Carbon Dioxide Zero-Emission Hydrogen System based on Nuclear Power

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- Back ground: Hydrogen supply for fuel cell vehicles
- CO_2 zero-emission hydrogen career system using a regenerative reformer
- Experimental demonstration
- Evaluation of the hydrogen career system

Hydrogen for FC
-A fuel cell is environmental friendly?-

Problems of H_2 supply to a conventional fuel cell vehicle

- Compressed H_2 fuel : high-energy consumptions for production and pressurization, and explosiveness

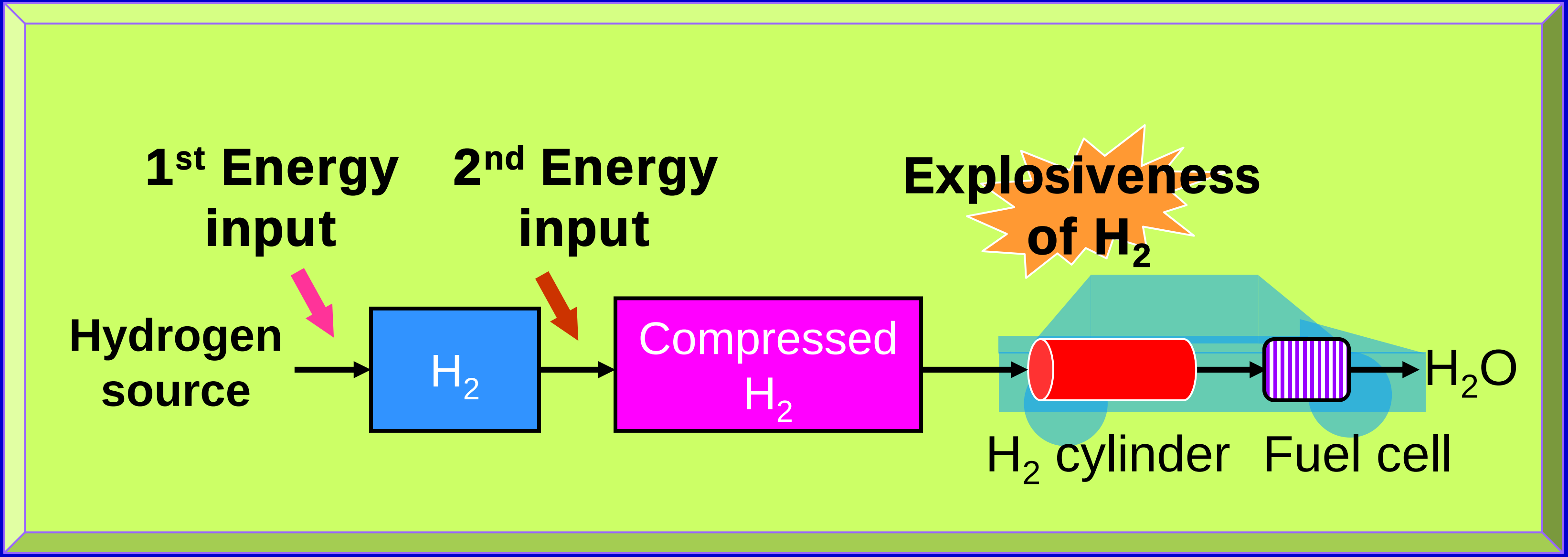


Fig. Subjects for hydrogen supply to a fuel cell vehicle

Fuel reforming for hydrogen supply to a fuel cell vehicle

Problems of H_2 supply to a conventional fuel cell vehicle

- Fuel Reforming: complex structure, and CO_2 emission

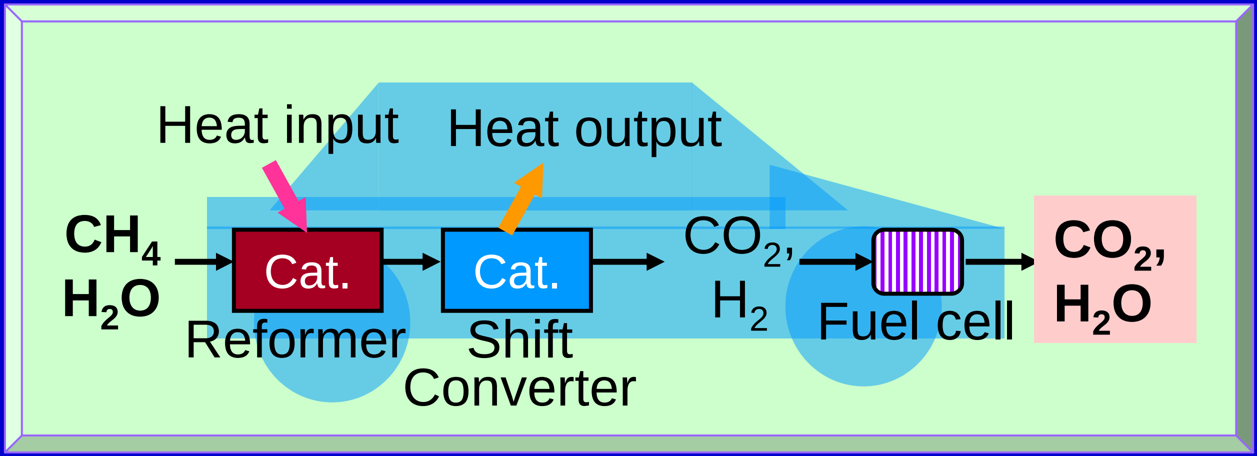


Fig. Conventional reforming system for a FC vehicle

Regenerative Reforming
-Use of chemical absorption-

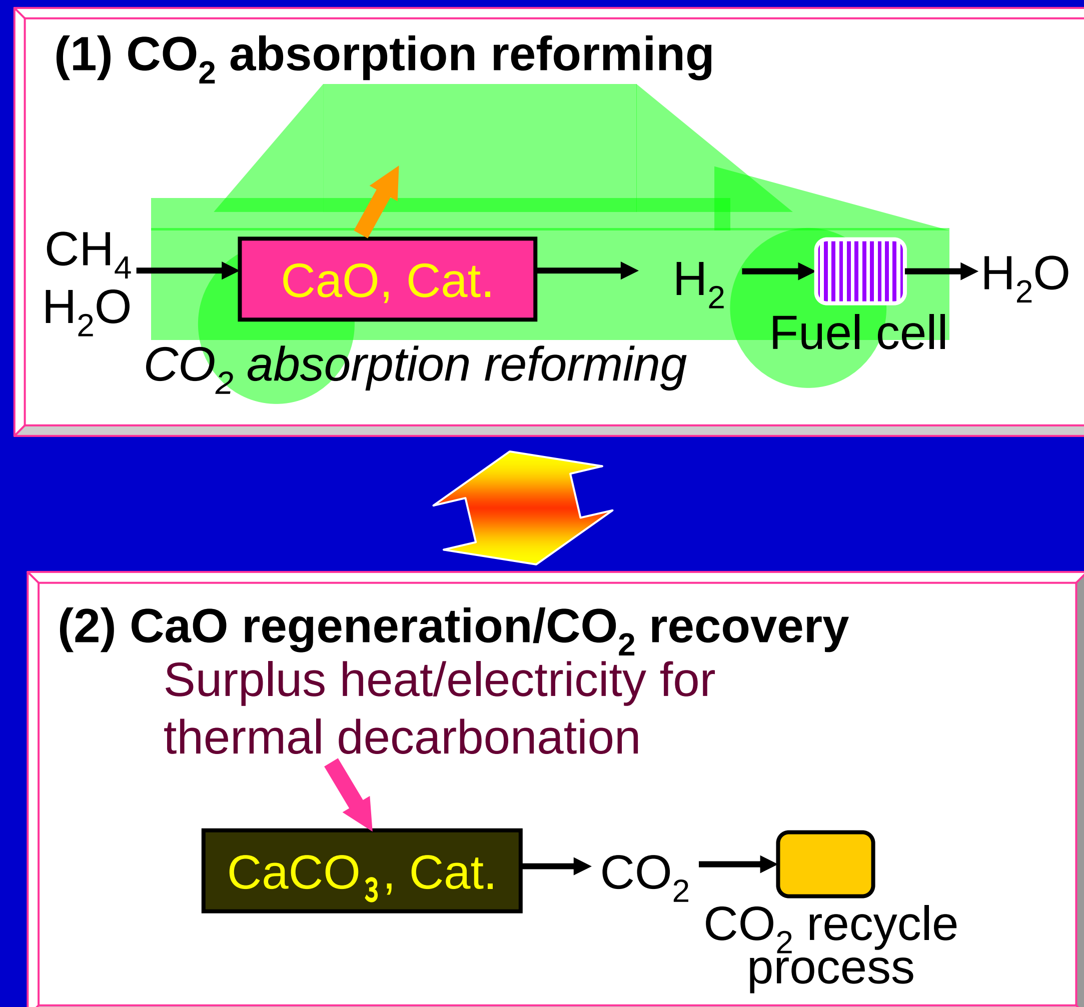
- Fuel reforming for methane
  - $CH_4 + H_2O \leftrightarrow 3H_2 + CO$, $\Delta H^o_1 = +205.6$ kJ/mol
  - $CO + H_2O \leftrightarrow H_2 + CO_2$, $\Delta H^o_2 = -41.1$kJ/mol
- CaO carbonation
  - $CaO(s) + CO_2(g) \leftrightarrow CaCO_3(s)$, $\Delta H^o_3 = -178.3$ kJ/mol
- Regenerative reforming
  (CO_2 absorption reforming, self-heating)
  - $CaO(s) + CH_4(g) + 2H_2O(g) \leftrightarrow 4H_2(g) + CaCO_3(s)$, $\Delta H^o_4 = -13.3$ kJ/mol

Non-equilibrium reaction for hydrogen production

- Based on fuel reforming
- Separation processes for non-equilibrium reforming
  - Separating CO_2 from system using chemical absorption
- Merit of non-equilibrium reforming
  - Enhancement of hydrogen production
  - Use of exothermic reaction heat for endothermic reforming
  - Drop in reforming temperature
    - CH4 steam reforming: 700^{o}C -> 500^{o}C
  - Enhancement of high-carbon numbers reactant reforming
    - Kerosene, C_2H_5OH and higher hydrocarbon
  - Reuse of carbon dioxide
    - CO_2 zero-emission system
- Link with nuclear power system

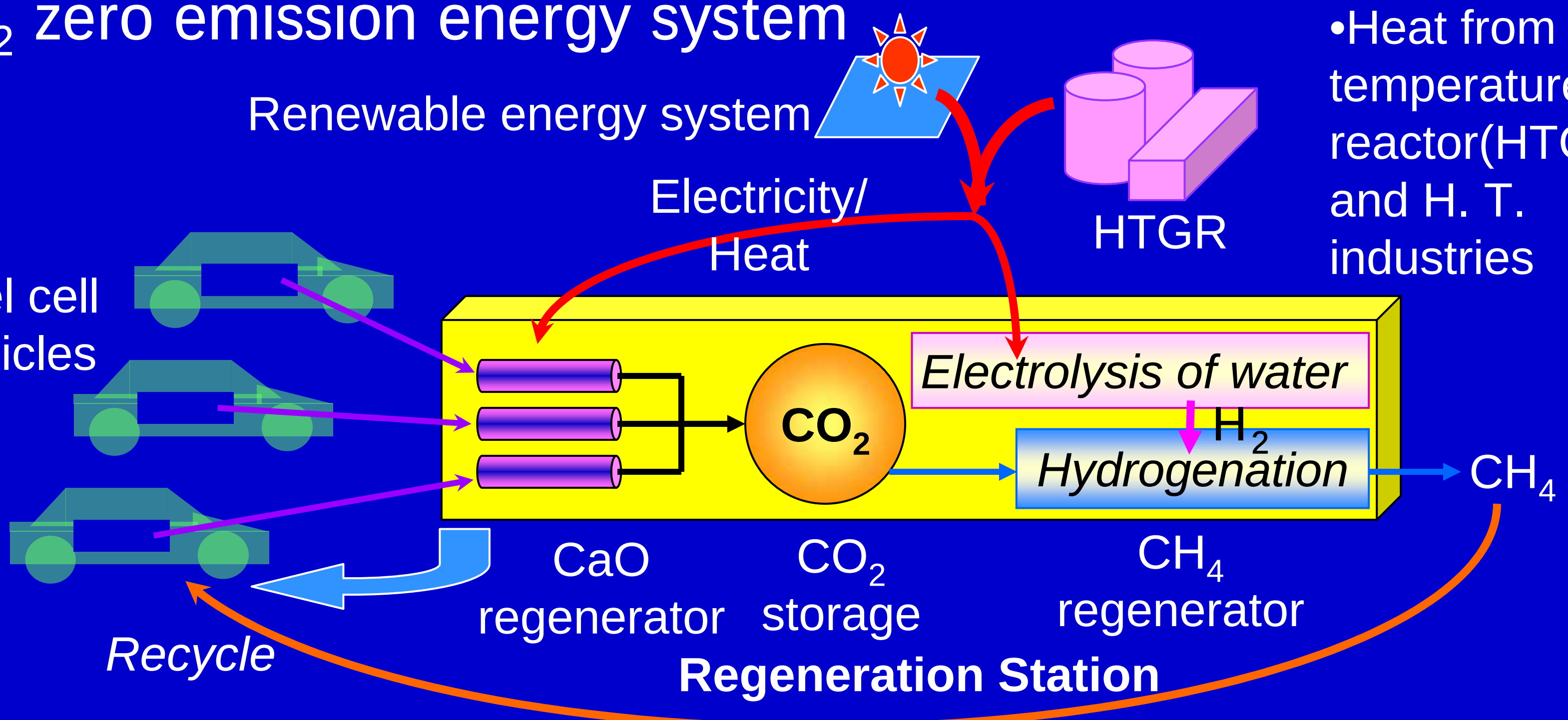
CO_2 zero-emission FC vehicle using the regenerative reformer

- Regenerative reforming
  - CO_2 recoverable, self heating, and simple reforming system
  - thermally regenerative
- CO_2 zero-emission FC vehicle
- Safety H_2 carrier system under low-pressure and high-density



CO_2 zero-emission hydrogen career system

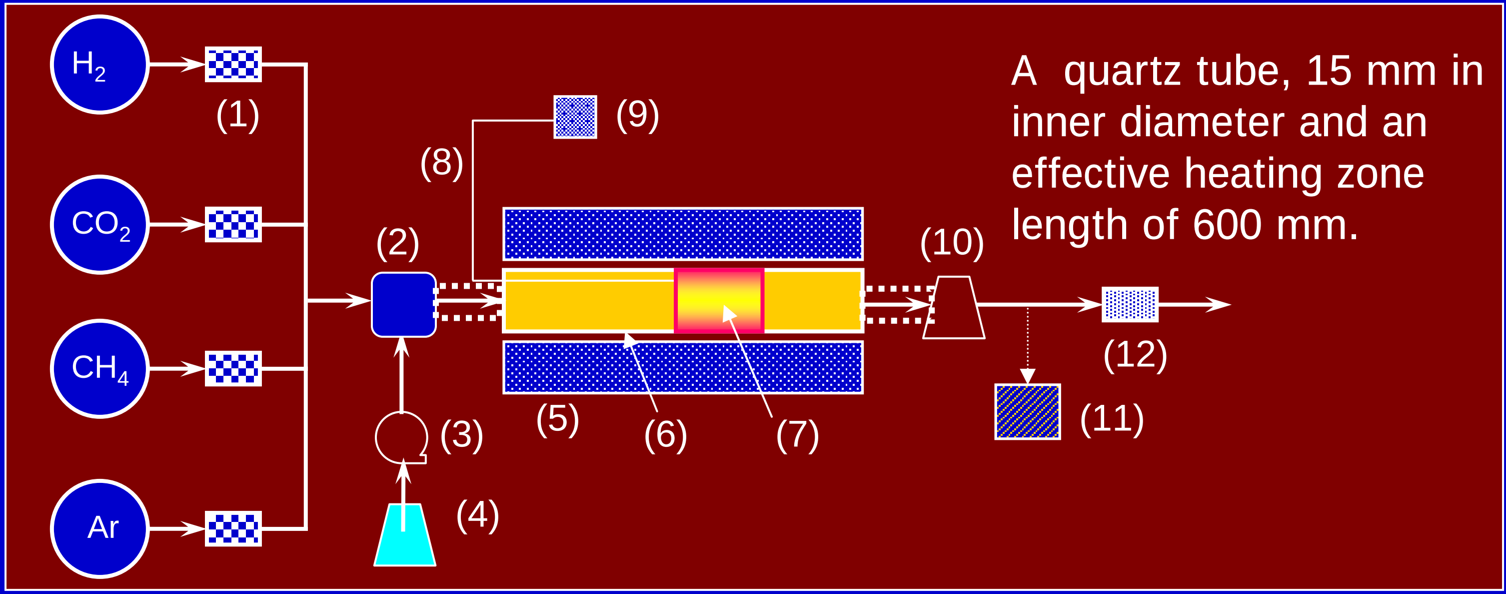
- Hydrogen system driven by surplus electricity and heat from nuclear power plants, and unstable energy.
- Safe and compact hydrogen transportation
- CO_2 zero emission energy system



- Electricity from nuclear power plants
- Heat from high-temperature gas reactor(HTGR) and H. T. industries

Experiment of the regenerative reformer

- Demonstration of the possibility of the regenerative reforming system
- For polymer electrolyte fuel cell (PEFC) operated at a hydrogen pressure of less 0.3 MPa.



(1) flow meter, (2) evaporator, (3) micro-feeder, (4) water reservoir, (5) electric furnace, (6) reactor tube, (7) reactor bed, (8) thermocouple, (9) furnace heating controller, (10) liquid-gas separator, (11) gas chromatograph, (12) soap flow meter

CO_2 absorption reforming

- During the initial 60 min, hydrogen production was higher than the equilibrium concentration of conventional reforming.
- Charged CaO absorbed well CO_2 by carbonation. CO_2 <1%
- CO was removed, <1%
- Low-temperature reforming (conventional reform. temp. > 700ºC)

(a) regenerative reformer (RGR)

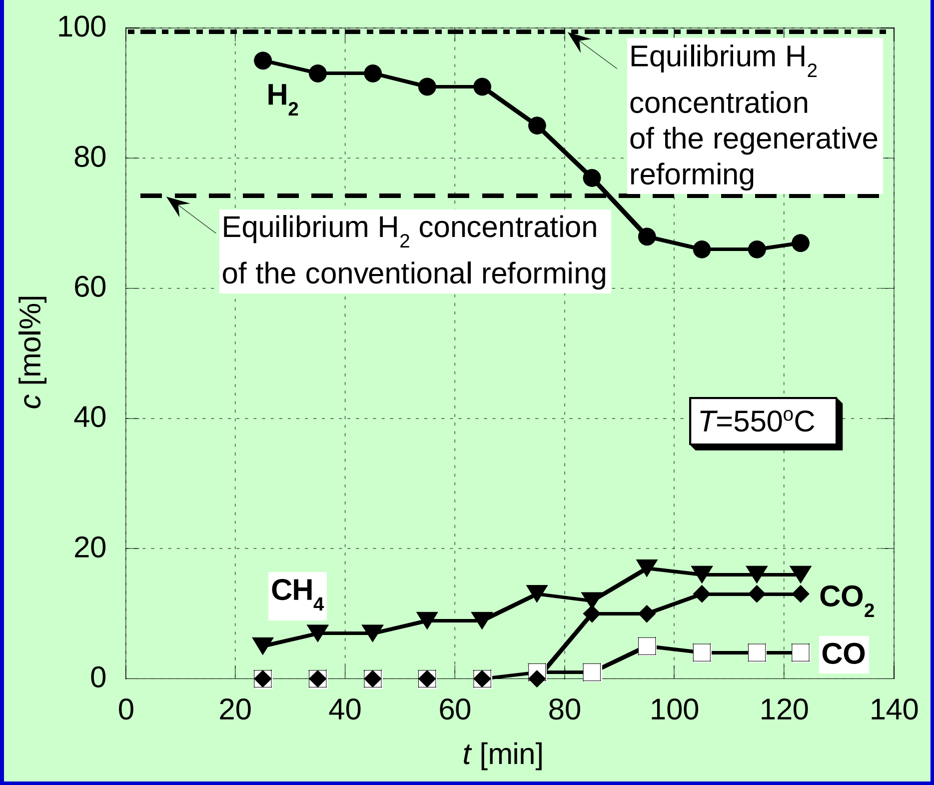


Fig. Temporal change of effluent composition of the regenerative reformer at 550°C

CO_2 removal from reforming gas

- Effluent CO_2 concentration from RGR at 550°C was less than 1%.

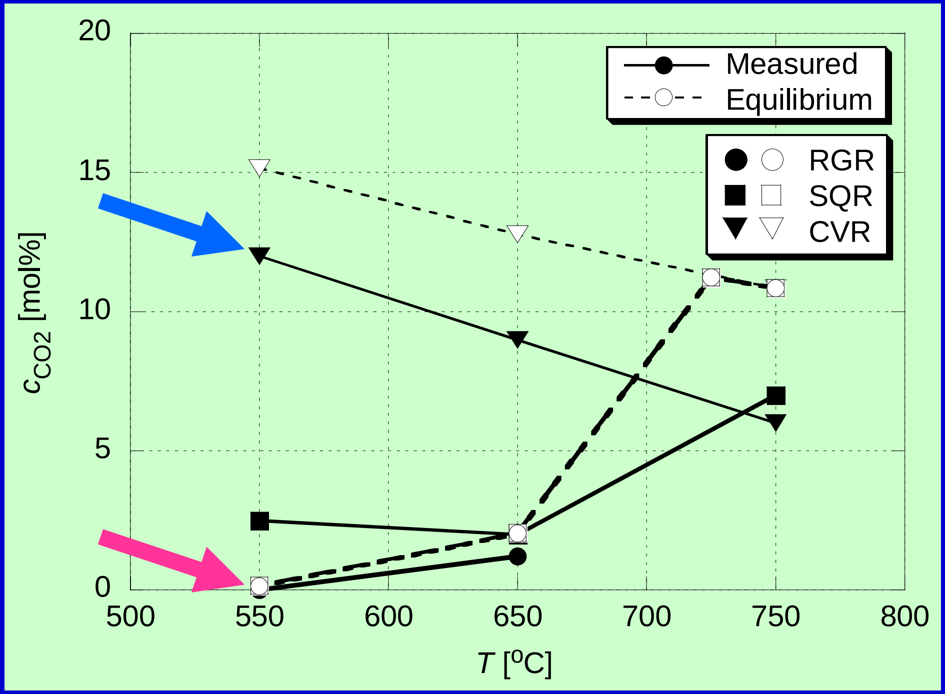
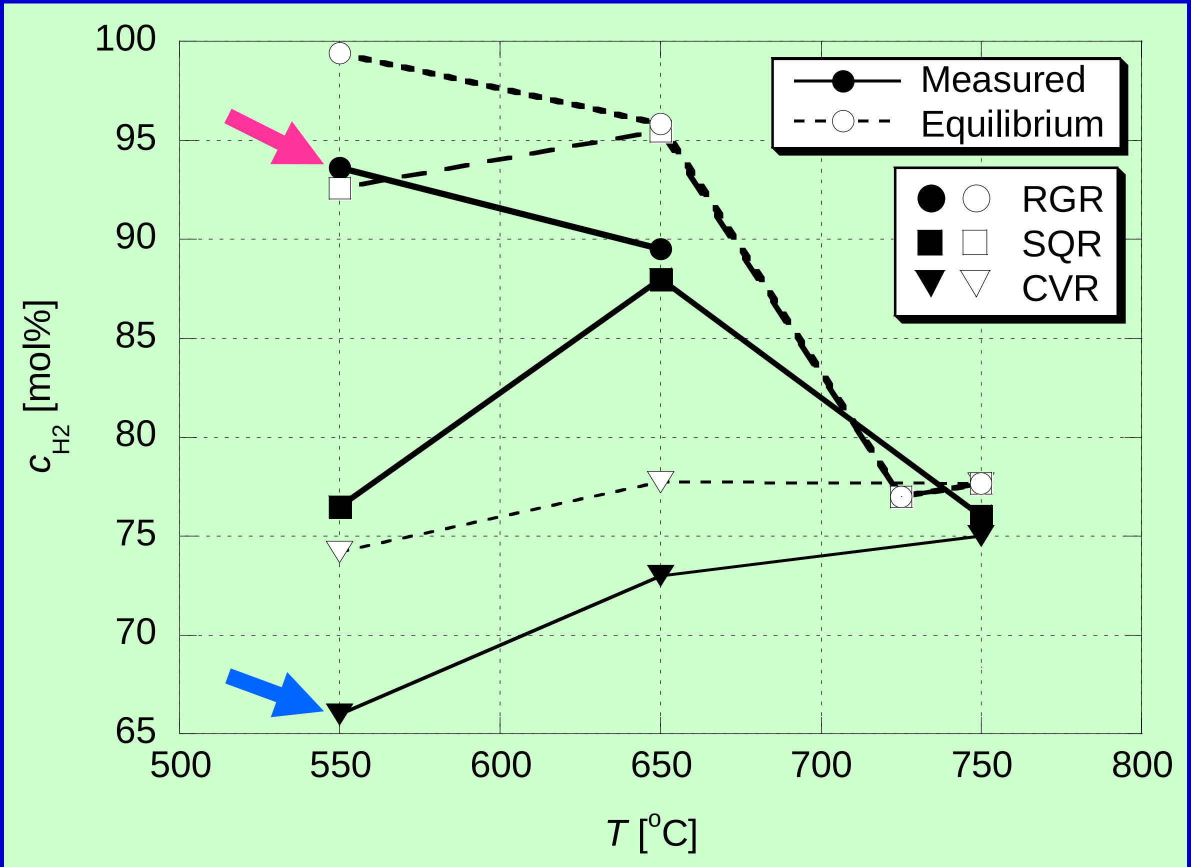


Fig. Effect of bed temperature on effluent carbon dioxide concentration of the reformer comparing with other type reformers.

H_2 productivity

- 94% of H_2 production was measured by the RGR at 550°C.



Effect of bed temperature on hydrogen production concentration of the reformers.

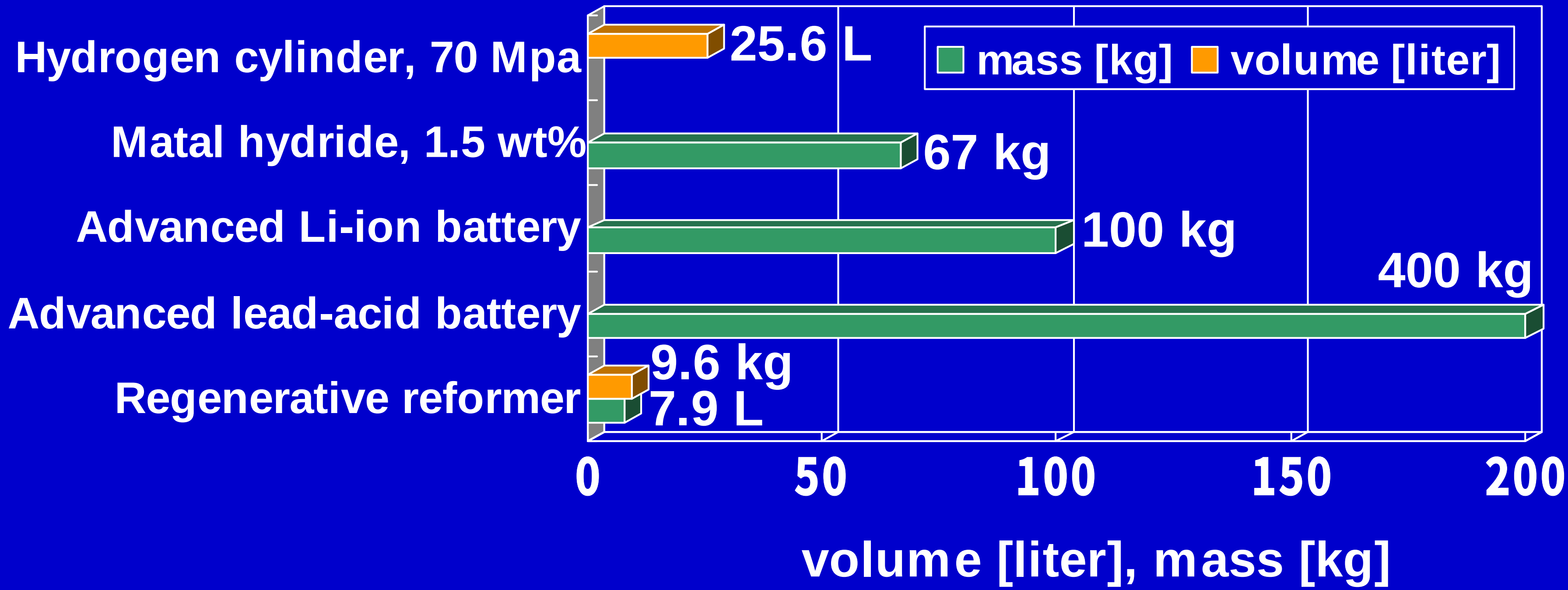
Estimation of a zero emission vehicle

- 1 kg of H_2 in order to drive for 100 km
- 7.46 kg (9.04 liters) of CaO was required for the RGR.

SSR-FC Vehicle		
Viehcle mileage	km	100
Hydrogen requirement	kg	1.0
Hydrogen production conc	mol%	94
CaO requirement mass	kg	7.94
CaO requirement volume	liter	9.62
Recovered CO_2	kg	5.5

Comparison between H_2 systems

Table: Scale of energy storage facilities for 100 km mileage, 14.7 kWh, 500 mol-H_2 (= Petroleum of 4 L, 2.8 kg)



Estimation of the zero-emission hydrogen career system

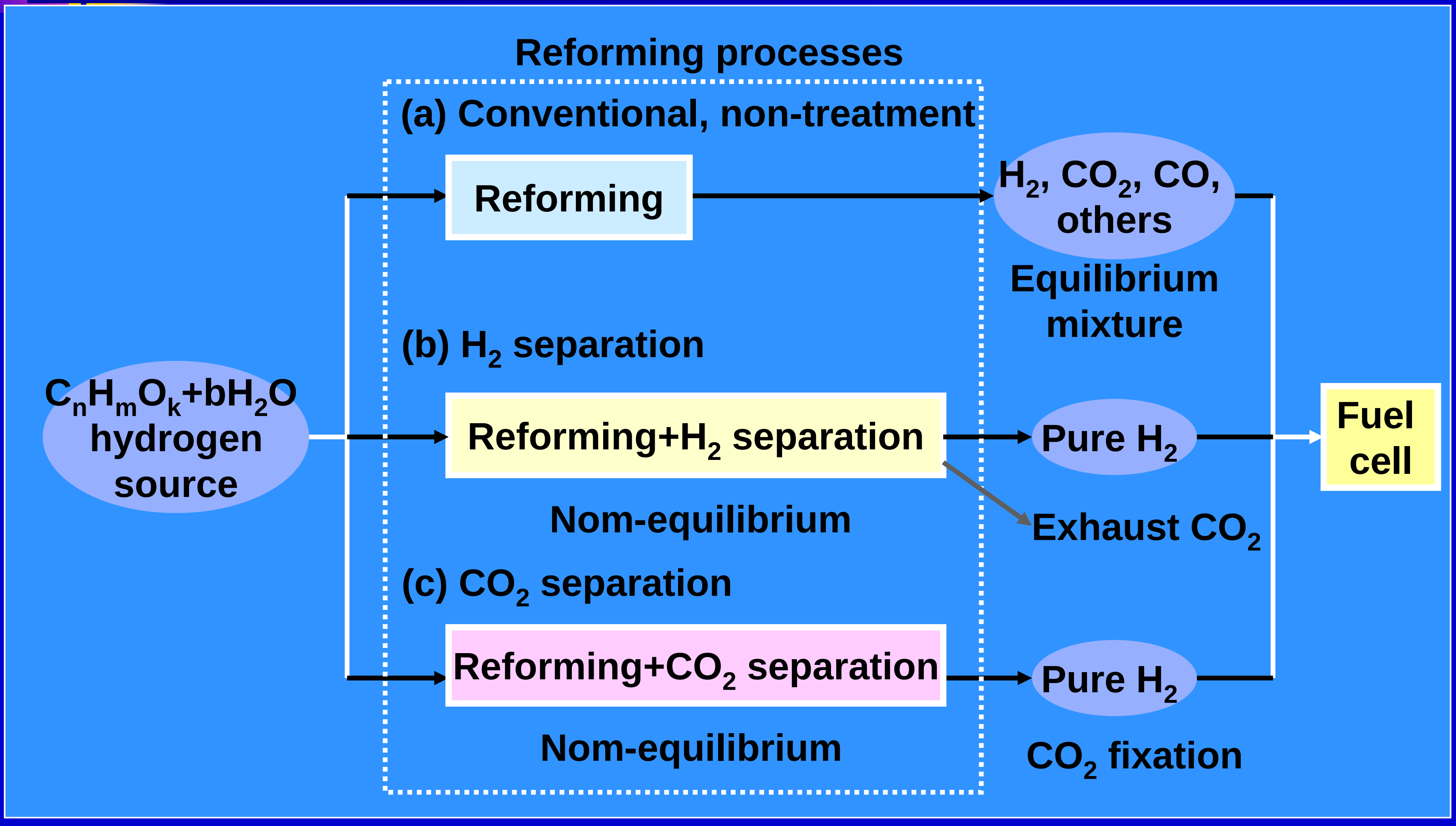
- Nighttime surplus electricity of **1 GW for 8 hours** was used for the regeneration at the regeneration stations.
- The RGR packages of **1.3 million pieces/day** are able to be regenerated in the stations.
- **CO_2 of 7.1×10^3 ton/day** is expected to be recovered from the stations.

Power plant		
Power plant output	GW	1
Night time operation duratio	h	8
Total Electricity amount	GWh	8
	GW	2.88E+04
FC Vehicle		
Viehcle mileage	km	100
Hydrogen requirement	kg	1
Hydrogen production conc	mol%	94
CaO requirement mass	kg	7.94
CaO requirement volume	liter	9.62
CO2	kg	5.5
CO2	mol	125
dH for regeneration	kJ/mol-CO_2	178
Regeneration station		
Requirement reaction heat	kJ/piece	2.23E+04
Cell piece	pieces	1.29E+06
CO2 amount	kg	7.12E+06
	m3(STP)	3.62E+06

Conclusions

- The regenerative reformer was applicable to a practical CO_2 zero-emission reforming with safety hydrogen supply.
- The required amount of CaO for the reformer was expected to be small enough comparing with other hydrogen storage system or batteries.
- The system can utilize surplus electricity generated from renewable energy system and nuclear power plant.
- Electricity of 1 GW for 8 h can regenerate 1.3 million of reforming packages, and recover 7.1 ton of CO_2.
- The hydrogen career system using the regenerative reformer would widen need of those power plants because the system realizes new vehicle system of total CO_2 zero-emission.
- The hydrogen career system also contributes to load leveling of power plant operation.

Shifting into non-equilibrium by separation



Unstable Operation

-Load leveling for Economical Plant Operation-

- Load change and unstable operation
  - Low-annual operation rate
  - Uneconomic
- Load leveling for 100% operation
  - Energy storage
  - Energy conversion

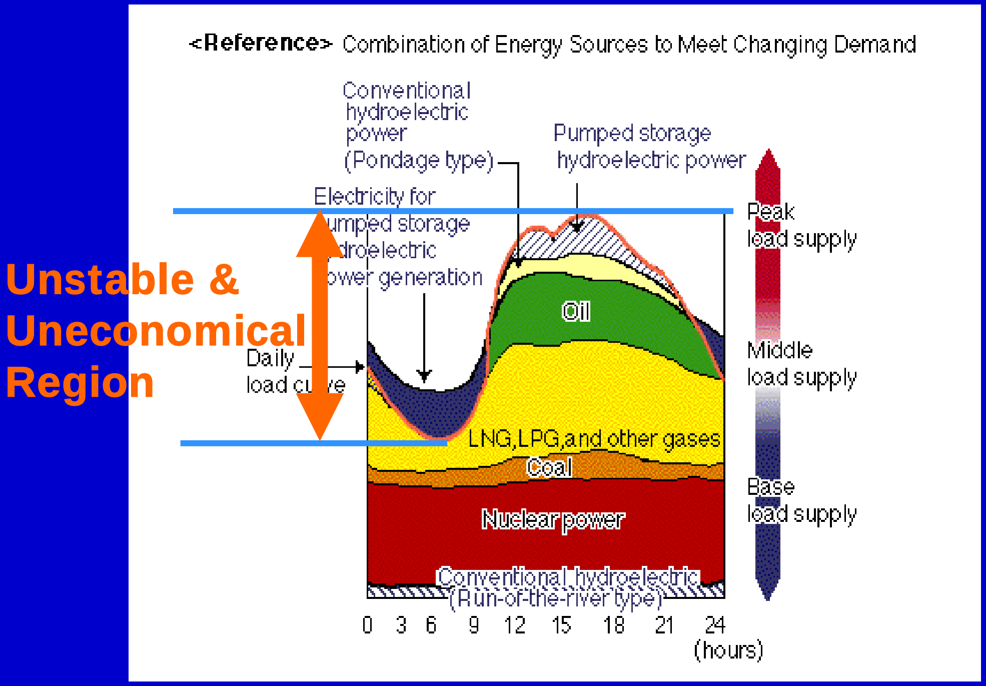


Fig. A daily load change in a summer day in Japan

Tokyo Electric Power Co. http://www.tepco.co.jp/

Peak Electric Load (2001)
Japan=181 GW
Tokyo area=64 GW (24 Jul.), 51 GW (15 Jan.)

Diversification of energy supply and demand

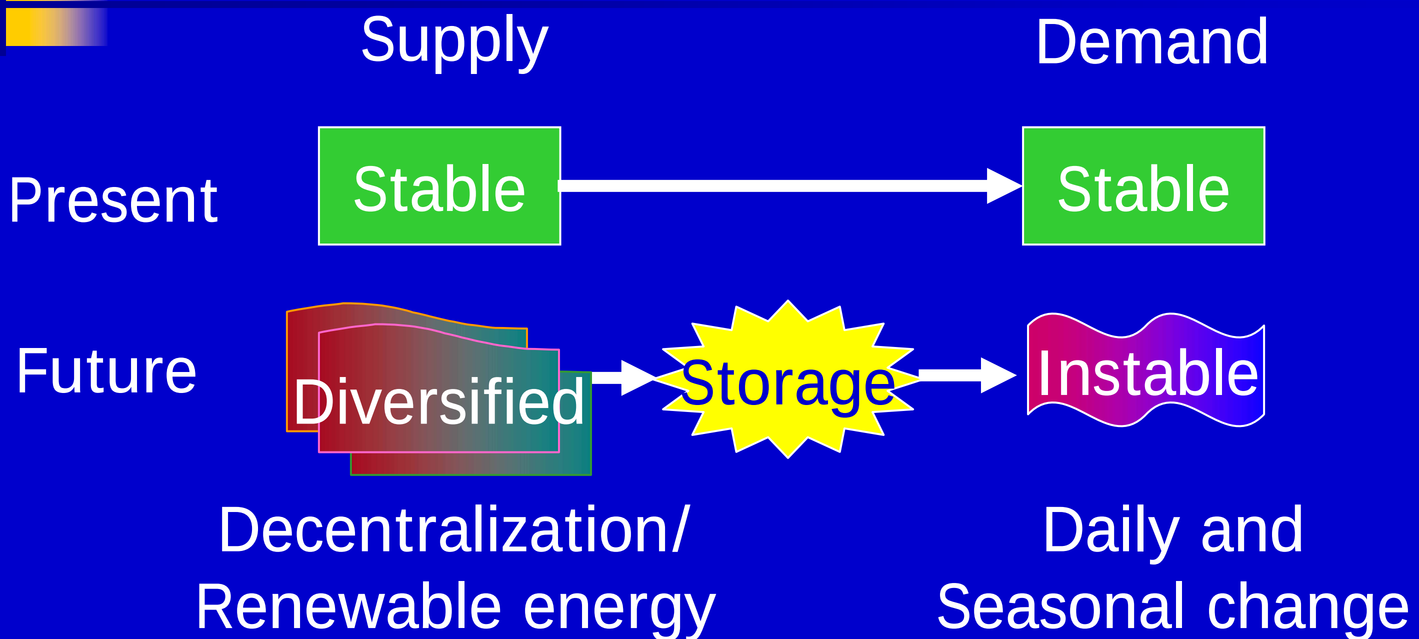
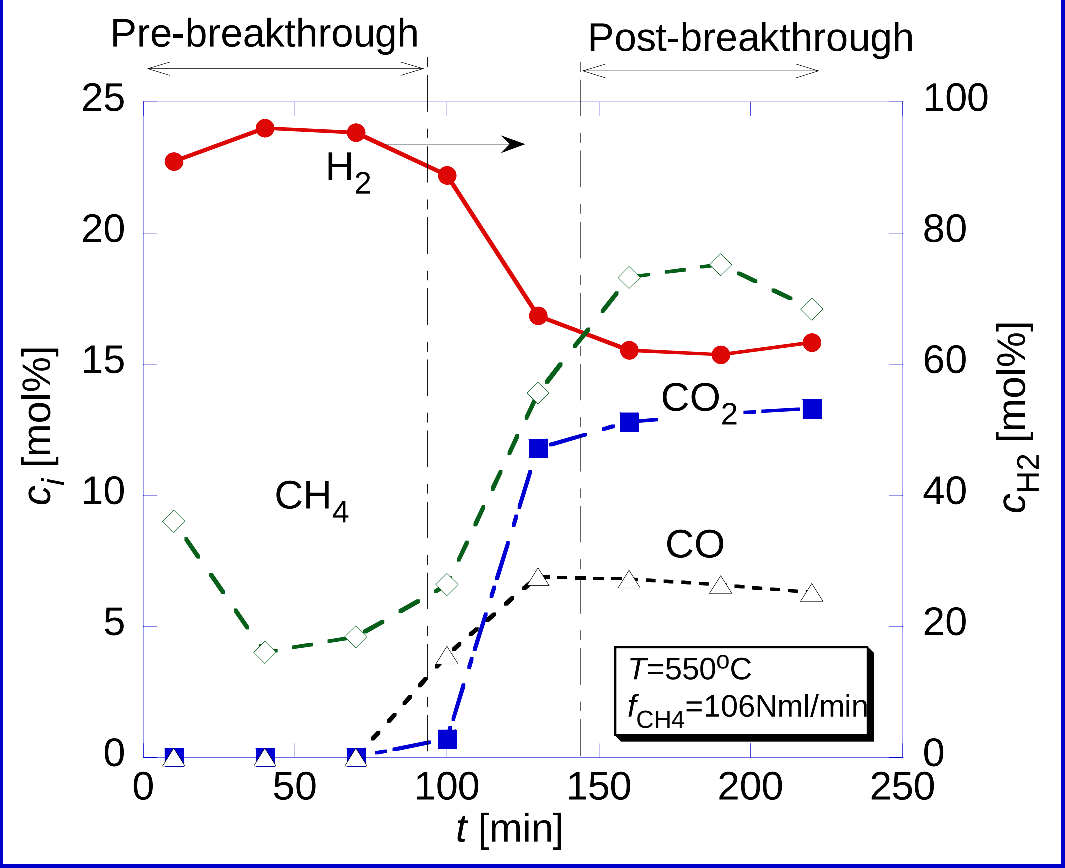
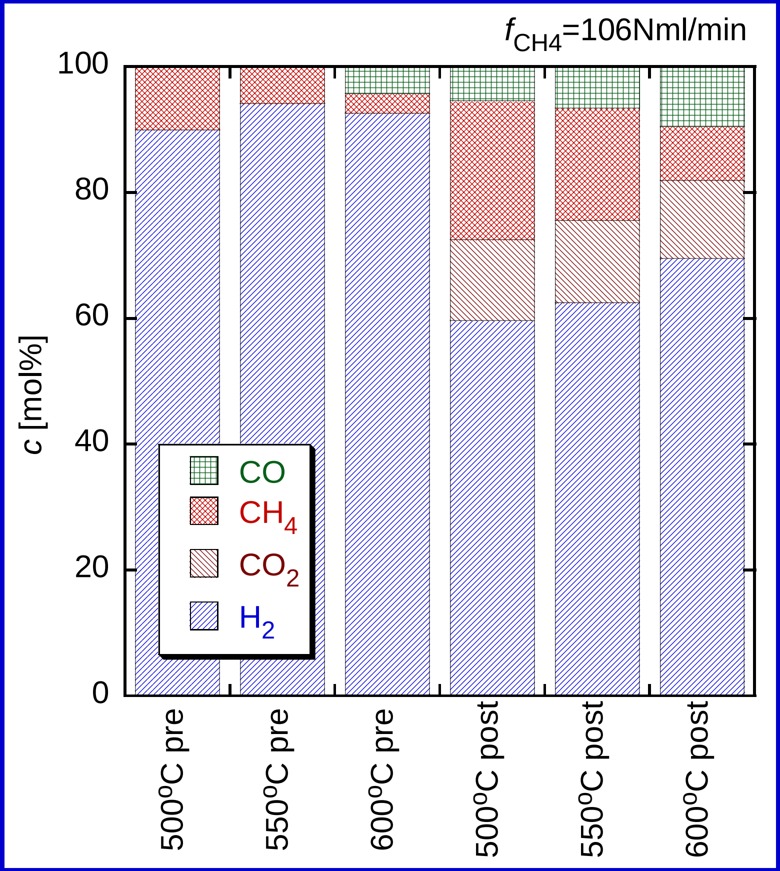


Fig. Forecast of the change of energy flow pattern

- Future society needs high-efficient tech. of,
  - Energy storage
  - Energy transportation
  - Energy conversion

Use of chemical reaction


Pre-breakthrough
Post-breakthrough
H2
CO2
CH4
CO
T=550°C
fCH4=106Nml/min
ci [mol%]
cH2 [mol%]
t [min]
0
5
10
15
20
25
0
20
40
60
80
100
0
50
100
150
200
250



f_{CH4}=106Nml/min
100
80
60
40
20
0
c [mol%]
CO
CH4
CO2
H2
500°C pre
550°C pre
600°C pre
500°C post
550°C post
600°C post