YNU

Hydrogen-Related Technologies Toward Future Carbon Neutrality

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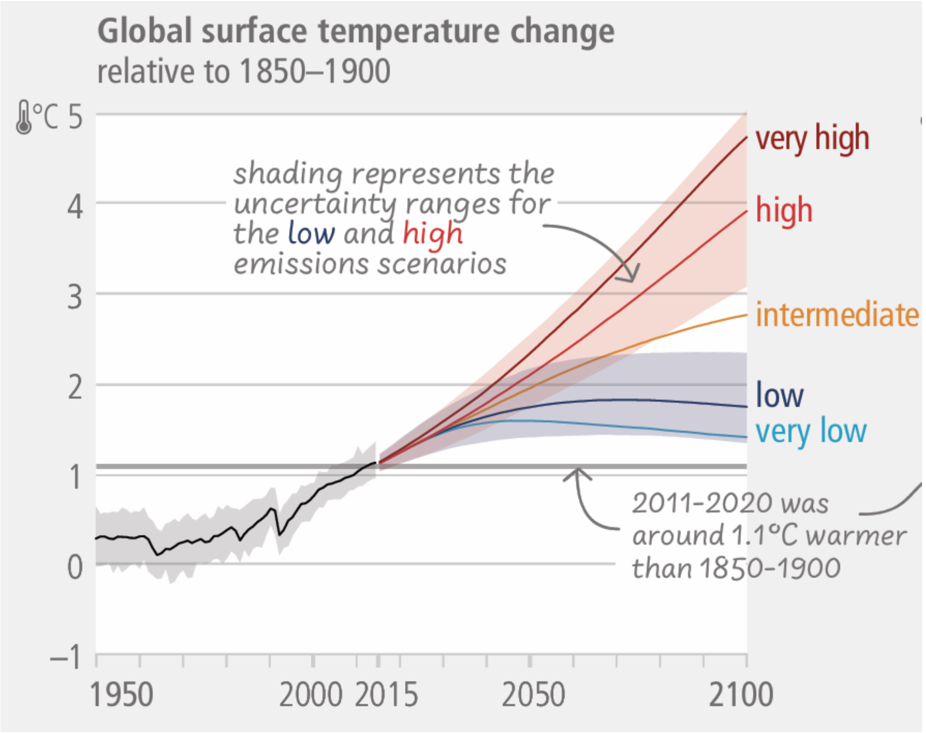
Basic Concept of Utilization of Hydrogen as an Energy Source

Climate Change



- Increase of temperature can not be avoided. Only suppression is possible.
- Temperature rise is closely related with the increase in the atmospheric CO_2 concentration
- Temperature rise below 2 degrees Celsius is the long-term goal of Paris Agreement.

Climate change can cause destruction of ecosystems, adverse effects on human health, decrease in food production, and so on.

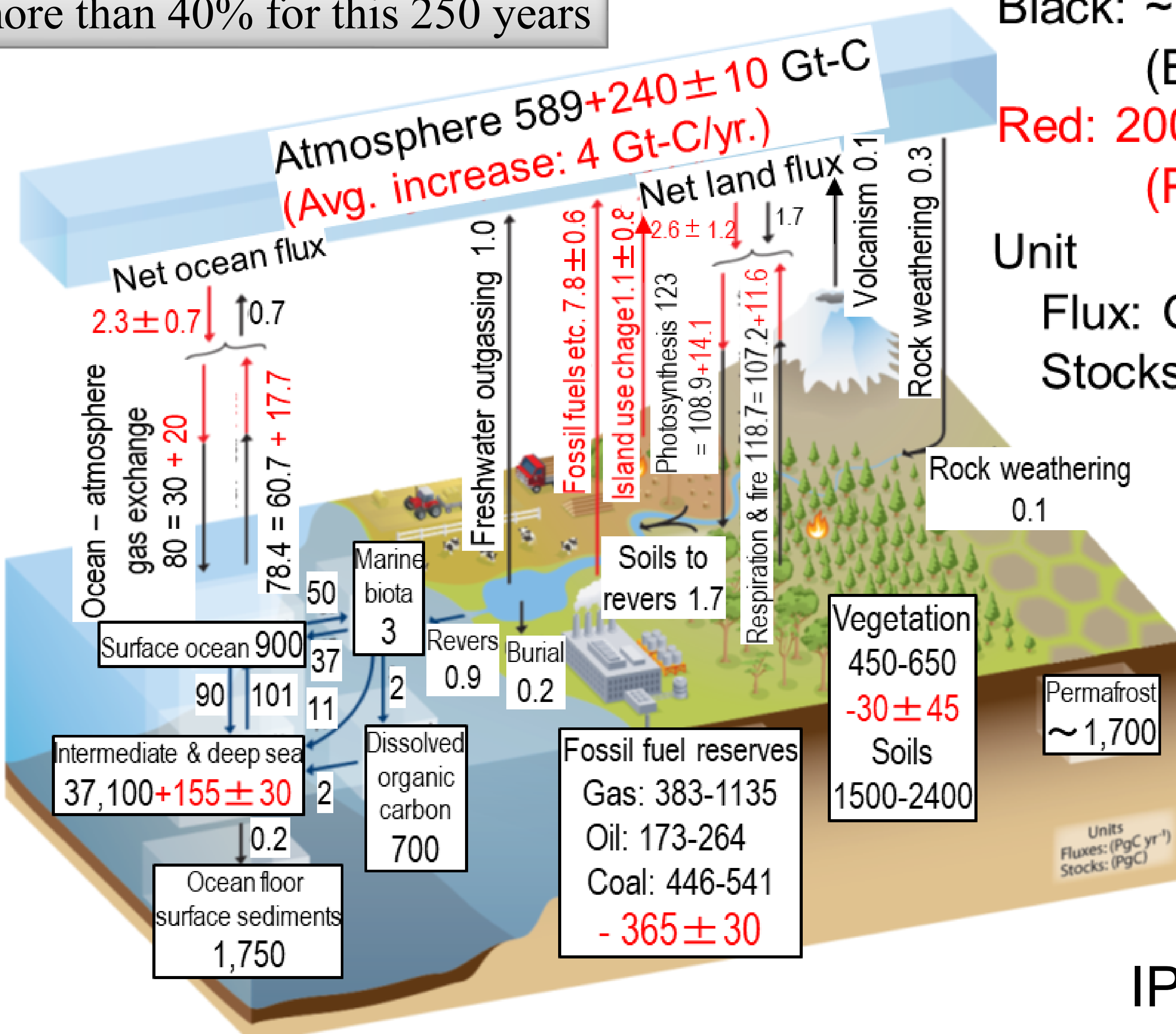
The emission of CO_2 must be reduced to net zero level for sustainable society.

Carbon Cycle on the Earth

CO_2 in atmosphere increased more than 40% for this 250 years

Black: ~1750
(Before industrial era)
Red: 2000-2009
(Present)

Unit
Flux: Gt-C / yr.
Stocks: Gt-C



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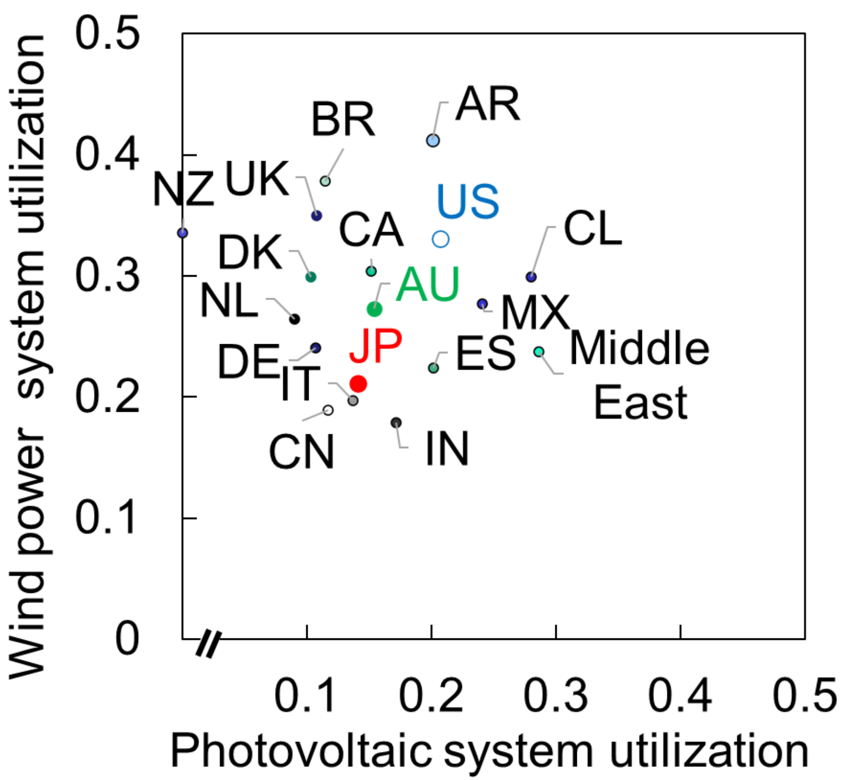
Importance of Energy Carrier



Utilization efficiency of photovoltaics and wind powers by countries.

- Utilization efficiency of photovoltaics is below 30%.
- Those of wind power is usually 20～40%.
- Renewable energy distributes unevenly in the world

Energy transportation and storage is important to balance supply and demand, using an energy carrier.

1. Significance of Using Hydrogen

Hydrogen is expected to play various roles such as energy conservation, decarbonization of fuel and promotion of introduction of renewable energy.

Roles of hydrogen

1. Lower energy consumption and energy conservation

Fuel cells, which generate electricity by reacting hydrogen with oxygen, can reduce energy consumption because they can use energy more efficiently than thermal power generation combusting fossil fuels or internal combustion engines of vehicles.

2. Decarbonization of difficult-to-electrify areas

In the areas difficult to decarbonize by electrification such as use of high-temperature heat in the industrial sector and transportation fuels for vessels and air planes, hydrogen is available as a fuel. Furthermore, it is available as an element because it is possible to manufacture basic chemicals and hydrogen-based reduce iron from hydrogen. As use of hydrogen emits no CO_2, fuel decarbonization is expected.

3. Promotion of introduction of renewable energy

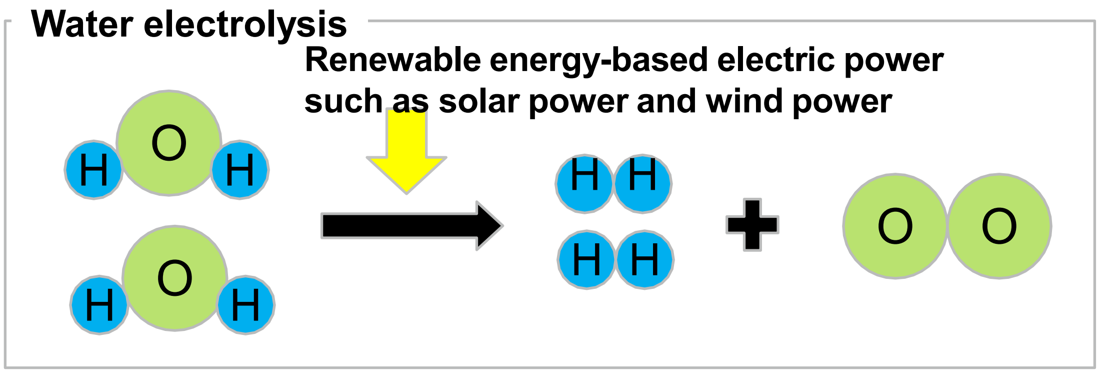
As hydrogen can be easily produced from electric power and stored for a long period, it can be expected as a mechanism to use and adjust renewable energy whose output differs greatly on the weather, etc. (sector coupling).

Source: Ministry of the Environment “Hydrogen Supply Chain and Platform for Decarbonization”

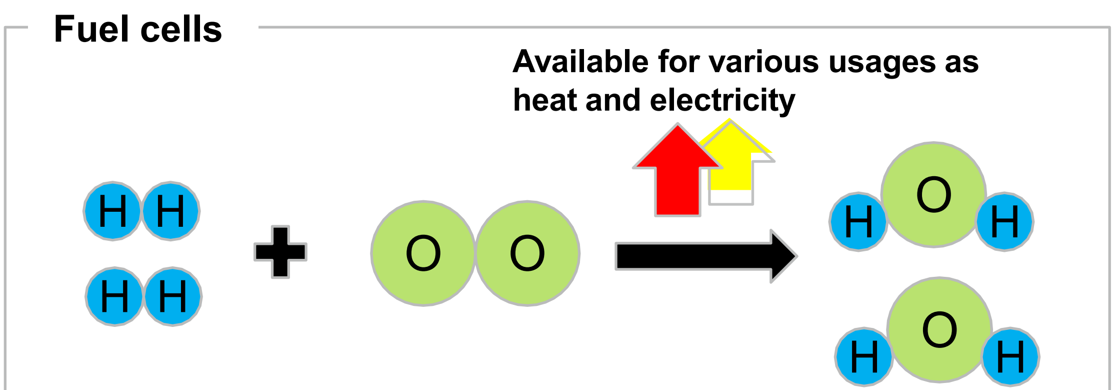
1. Significance of Using Hydrogen
(1) Decarbonization

- **Use of hydrogen emits no CO_2 because it contains no carbon.**
- **If renewable energy-based electric power is used for water electrolysis, no CO_2 is emitted even when producing hydrogen.**

Reaction principle of water electrolysis and fuel cells



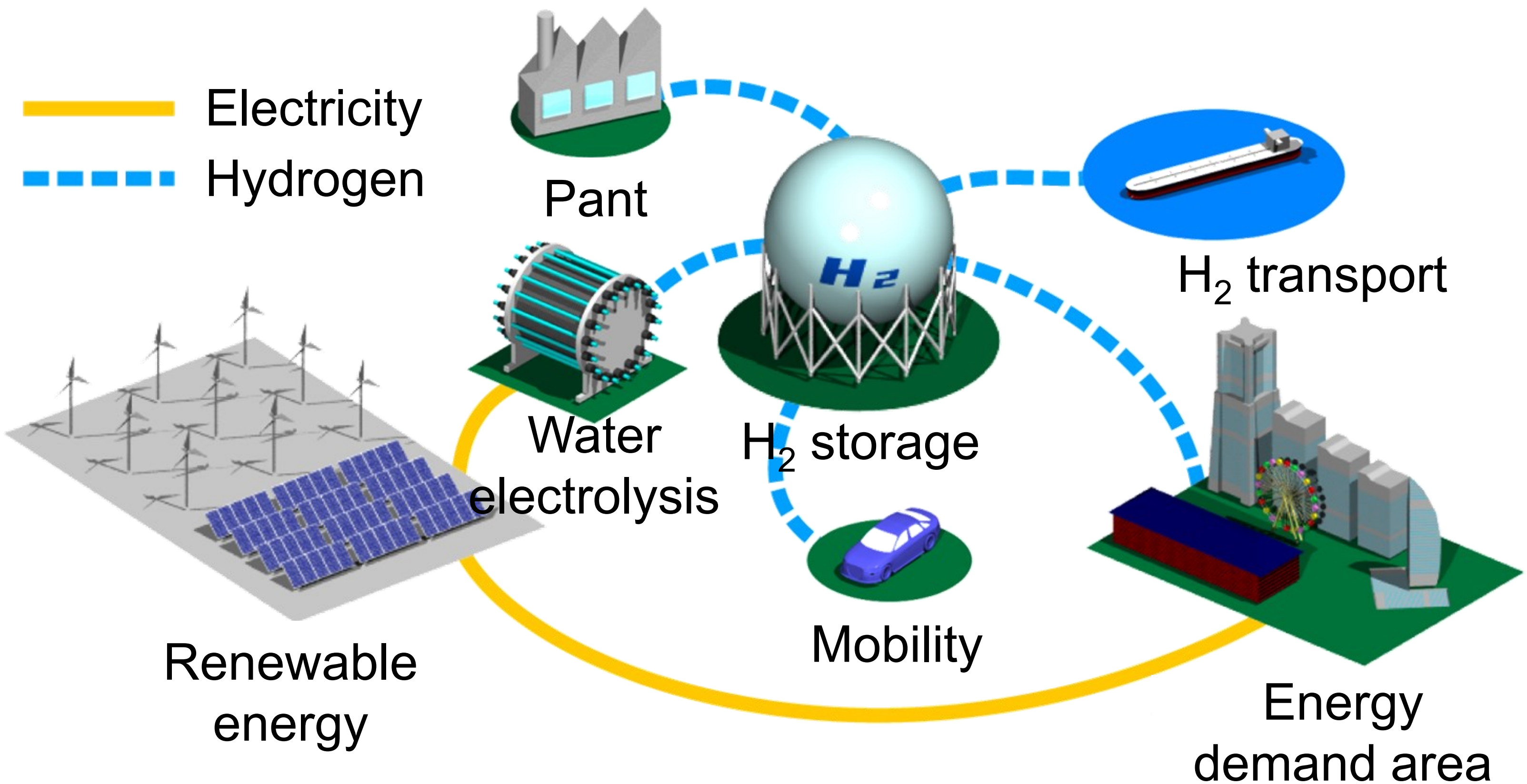
Reaction formula:
$2H_2O \rightarrow 2H_2 + O_2$



Source: Ministry of the Environment “Hydrogen Supply Chain and Platform for Decarbonization”

Reaction formula:
$2H_2 + O_2 \rightarrow 2H_2O$

H_2-Related Technologies to Support H_2 Supply Chains



Various technologies for (1) production, (2) storage and transportation, and (3) utilization of H_2 are necessary to establish H_2-based society.

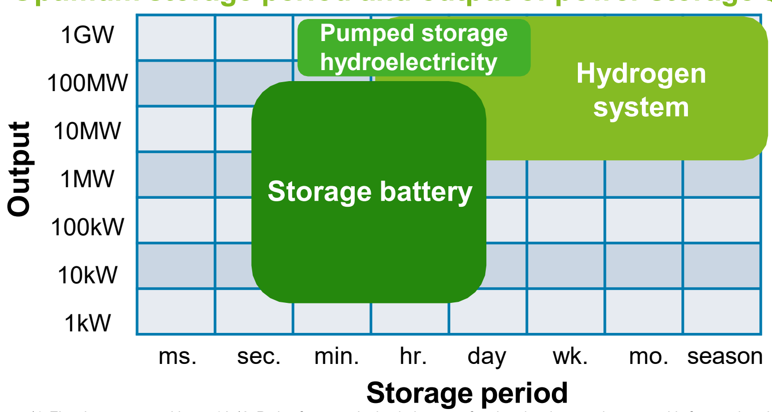
1. Significance of Using Hydrogen
(2) Promotion of introduction of renewable energy

As hydrogen is storable in a large quantity for a long period, it can respond to demand fluctuations and surplus power at the time of mass introduction of renewable energy.

Comparison of power storage technology

Method	Energy density [Wh/L]*1	Conversion efficiency [%]*2	Facility cost: Water electrolysis [¥10,000/kW]	Facility cost: Storage part*3 Capacity [¥10,000/kWh]	Facility cost: Storage part*3 6-hour rate/ Weekly rate [¥10,000/kW]	Facility cost: Generation part*4 [¥10,000/kW]	Facility cost: Total cost [¥10,000/kW]	Supply and demand control interval: min.	hr.	day	mo.
Hydrogen system (Water electrolysis, storage tank, fuel cells)	600*5	22-50	45	0.7	4.2 / 117.6	40	89.2 / 202.6		●	●	●
Storage batteries	20-400	75-95	―	5	30 / 840	―	30 / 840	●	●	●	
Pumped storage hydroelectricity (Regulating reservoir, power generator)	0.1-0.2	50-85	―	2.3	13.8 / 386.4	14	27.8 / 400.4	●	●	●	

Optimum storage period and output of power storage technology



Advantage 1: High-capacity storage

Disadvantage: Low conversion efficiency

Advantage 2: Long-term storage

Collaborated by industry, government and academia, efforts have been made to produce hydrogen and improve conversion efficiency for storage.

*1: Electric energy storable per 1 L *2: Ratio of energy obtained when transforming electric power into a storable form and getting it back as electric power *3: Cost per 1 kW calculated in terms of 6-hour rate and weekly rate *4: Cost for about 1.2 MW
*5: For 20,000,000 Pa compressed hydrogen. Source: Prepared by reference to National Research and Development Agency, NEDO Technology Strategy Center, HyGrid Workshop "Development Potential of Hybrid Grid Using Hydrogen" (Apr. 2014).

1. Significance of Using Hydrogen
(3) Response to emergency

A fuel cell vehicle can be used as an emergency power source in the cases of disasters.

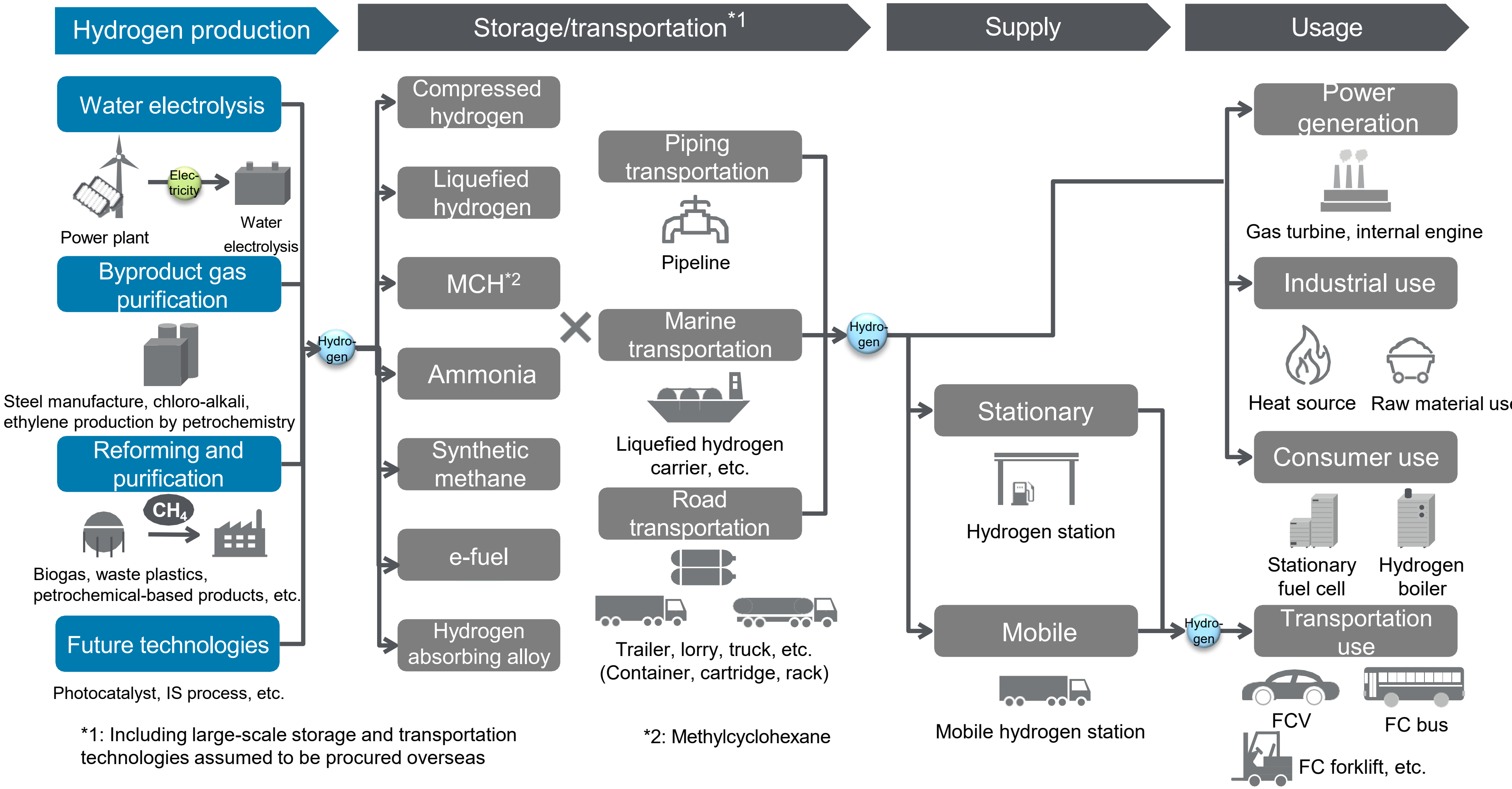
Conversion of required electric energy into the form of FC bus/FCV in emergency cases of main facilities

	Hospital	Convenience store	Shelter (school)	Gas station
Electric energy required in case of emergency	963 kWh/day (Only the facility capable of conducting emergency medical care) Normally required is 10% of 9,628 kWh/day.	235 kWh/day, 47% (Only refrigeration equipment) Normally required is 47% of 500 kWh/day.	100 kWh/day (Lighting and water heating for 200 persons)	16 kWh/day, 19% (Only oil supply equipment) Normally required is 19% of 82 kWh/day.
FC buses required to maintain electric energy for 1 day in case of emergency (455 kWh/unit) * When externally supplying the power, the Electricity Business Act restricts the output to less than 10 kW.	2 units 	0.5 units 	0.22 units 	0.03 units 
FCVs required to maintain electric energy for 1 day in case of emergency (120 kWh/unit)	8 units 	2 units 	0.83 units 	0.15 units 

Source: Ministry of the Environment "Hydrogen Supply Chain and Platform for Decarbonization". Prepared by Ministry of the Environment by reference to Agency for Natural Resources and Energy, Hydrogen and Fuel Cell Promotion Office "Fuel Cell Vehicles" (Mar. 2014).

2. Classification of Hydrogen Supply Chain
(1) Production technology

Except for future technologies, there are mainly 3 kinds of hydrogen producing methods, allowing its production from various energy sources.



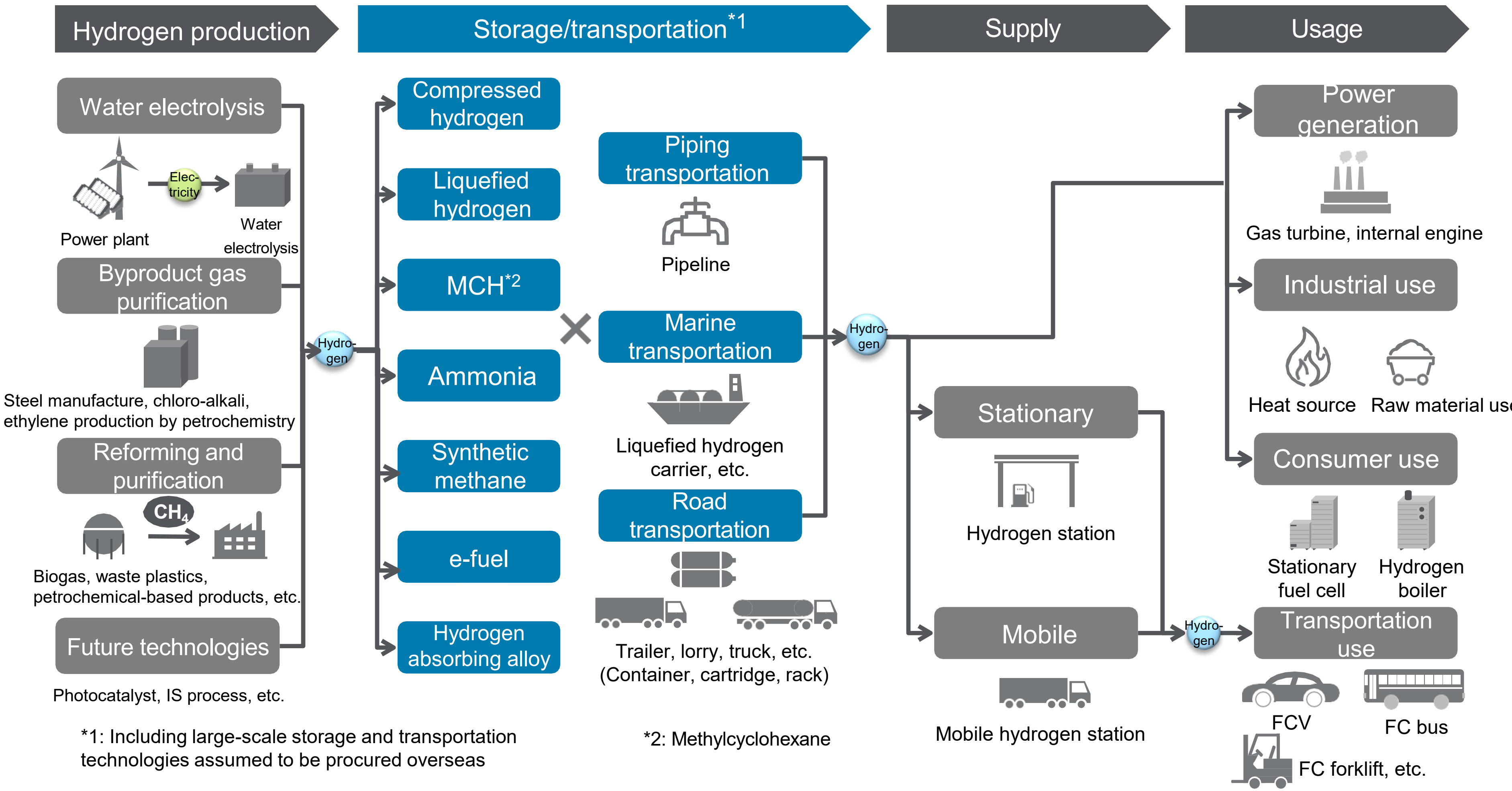
*1: Including large-scale storage and transportation technologies assumed to be procured overseas

*2: Methylcyclohexane

Source: Ministry of the Environment "Hydrogen Supply Chain and Platform for Decarbonization"

2. Classification of Hydrogen Supply Chain
(2) Storage and transportation technologies

There are many ways to store and transport hydrogen. It is necessary to choose an optimum method according to a transportation distance and volume.



*1: Including large-scale storage and transportation technologies assumed to be procured overseas

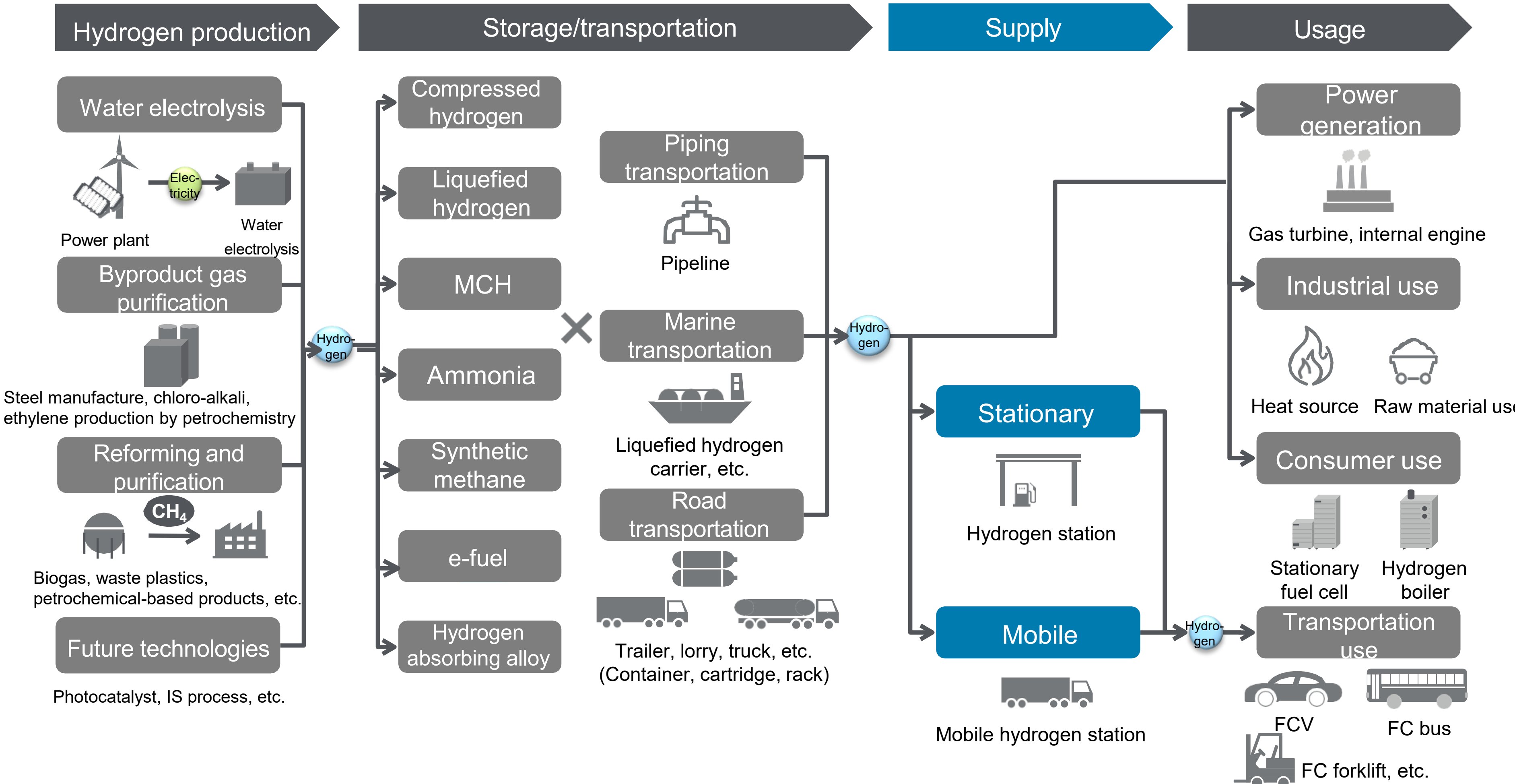
*2: Methylcyclohexane

Source: Ministry of the Environment "Hydrogen Supply Chain and Platform for Decarbonization"

2. Classification of Hydrogen Supply Chain

(3) Supply technology

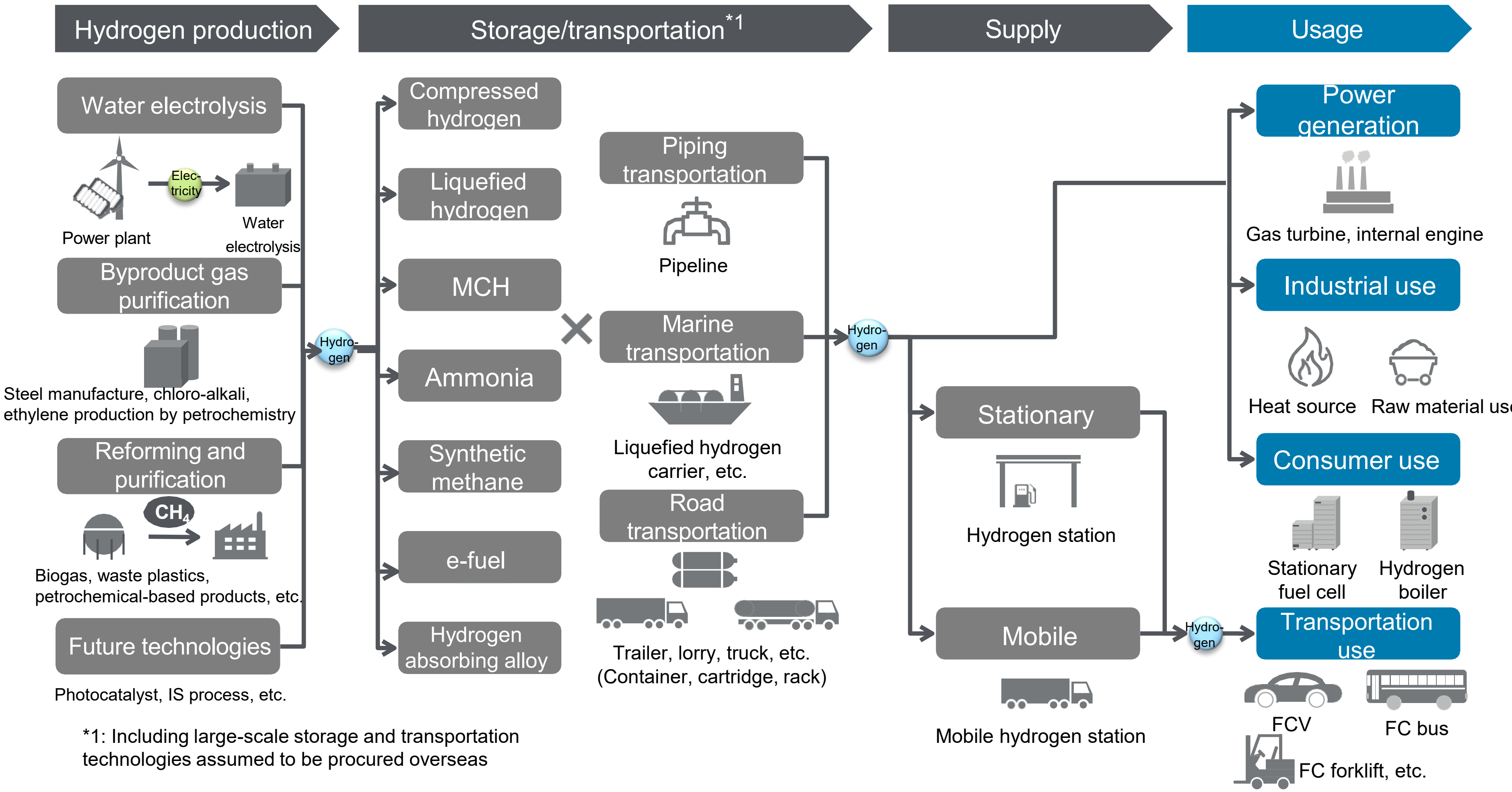
For hydrogen supply, hydrogen stations have been installed mainly for mobility. They are largely classified into the stationary and mobile types.



Source: Ministry of the Environment “Hydrogen Supply Chain and Platform for Decarbonization”

2. Classification of Hydrogen Supply Chain
(4) Technologies used

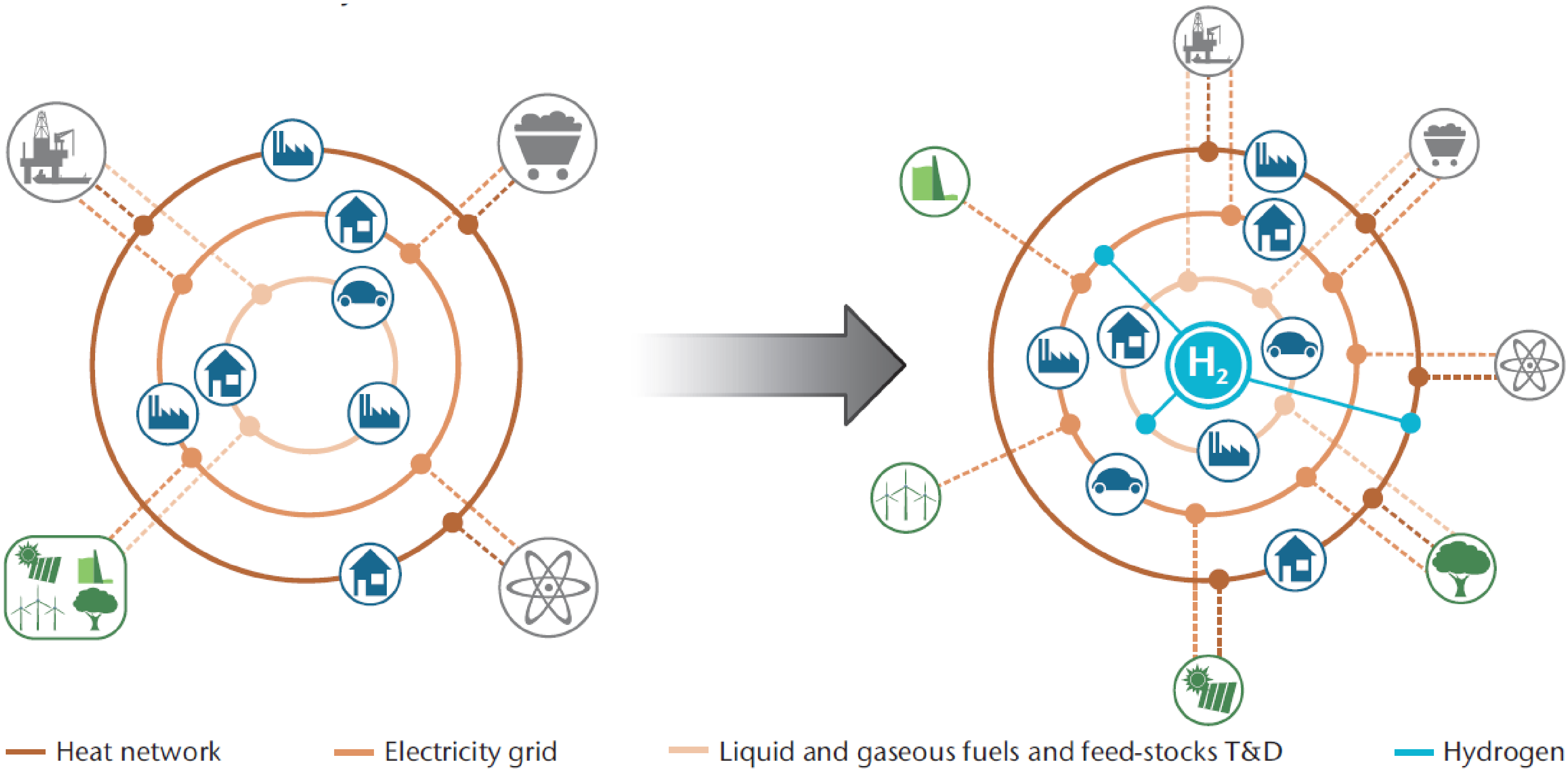
Usage of hydrogen is classified into "transportation use", "consumer use", "industrial use" and "power generation", depending on the purpose.



*1: Including large-scale storage and transportation technologies assumed to be procured overseas

Source: Ministry of the Environment "Hydrogen Supply Chain and Platform for Decarbonization"

Sector Coupling by Hydrogen



- H_2 can connect different energy sectors.
- If a country introduce H_2 to various sectors, the materials and energy cycles can be efficient and environmentally benign.
- But also, a country can introduce H_2-related technology to a part of industries to reduce CO_2 emission.

Types of Hydrogen

CO_2 emission

Gray hydrogen
- Hydrogen produced from fossil fuels with emitting CO_2.

No CO_2 emission

Green hydrogen
- Hydrogen produced by water electrolysis powered by renewable energy

Blue hydrogen
- Hydrogen produced from fossil fuels with recovering emitted CO_2 (CCS).

Yellow hydrogen
- Hydrogen produced by water electrolysis powered by nuclear power.

White hydrogen
- Natural hydrogen

Introduction of Scenario Analysis to 2050 Carbon Neutrality in Japan

Hydrogen Energy Systems Society of Japan (HESS)

Example of Scenario Analysis in Japan

- HESS is a membership, non-profit organization established in 1973
- HESS is Japan's leading organization on hydrogen energy and co-organizes international conferences held in Japan, such as HYPOTHESIS XIX (2024), 8th WHTC, Tokyo, Japan (2019), 15th WHEC, Yokohama – Japan (2004), and 1980 – 3rd WHEC, Tokyo – Japan (1980)
- “Scenario Analysis for Future Outlook of Hydrogen Energy toward Carbon Neutrality for Japan” is published on the Journal of the Hydrogen Energy Systems Society of Japan as the 50th Anniversary of the HESS

Scenario Analysis for Future Outlook of Hydrogen Energy toward Carbon Neutrality for Japan

—The 50th Anniversary of the Hydrogen Energy Systems Society of Japan—

Shigenori Mitsushima [1], Yoshiyuki Kuroda [1], Tatsuya Okubo [2], Masashi Oya [2], Hiroshi Tsujigami [3], Yuki Ishimoto [4], Koji Matsuoka [5], Yoshinori Shirasaki [6], Tatsuoki Kono [7], Takamichi Ochi [2], Hiroshi Hamasaki [2], Shigeo Satokawa [8]

[1]Yokohama National University, [2]Deloitte Tohmatsu Consulting LLC, [3]Iwatani Corp., [4]The Institute of Applied Energy, [5]ENEOS Corp., [6]Tokyo Gas Co., LTD., [7]University of Tokyo, [8]Seikei University

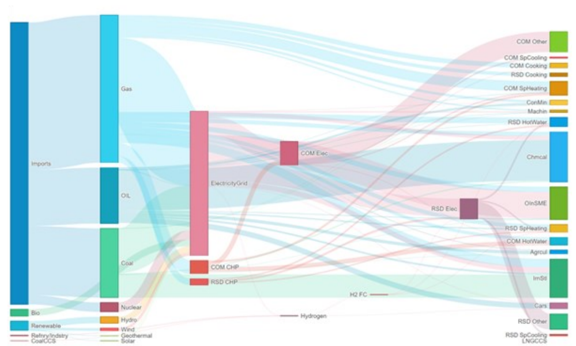
Journal of the Hydrogen Energy Systems Society of Japan, 49(2), 68 – 84 (2024) in Japanese

Analysis Model

- Use linear programming to calculate the combination of energy system technologies with the lowest total cost of assets
- A program to analyze the state of long-term energy under the IEA ETSAP
- Used for long-term energy scenario analysis by the IEA and governments around the world
- The model includes the grid status in Japan, including future enhancement, the amount of renewable energy that can be introduced at each location, and the installation cost.
- Costs related to technologies related to hydrogen production, transportation, and utilization are allocated for each scenario.

What can be analyzed? Illustrative

It gives optimum energy system to minimize total cost asset

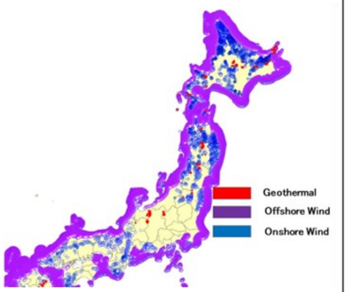


What does model have? Illustrative

Various information for energy

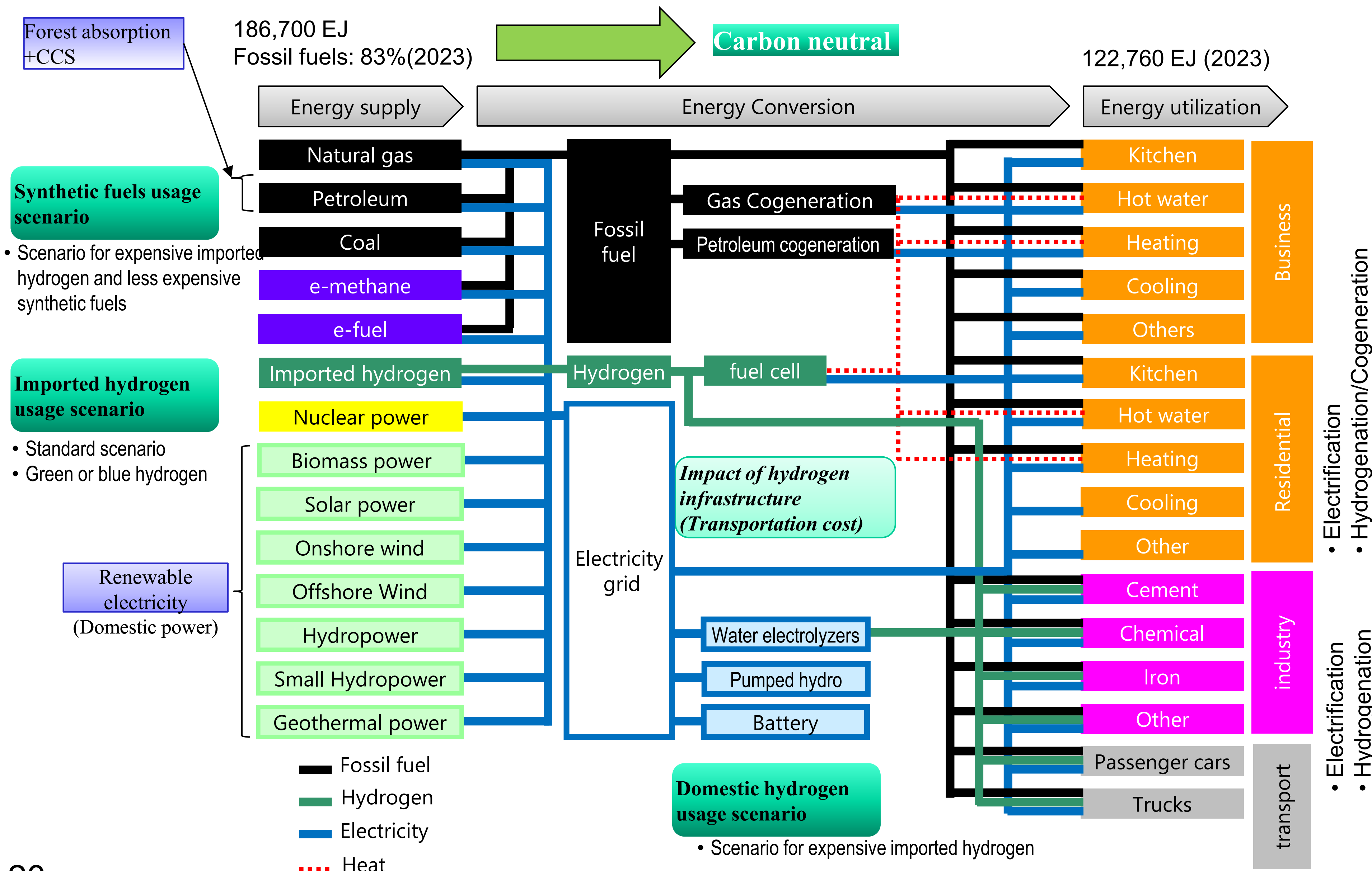
[Grid]

[RE potential]

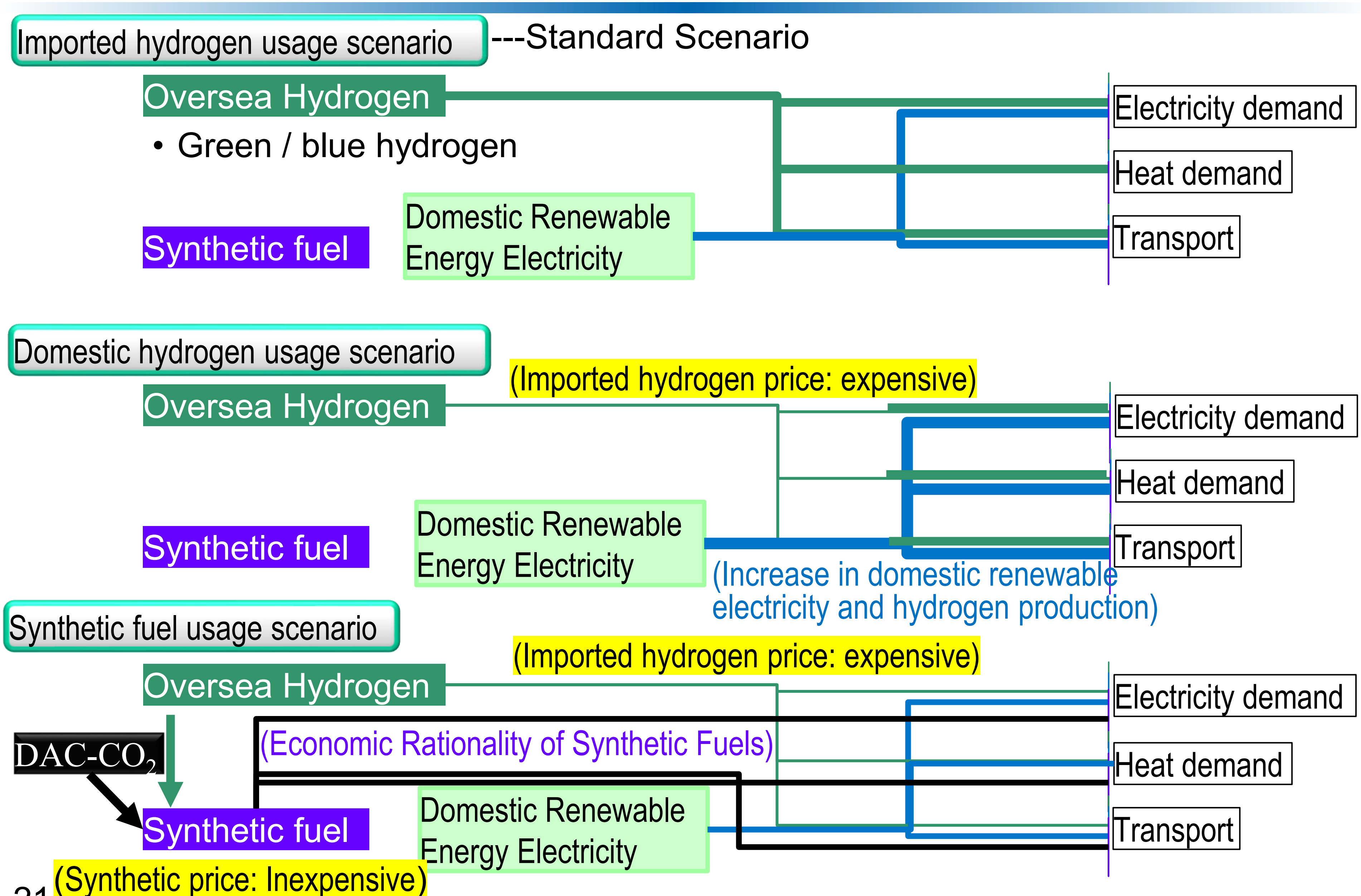


Population, Location and capacity of power generation plant, etc.

Conceptual Diagram of the Energy System

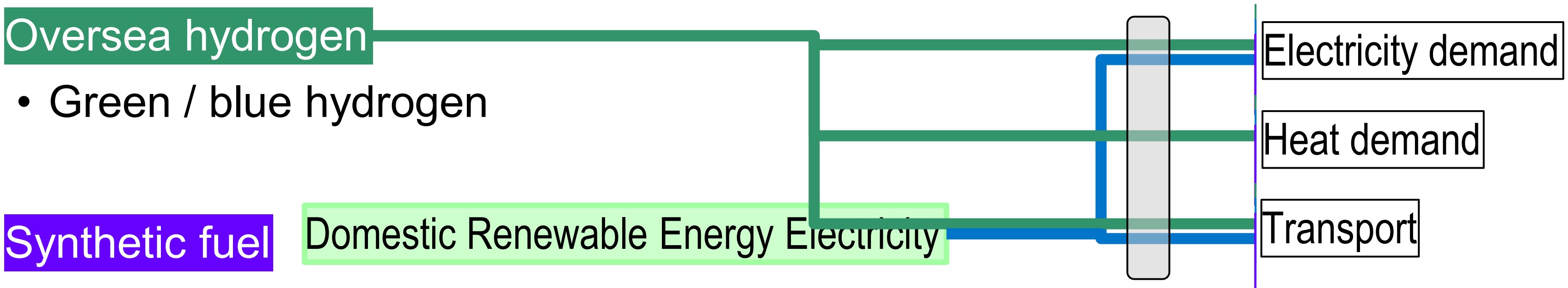


Main Configurations of Scenarios



Extension of the Scenarios

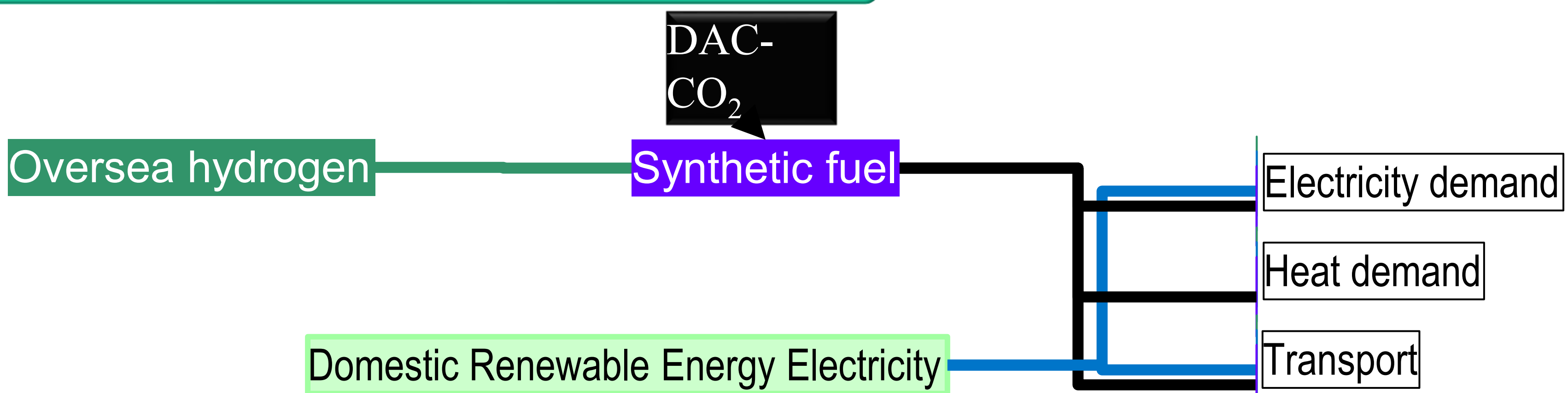
Imported hydrogen usage scenario ---Standard Scenario+(Impact of short-distance transportation)



- Examination of the relationship between infrastructure and energy utilization technology

<Example of exclusion scenarios>

Domestic synthetic fuel scenario using imported hydrogen



- It does not make sense that oversea transporting hydrogen, which has a high cost, procure CN-CO_2 in Japan, where renewable energy is scarce

Assumptions of Each Scenario

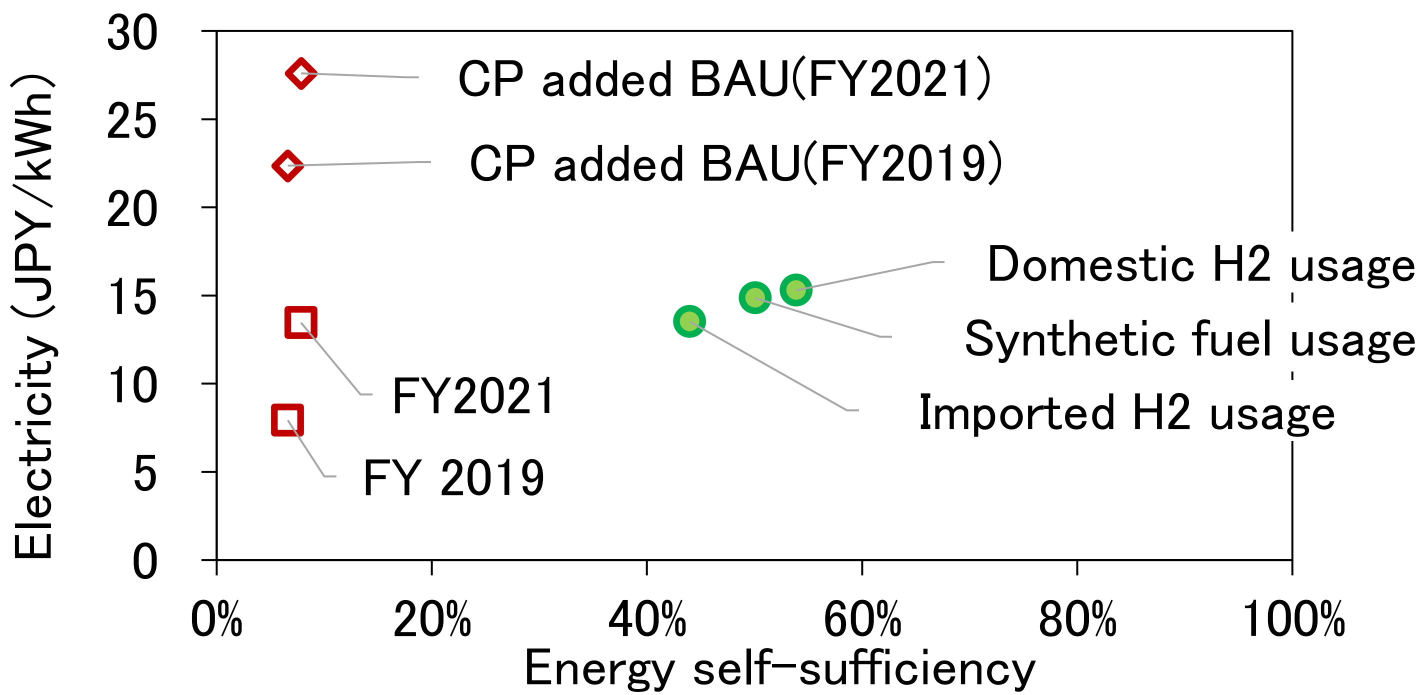
		Imported Hydrogen Usage Scenario	Synthetic Fuels Usage Scenario	Domestic Hydrogen Usage Scenario
Fuel	hydrogen Import price	2.89 JPY/MJ (37 JPY/Nm^3)	3.83 JPY/MJ (49 JPY/Nm^3)	
	e-methane Import price	7.31 JPY/MJ	4.51 JPY/MJ	7.31 JPY/MJ
	e-fuel Import price	8.18 JPY/MJ	4.51 JPY/MJ	8.18 JPY/MJ
	Fuel imports	No upper limit		
Power generation	Solar installation price	Residential solar power: 105,000 - 140,000 JPY/kW Commercial solar power: 88,000 – 135,000 JPY/kW		
	Wind installation price	Offshore wind: 211,000 – 311,000 JPY/kW Onshore: 108,000-293,000 JPY/kW		
	CCS capacity	< 9,000,000 tons/year		
	Nuclear Power Plant Restarts	only 12 units will remain (7 units in 2050)		
Infra-structure	Long-distance H_2 transportation	5 JPY/Nm^3 (From the port to the vicinity of large-scale or small-lot demand areas)		
	Short-distance H_2 transportation	5 JPY/Nm^3 (55 JPY/Nm^3 for examination of the impact of Hydrogen Infrastructure)		
Storage	Power grid installation	Master plan of the OCCTO is the lower limit		
	Water electrolyzer	52,000 JPY/kW		
	Battery	60,000 JPY/kWh		

Japanese official hydrogen price target:
30 JPY/Nm^3 by 2030
20 JPY/Nm^3 by 2050
with optimization of blue and green hydrogen

This scenario is based on green hydrogen

Energy Self-Sufficiency and Electricity Price in Each Scenario

- In BAU (Business as usual), the carbon price of the IEA's NZE case is added to the current price, so electricity (energy) prices become more than doubled ⇨ 【R&D and social implementation for CN】
- Regardless of the scenarios, Japan's introduction of renewable electricity is advancing, and its self-sufficiency rate is at least 40%.
- Within the assumed energy price range, the difference in electricity (energy) prices between scenarios is about a few JPY/kWh



Main Technology, Facility Scale, and Capital Investment

1 US$ ≡ 110 JPY		Facility scale (top) Capital investment (bottom)		
		Imported H_2 usage	Synthetic fuel usage	Domestic H_2 usage
Overseas	Renewable electricity	1783.2 GW 60.3 trillion JPY	1874.6 GW 63.4 trillion JPY	1522.5 GW 51.5 trillion JPY
	Water electrolyzers	594 .4 GW 30.9 trillion JPY	624.9 GW 32.5 trillion JPY	507.5 GW 26.4 trillion JPY
	Synthesis Reactor	6.0 GW 0.5 trillion JPY	249.5 GW 15.5 trillion JPY	6.8 GW 0.6 trillion JPY
	Marine transportation, etc.	226.5 trillion JPY	48.8 trillion JPY	325.2 trillion JPY※
Domestic	Renewable electricity	410.9 GW 77.1 trillion JPY	482.0 GW 94.6 trillion JPY	554.7 GW 112.2 trillion JPY
	Water electrolyzers	0.4 GW 0.02 trillion JPY	13.1 GW 0.7 trillion JPY	56.0 GW 2.9 trillion JPY
	Power grid	x 1.9 of current 7.8 trillion JPY	x 2.2 10.6 trillion JPY	x 2.3 10.9 trillion JPY
	Domestic Hydrogen Transportation	30.3 trillion JPY	7.9 trillion JPY	23.7 trillion JPY
	Residential Fuel Cells	25.0 GW 5.5 trillion JPY	11.5 GW 2.5 trillion JPY	20.8 GW 4.6 trillion JPY
	Fuel Cell Vehicles	3,172,000 cars 15.2 trillion JPY	2,232,000 cars 11.2 trillion JPY	2,264,000 cars 11.3 trillion JPY

Unlike conventional fossil fuels, surplus production is difficult to generate, and investment and development are essential for imports from overseas

- Including CN-CO_2 production of the synthetic fuel usage scenario, the largest investment in both renewable energy and hydrogen production is needed
- Investment in the production of synthetic fuels is more than marine transportation of hydrogen using energy carrier
- If direct use of hydrogen decreases, such as the high cost of short-distance transportation of hydrogen, it will be necessary to strengthen the power system
- The imported hydrogen usage scenario has the highest share of hydrogen, so investment in domestic transportation and hydrogen utilization is the largest

※Transportation investment is based on the assumption that the unit price of transportation will decrease as the volume increases

Issues for Industrialization of H_2-Related Technologies

Industrialization of H_2-Related Technologies

Important points for industrialization

Technology development

Europe, USA, Japan, China...

Economic efficiency

- Performance
- Mass production

Laws and regulations

- Domestic regulations
- International standard

Field of industrialization

Existing applications

- Industrial gas
- Refinery
- Ammonia production

Applications in the middle stage

- Fuel cell forklift
- Fuel cell vehicle

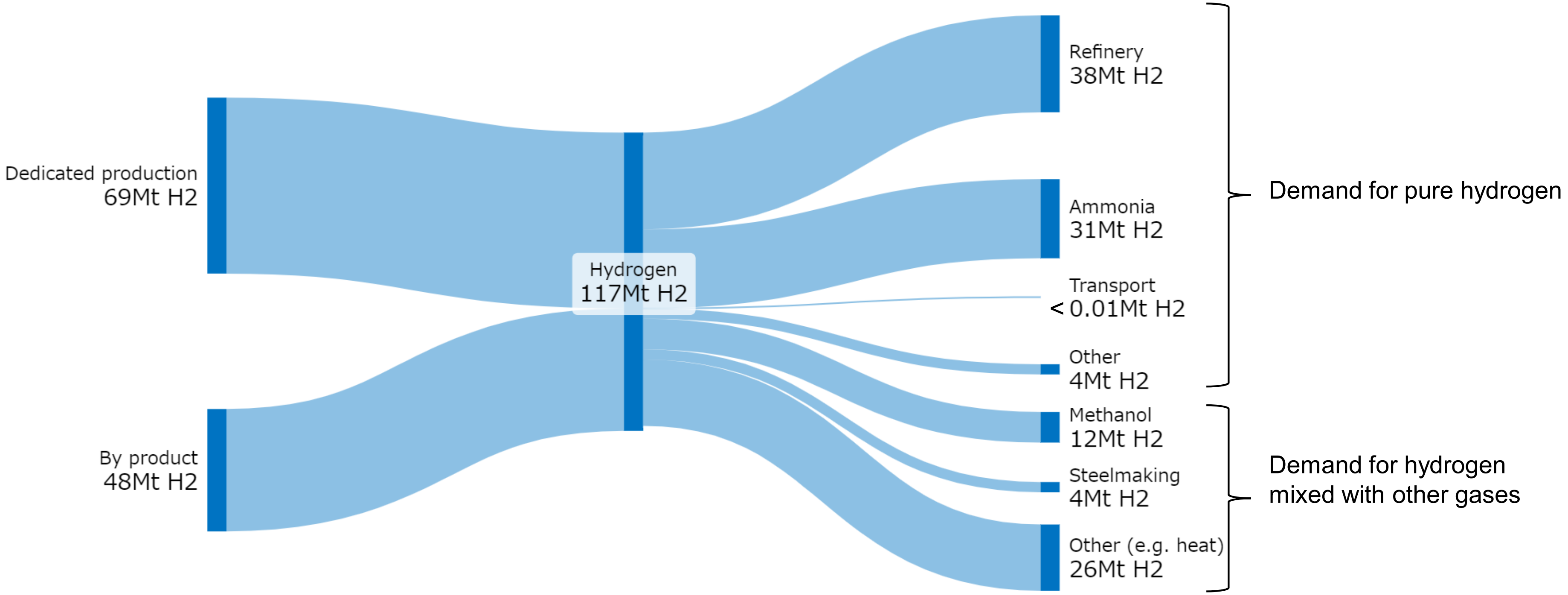
Future applications

- Heavy duty vehicles
- Steel industry
- Carbon recycling
- e-fuel power generation

Existing Applications

Industrial gas, refinery, and ammonia production

- Industrial H_2 is produced as dedicated and as by product.
- Most H_2 is for refinery and ammonia production.
- Fossil fuels are used as H_2 sources and recovery of CO_2 is hardly conducted for the H_2 production.



Applications in the Middle Stage

Fuel cell forklift

- 60,000 FC forklifts have been introduced in supermarkets and distribution warehouses in the U.S.
- National Renewable Energy Laboratory (USA) analyzed that FC forklifts are more competitive than those powered by secondary batteries.

Fuel cell vehicles

- Long driving distance (~650 km per a charge)
- Short refueling time (3 minutes)
- Need for establishing hydrogen fueling stations
- Mirai (Toyota), CR-V eFCEV (Honda), NEXO (Hyundai), and iX5 Hydrogen (BMW)
- 87,600 FCVs are introduced in the market at the end of 2023.

Future Applications

- Heavy duty vehicles
  →Fuel cells for trucks
- Aircrafts and ships
  →Difficult to be electrified. H_2 and e-fuels are expected.
- Steelmaking industry
  →H_2 is used as reducing agent instead of cokes.
- Basic chemicals (ammonia and methanol)
  →Production of basic chemicals from green H_2
- Gas turbine
  →Novel gas turbines for H_2 only or H_2-mixed gas are developed.
- Boiler and industrial furnace
  →H_2 can be used as fuels, but the price of H_2 should be lowered to be more competitive.

Hydrogen Supply Chains

Japan

- Demonstration test of LOHCs is ongoing through Green Innovation Fund.

Europe

- Repurposing of natural gas pipelines for H_2 pipelines through European Hydrogen Backbone.
- Establishing H_2 infrastructure through Important Project of Common European Interest (IPCEI)

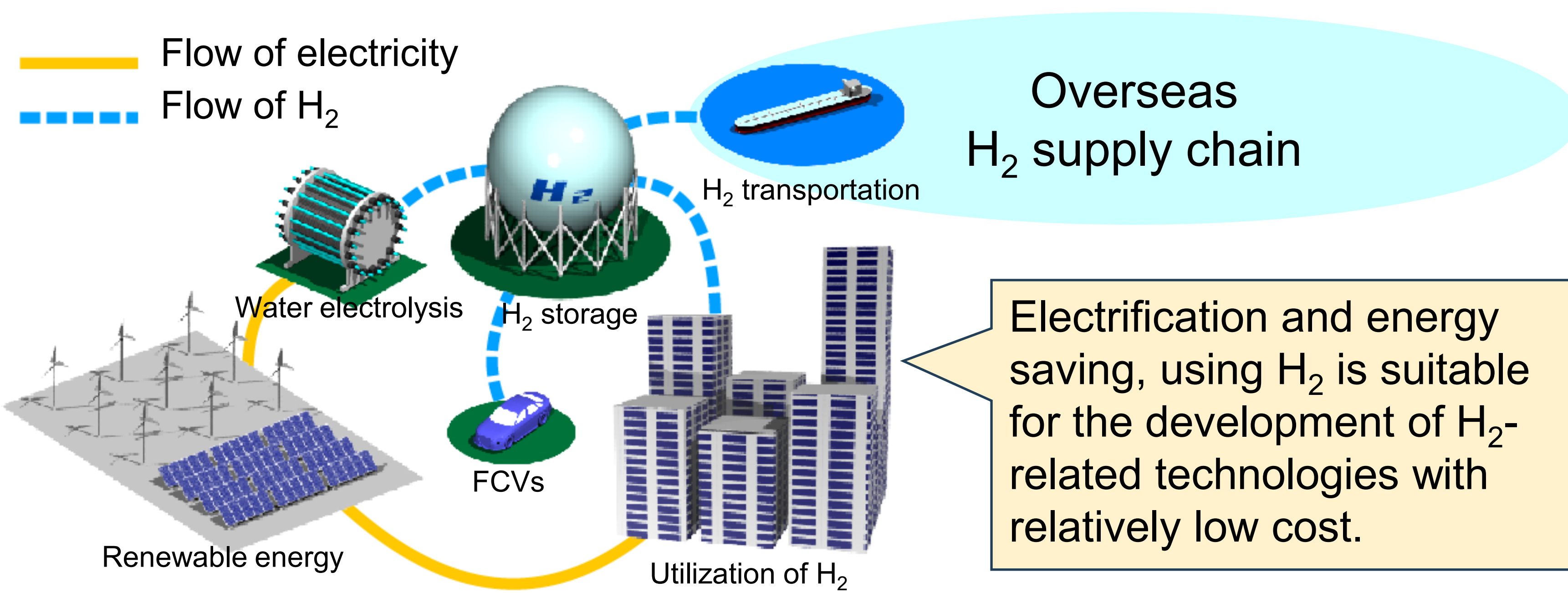
USA

- Establishing H_2 infrastructure, including job creation, through Regional Clean Hydrogen hub

Toward Industrialization of H_2-Related Technologies

- Constructing H_2 supply chain in and out of the country is necessary.
- It is useful for a country to focus on a technology for which the country will have competitiveness (in the future).

Technology development	Economic efficiency	Laws and regulations



Electrification and energy saving, using H_2 is suitable for the development of H_2-related technologies with relatively low cost.

Summary

- H_2 is quite promising for the efficient use of renewable energy in out society without emission of CO_2.
- Various H_2-related technologies are developed and some of them are in the practical stage.
- To establish all of technology, economy, and laws and regulations, and H_2 supply chain is important to introduce H_2-related technologies in our society.

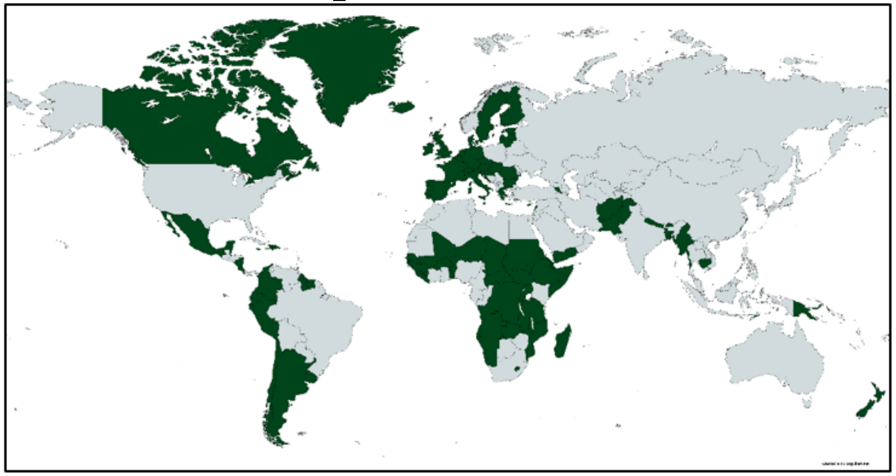
Target of Carbon Neutrality by Countries

Recently, >150 countries or regions have committed time-bound target for carbon neutrality.

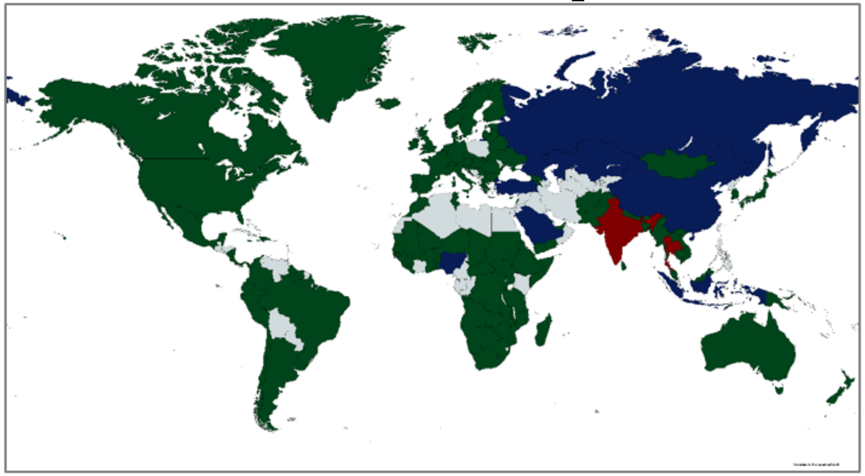
Countries or regions where committed carbon neutral with period

By 2050: 144 (42.2%)
By 2060: 152 (80.6% China and Russia)
By 2070: 154 (88.2% India+)

At the end of COP25 (Dec. , 2019): 121 countries, 17.9% of total CO_2 emission



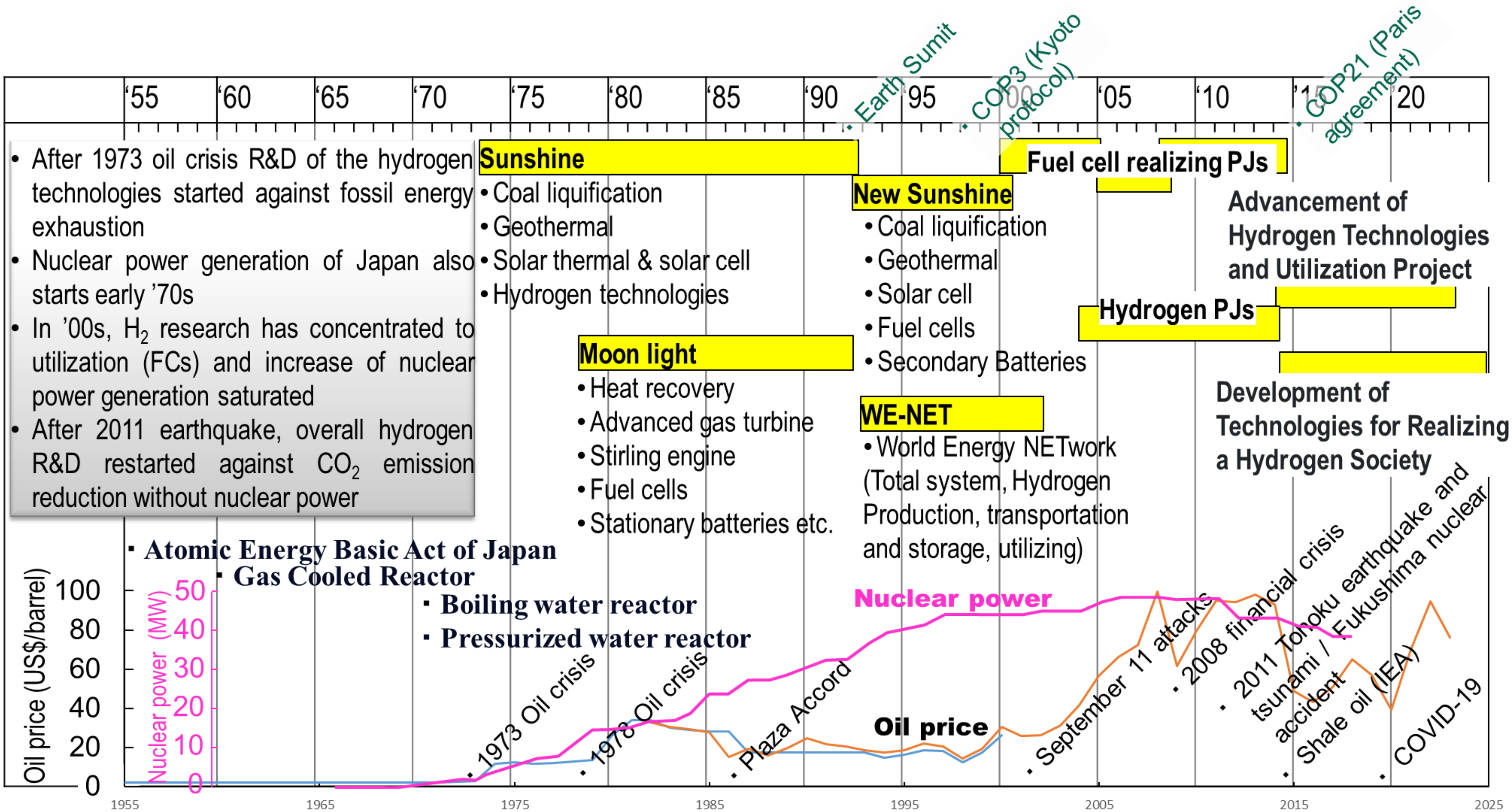
At the end of COP26 (Nov. , 2021): more than 150 countries, 88.2% of total CO_2 emission



■: CN by 2050 ■: CN by 2060 ■: CN by 2060

 https://www.rite.or.jp/news/events/pdf/kihara-ppt-kakushin2021.pdf (in Japanese)

History of H_2-Related Projects in Japan



- '70–'80: H_2 technology is developed for fuels alternative to oils.
- '90–: developed for environmental issues and carbon neutrality.
- Development of infrastructure and legal framework are also important.

Supply Chains for Hydrogen-Related Technologies

It is important to establish both H_2 supply chains (left to right) and supply chains of equipment and facilities (top to bottom.)

Supply chains of equipment and facilities

Mining

Material production

Manufacturing

Hydrogen supply chains

Primary energy	Production	Storage	Transport /Delivery	Utilization
Fossil fuels with CCS - Natural gas, coal Renewable energy - Solar, wind, biomass etc.	Reforming Gasification Electrolysis Fermentation etc.	Compressed hydrogen Liquid hydrogen Ammonia Liquid Organic Hydrogen carriers (LOHC) Metal hydrides Etc.	Trucks, Tankers Ships Trains Pipelines	Mobility - Passenger vehicles, Heavy duty vehicles, trains Industries - Steelmaking, chemical feedstocks, heat, material handling Power - Gas turbines, gas engines, fuel cells etc.

Decommissioning/waste treatment

Hydrogen supply chains

Primary energy

- Fossil fuels with CCS
  - Natural gas, coal
- Renewable energy
  - Solar, wind, biomass etc.

Production

- Reforming
- Gasification
- Electrolysis
- Fermentation etc.

Storage

- Compressed hydrogen
- Liquid hydrogen
- Ammonia
- Liquid organic hydrogen carriers (LOHC)
- Metal hydrides etc.

Transport/delivery

- Trucks, tankers
- Ships
- Trains
- Pipelines

Utilization

- Mobility
  - Passenger vehicles, heavy duty vehicles, trains
- Industries
  - Steelmaking, chemical feedstocks, heat, material handling
- Power
  - Gas turbines, gas engines, fuel cells etc.

Characteristics of H_2 among Fuels

Table 1 Enthalpy changes and Gibbs energy changes in combustion reactions of LHV for various fuels at 25℃

Fuel	ΔH_0 / kJ L^{-1}	ΔG_0 / kJ L^{-1}	ΔH_0 / kJ g^{-1}	ΔG_0 / kJ g^{-1}
H_2(g)	–10.8	–10.2	–120	–113
CO(g)	–12.6	–11.5	–10.1	–9.2
CH_4(g)	–35.8	–35.8	–50.1	–49.9
CH_3OH(l)	–15,767	–16,928	–19.9	–21.4
C_6H_{14}(l) (n-Hexane)	–29,298	–30,286	–44.7	–16.7
C_6H_6(l) (Benzene)	–35,179	–35,639	–40.1	–40.7
C (carbon black)	–20,800	–25,813	–9.2	–11.4

- High mass energy density but low volume energy density
  Relatively low theoretical efficiency ($\Delta H_0/\Delta G_0$)
- Rapid combustion, wide explosive range (4.0–75 vol%)

→ Transportation technology (liq. H_2, NH_3, and LOHC) is important.

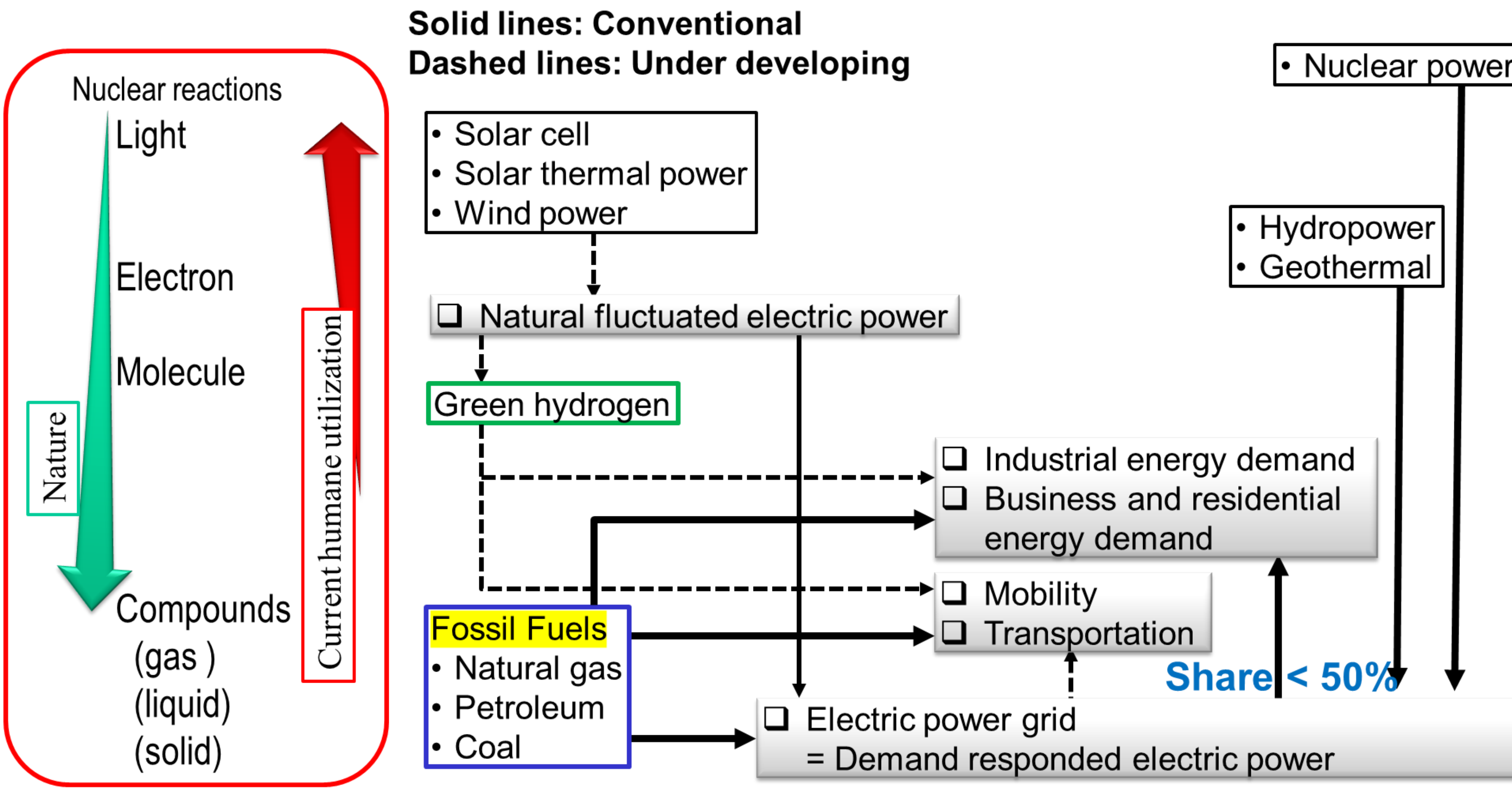
Characteristics of H_2 Carriers

- Several H_2 containing compounds are regarded as H_2 carriers.
- H_2-absorbing alloys are also used for H_2 storage, whereas they are mostly used for stationary storage because of their high density.

Table 2 Characteristics of typical hydrogen carriers.

	b.p. (℃)	density (g/cm³)	Carrier	Usage	$\Delta H_{\text{H2 combustion}}$		$\frac{\Delta H_{\text{H2 dehydrogenation}}}{\Delta H_{\text{H2 combustion}}}$	$\Delta H_{\text{direct combustion}}$	
					[Wh/kg]	[Wh/L]		[Wh/kg]	[Wh/L]
Comp. H_2** (70 MPa)	-253	0.0382	—	Direct	33,322	1,274	N/A	33,322	1,274
Liq. H_2	-253	0.0706	—	Vaporization	33,322	2,353	N/A	33,322	2,353
Liq. NH_3	-33.4	0.601	N_2	Dehydrogenation /Direct	5,916	3,556	12.70%	5,167	3,105
Methylcyclo-hexane	101	0.769	Toluene	Dehydrogenation	2,052	1,578	27.20%	-12,929	-9,955
Liq. CH_4	-165	0.46	CO_2	Direct/Reforming	16,752	7,706	26.10%	13,899	6,393
CH_3OH	64.7	0.792	CO_2	Direct/Reforming	6,290	4,980	18.10%	5,535	4,383

Role of H_2 To Utilize Renewable Energy



H_2 is used as an energy carrier to eliminate imbalance of renewable energy.

Scarcity of Iridium for SPEWE

The scarcity of iridium is a crucial issue on the installation of SPEWE for full decarbonization.

Required capacity of water electrolyzer

Worldwide fossil energy demand for transportation 10^{20} J

→ equivalent to H_2 of 700 $\mathrm{Mt_{H_2}}$

*H_2 HHV of 285.8 kJ/mol

Using SPEWE at the cell voltage ≈ 1.79 V

(long term efficiency: ≈ $70\%_{\mathrm{LHV}}$)

→ average electric power ≈ 3800 GW

Because renewable energy is fluctuating, electrolyzer of ≈ 12000 GW will be required to supply H_2 for transportation.

*average electric power is roughly 1/3 of the peak power.

Required Ir to install enough SPEWE

Annual production of Ir: ≈ 4 ton/y

Current requirement of Ir for SPEWE: ≈ 0.5 $\mathrm{g_{Ir}}$/kW

→ 6000 $\mathrm{ton_{Ir}}$ is necessary (at least ≈ 1500 years)

[1] The parameters were referred to the following paper,
M. Bernt, A. Siebel, H. A. Gasteiger, *J. Electrochem. Soc.* **2018**, *165*, F305.

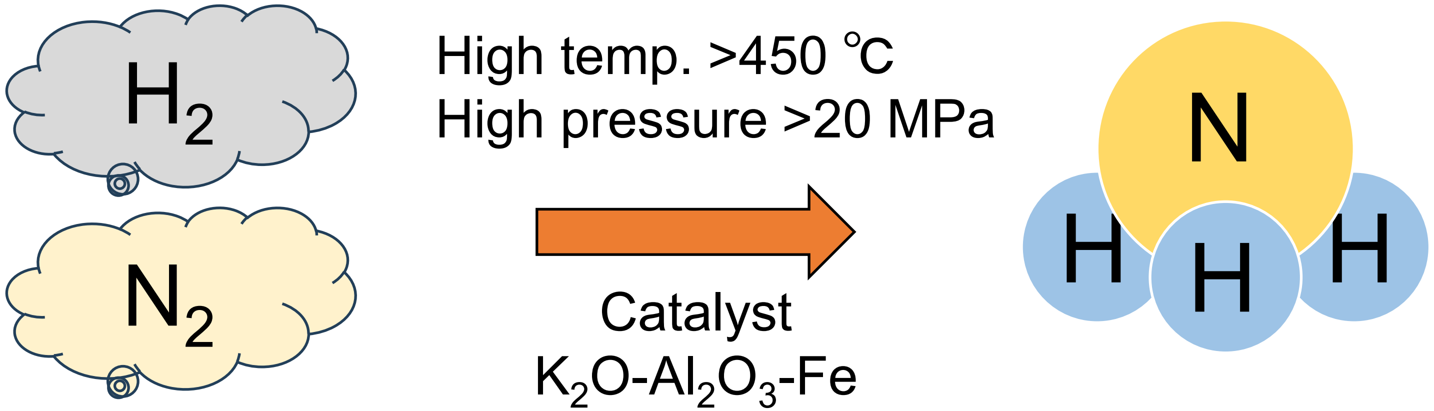
Types of Fuel Cells

Name of Fuel Cells (Abbr.)	Alkaline (AFC)	Polymer Electrolyte (PEFC)	Phosphoric Acid (PAFC)	Molten Carbonate (MCFC)	Solid Oxide (SOFC)
Electrolyte Ion-conductive species	Potassium hydroxide OH^-	Polymer electrolyte membrane H^+	Phosphoric acid H^+	Molten carbonate CO_3^{2-}	Stabilized zirconia O^{2-}
Fuel	H_2	H_2	H_2	H_2, CO	H_2, CO
Main Features	・Relatively low operating temperature ・Wide range of material selection	・High power density ・Low operating temperature	・Compact system ・Effective use of waste heat	・High voltage ・High overall efficiency	・Internal reforming of fuel is possible due to high temperature operation
Application	Special applications such as space and military use	Fuel cell vehicle, Bus, Cogeneration for home stationary use	Sewage treatment plants, beer breweries, hotels, data centers, etc.	Hospitals and Beer Breweries	Cogeneration for home stationary use, Triple combined cycle

Production of Ammonia

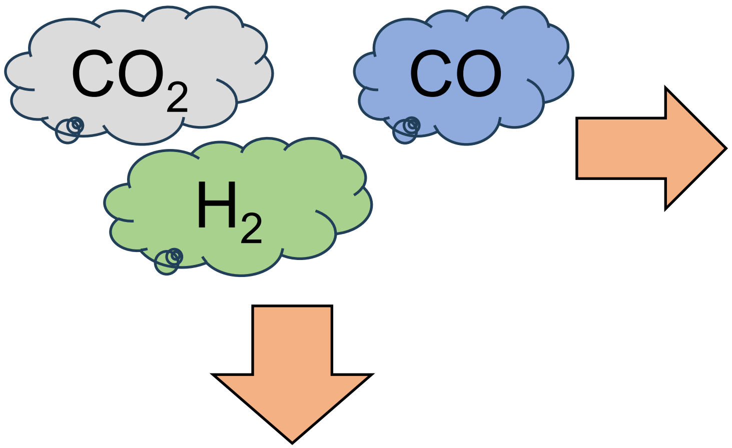
Haber–Bosch process

Established in 1913 by Frits Haber, Carl Bosch, and Alwin Mittasch.



- Hydrogen (H_2) is currently produced from natural gas with emission of CO_2.
  →1.9 ton of CO_2 emission to produce 1 ton of ammonia.
- Key point is to use green hydrogen with better catalyst that enables production of ammonia at milder conditions (<450 ℃, <10 MPa).

Products of Synthetic Fuels



e-Methane

- mixed with natural gas for pipeline transportation.
- Minimum change in infrastructure

e-Fuels (Liquid hydrocarbons)

- Mixture of LP gas, naphtha, various oils, wax, etc.
- Separation and isomerization are required

e-Fuels (Methanol)

- Produced from CO and/or CO_2 with H_2.
- Various oils are produced from methanol by the methanol-to-gasoline (MTG) reaction.

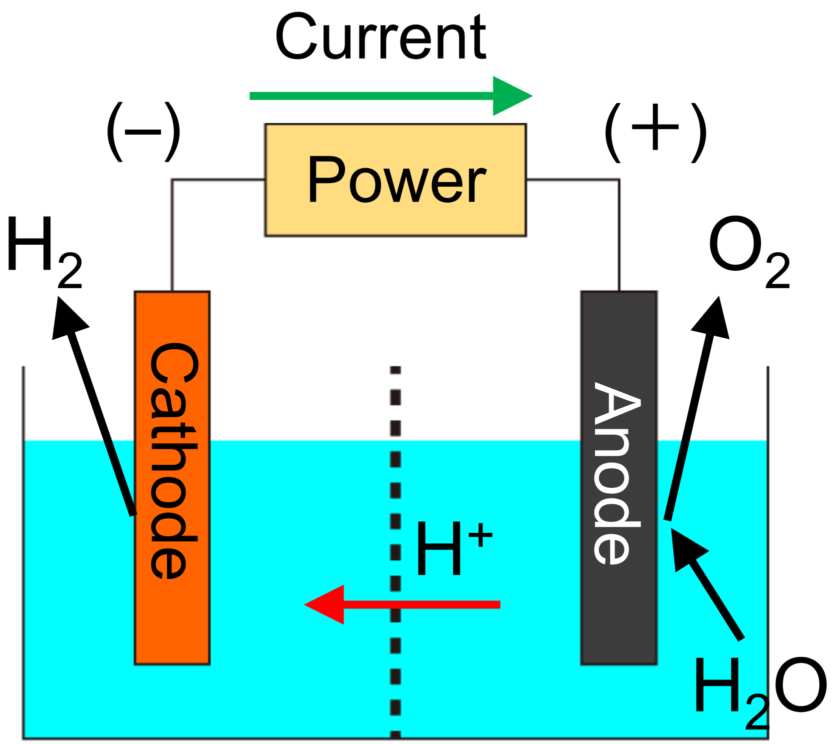
Characteristics of Hydrogen Absorbing Alloys

$$\mathrm{M} + \mathrm{H_2} \rightleftarrows \mathrm{MH_2} + \mathrm{heat}$$

High pressure Low pressure

- Hydrogen storage for stationary use.
- For transportation of hydrogen, hydrogen absorbing alloys are expected as low pressure media which is suitable for applications compliance with regulations.
- Thermochemical compressor for pressurized hydrogen
- Anode material for Ni-MH battery.

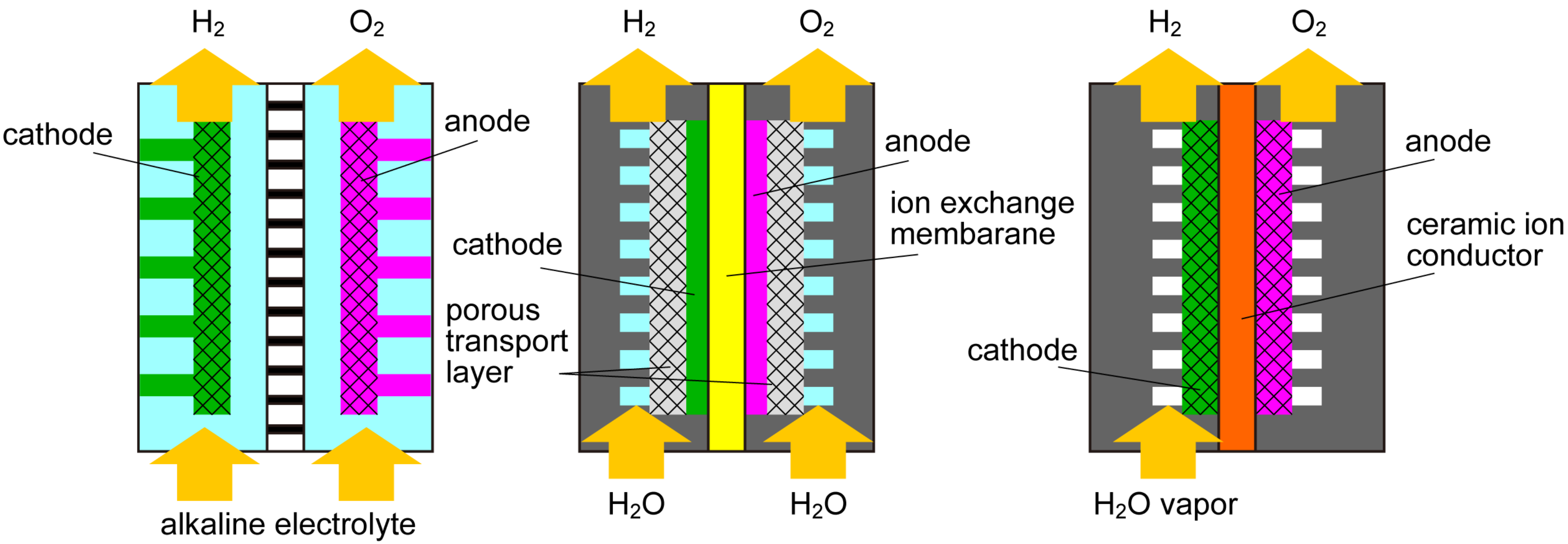
To Produce H_2: Water Electrolysis



- H_2O is split into H_2 and O_2 by the application of electric power.
- No CO_2 is emitted during the production of hydrogen, if renewable electricity is used.

- Highly efficient and environmentally benign method to produce H_2 from renewable energy.
- The price of H_2 depends on the price of electricity.
- Clean water is necessary for most water electrolysis.

Types of Water Electrolysis



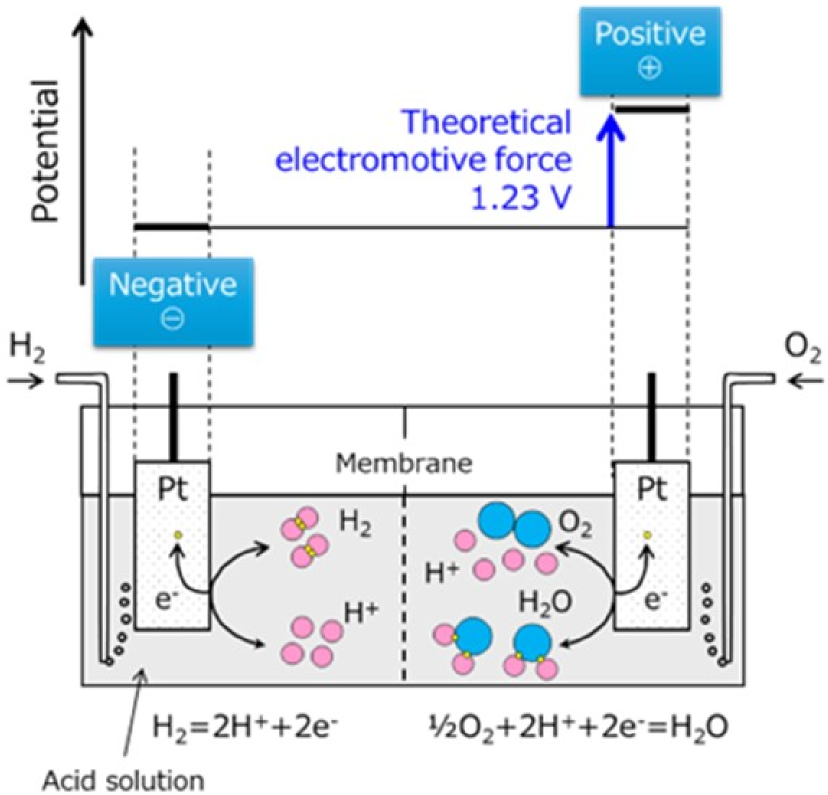
Alkaline water electrolysis

Proton exchange membrane water electrolysis

Solid oxide electrolyzer cell

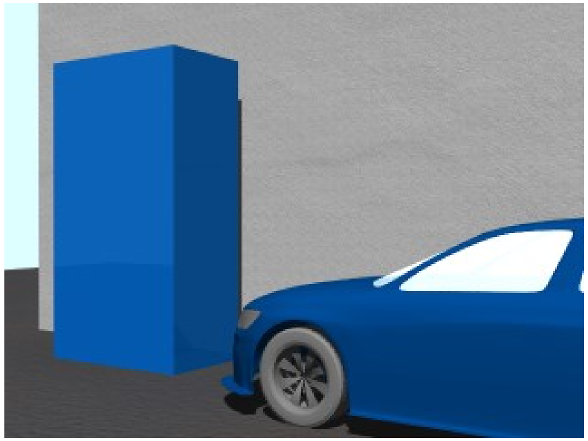
Alkaline water electrolysis	Proton exchange membrane water electrolysis	Solid oxide electrolyzer cell
• Low cost • Long history (>100yrs) • Moderate efficiency	• High efficiency • New technology • Expensive (Ir and Pt) • Use of fluorinated materials	• High efficiency • Emerging technology • Requirement for stable heat source

To Use H_2: Fuel Cells



- Generating electricity, using H_2 as a fuel.
- No CO_2 is emitted during the generation of electricity.
- Heat is also recoverable other than electricity (co-generation system).
- High theoretical energy efficiency (94% based on LHV).
  cf. Thermal plant: ca. 50% based on LHV

Characteristics of Fuel Cells



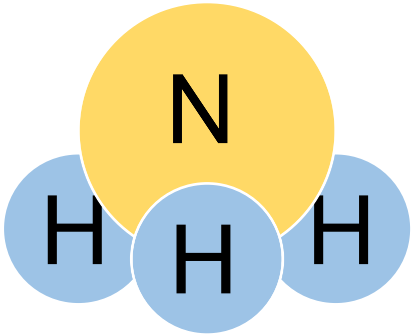
Polymer electrolyte fuel cells (PEFCs)

- Mobility & stationary use
- Low operation temp. 80–120 ℃
- Scarcity and cost of platinum
- H_2 fuel must have quite high purity (Catalyst poisoning by CO)

Solid oxide fuel cells (SOFCs)

- Stationary use
- High operation temp. 700–1000 ℃
- Noble metal is not required.
- Less limitation in purity of H_2 fuel

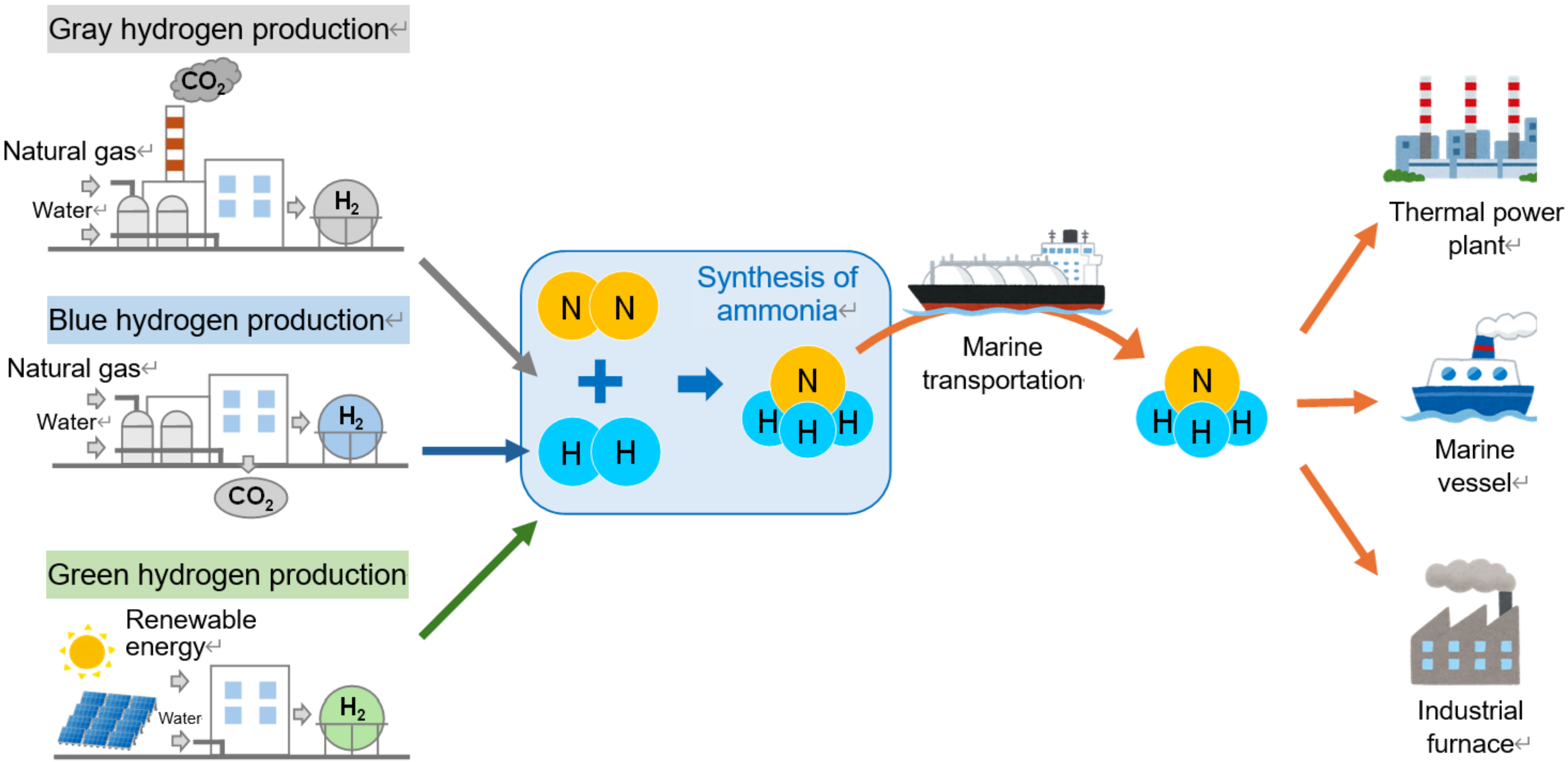
To Transport H_2: Ammonia Fuels



Ammonia

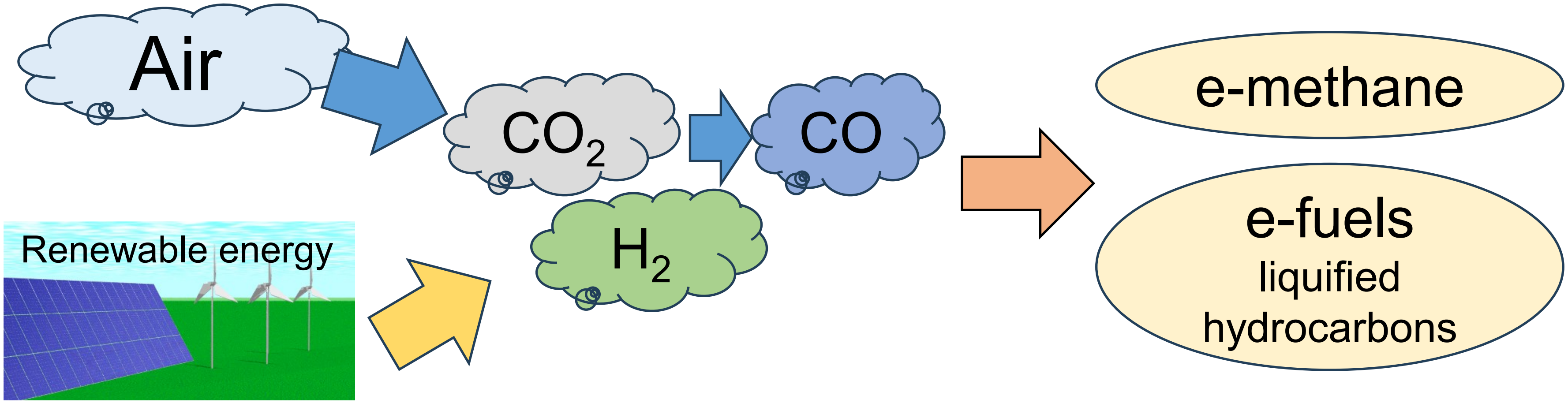
- Important basic chemicals
- Worldwide production 200 million tons/yr
  80% is used as fertilizer
- Produced from H_2 and N_2 by Harbor–Bosch process
- Liquified by compression at 1 MPa
- No emission of CO_2 upon combustion
  →Carbon-free fuels
- Co-firing of ammonia with coal or combustion of ammonia only is expected for thermal power.
- Highly toxic
  →Important to prevent leakage

Ammonia as a Hydrogen Carrier



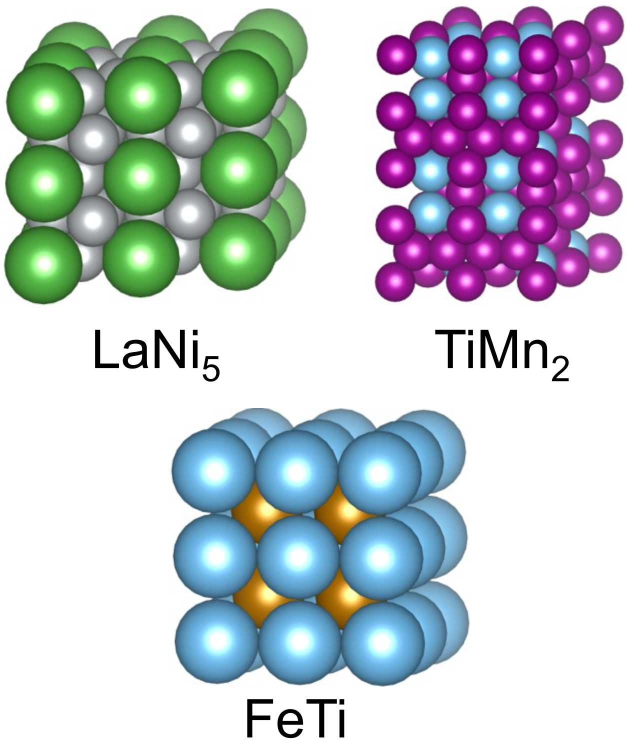
- Ammonia is produced from H_2 and used as a clean energy.
- Volumetric energy density of ammonia (12.8 GJ m^{-3}) is much higher than that of H_2 (0.01 GJ m^{-3}).
- Maintaining supply chain of ammonia is important.

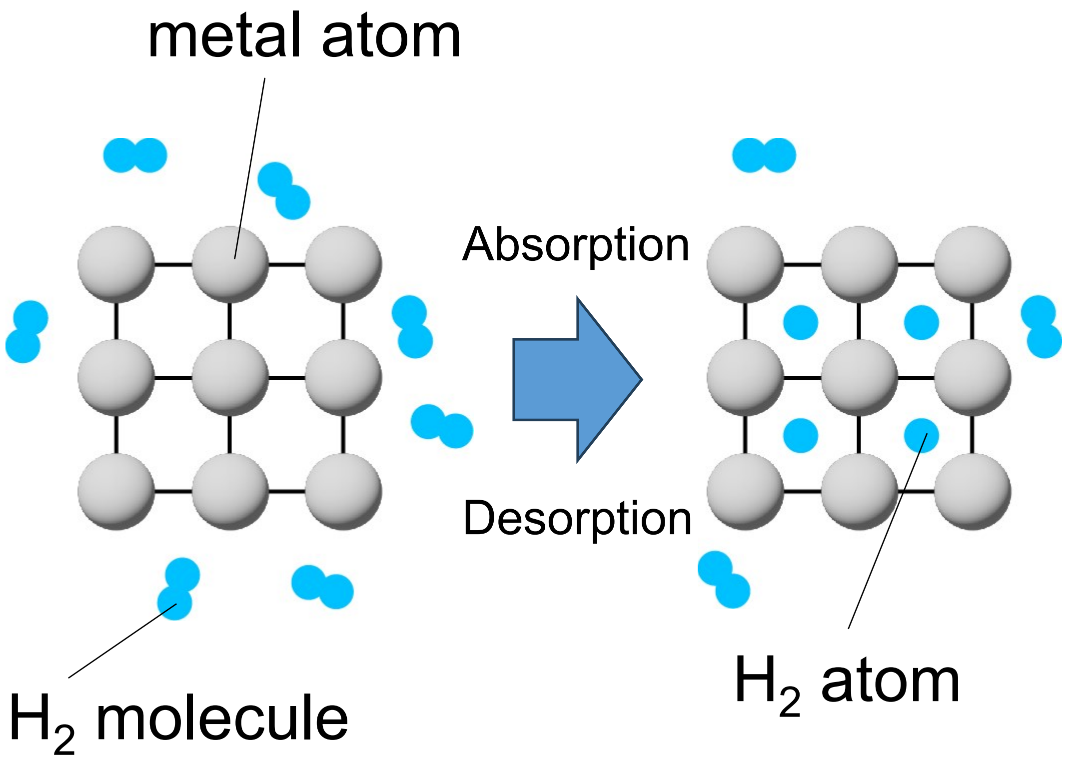
To Transport H_2: Synthetic Methane and Synthetic Fuels



- e-Methane and e-fuels are produced from aerobic CO_2 and green H_2 by catalytic processes.
- Combustion of e-methane and e-fuels emit CO_2, although they are originally produced from equivalent amount of CO_2 from air.
  → They do not increase the amount of CO_2 in atmosphere.
- Direct air capture (DAC) technology is necessary to promote the production of e-methane and e-fuels.

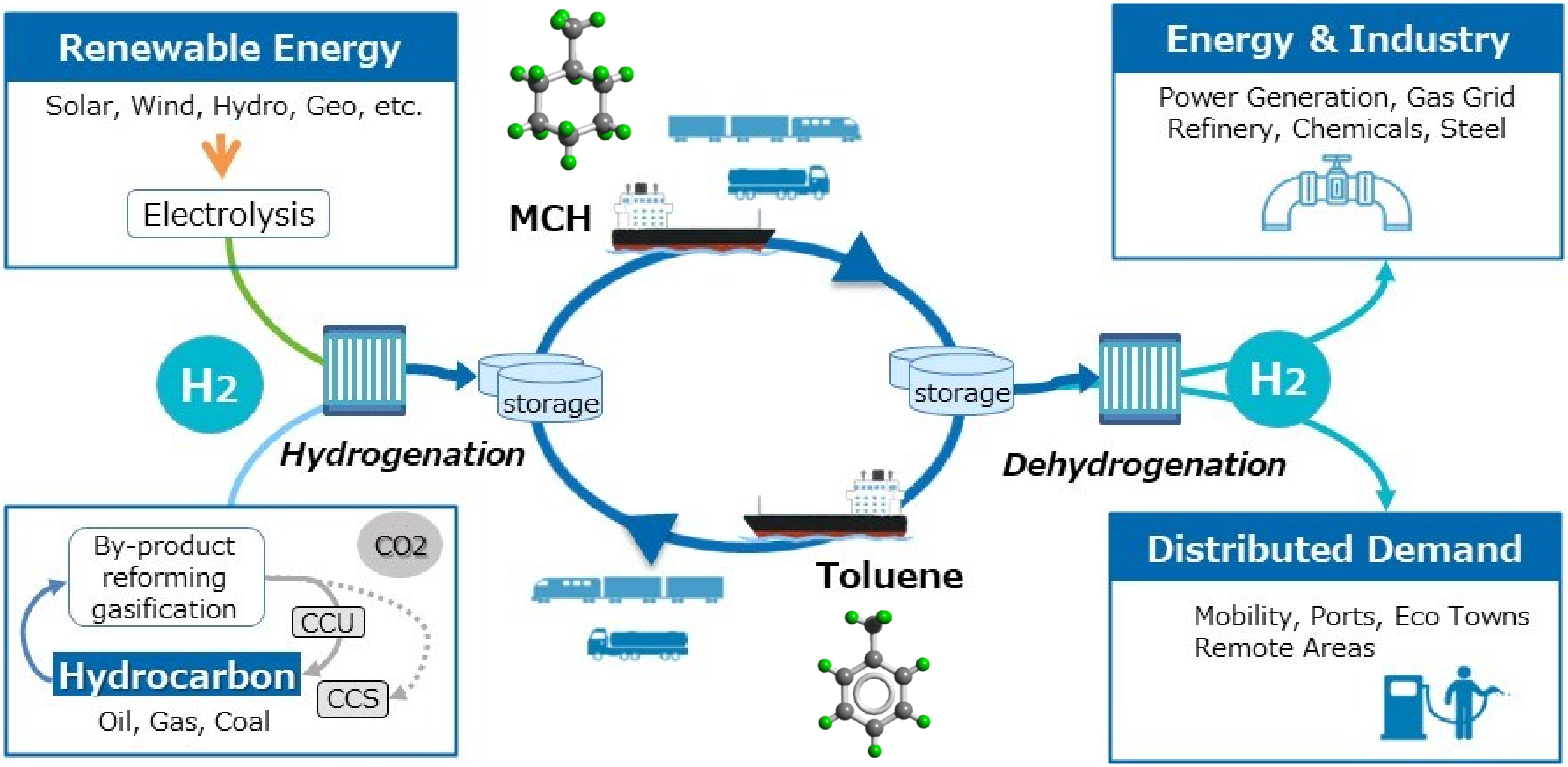
To Transport H_2: Hydrogen Absorbing Alloys





- High volumetric density of H_2 in a solid
- Used for storage of H_2

To Transport H_2: Liquid Organic Hydrogen Carrier



- The transportation of H_2 gaseous at room temperature is disadvantageous to other energy carriers.
- Hydrogenated liquid organic compound (organic hydride) is useful as H_2 carriers for transportation.
- Detail will be explained in the lecture by Dr. Okada.

To Transport H_2: Liquified Hydrogen

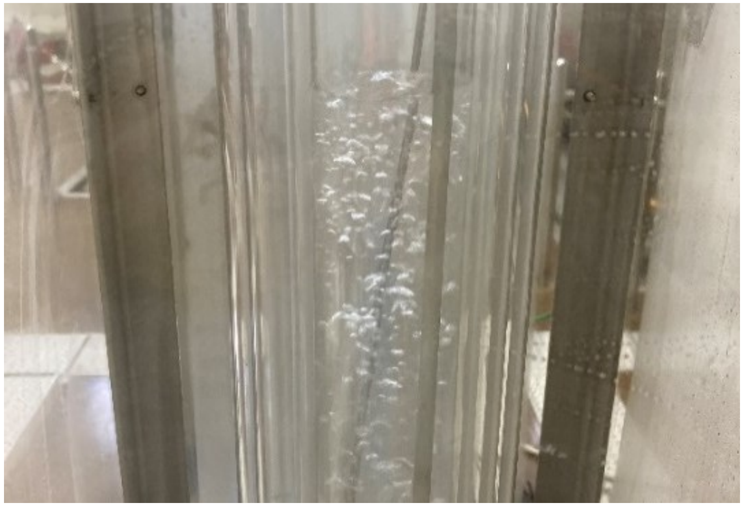


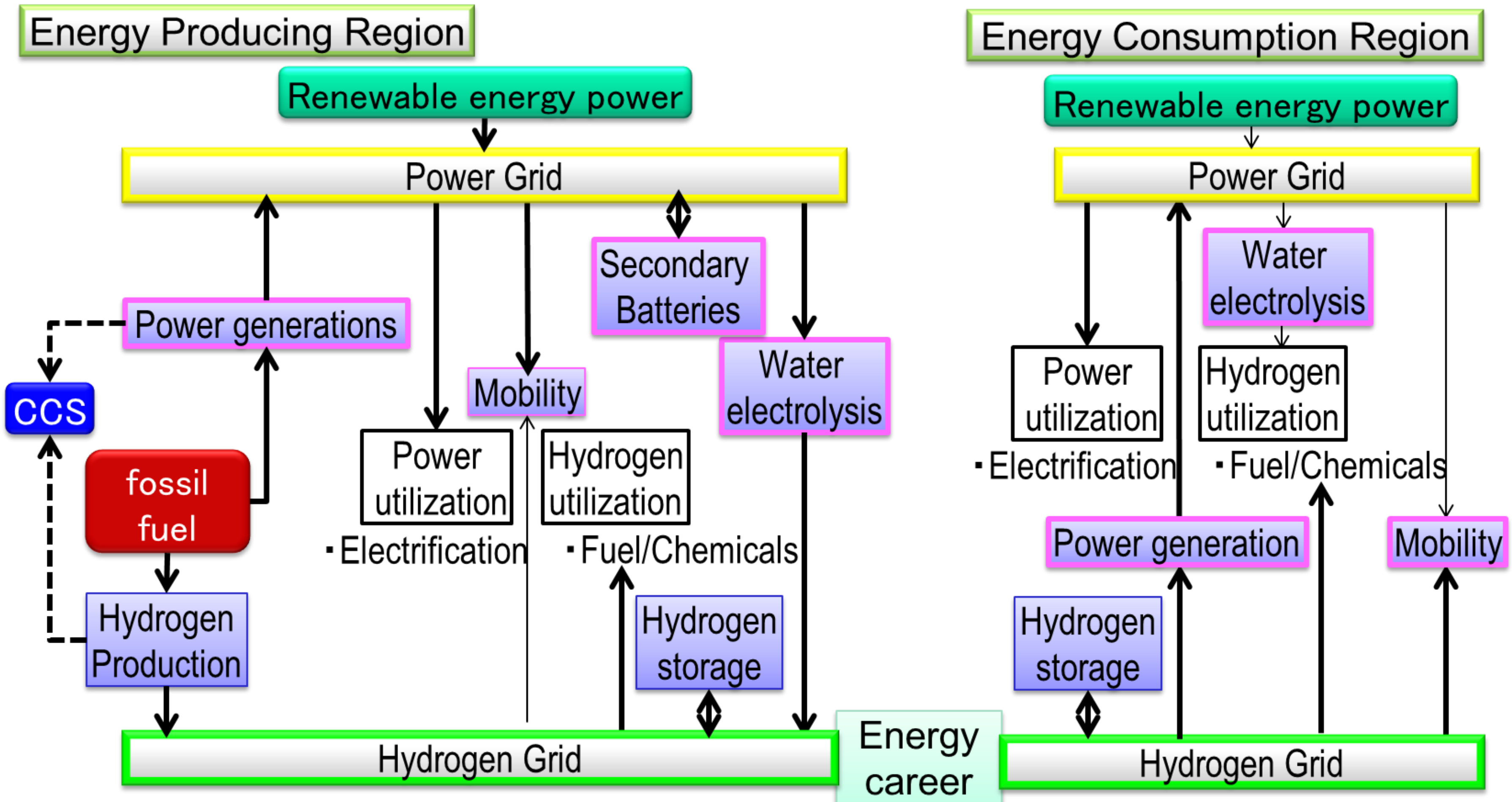
Photo of liq. H_2

- H_2 liquified at –253 ℃
- No byproduct
- 1.75 times the capacity of a high-pressure H_2 tank
- Large energy requirement for liquification, but small requirement for gasification.
- Boiling off should be suppressed.

Liq. H_2 tank truck

- Land transportation of liq. H_2 is established.
- Maritime transportation is under development.

H_2 Energy System Based on Renewable Energy



- Energy producing region (left side) produces H_2.
- Energy consumption region (right side) receive H_2 and uses it for energy source like a primary energy as well as for chemical processes.