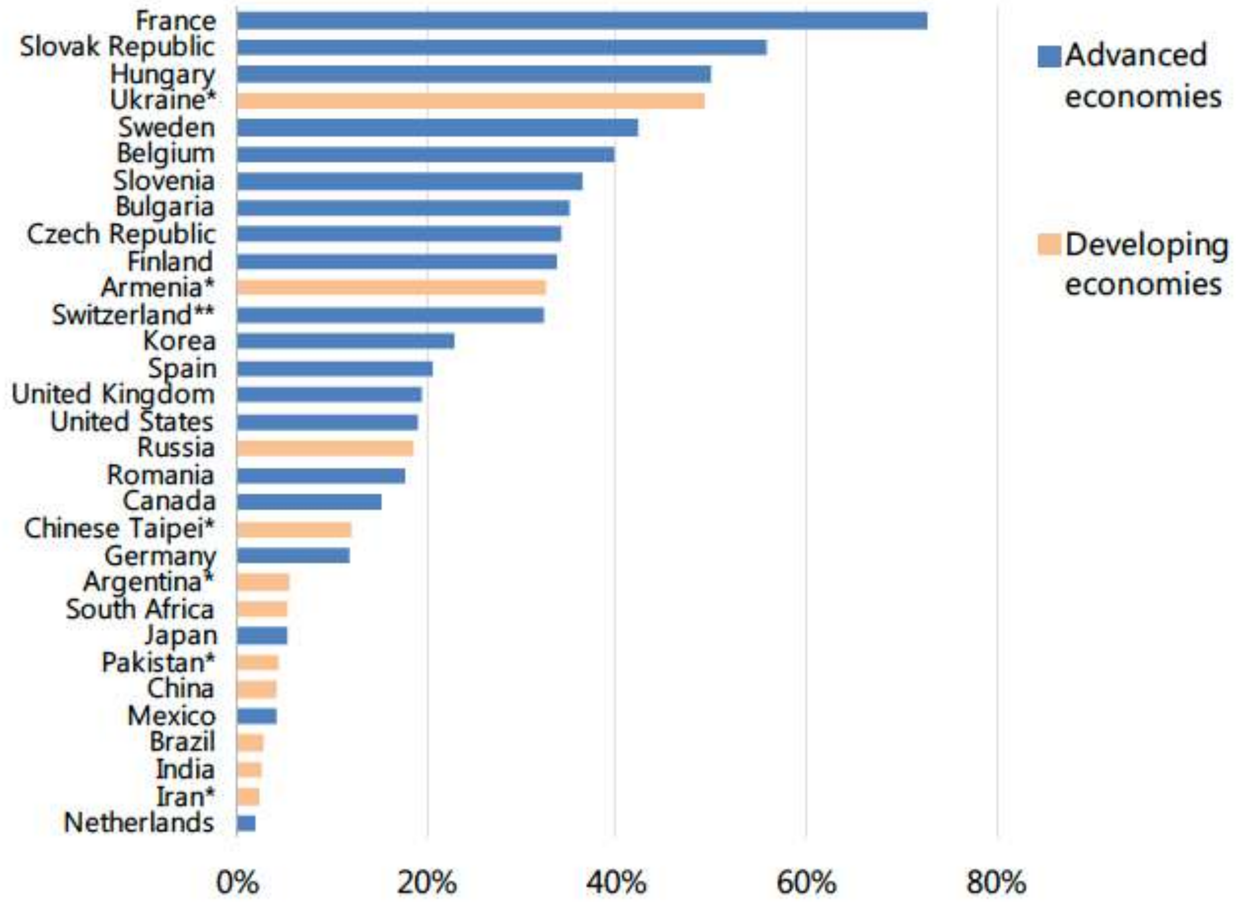
Problems /



Nuclear Power

- Why nuclear power? What is it used for? What are its main advantages over other forms of energy?
- How important is nuclear power for the production of electricity? How much electricity, worldwide, is produced by nuclear power plants?

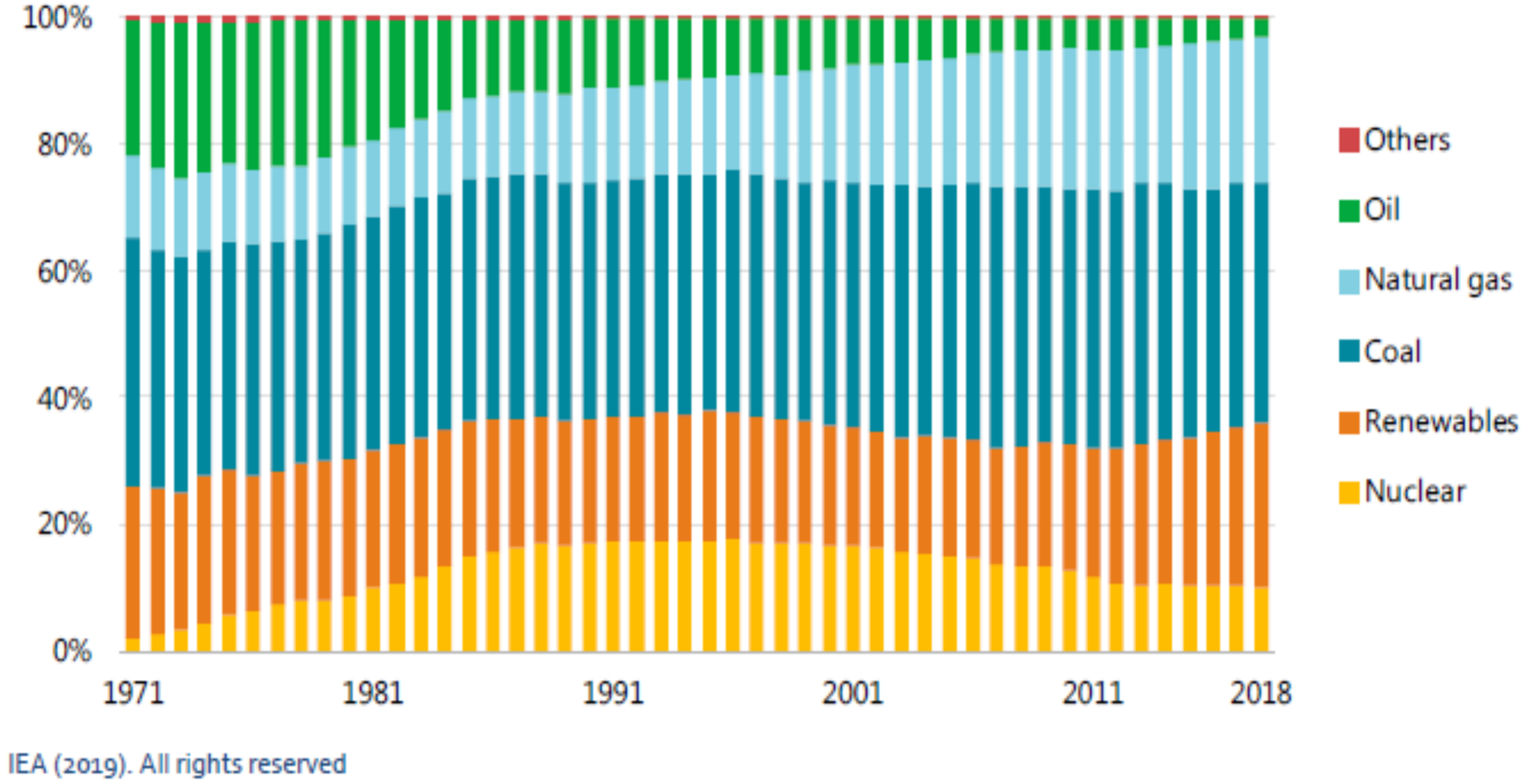
Electricity from Nuclear Power Plants



*2016 data; **2017 data.

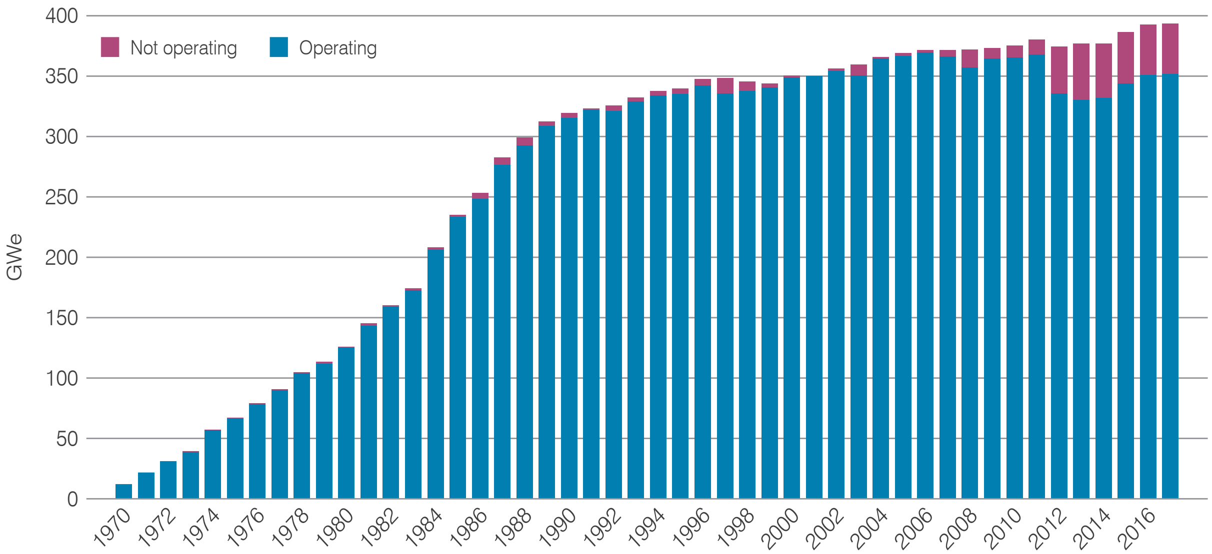
Source: IEA, 2019

Share of energy sources in global electricity generation



Source: IEA, 2019

World nuclear generation capacity & Type



Source: World Nuclear Association, IAEA PRIS

Table 1. Operable nuclear power reactors at year-end 2017

	Africa	Asia	East Europe & Russia	North America	South America	West & Central Europe	Total
BWR		28		36		11 (-2)	75 (-2)
FNR		1	2				3
GCR						14	14
LWGR			15				15
PHWR		25		19	3	2	49
PWR	2	86 (+3)	33	65	2	104	292 (+3)
Total	2	140 (+3)	50	120	5	131 (-2)	448 (+1)

Source: World Nuclear Association, IAEA PRIS

Table 2. Shut down reactors in 2017

	Country	Capacity (net)	First grid connection	Permanent shutdown	Type of reactor
Gundremmingen B	Germany	1284 MWe	16 March 1984	31 December 2017	BWR
Kori 1	South Korea	576 MWe	26 June 1977	18 June 2017	PWR
Monju	Japan	246 MWe	29 August 1995	5 December 2017	FNR
Oskarshamn 1	Sweden	473 MWe	19 August 1971	19 June 2017	BWR
Santa Maria De Garoña	Spain	446 MWe	2 March 1971	2 August 2017	BWR

Source: World Nuclear Association, IAEA PRIS

Table 3. Reactors under construction by region year-end 2017 (change since 2016)

	BWR	FNR	HTR	PHWR	PWR	Total
Asia	4	1	1	4	30	40
East Europe & Russia					11	11
North America					2 (-2)	2 (-2)
South America					2	2
West & Central Europe					4	4
Total	**4**	**1**	**1**	**4**	**49 (-2)**	**59 (-2)**

Source: World Nuclear Association, IAEA PRIS

The four construction starts in 2017 are listed in Table 4.

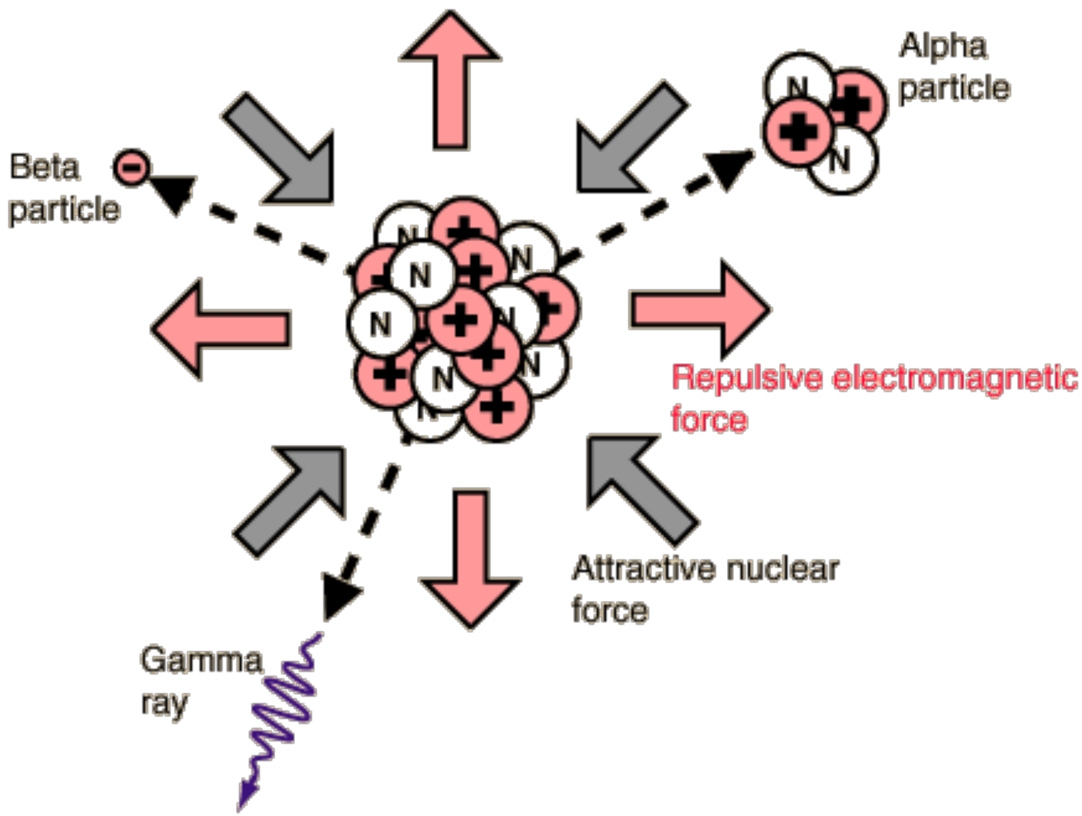
Table 4. Reactor construction starts 2017

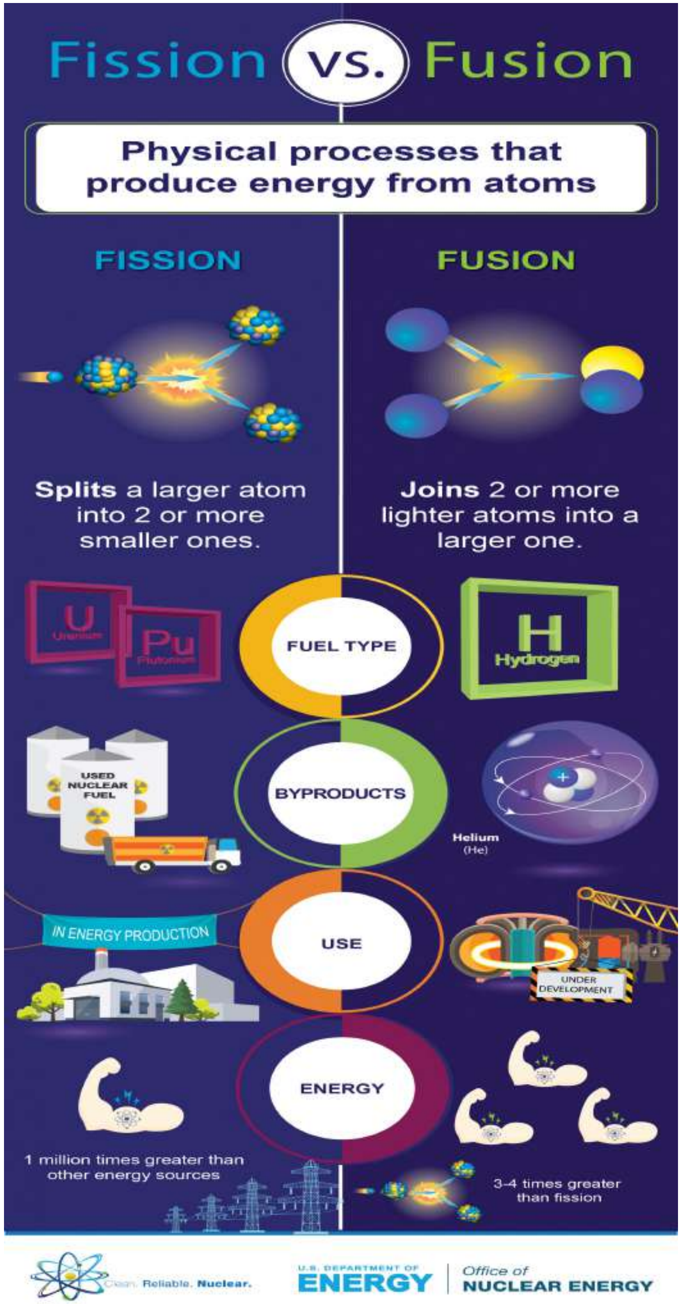
Reactor	Country	Capacity (MWe)	Start of construction	Type of reactor
Kudankulam 3	India	917	29 June 2017	PWR (VVER)
Kudankulam 4	India	917	23 October 2017	PWR (VVER)
Rooppur 1	Bangladesh	1080	30 November 2017	PWR (VVER)
Shin-Kori 5	South Korea	1340	1 April 2017	PWR

Source: World Nuclear Association, IAEA PRIS

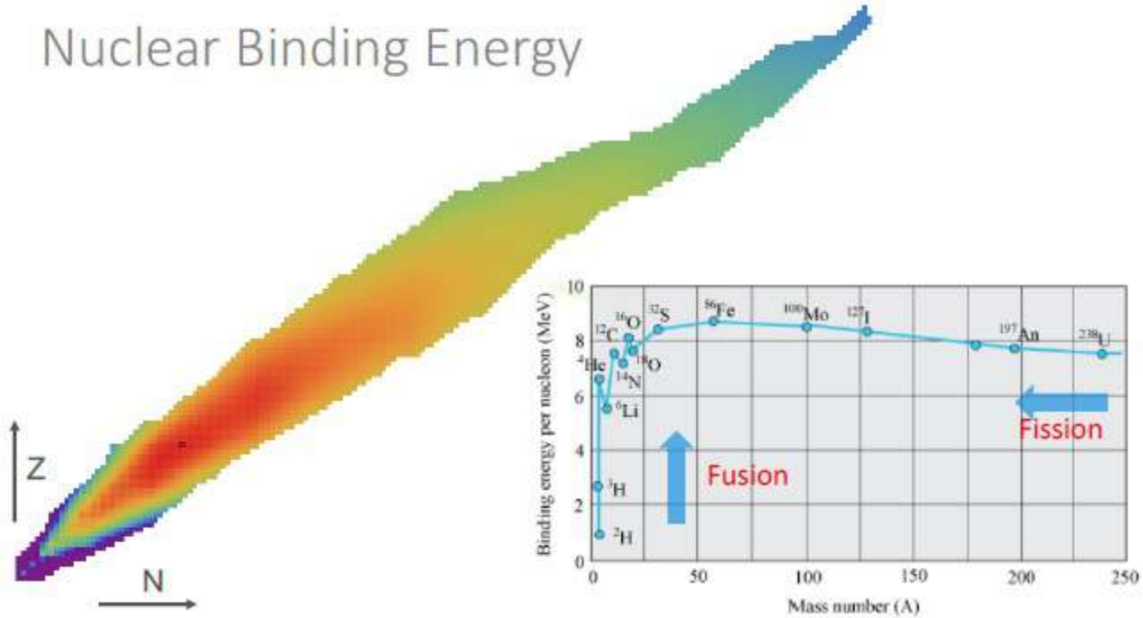
Nuclear Radiation

- What is nuclear radiation (ie, “radioactivity”)?
- How is it emitted?





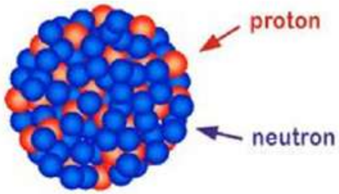
Nuclear Binding Energy



Source: TU Delft

Fission reaction

$$n + {}^{235}\text{U} \rightarrow {}^{236}\text{U} \rightarrow 2 \text{ Fission Products}$$
$$+ \nu\ (\approx 2.5)n$$
$$+ 6\ \beta$$
$$+ 10\ \gamma$$
$$+ \text{neutrinos}$$
$$+ \text{kinetic energy } (\approx 200 \text{ MeV})$$

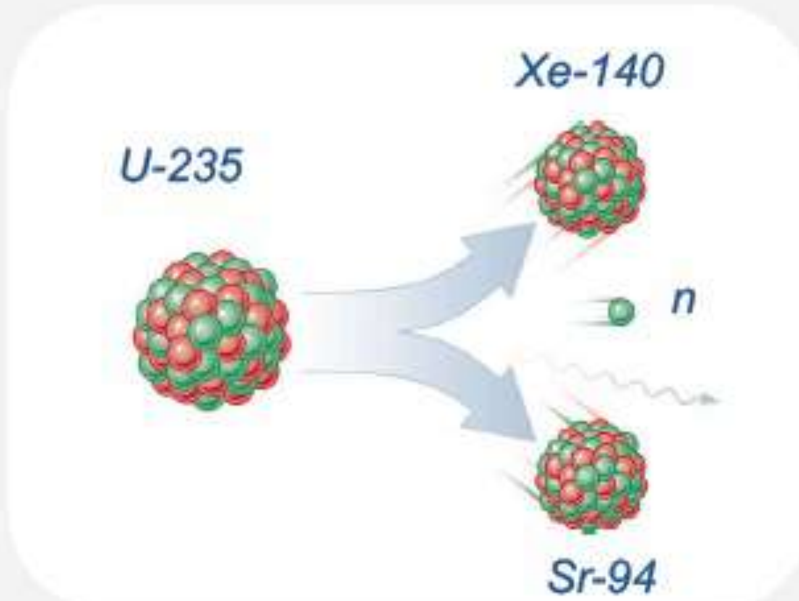


Uranium Nucleus

Nuclear energy from fission

$E=Mc^2$

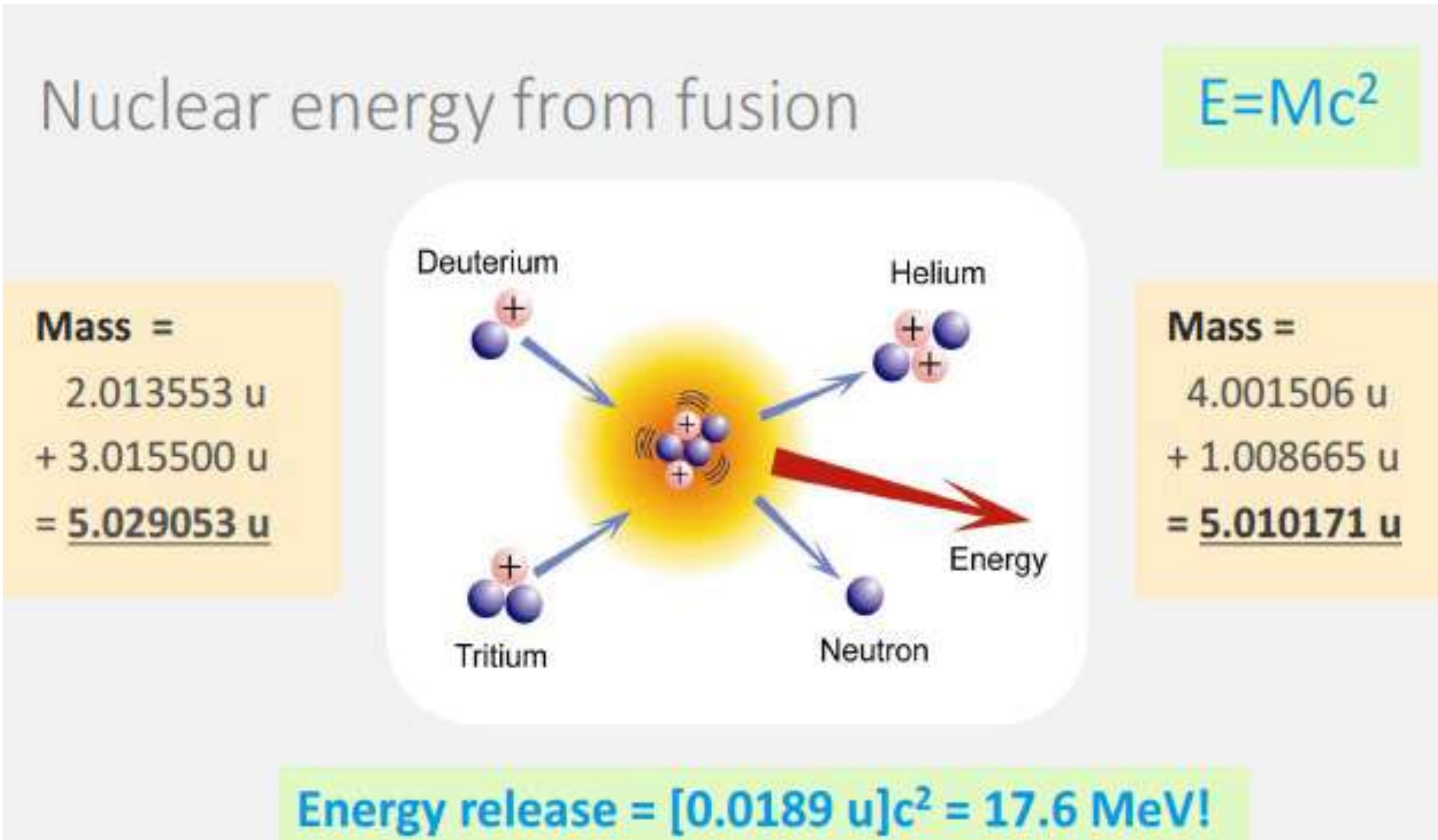
Mass (^{235}U) =
<u>235.04393 u</u>



Mass =
139.92165 u
+ 93.91536 u
+ 1.00866 u
= <u>234.84567 u</u>

Energy release = [0.198 u]c^2 = 185 MeV!!

Source: TU Delft



Source: TU Delft

Decay of Radioactive Isotopes

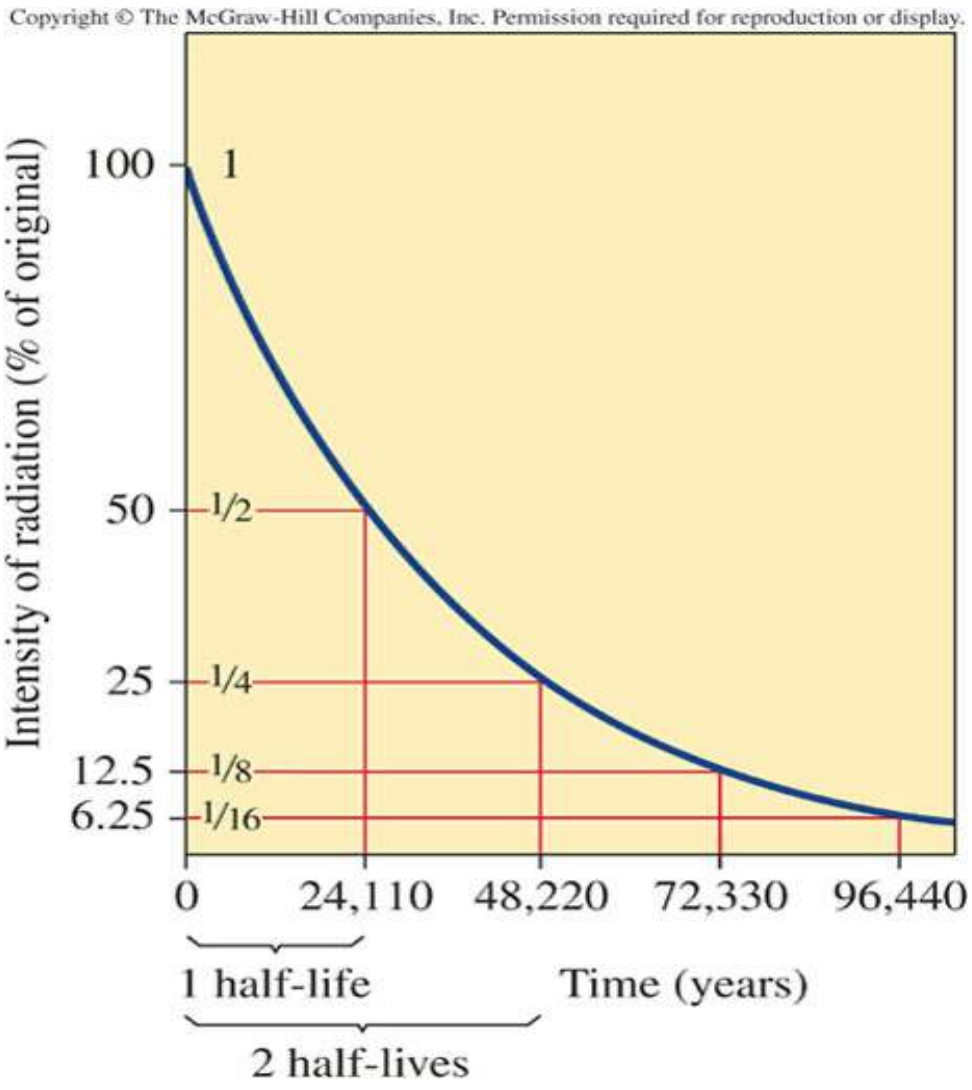
- Some atomic nuclei are inherently unstable; they decay to other nuclei (other elements) while emitting radiation

- These radioactive nuclei are called *radionuclides* or *radioisotopes*.

- Radiation is emitted as a rate unique to each isotope
  - Characterized by the *half-life* or *natural lifetime*

$$t_{1/2} = 0.693\tau$$

  - This rate ***cannot be changed*** by any chemical transformation



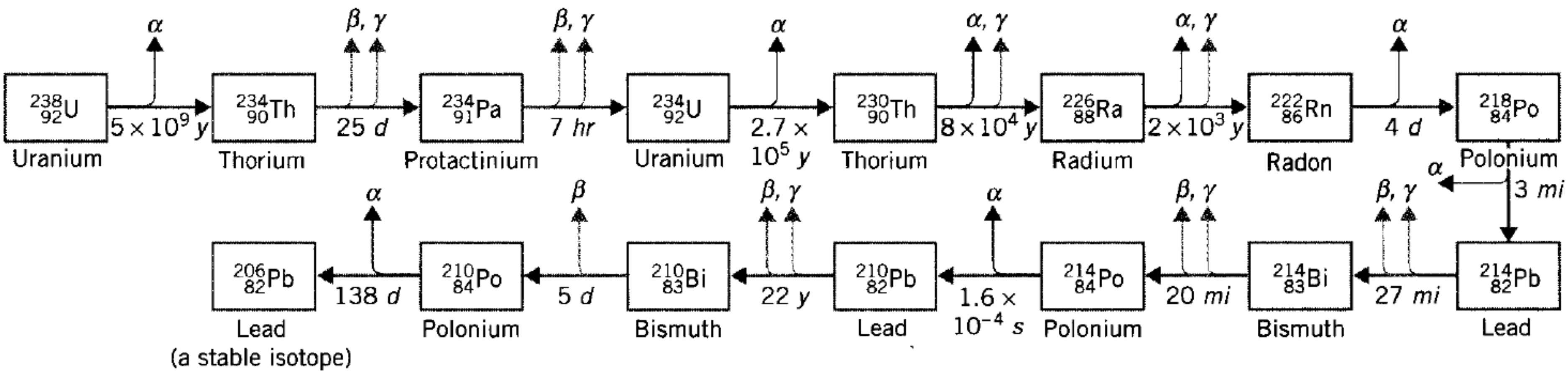
Half-Lives of Some Radioisotopes

Table 7.5 Half-Lives for Selected Isotopes

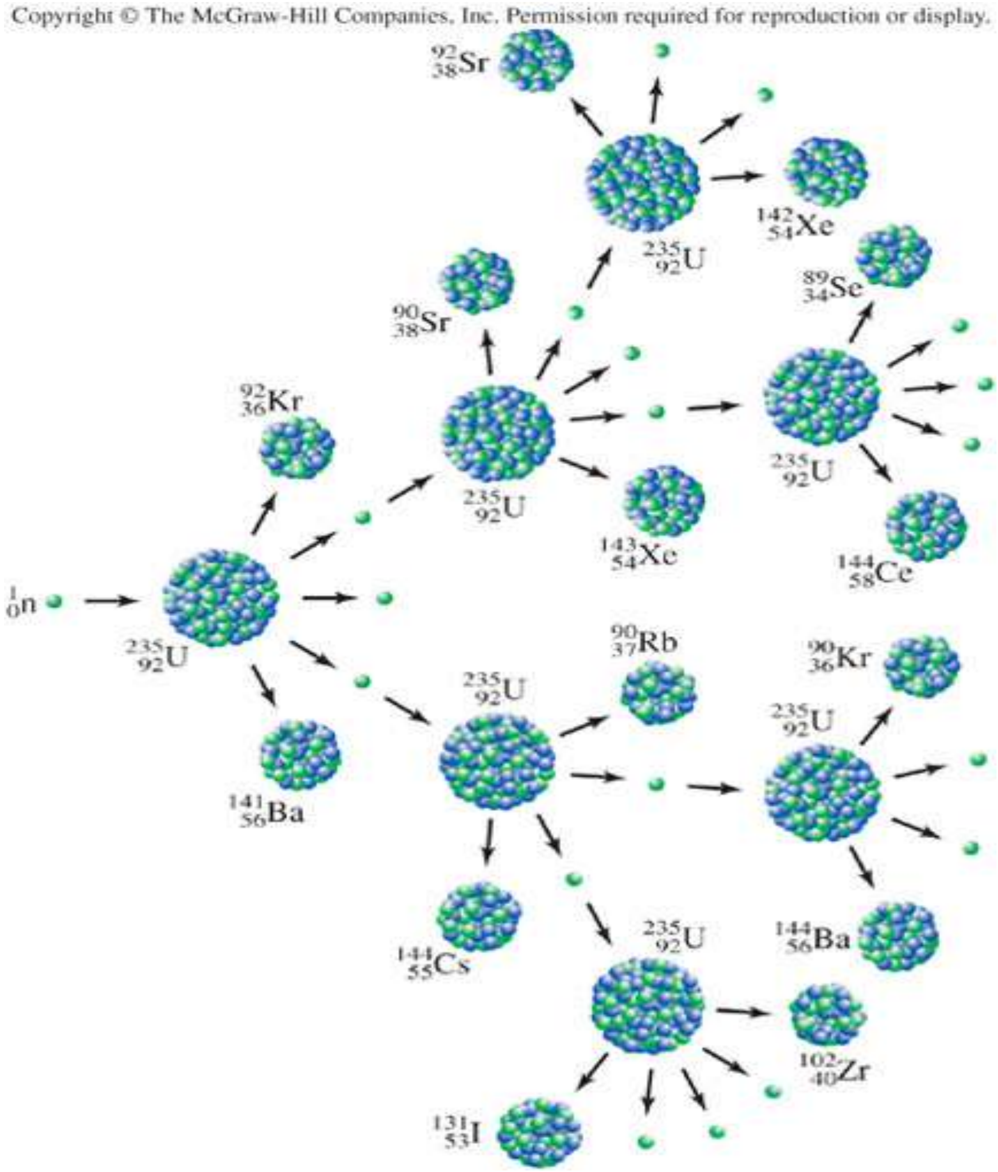
Radioisotope	Half-life
Uranium-238	4.5×10^9 years
Potassium-40	1.3×10^9 years
Plutonium-239	24,110 years
Carbon-14	5715 years
Cesium-137	30.2 years
Strontium-90	29.1 years
Thorium-234	24.1 days
Radon-222	3.82 days
Iodine-131	8.04 days
Plutonium-231	8.5 minutes
Polonium-214	0.00016 seconds

Uranium-238 Decay Series

- Uranium
  - Most common isotope is uranium-238
    - Class exercise: write the symbol for U-238
  - Note
    - U-235 (***NOT U-238***) is the fuel for most nuclear power plants worldwide
  - U-238 decomposes via a series of spontaneous nuclear reactions
    - Ultimate product is ***lead-206***
    - Produces a series of radioactive intermediates in its decay series
    - One of them is famous: ***radon-222***



Nuclear Chain Reactions



- Chain reaction
  - Neutron products induce further fission rxns
  - Daughter reactions produce still more neutrons that can induce reactions, etc
- *Generation ratio*
  - Defined as the fraction of neutron products that can induce a further (neutron-producing) fission rxn
  - Needs to be controlled at exactly 1.00000 (etc)
    - Too small: rxn is rapidly quenched
    - Too large: boom! (It "goes critical")
- How is the generation ratio controlled? Wait and see…

Nuclear Power

- There is a lot a power contained in an atomic nucleus. But natural radioactive decay – such as alpha and beta decay – is not controllable. So how do can we harness nuclear energy in a controllable fashion?

- Answer: Neutron-induced nuclear fission, such as the following rxn:

$$^{235}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{236}_{92}\mathrm{U} \rightarrow ^{141}_{56}\mathrm{Ba} + ^{92}_{36}\mathrm{Kr} + 3^{1}_{0}n$$

- ***Key: control the concentration and energy of neutrons that induce the reaction!***
- Lots of excess energy carried away by the neutron products
  - This energy can be used to create steam, electricity, etc
- Fission products are radioactive
  - Other products are possible, too.
- *Exercise*: write a balanced equation for the neutron-activated fission of U-235 to produce Te-137 and Zr-97. How many neutrons are produced?

Thorium utilisation in experimental and nuclear power reactor [43].

Name and location	Type of reactor	Power	Fuel	Period
CIRUS, India	MTR, thermal	40MWt	"J" rod of Th and ThO_2	1960–2010
Indian point, USA	LBWR PWR, (pin assembly)	285MWe	Th + ^{233}U (oxide pellets)	1962–1980
Elk river, USA	BWR	24MWe	Th + ^{235}U + ^{238}U (oxide pellets)	1963–1968
MSRE, ORNL, USA	MSR	7.5MWt	U^{233} molten fluoride	1964–1969
Peach bottom, USA	HTGR, experimental (prismatic core)	40MWe	Th + ^{235}U, Coated fuel particles, Oxide & Dicarbides	1966–1972
Dragon, UK OECD- Euratom	HTGR, Experimental (Pin-in-Block Design)	20MWt	Th + ^{235}U, Coated fuel particles, Oxide & Dicarbides	1966–1973
AVR, Germany	HTGR, Experimental (Pebble-bed reactor)	15MWe	Th + ^{235}U, Coated fuel particles, Oxide & Dicarbides	1967–1988
Lingen, Germany	BWR (Irradiation testing)	60MWe	(Th, Pu)O_2 pellets	1973
SUSPOP/KSTR KEMA, Netherland	Aqueous Homogenous Suspension	1MWt	Th + HEU, Oxide pellet	1974–1977
Fort St Vrain, USA	HTGR, power (Prismatic core)	330MWe	Th + ^{235}U, Coated fuel particles, Dicarbides	1976–1989
Shippingport, USA	LWBR PWR, (Pin Assembly)	100MWe	Th + ^{233}U (Oxide pellets)	1977–1980
THTR-300, Germany	HTGR, Experimental (Pebble-bed reactor)	300MWe	Th + ^{235}U, Coated fuel particles, Oxide & Dicarbides	1985–1989
FBTR, India	LMFBR, Pin Assembly	40MWt	ThO_2 Blanket	1985-present
DHRUVA, India	MTR Thermal	100MWt	"J" rod of ThO_2	1985-date
KAMINI, India	MTR, Thermal (for Research)	30kWt	Al + ^{233}U	1996-date
KAPS 1& 2; KGS 1& 2; RAPS 2, 3, & 4, India	PHWR, (Pin Assembly)	220MWe	ThO_2 pellets for initial flux flattening	new existing
NRU & NRX, Canada	MTR (Pin Assembly)	–	Th + ^{235}U, Test fuel	–

Source: Humphrey, 2018

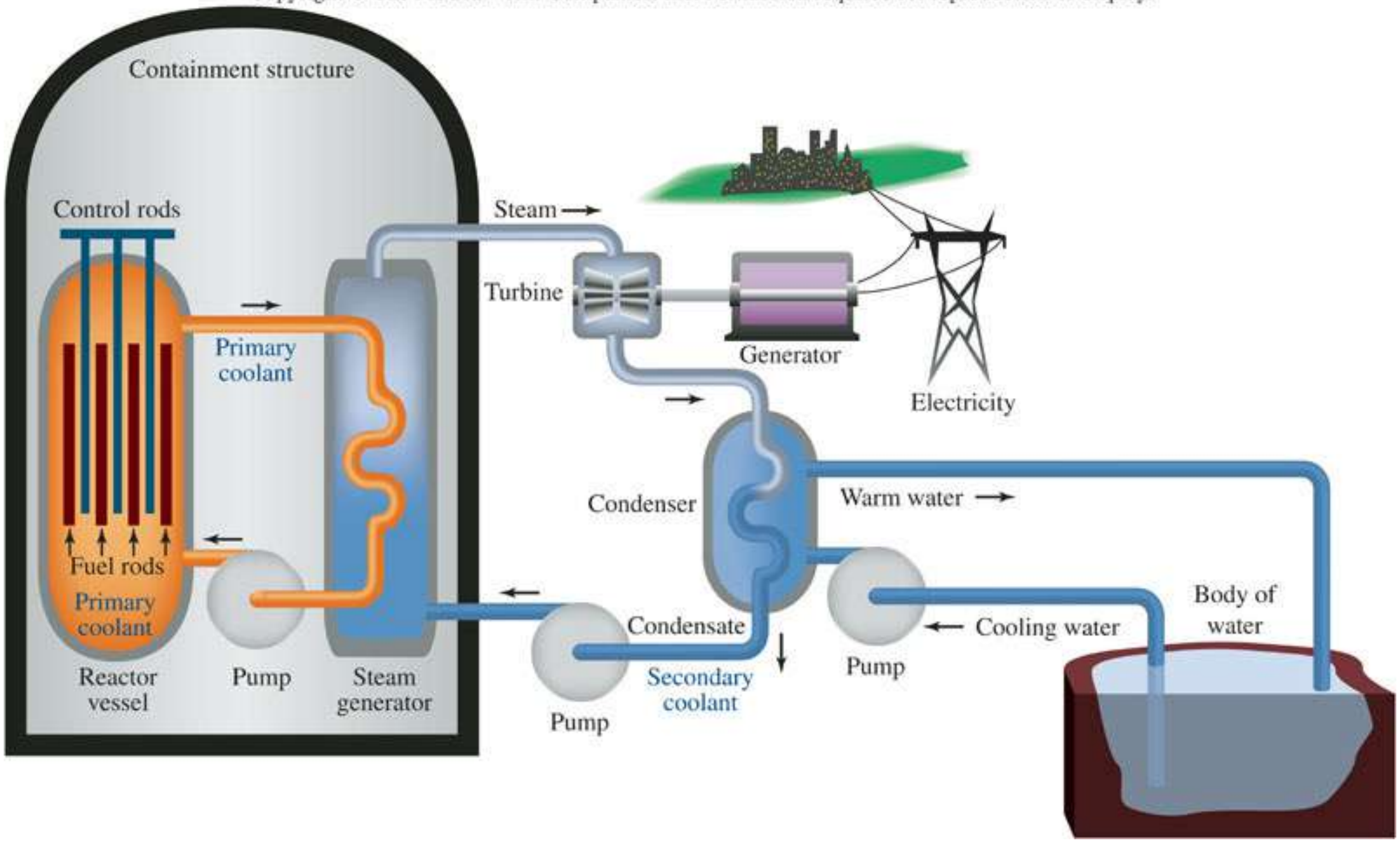
Candidate thorium cycles. Author.

Core type	Configuration	Coolant	Moderator
Molten salt	Two fluid reactor	Li fluoride	Graphite
		Be fluoride	Graphite
	Single fluid reactor	LBF eutectic	
Solid core rod bundles	CANDU	Deuterium	Deuterium
	Thorium blanket	Molten salt	Graphite
	Energy amplifier	Molten lead	None
TRISO (Prismatic)	VHTR/HTGR	Helium	Graphite
	LS-VHTR	Liquid salt	Graphite
TRISO (Pebble bed)	Thorium/uranium mixed-fill pebbles	Helium	Graphite
	Mixture of thorium and uranium pebbles	Helium	Graphite
	LS-VHTR	Liquid salt	Graphite

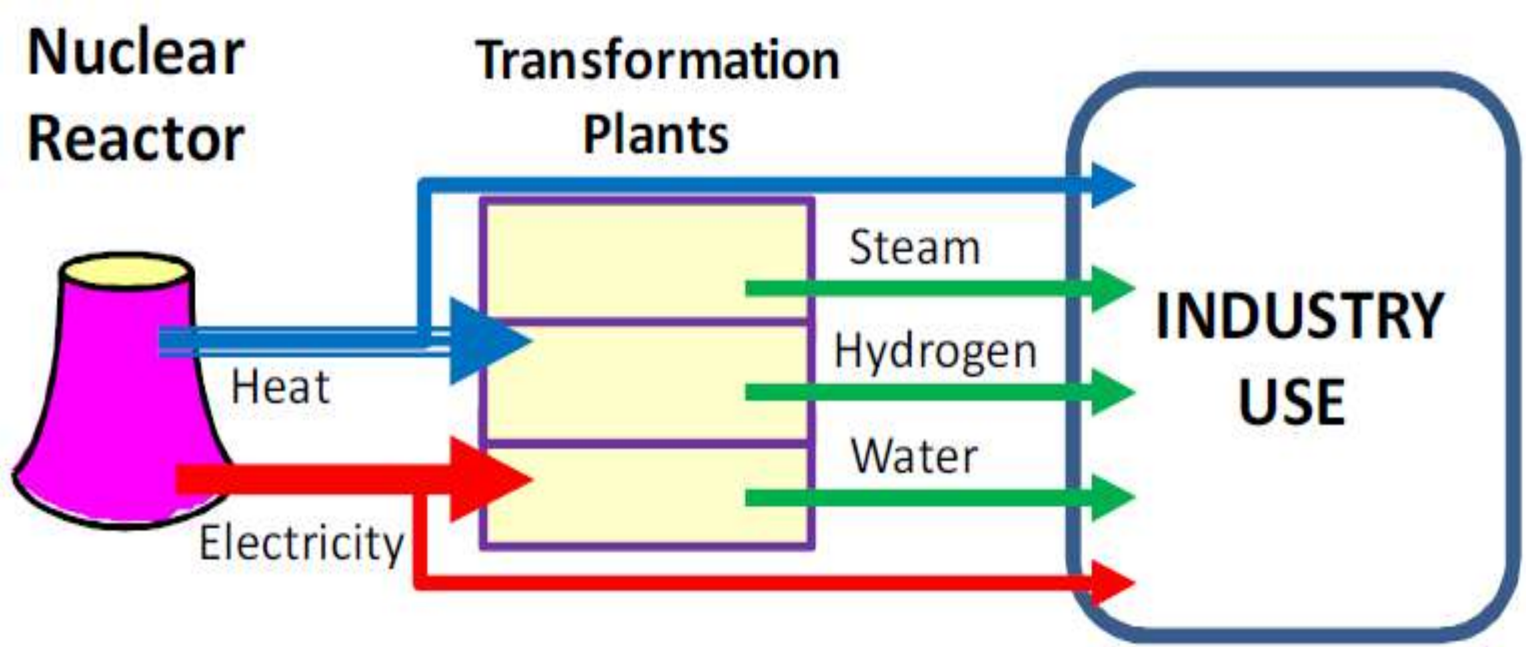
Source: Schaffer, 2013

Nuclear Power Plants

Nuclear Power Plants



Coupling a nuclear reactor to an on-site industrial plant

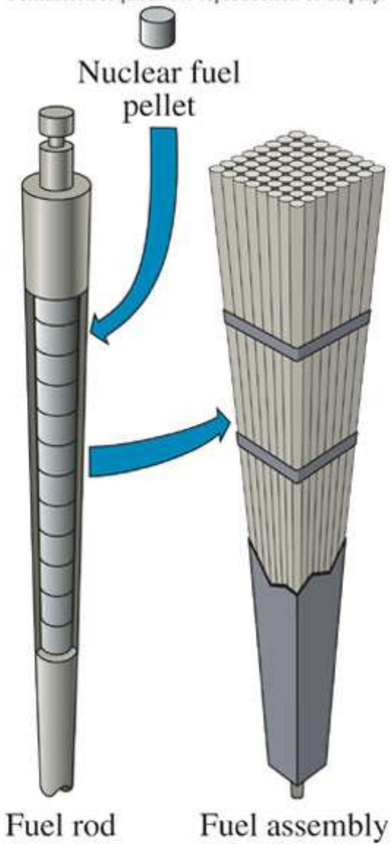


Source: IAEA

Elements in the Nuclear Reactor

- Fuel Rods
  - Contain the fissionable material
    - Also contain a built-in neutron source as initiator
    - Usually Be-9 is used; alpha particles cause neutron release
  - Eventually are "spent" and must be removed
    - Handling and long-term storage is the biggest safety/environmental problem with nuclear fission. Hasn't been solved to everyone's satisfaction.
  - Material: uranium oxide (usually "enriched" with U-235)
- Control Rods
  - Absorb all the neutrons
    - Cadmium, silver, indium rods all used
  - Used to control power output
    - Or for emergency shutdown
- Moderator (Primary Coolant)
  - Usually an aqueous solution of boric acid
- Secondary Coolant
  - Powers the steam generator (ie, the heat engine)

Nuclear Fuel



Reactor technology evolution

CURRENT/SHORT TERM

Light Water Reactors (LWRs)

- Pressurized Water Reactor (PWR)
- Boiling Water Reactor (BWR)

Heavy Water Reactor (PHWR)

- Pressurized Heavy Water Reactor (CANDU)

INTERMEDIATE TERM (>20 years)

Brayton Cycle Gas (He or CO_2) Cooled Reactor (GCR-GT)

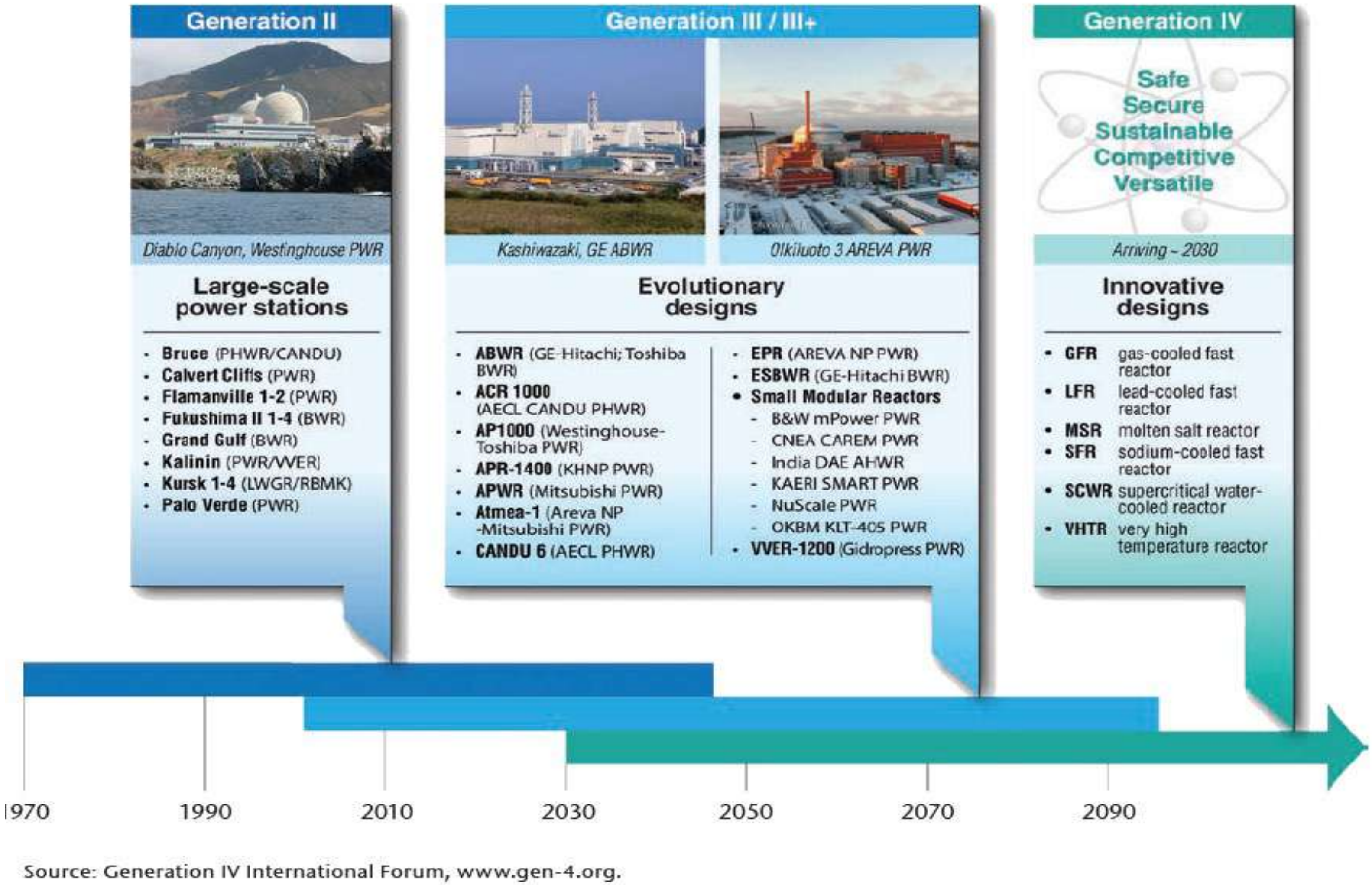
LONG TERM (>50 years)

Fast Breeder ($^{238}U \Rightarrow {}^{239}Pu$-based)

Thermal Breeder ($^{232}Th \Rightarrow {}^{233}U$-based)

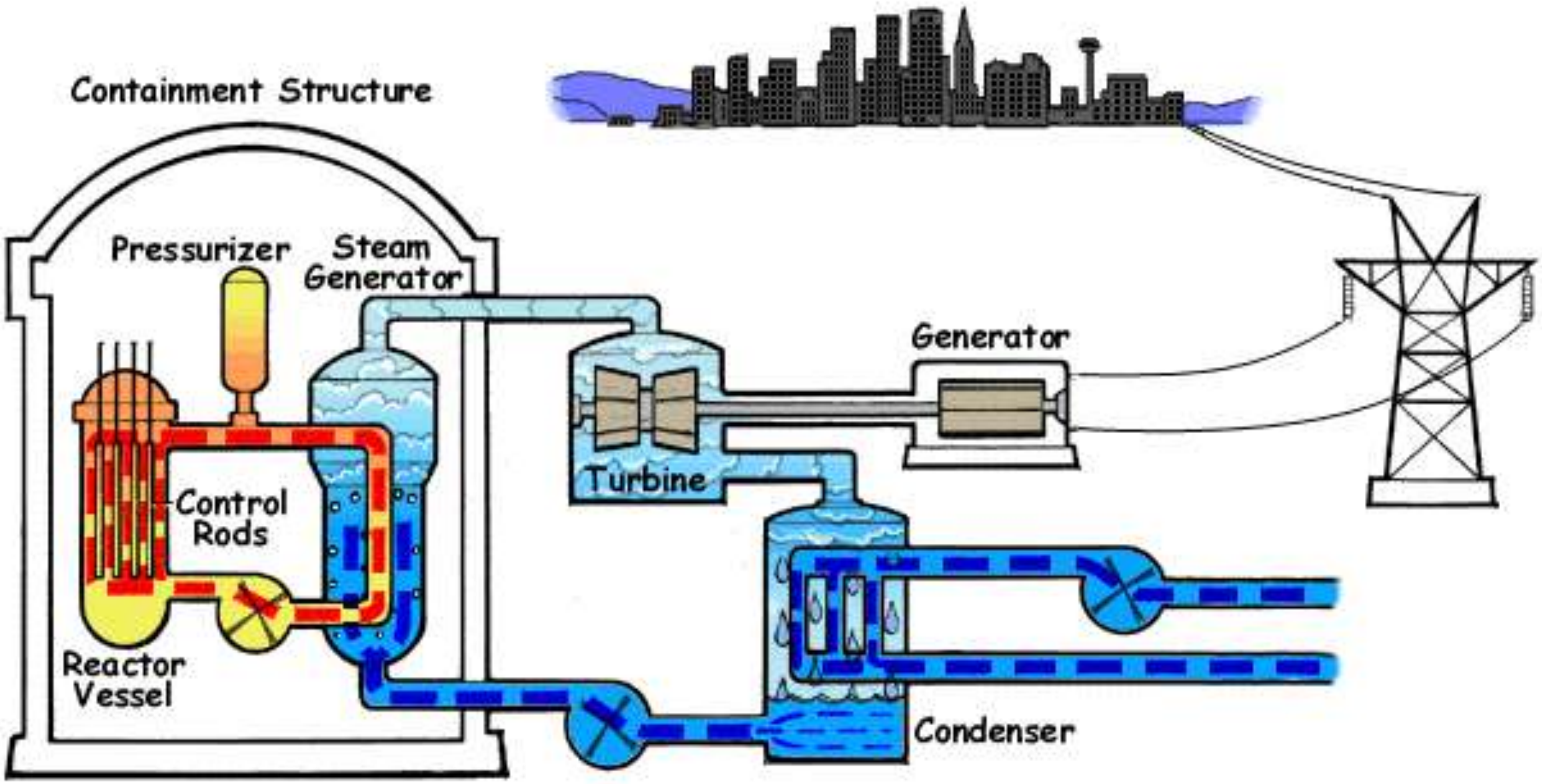
Type	Coolant	Moderator	Coolant Temperature (C)	Deployment	Current Population
Pressurized Water (PWR)	Light Water	Light Water	300	Most nuclear countries	265
Boiling Water (BWR)	Light Water	Light Water	300	Most nuclear countries	94
RBMK	Light Water	Graphite	300	Former USSR*	16
Pressurized Heavy Water (PHWR)	Heavy Water	Heavy Water	300	Canada, Korea, China, Argentina, India, Pakistan	44
Gas-Cooled (GCR)	Carbon Dioxide, Helium	Graphite	600	UK, Russia	18
Liquid Metal-Cooled (LMFBR)	Sodium, Lead, Lead-Bismuth	None	600	France, UK, Japan, Russia; former USSR, China and India	2

Evolution Fission Reactor Technology

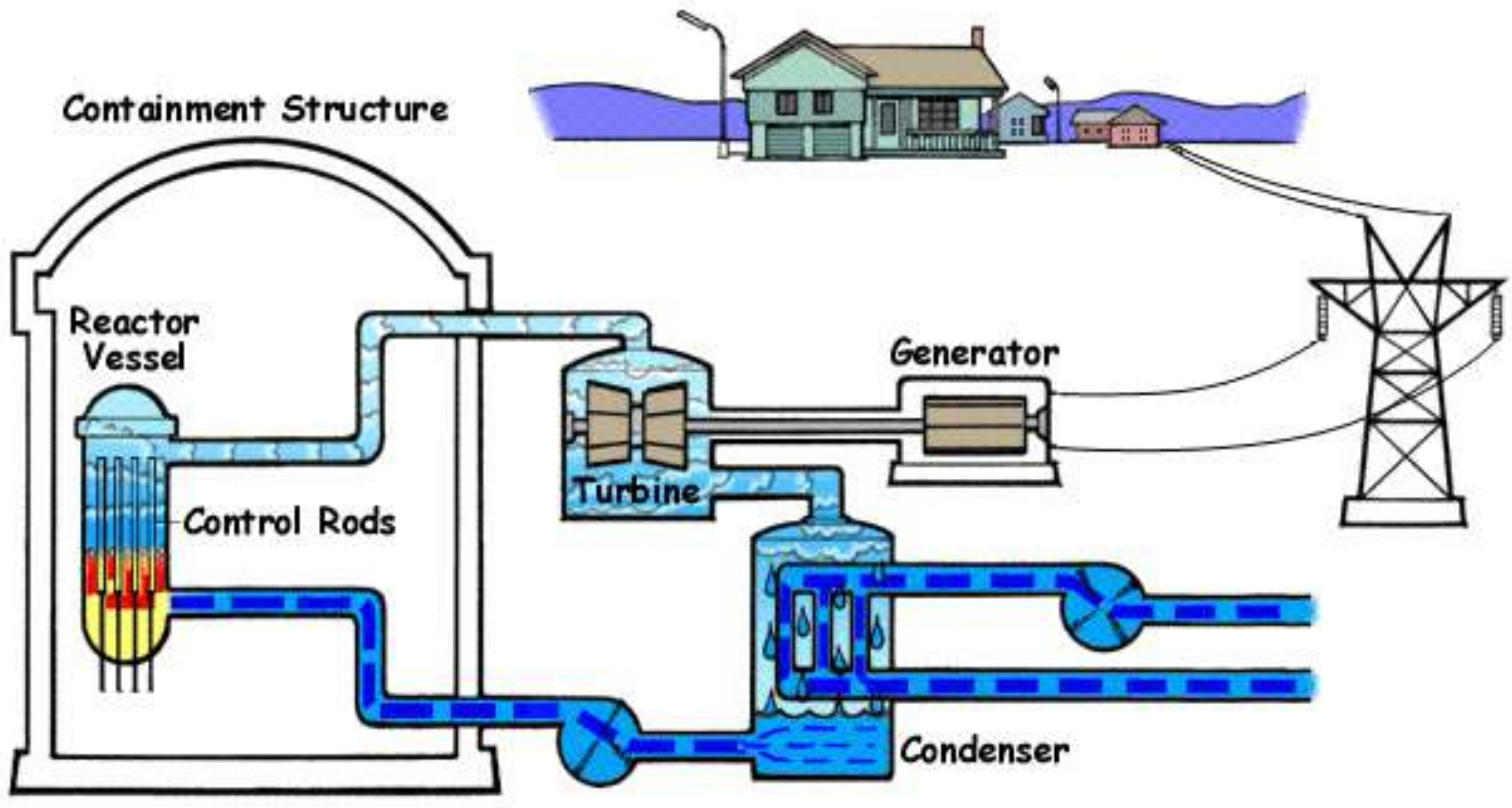


Source: IEA, 2015

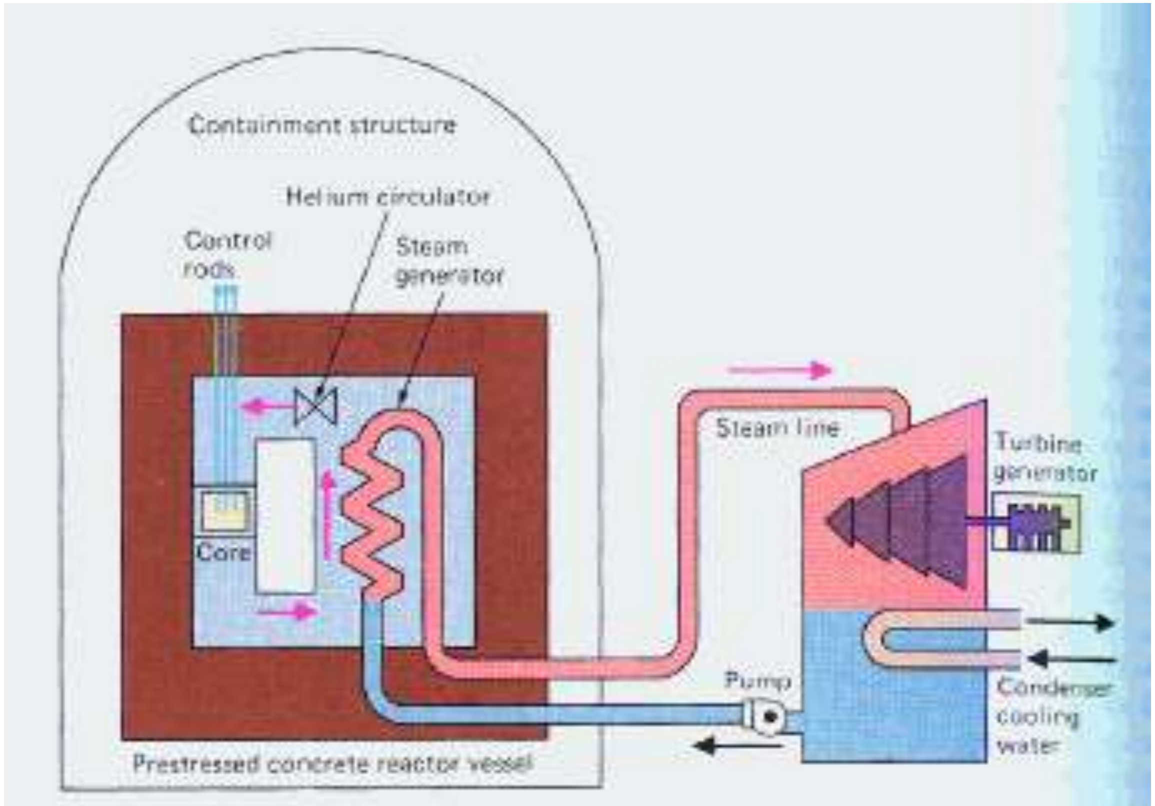
PWR


Containment Structure
Pressurizer
Steam Generator
Generator
Control Rods
Turbine
Reactor Vessel
Condenser

BWR


Containment Structure
Reactor Vessel
Control Rods
Turbine
Generator
Condenser

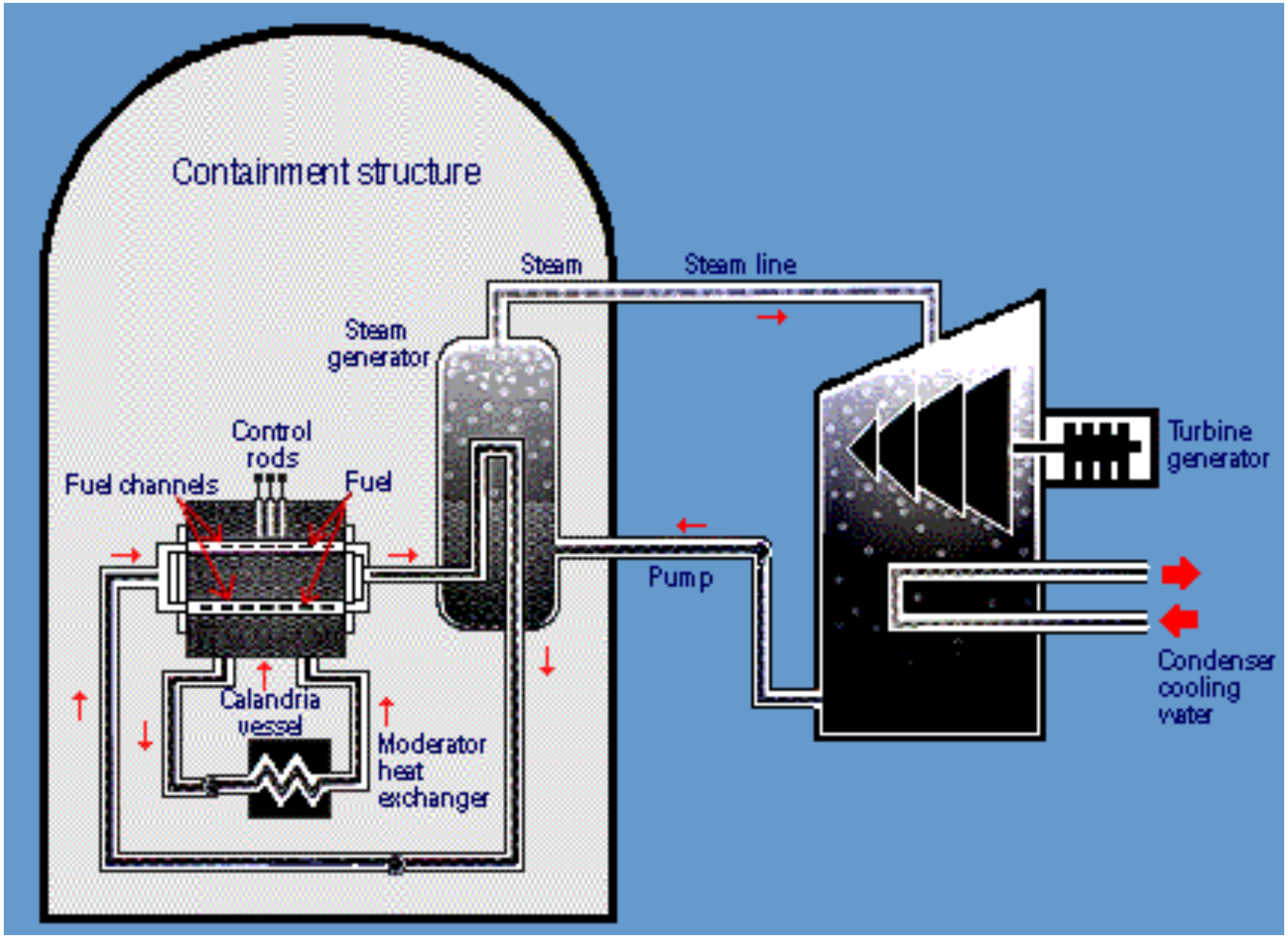
HTGR



High-Temperature, Gas-Cooled Reactor (HTGCR) This type of reactor uses graphite as a moderator and the inert gas helium as the reactor-core coolant. A steam generator forms steam and a secondary loop is used to transfer steam to the turbine.

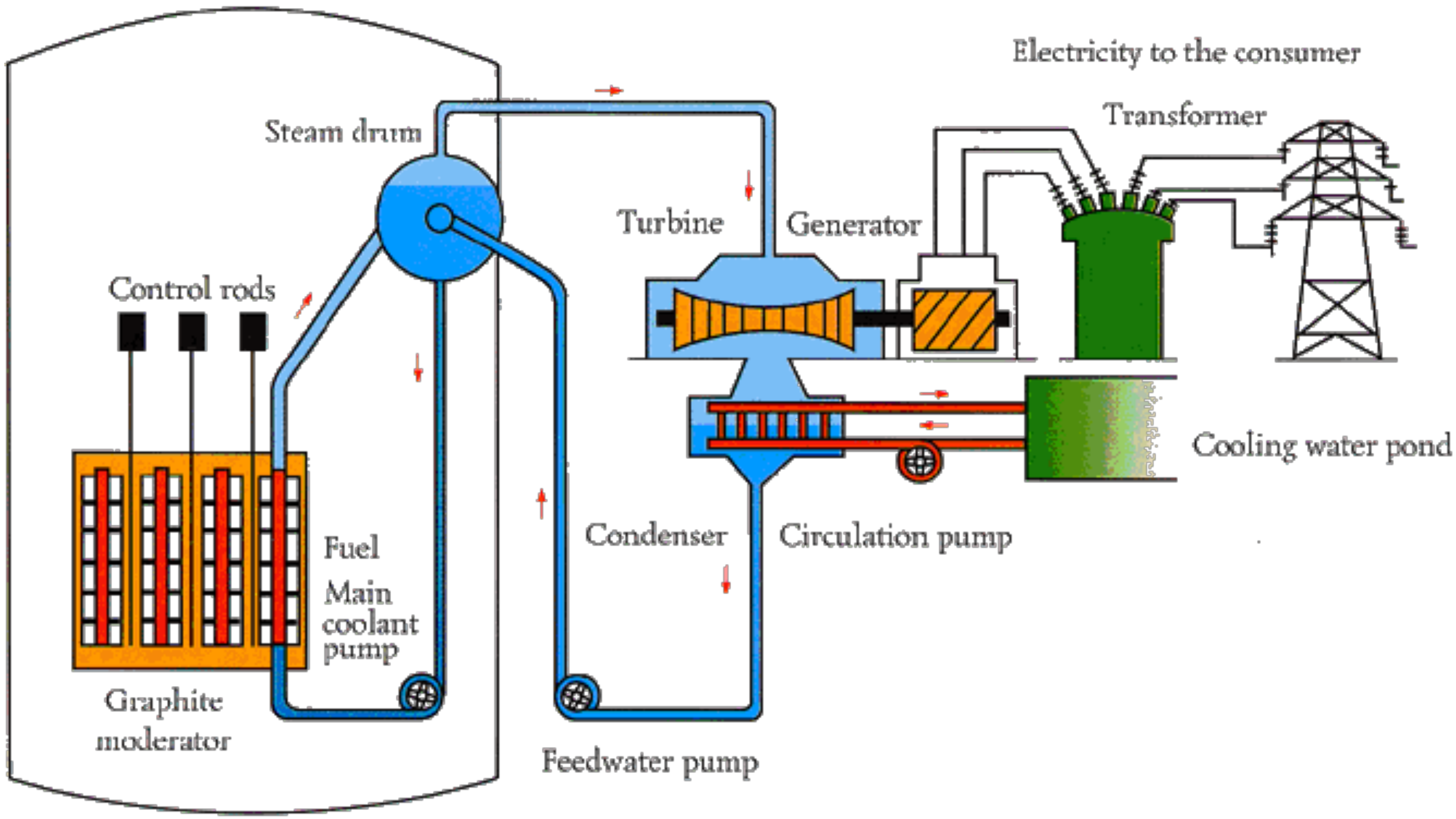
Source: Atomic Industrial Forum. U.S. Council for Energy Awareness.

CANDU-PHWR



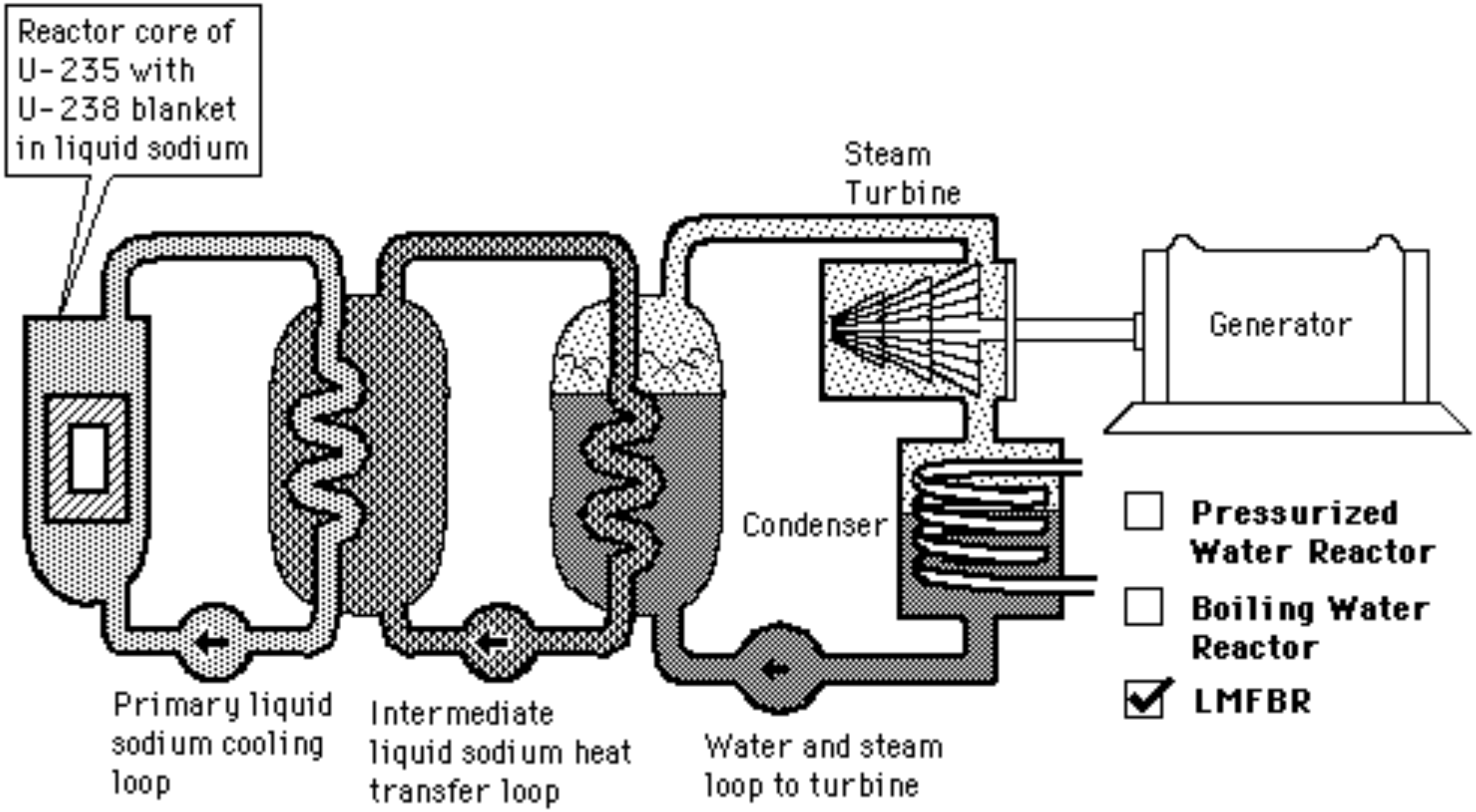
Containment structure
Steam
Steam line
Steam generator
Control rods
Fuel channels
Fuel
Turbine generator
Pump
Condenser cooling water
Calandria vessel
Moderator heat exchanger

PTGR



Note: this is a RBMK reactor design as made famous at Chernoybl.

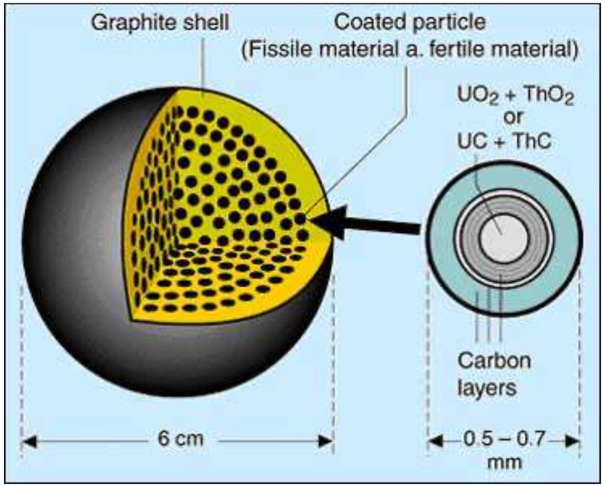
LMFBR

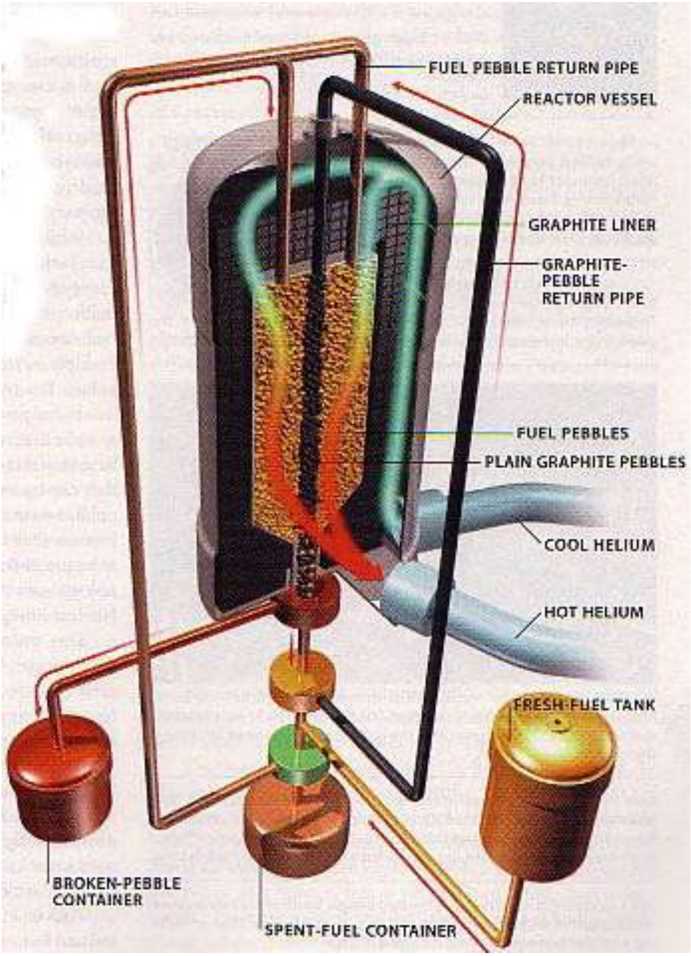


Reactor core of
U-235 with
U-238 blanket
in liquid sodium
Steam
Turbine
Generator
Condenser
Pressurized
Water Reactor
Boiling Water
Reactor
LMFBR
Primary liquid
sodium cooling
loop
Intermediate
liquid sodium heat
transfer loop
Water and steam
loop to turbine

Pebble Bed Reactor

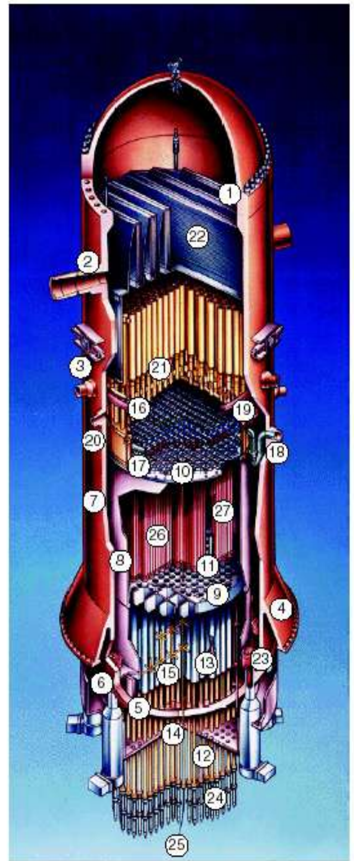
- No control rods.
- He cooled
- Use of Th fuel cycle





Advanced Boiling Water Reactor (ABWR)

- More compact design cuts construction costs and increases safety.
- Additional control rod power supply improves reliability.
- Equipment and components designed for ease of maintenance.
- Two built and operating in Japan.

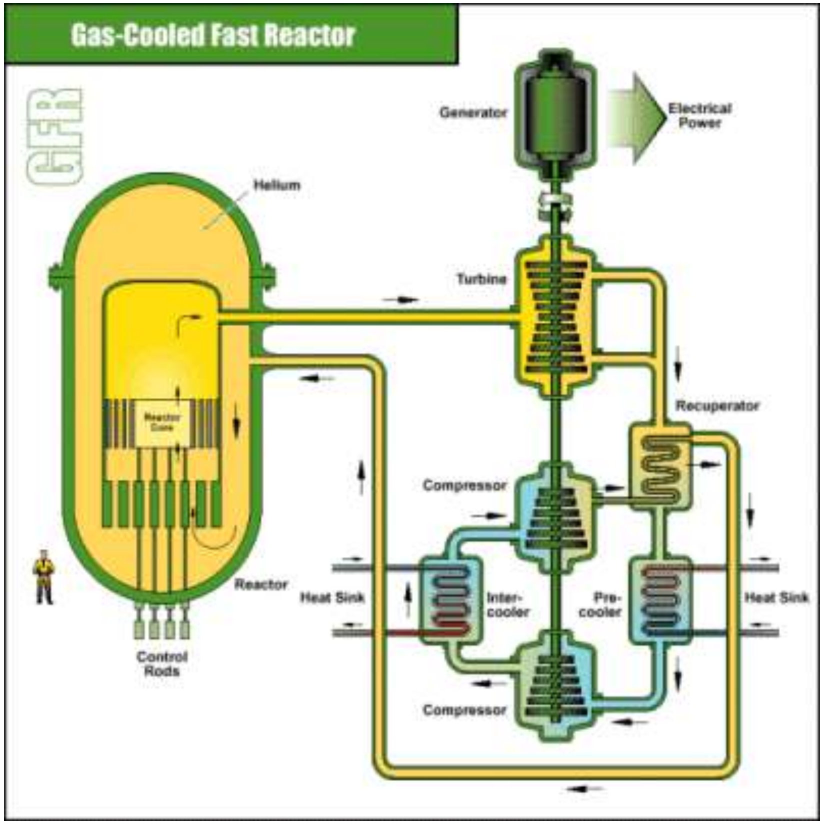


1 - Vessel flange and closure head
2 - Steam outlet flow restrictor
3 - Feedwater nozzle
4 - Vessel support skirt
5 - Vessel bottom head
6 - RIP penetrations
7 - Forged shell rings
8 - Core shroud
9 - Core plate
10 - Top guide
11 - Fuel supports
12 - Control rod drive housings
13 - Control rod guide tubes
14 - In-core housing
15 - In-core instrument guide tubes
16 - Feedwater sparger
17 - High pressure core flooder (HPCF) sparger
18 - HPCF coupling
19 - Low pressure flooder (LPFL)
20 - Shutdown cooling outlet
21 - Shroud head and steam separator assembly
22 - Steam dryer assembly
23 - Reactor internal pumps (RIP)
24 - Fine motion control rod drives
25 - Local power range monitor
26 - Fuel assemblies
27 - Control rods

Figure 3-1. ABWR Reactor Assembly

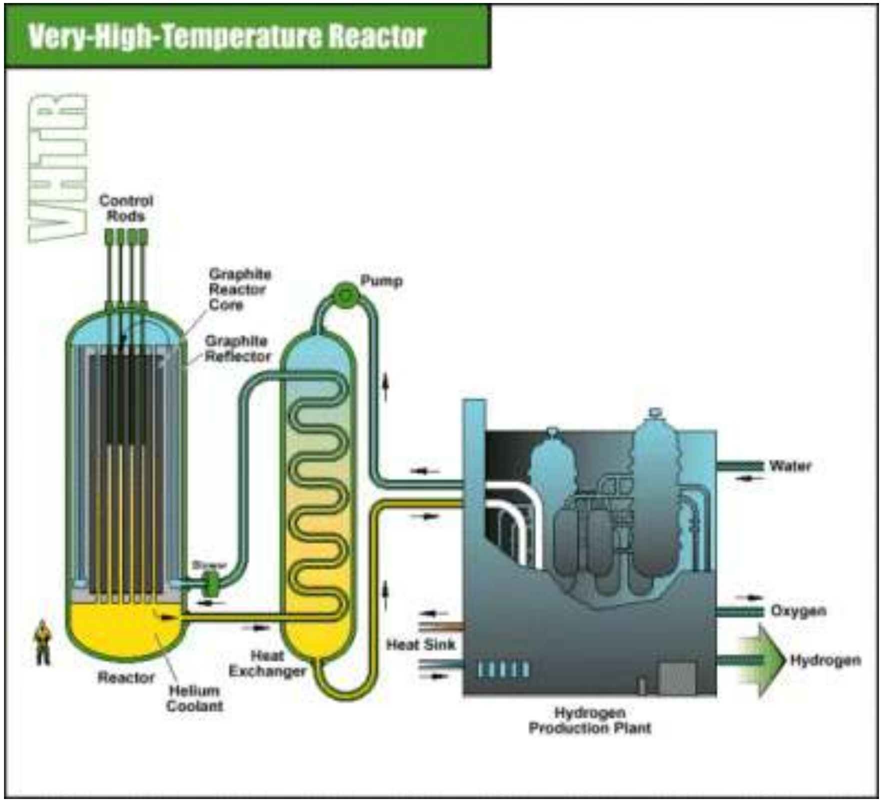
Gas Cooled Fast Reactor (GFR)

- The Gas-Cooled Fast Reactor (GFR) system features:
  - fast-neutron-spectrum
  - helium-cooled reactor (Brayton Cycle)
  - closed fuel cycle (includes reprocessing)



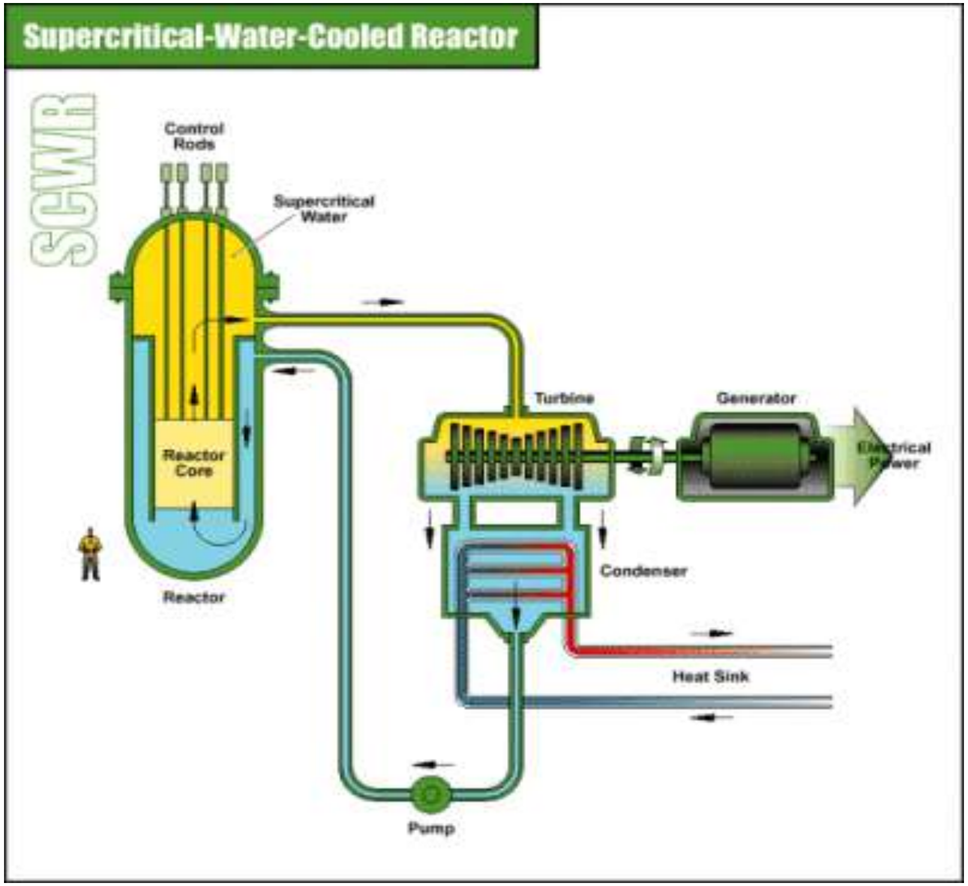
Very High Temperature Reactor (VHTR)

- The Very-High-Temperature Reactor (VHTR) is
  - graphite-moderated (thermal spectrum)
  - helium-cooled reactor
  - once-through uranium fuel cycle (no reprocessing)
  - core outlet temperatures of 1,000 ∘C



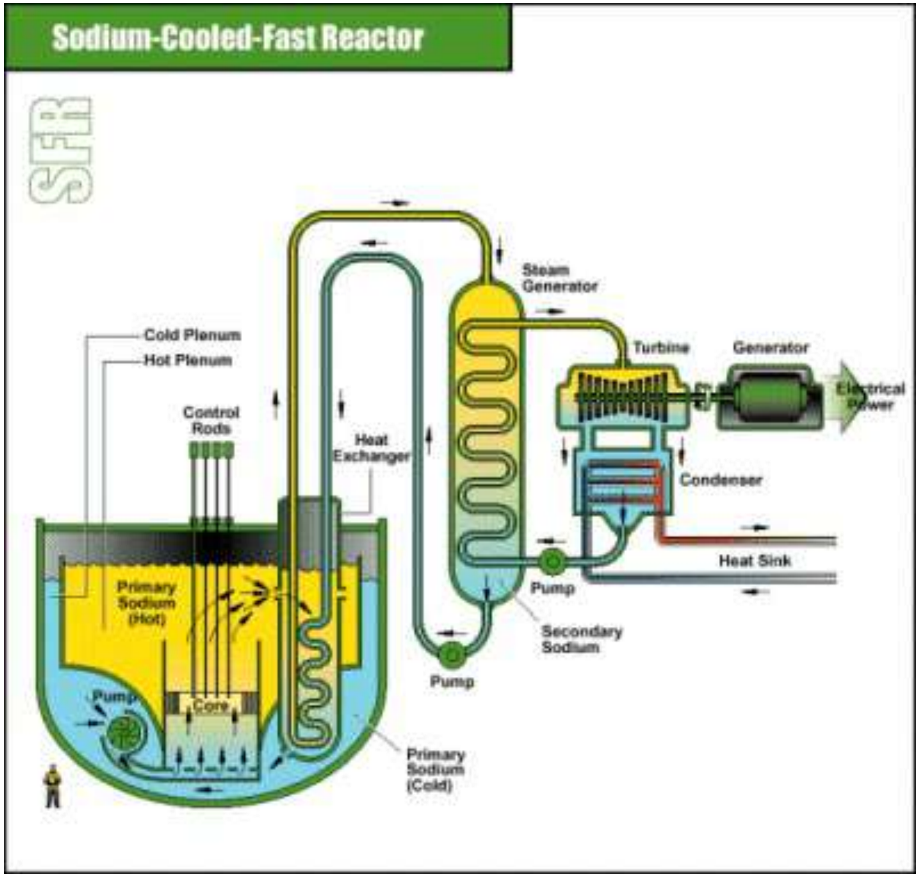
Supercritical Water Cooled Reactor (SCWR)

- The Supercritical-Water-Cooled Reactor (SCWR) system:
  - high-temperature
  - high-pressure water-cooled reactor that operates above the thermodynamic critical point of water (374 degrees Celsius, 22.1 MPa, or 705 degrees Fahrenheit, 3208 psia).



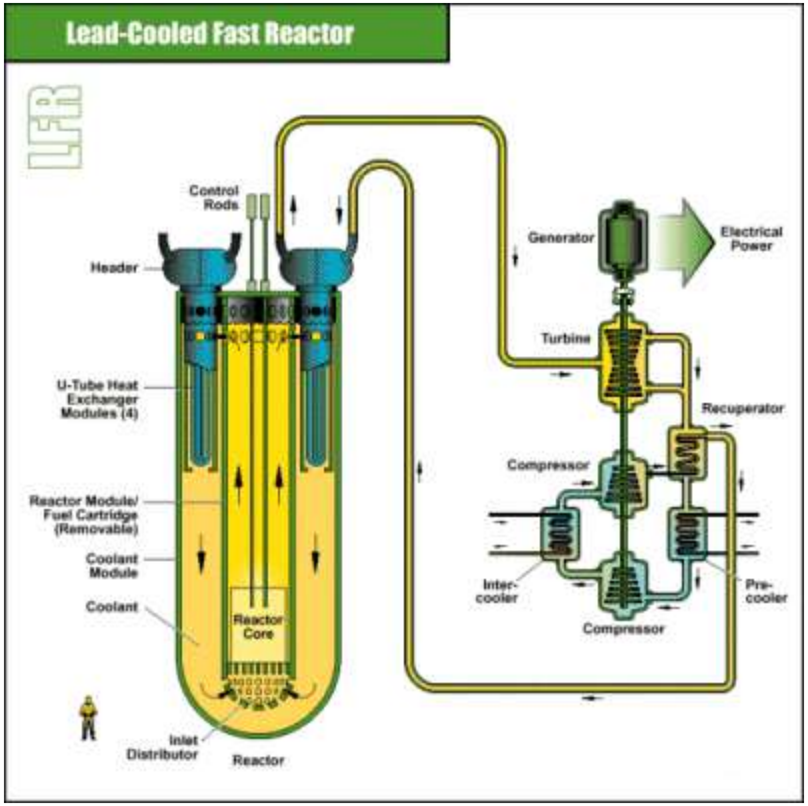
Sodium Cooled Fast Reactor (SFR)

- The Sodium-Cooled Fast Reactor (SFR) system features:
  - fast-spectrum (facilitates breeding)
  - sodium-cooled reactor
  - closed fuel cycle (reprocessing) for efficient management of actinides and conversion of fertile uranium.
  - Rankine Cycle



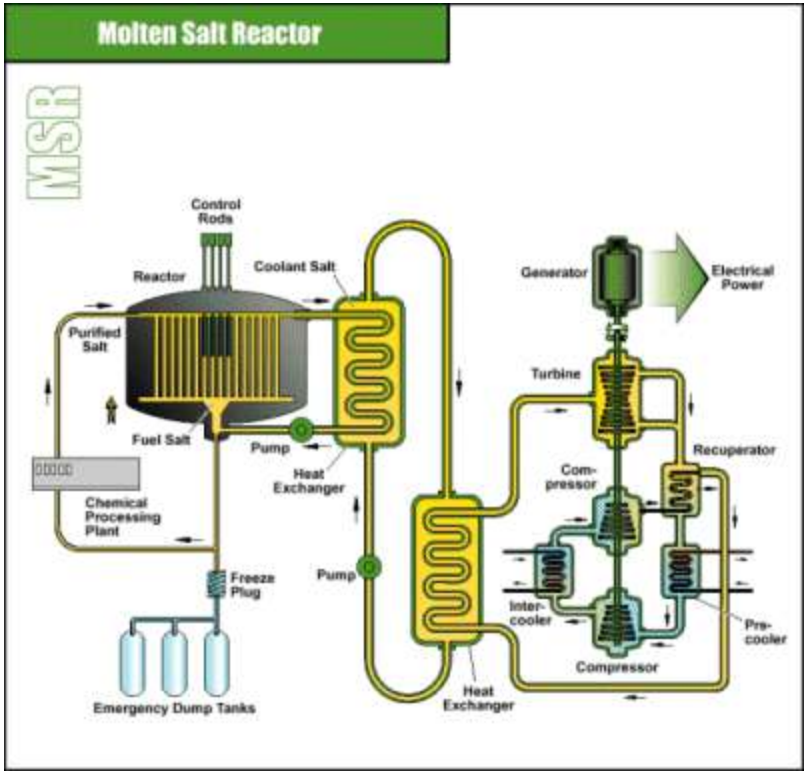
Lead Cooled Fast Reactor (LFR)

- The Lead-Cooled Fast Reactor (LFR) system features:
  - fast-spectrum lead or lead/bismuth eutectic liquid metal-cooled reactor
  - closed fuel cycle (reprocessing) for efficient conversion of fertile uranium and management of actinides.
  - Brayton Cycle
  - higher temperature enables the production of hydrogen by thermochemical processes.
  - very long refueling interval (15 to 20 years) (proliferation resistant)



Molten Salt Reactor (MSR)

- The Molten Salt Reactor (MSR) system produces fission power in a circulating molten salt fuel mixture
  - epithermal-spectrum reactor
  - full actinide recycle fuel cycle.
  - Brayton cycle
- Molten fluoride salts have excellent heat transfer characteristics and a very low vapor pressure, which reduce stresses on the vessel and piping.



Reactor technology

This Roadmap recommends the following actions:	*Proposed timeline*
Governments to recognise the value of long-term operation to maintain low-carbon generation capacity and security of energy supply, provided safety requirements are met. Clearer policies are needed to encourage operators to invest in both long-term operation and new build so as to replace retiring units.	2015-30
R&D in ageing of systems and materials is needed to support safe, long-term operation of existing nuclear power plants (NPPs) for 60 years operation or more.	Ongoing
Vendors to optimise Gen III designs to improve constructability and reduce costs. The learning rate from new build construction needs to be accelerated by rapidly integrating lessons learnt from FOAK projects (design optimisation, project management, supply chain, interactions with regulators) to ensure that NOAK plants are built on time and to budget.	Ongoing
To open up the market for small modular reactors (SMRs), governments and industry should work together to accelerate the development of SMR prototypes and the launch of construction projects (about 5 projects per design) needed to demonstrate the benefits of modular design and factory assembly.	2015-25
Governments to recognise the long-term benefits of developing Generation IV (Gen IV) systems in terms of resource utilisation and waste management, and support R&D and development of at least one or two Fast Breeder Reactor Gen IV prototypes.	2015-30
Public-private partnerships need to be put in place between governments and industry in order to develop demonstration projects for nuclear cogeneration in the area of desalination or hydrogen production.	2015-30
Incorporate feed-back from operation of Gen IV prototypes to develop FOAK Gen IV commercial plants.	2030-40

Table 3: Examples of Gen III reactor designs

Vendor	Country	Design	Type	Net capacity (MW)	In operation*	Under construction*
AREVA	France	EPR	PWR	1 600	0	4 (Finland, France, China)
AREVA/MHI	France/ Japan	ATMEA	PWR	1 100	0	0
CANDU Energy	Canada	EC6	PHWR	700	0	0
CNNC-CGN	China	Hualong-1	PWR	1 100	0	0
GE Hitachi – Toshiba	United States/ Japan	ABWR	BWR	1 400-1 700	4 (Japan)	4 (Japan, Chinese Taipei)
GE Hitachi		ESBWR	BWR	1 600	0	0
KEPCO/KHNP	Korea	APR1400	PWR	1 400	0	7 (Republic of Korea, United Arab Emirates)
Mitsubishi	Japan	APWR	PWR	1 700	0	0
ROSATOM	Russia	AES-92, AES-2006	PWR	1 000-1 200	1	10 (Russia, Belarus, China, India)
SNPTC	China	CAP1000, CAP1400	PWR	1 200-1 400	0	0
Westinghouse/ Toshiba	United States/ Japan	AP1000	PWR	1 200	0	8 (China, United States)

*: As of 31 December 2014.

SMRs under development

Design	Net output per module (MW)	Type	Designer	Country	Status
			Light-water cooled		
KLT-40S	70	Floating PWR	OKBM Afrikantov	Russia	Pre-commissioning testing
CAREM	30	PWR	CNEA	Argentina	Under construction
SMART	100	PWR	KAERI	Korea	Certified design, feasibility study to construct in Saudi Arabia (desalination)
NuScale	50 (× 12)	PWR	NuScale Power	United States	Licensing process, two projects planned in the United States (Idaho and Tennessee)
SMR-160	160	PWR	Holtec International	United States	Preliminary design
BWRX-300	300	BWR	GE Hitachi	United States	Conceptual design
(no name)	220	PWR	Rolls Royce	United Kingdom	Conceptual design
(no name)	170	PWR	CEA/EDF/Naval Group/ TechnicAtome	France	Conceptual design
			Generation IV (non-light-water cooled)		
HTR-PM	210	HTGR	Tsinghua University	China	Under construction
ACP100	100	PWR	CNNC	China	Start of construction planned for end of 2019
SC-HTGR	272	HTGR	Framatome	United States	Conceptual design
Xe-100	35	HTGR	X-energy LLC	United States	Conceptual design
4S	10	LMFR	Toshiba	Japan	Detailed design
EM2	265	GMFR	General Atomics	United States	Conceptual design
IMSR	190	MSR	Terrestrial Energy	Canada	Basic design
ThorCon	250	MSR	Martingale Inc	United States	Basic design

Notes: BWR = boiling water reactor; CEA = Alternative Energies and Atomic Energy Commission; CNEA = Comisión Nacional de Energía Atómica (Argentina); CNNC = China National Nuclear Corporation; GMFR = gas-cooled modular fast reactor; HTGR = high-temperature gas-cooled reactor; KAERI = Korea Atomic Energy Research Institute; LMFR = liquid metal fast reactor; MSR = molten salt reactor; PWR = pressurised water reactor.

Sources: OECD NEA and IAEA.

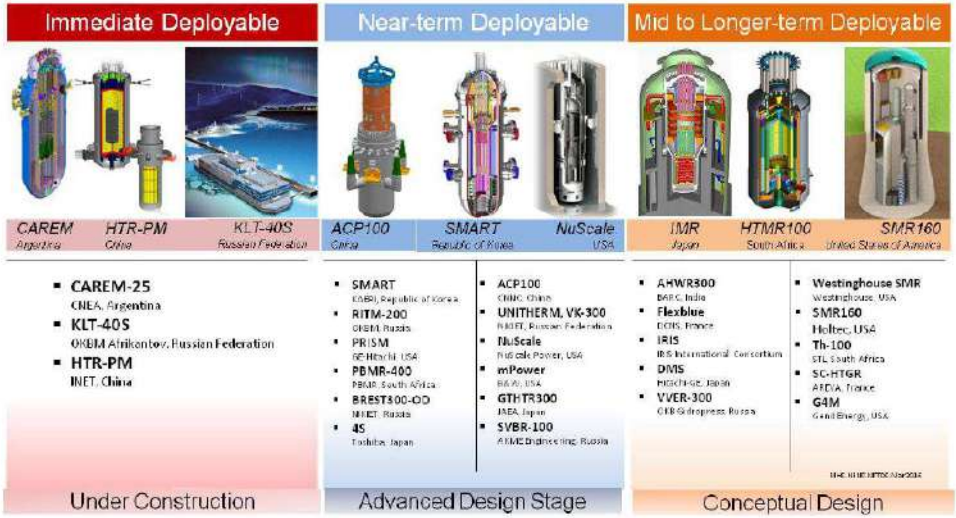


FIG. B-4. Status of SMR deployment

Source: IEA, 2019

FIG. B-1. WWER-1000 NPP under construction at the Kudankulam nuclear site. (Photo: IAEA)

FIG. B-2. The BN-800 commercial fast reactor at the Beloyarsk NPP, Russian Federation, was connected to the grid in December 2015. (Photo: Rosenergoatom)

FIG. B-3. Construction site (left) and the steam generator (right) of the HTR–PM at Shidao Bay, Weihai City, China (Photos: Institute of Nuclear and New Energy Technology)

Box 7: Nuclear fusion: A long-term source of low-carbon electricity

Nuclear fusion, the process that takes place in the core of our Sun where hydrogen is converted into helium at temperatures over 10 million °C, offers the possibility of generating base-load electricity with virtually no CO_2 emissions, with a virtually unlimited supply of fuel (deuterium and tritium, isotopes of hydrogen), small amounts of short-lived radioactive waste and no possibility of accidents with significant off-site impacts. However, the road to nuclear fusion power plants is a long route that still requires major international R&D efforts. The International Thermonuclear Experimental Reactor (ITER) is the world's largest and most advanced fusion experiment, and is designed to produce a net surplus of fusion energy of about 500 MW for an injected power (to heat up the plasma) of 50 MW. ITER will also demonstrate the main technologies for a fusion power plant. According to the *Roadmap to the Realisation of Fusion Electricity* (EFDA, 2012), ITER should be followed by a prototype for a power-producing fusion reactor called DEMO. During the period from 2021 to 2030, exploitation of ITER and design and construction of a prototype for a power-producing fusion reactor called DEMO.

DEMO should demonstrate a net production of electricity of a few hundreds of MW, and should also breed the amount of tritium needed to close its fuel cycle. Indeed, while deuterium is naturally abundant in the environment, tritium does not exist in nature and has to be produced. Thus, it is essential that tritium-breeding technology is tested in ITER and then demonstrated at large scale in DEMO. DEMO will also require a significant amount of innovation in other critical areas such as heat removal and materials. Beyond the demonstration of fusion power, the success of the technology as a source of electricity will require that it is competitive with respect to other low-carbon technologies such as renewables or nuclear fission. Major efforts in reducing the capital costs of fusion reactors through optimised designs and materials will be needed.

FIG. B-6. Aerial view of the ITER construction site in August 2015 (left). As of 21 October 2015 (right), the 200° segment of the ITER bioshield, the 3.2-metre-thick 'ring' that will surround the machine, was constructed (Photos: ITER).

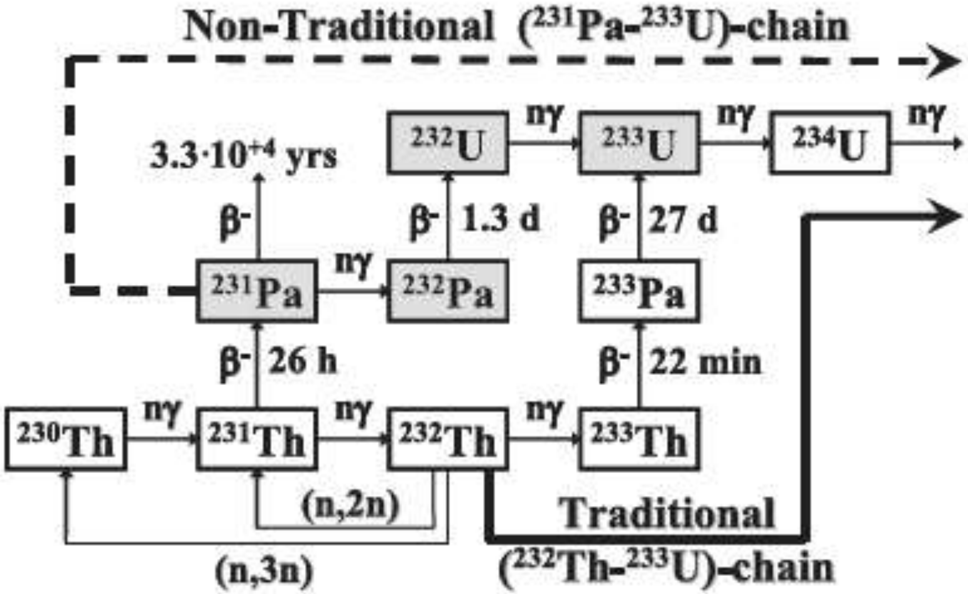


Fig. 1. Chains of nuclide transformations in the thorium–uranium fuel.

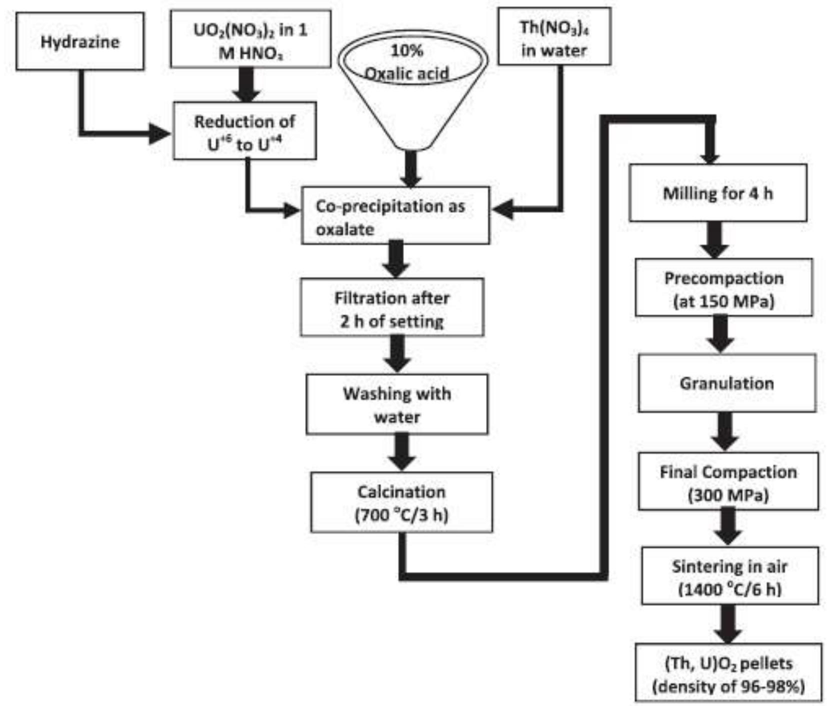
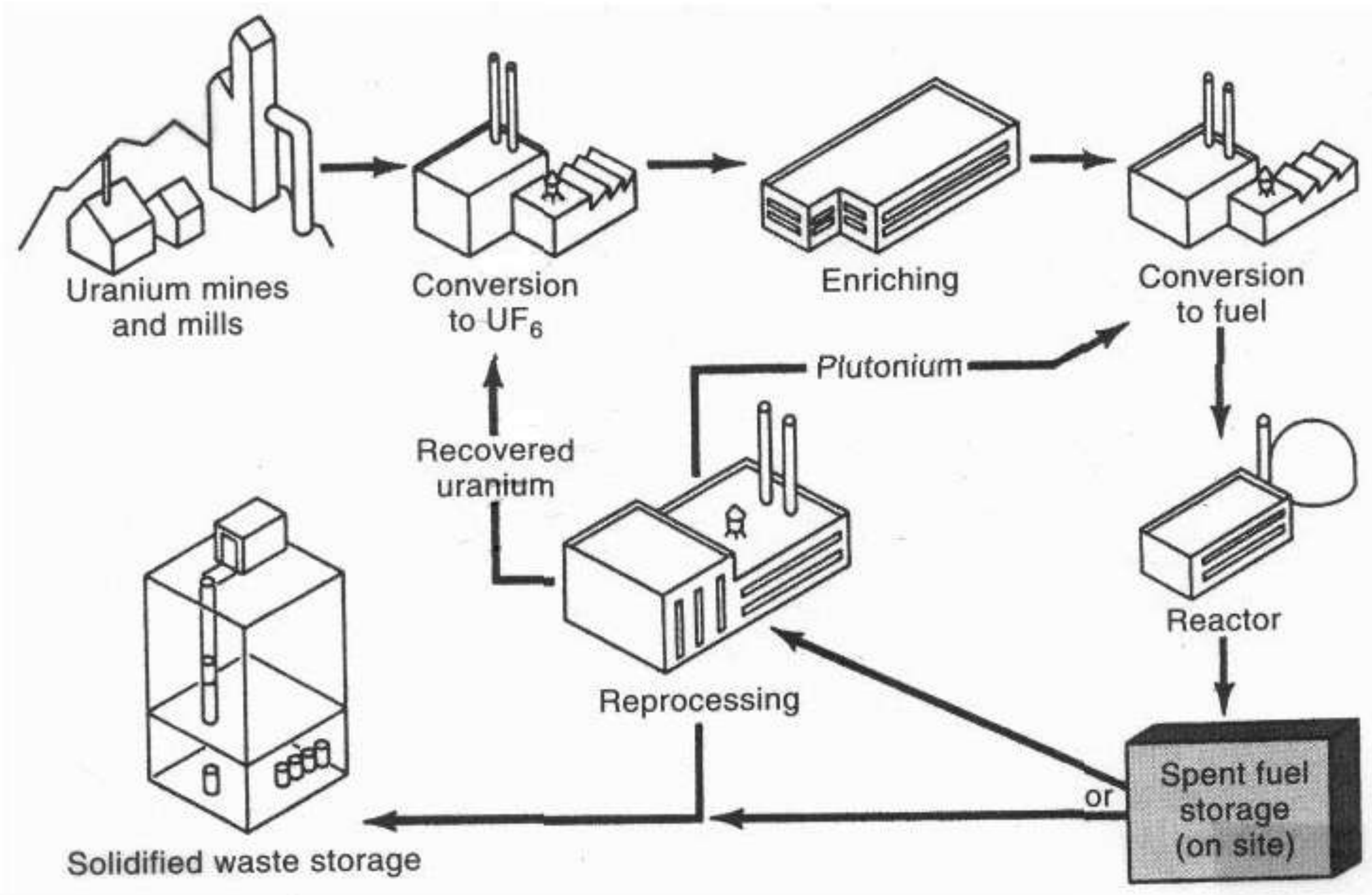
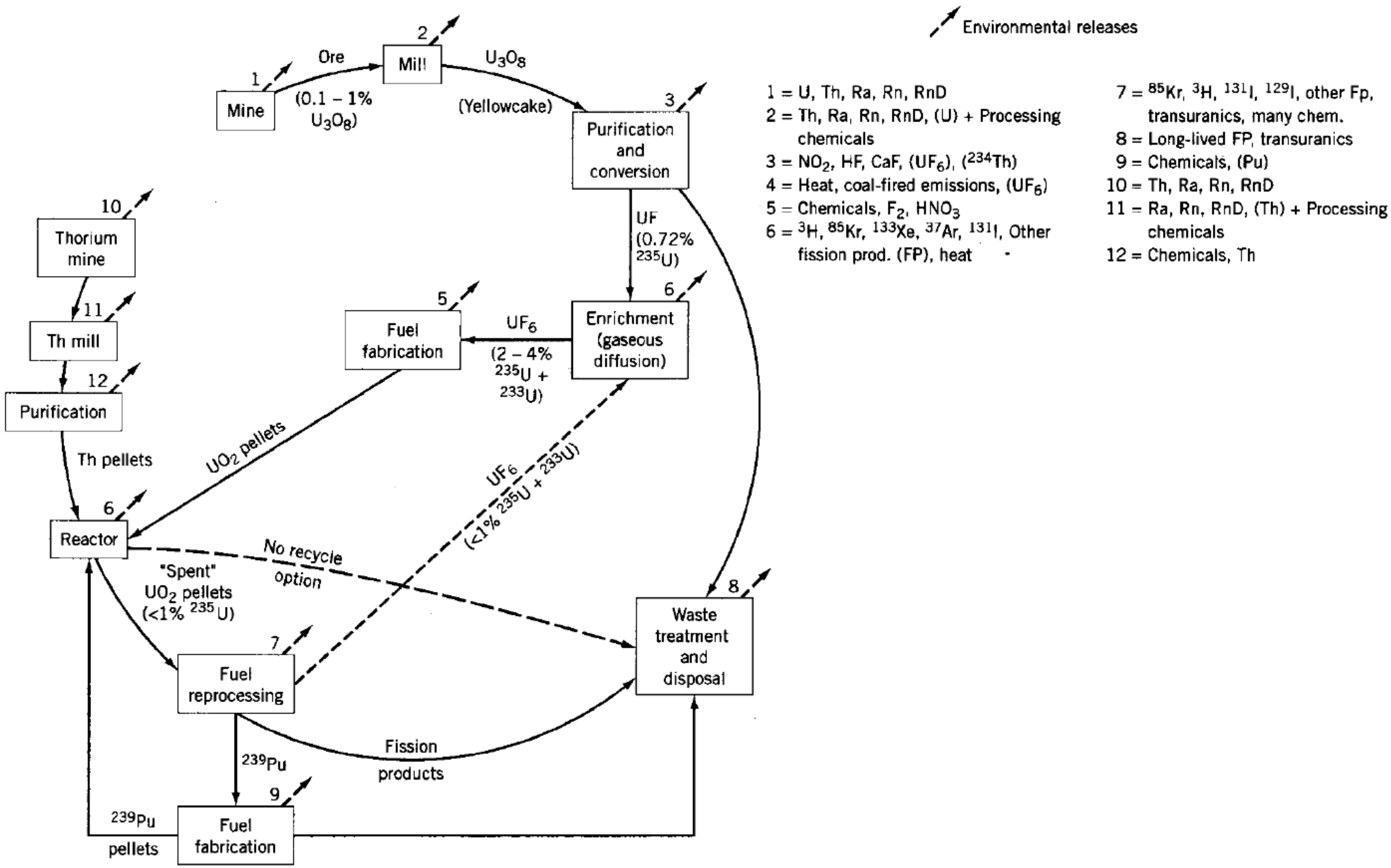


Fig. 9. Flow-sheet of fabrication of ThO_2–UO_2 pellets by co-precipitation process [72].

Again, the Nuclear Fuel Cycle



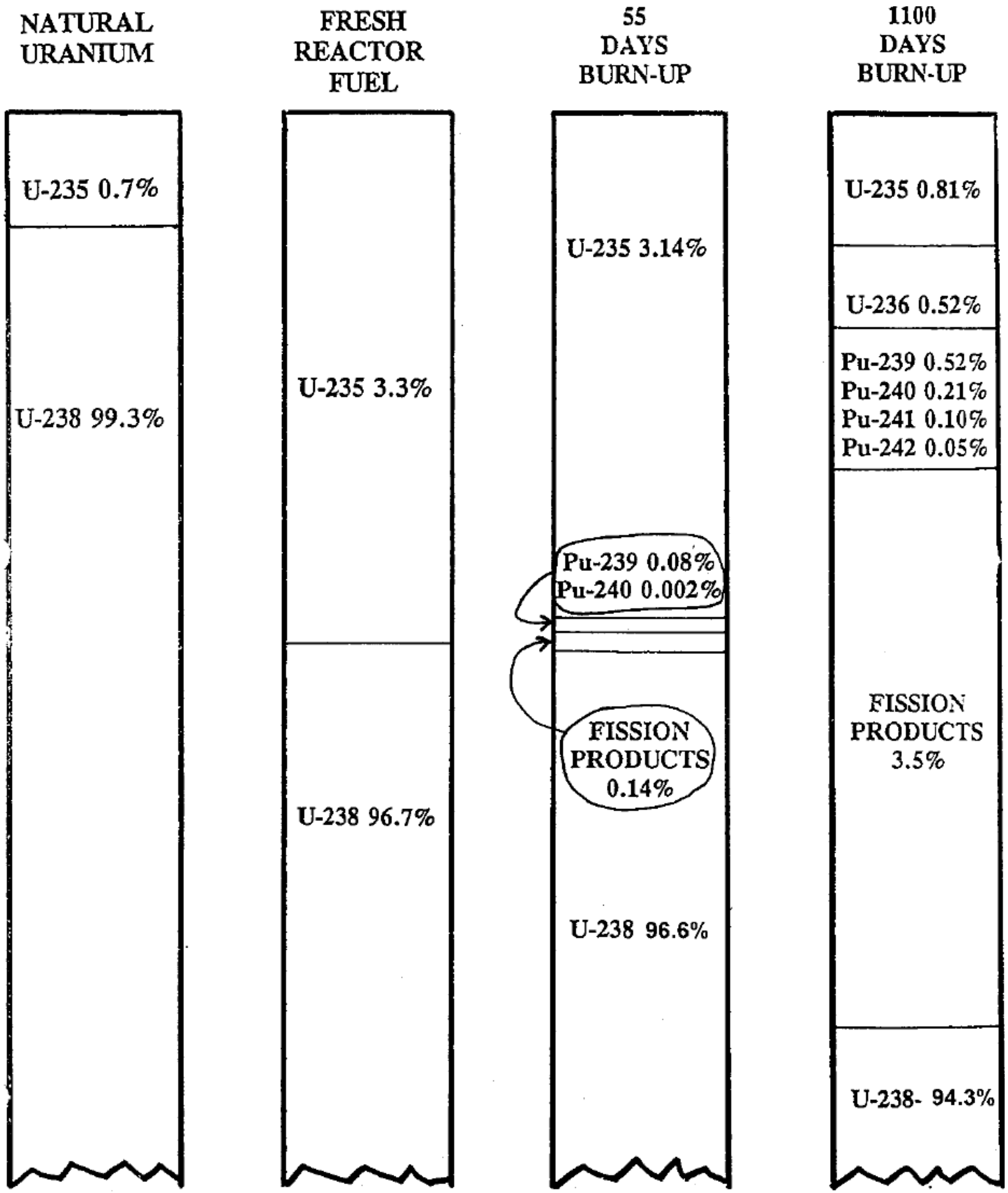
Pollution during the Nuclear Fuel Cycle



Spent Nuclear Fuel

- Fission Products
  - Lighter isotopes resulting from fission of U-235
    - Many are radioactive
  - Some fission products of concern
    - Strontium-90 (28.8y half-life) and cesium-137 (30y half-life)
      - Intermediate half-life means they are pretty radioactive but they are problems for over a century
      - Sr-90 the most dangerous part of nuclear fallout; mimics calcium (incorporated in bones, not excreted as readily as Cs-137)
    - Iodine-131 (8d half-life)
      - Intensely radioactive but short-lived
      - Volatile, hence highly mobile in the environment
        - » Particularly a concern in accidental leaks/spills
- Transuranics (Actinides)
  - Heavier elements than uranium
    - Created by neutron-capture that is not followed by fission
      - Most products are both highly toxic and radioactive
    - Plutonium (Pu) isotopes a major product
      - Many are fissionable
      - Can be used to fashion nuclear weapons

Composition of Nuclear Fuel



- Natural uranium ore contains too much U-238 and must be *enriched* prior to use.
- The fuel is "spent" when the U-235 decreases to levels near normal
- In the meantime, *fission products* and *transuranics* have been produced.
- Plutonium and other transuranics are produced through a combination of neutron capture and alpha/beta decay.

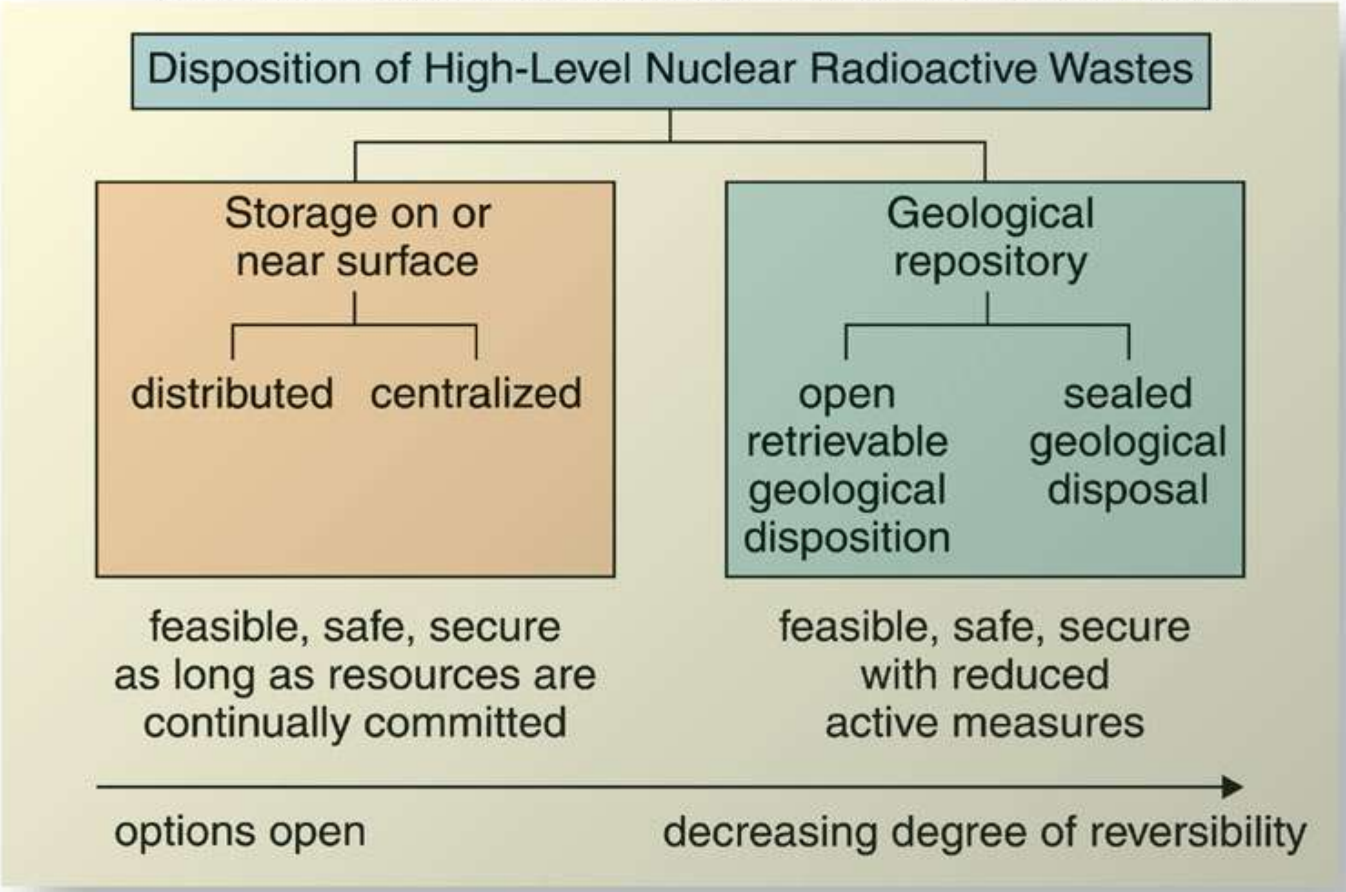
Radioactive Wastes in Spent LWR Fuel

Fission Products		Actinides	
Nuclide	**Half-life (years)**	**Nuclide**	**Half-life (years)**
^{90}Sr	28.8	^{237}Np	2.1×10^6
^{99}Tc	210,000	^{238}Pu	89
^{106}Ru	1.0	^{239}Pu	2.4×10^4
^{125}Sb	2.7	^{240}Pu	6.8×10^3
^{134}Cs	2.1	^{241}Pu	13
^{137}Cs	30	^{242}Pu	3.8×10^5
^{147}Pm	2.6	^{241}Am	458
^{151}Sm	90	^{243}Am	7.6×10^3
^{155}Eu	1.8	^{244}Cm	18.1

Activity (in curies*) after:	*10 years*	*100 years*	*1000 years*
Fission products	300,000	35,000	15
Actinides	10,000	2,200	600

*A curie is the unit used to express the amount of radioactivity contained in a sample. One curie is equal to 3.7×10^{10} decay events per second (irrespective of the type of radiation). (WASH-1250)

HLW Disposal Options



Radioactive Waste Disposal

- Types of radioactive waste
  - High-level waste (HLW)
    - Radiation levels higher
    - Long half-lives
    - Require permanent isolation from humans and ecosystems
    - Origins: nuclear power plants; nuclear weapons (vast majority)
  - Low-level waste (LLW)
    - Radioactivity levels much lower
    - Origin: laboratories, medical facilities, mining, pharmaceutical industry, military
    - Disposal somewhat similar to other types of hazardous (non-radioactive) waste
      - Usually sealed in canisters and buried
      - Special LLW disposal sites (2 in the US)
- 1982 Nuclear Waste Policy Act
  - Originally designated 3 sites for intensive studies: in Washington, Texas and Nevada
  - 1987 amendments designated Yucca Mountain (Nevada) as the sole site to be studied as a potential repository of HLW
  - July 2002, Senate cast final vote approving Yucca Mt as HLW respository

Box 9: Recycling of spent fuel (Case study 7)

Used nuclear fuel recycling is today a fully industrial process with more than 45 years of experience, allowing reuse of uranium and plutonium to manufacture new nuclear fuel, while conditioning the non-reusable parts in a stable waste form. In France alone, more than 30 000 tonnes of used fuel has been reprocessed to date, of which 20 000 tonnes was from French reactors. This has effectively reduced the interim storage capacity for used fuel by 50%, while allowing up to 20% annual savings on natural uranium consumption. The main steps of the process are the separation of reusable and non-reusable materials, conditioning of the non-reusable material and the fabrication of new fuel.

Figure 8: MOX fuel fabrication

Source: AREVA.

FIG. A-8. Waste containers and first disposal activities at Wolsong (Photos: Korea Radioactive Waste Agency)

FIG. A-6. The New Safe Confinement over Unit 4 of the Chernobyl NPP (left, view from the construction site; right, view from Unit 3). The structure is 108 metres high, 162 metres long and 257 metres wide, and weighs about 36 000 tonnes. (Photos: Chernobyl NPP)

FIG. A-7. Dismantling activities at turbine halls of Units 1 (left) and 2 (right) of Lithuania's Ignalina NPP (Photos: Ignalina NPP).

Communication and public acceptance

This roadmap recommends the following actions:	*Proposed timeline*
Development of education and information centres to support effective, transparent communication and public knowledge about the facts related to the nuclear industry. In newcomer countries, it will be particularly important to ensure broader public awareness of nuclear power development.	2015-30 and beyond
In many countries, the operator of the nuclear facility plays a front-line role in communicating with stakeholders in real-time during an event. In this case, the regulatory authorisation for activities involving a nuclear facility should include a review and acceptance of the operator's strategy and programme. Performance of the programme should also be assessed by the regulator on a periodic basis.	Ongoing
Targeted communication programmes with influential stakeholder groups such as politicians, media, teachers and local leaders need to be implemented to improve understanding about the benefits and risks of nuclear energy. Communication should be transparent and occur at regular intervals and via a range of personal, print and online sources.	Ongoing
Measures to be implemented to share information in a timely manner on any safety events proposed by national regulatory organisations.	Ongoing
National regulatory organisations need to implement communication mechanisms and tools for discussion between interested parties and the regulator.	Ongoing
Clear and regular communication with host municipalities in the identification and development of deep geological disposal sites. A process based on voluntary participation with clarified withdrawal conditions is recommended and should include alternative sites from the beginning.	2015-30 and beyond

Nuclear Power Investment

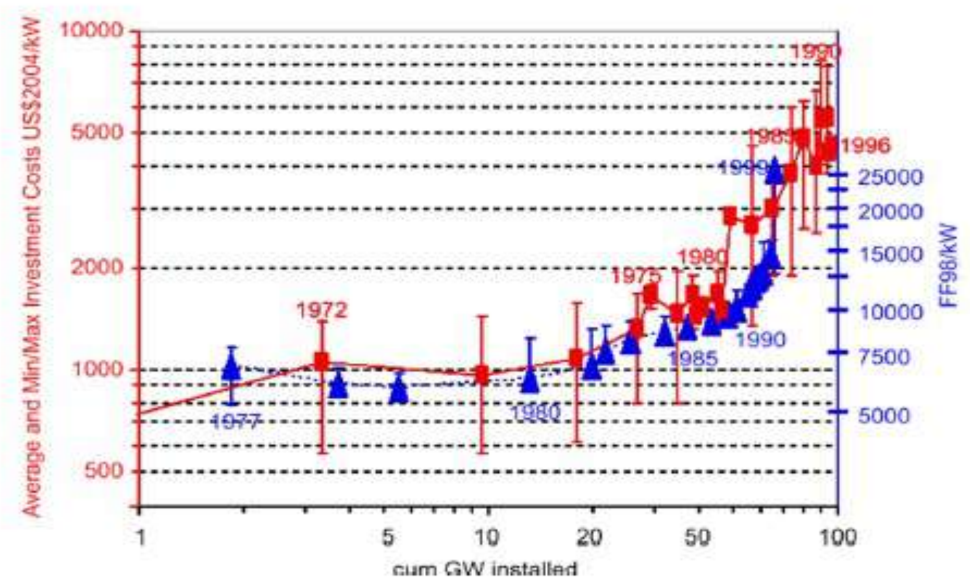


Fig. 1. Negative learning by doing in nuclear power, reprinted from Grubler (2010). Red squares denote US costs and blue triangles denote French costs. Data from Grubler (2010) were estimated before the release of reactor-specific costs from the French Cour des Comptes in 2012. See Boccard (2014) and Escobar-Rangel and Lévêque (2015) for discussion.

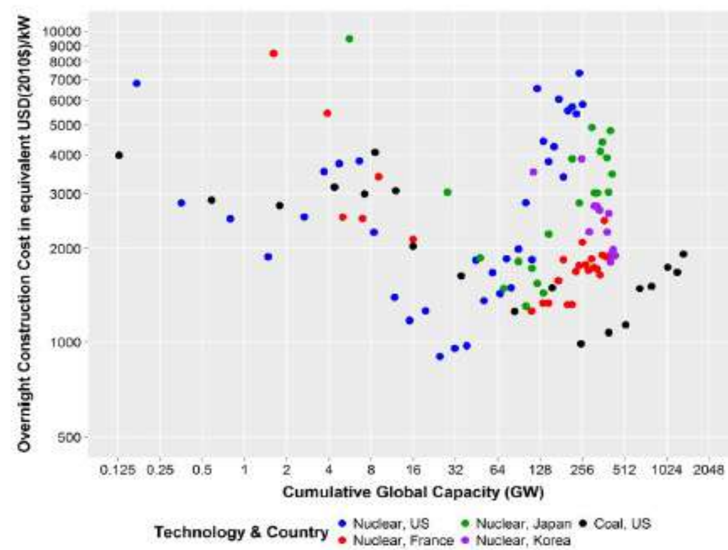
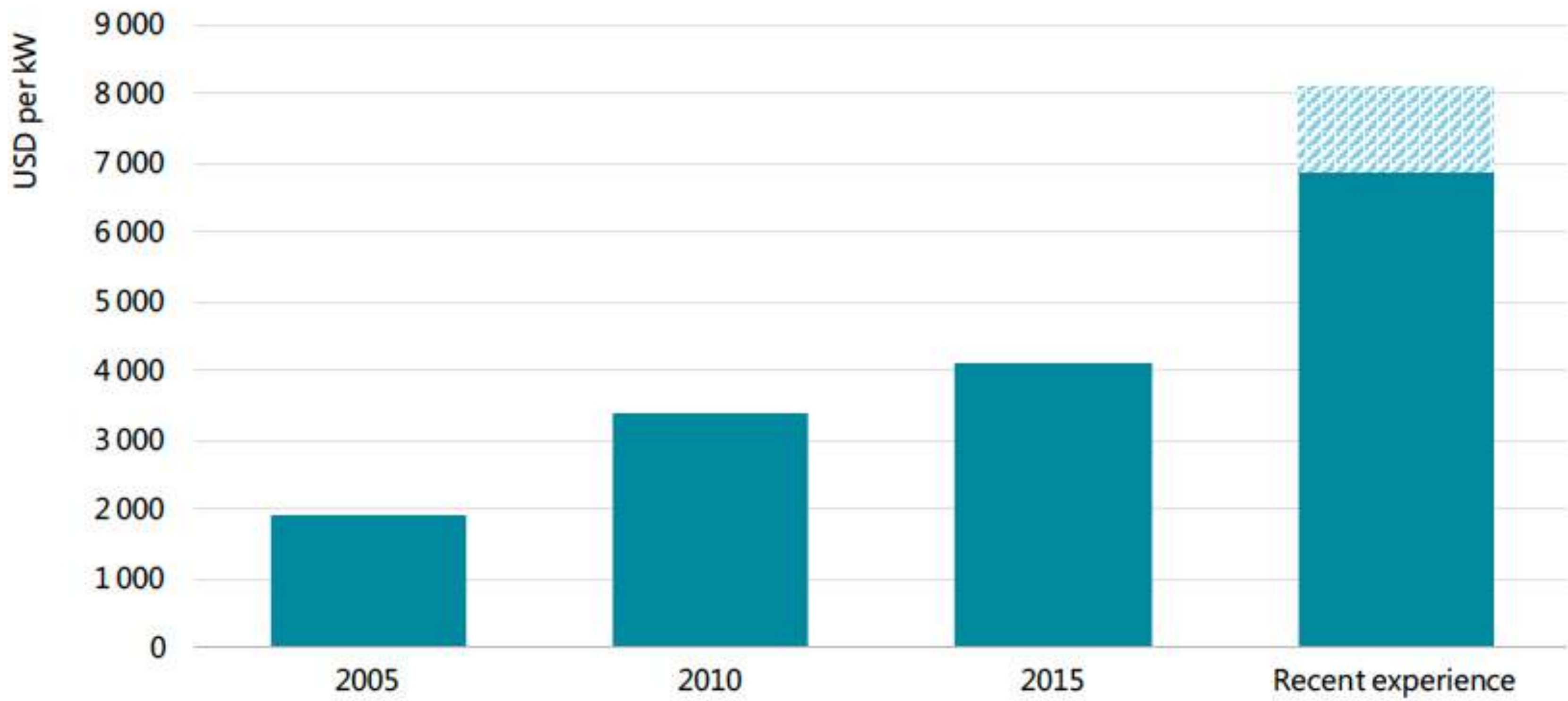


Fig. 14. Historical Cost Experience Curve of Coal Power compared with Cost Experience Curves of Nuclear Power. Coal power plants have generally been cheaper than nuclear power plants, but experienced a similar rise in costs more recently. Coal costs are from McNerney et al. (2011).

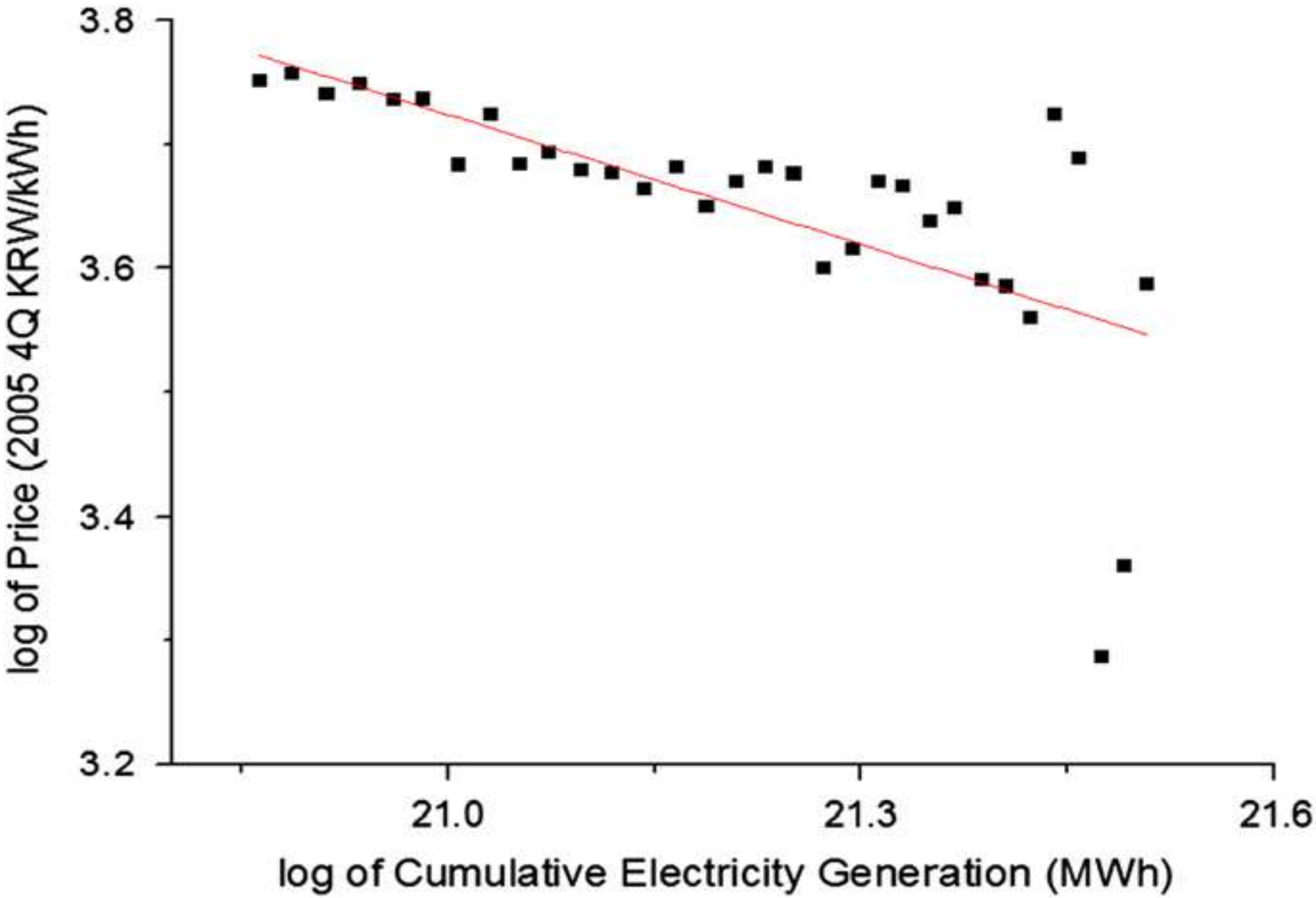
Source: Lovering et al, 2016

Projected overnight construction cost of nuclear power capacity and recent US and Europe



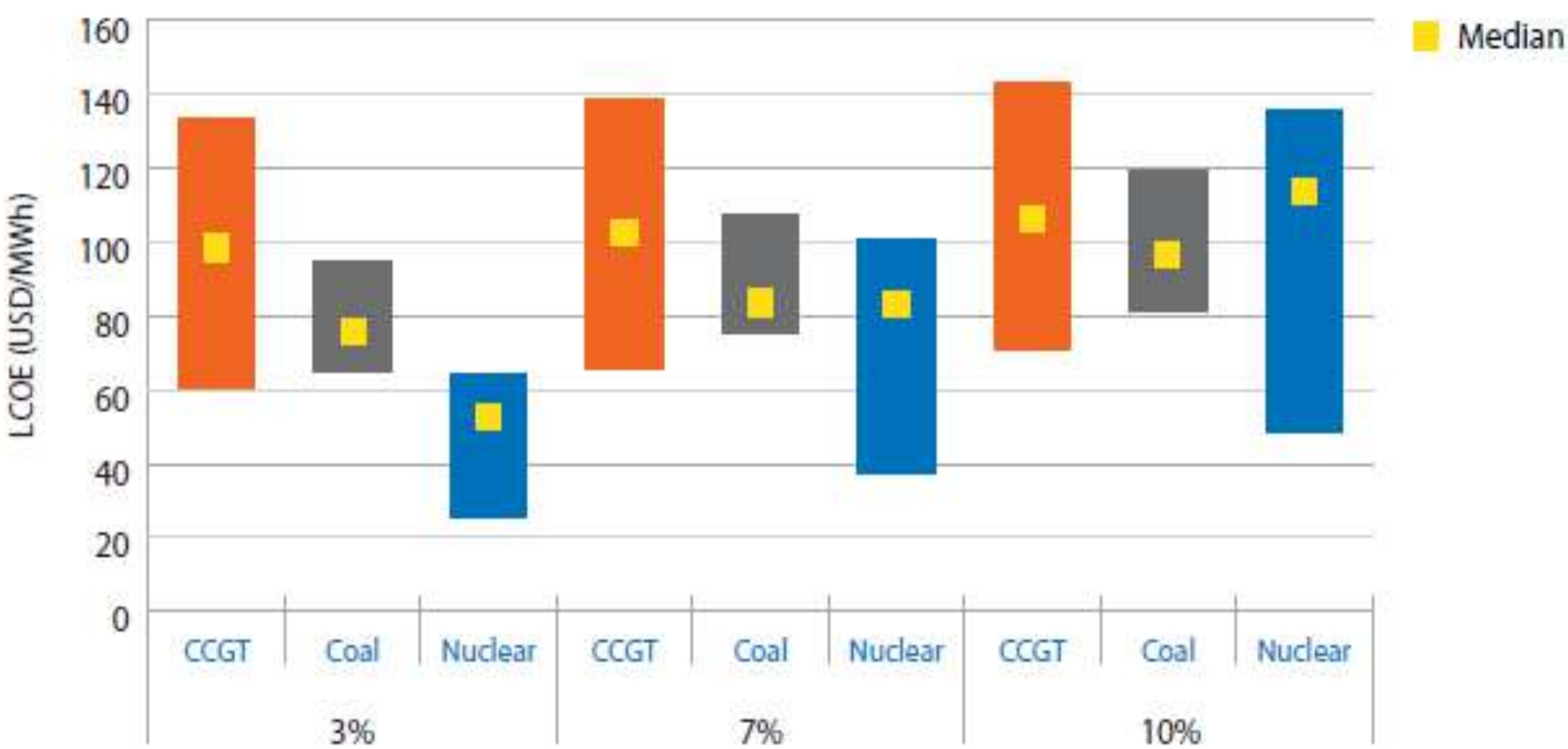
Source: IEA, 2019

Learning Curve



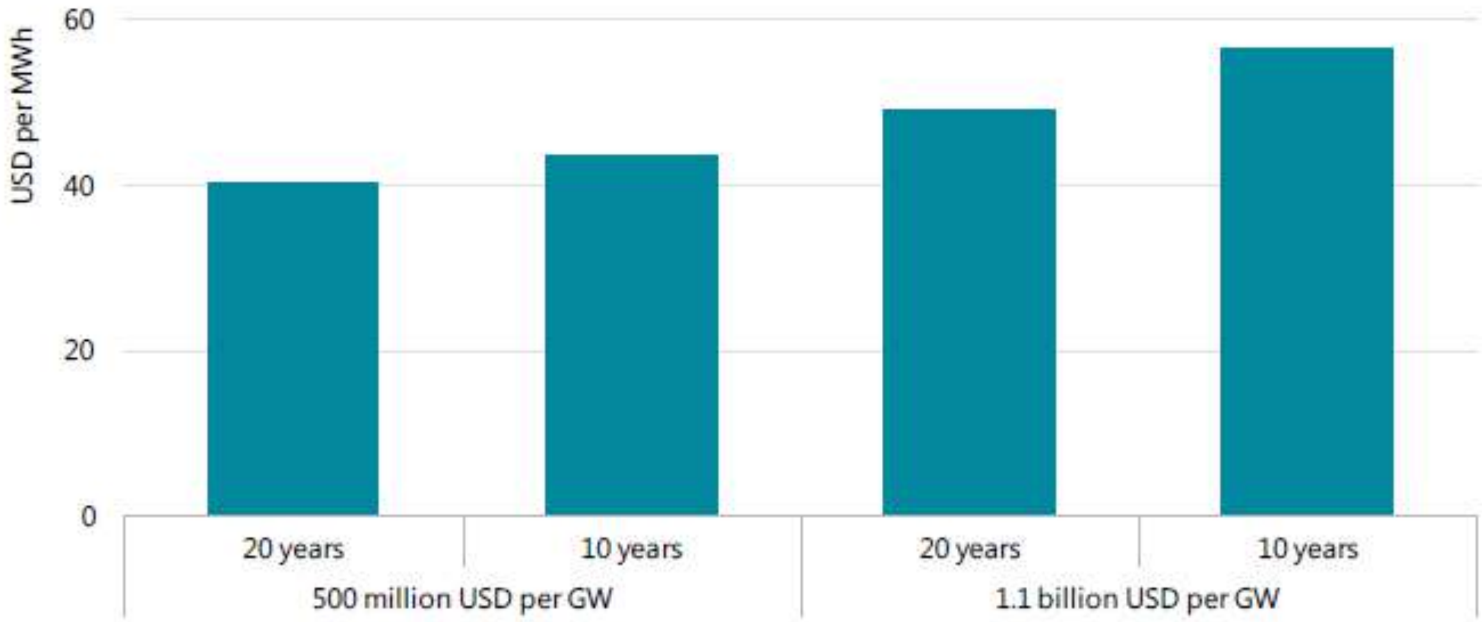
Nuclear Economics

Figure ES.1: LCOE ranges for baseload technologies (at each discount rate)



The ranges presented include results from all countries analysed in this study, and therefore obscure regional variations. For a more granular analysis, see Chapter 3 on "Technology overview".

LCOE



Note: LCOE is based on an 8% weighted-average cost of capital (WACC), 85% annual capacity factor, two year refurbishment period and USD 170 per kW annual O&M costs. LCOE is the average total cost to build and operate a power plant over its lifetime divided by the total energy output of the plant over the same period.

Source: IEA, 2019

Policy Issues

Many policy issues exist that affect the viability of the future of nuclear power:

- Licensing
- Risk insurance
- Reprocessing of spent nuclear fuel
- Nuclear waste repository
- Next generation reactor research
- Incorporation of hydrogen production into nuclear fuel cycle
- University nuclear engineering programs

Thank You