CARBON RECYCLE HYDROGEN CARRIER SYSTEM USING NUCLEAR POWER

Yukitaka Kato
Research Laboratory for Nuclear Reactors
Tokyo Institute of Technology

No. of Paper IAEA-CN-152-31
17th April, 2007
International Conference on Non-Electric Applications of Nuclear Power: Seawater Desalination, Hydrogen Production and other Industrial Applications
16 – 19 April 2007, JAEA, Oarai, Japan
Organized by the International Atomic Energy Agency; In co-operation with the OECD Nuclear Energy Agency and the International Desalination Association; Hosted by the Government of Japan through the Japan Atomic Energy Agency

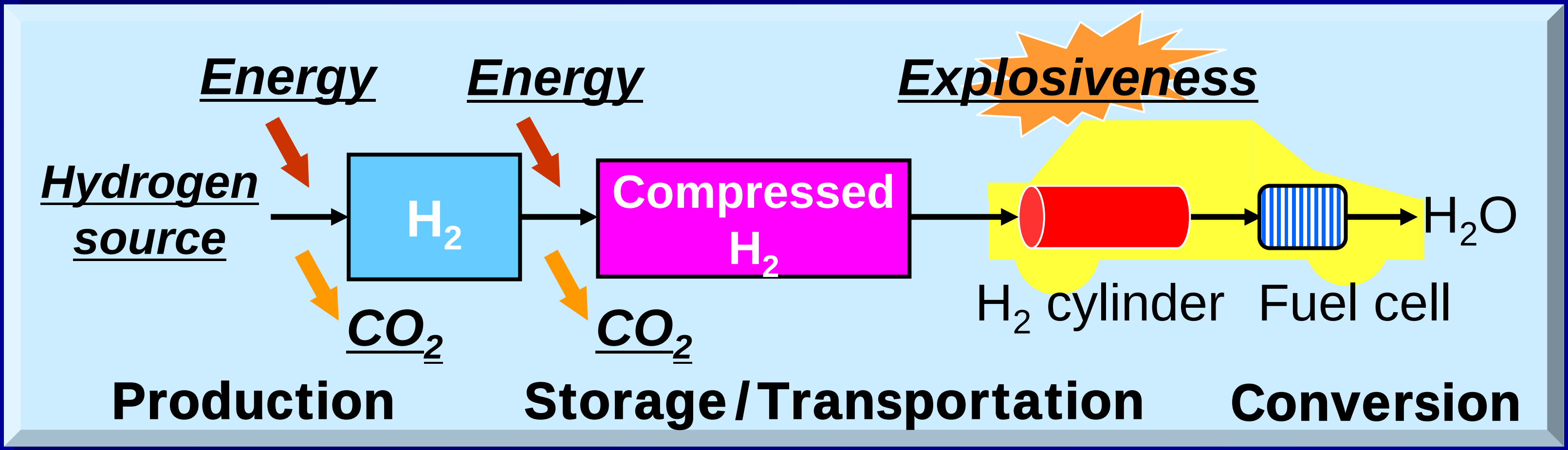
Contents

- Introduction
- H_2 supply for fuel cell vehicle
  - Non-equilibrium Technologies for hydrogen productions
- Carbon recycle hydrogen carrier system
  - Experiment
  - Evaluation for the carrier system with HTGR
- Synergy of bio-mass and nuclear for H_2
- Conclusions

Hydrogen supply for fuel cell vehicles

Hydrogen as an energy carrier

- Hydrogen(H_2) is vital as a non-electricity energy carrier
- H_2 is a promising energy source for vehicles
  - Fuel for fuel cells
  - Liquefaction of tar-sand, crude-oil, coal and bio-mass. Hydro-cracking : $C_nH_m + nH_2 \rightarrow nCH_4$
- Issues for H_2 system : Production energy and delivery
  - Consistency from production to use



Carbon recycle hydrogen carrier system

Regenerative Reforming
-Use of chemical absorption-

- Fuel reforming for methane
  - $CH_4 + H_2O \leftrightarrow 3H_2 + CO$, $\Delta H^\circ_1 = +205.6$ kJ/mol
  - $CO + H_2O \leftrightarrow H_2 + CO_2$, $\Delta H^\circ_2 = -41.1$ kJ/mol
- CaO carbonation
  - $CaO(s) + CO_2(g) \leftrightarrow CaCO_3(s)$, $\Delta H^\circ_3 = -178.3$ kJ/mol
- Regenerative reforming (CO_2 absorption reforming, self-heating)
  - $CaO(s) + CH_4(g) + 2H_2O(g) \leftrightarrow 4H_2(g) + CaCO_3(s)$, $\Delta H^\circ_4 = -13.3$ kJ/mol

CO_2 zero-emission FC vehicle

- 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

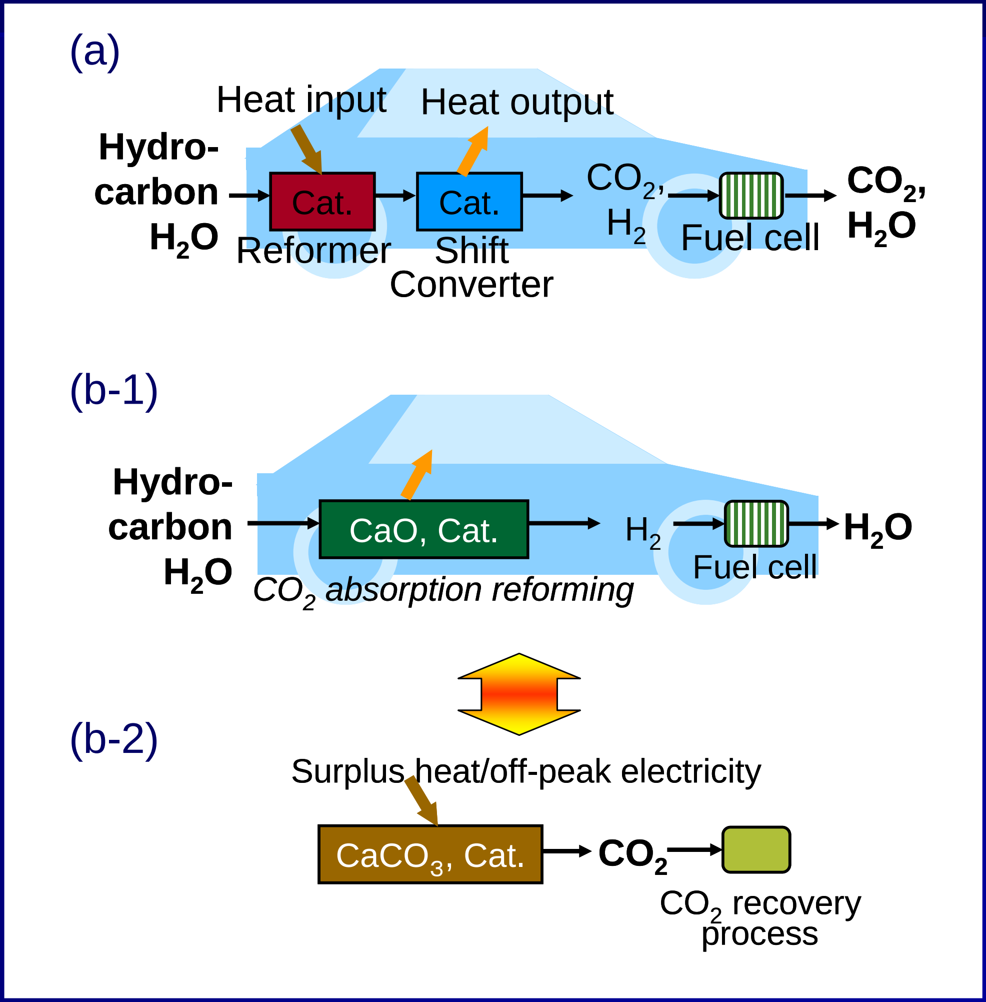
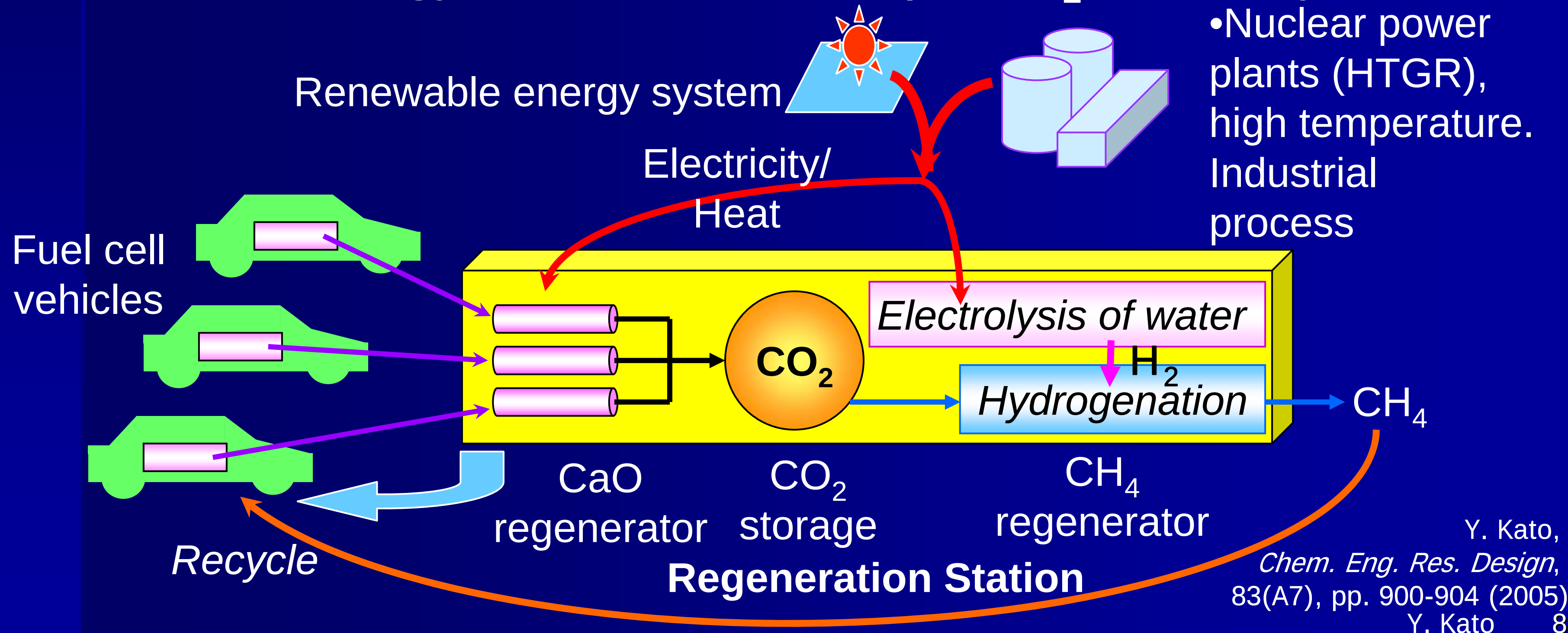


Figure 1. Concept of a zero CO_2 emission FC vehicle using a thermally regenerative reformer; (a) conventional reforming, (b-1,2) proposed thermally regenerative reforming, (b-1) reforming mode, (b-2) regenerating and CO_2 recovering mode

Carbon recycle type nuclear hydrogen carrier system

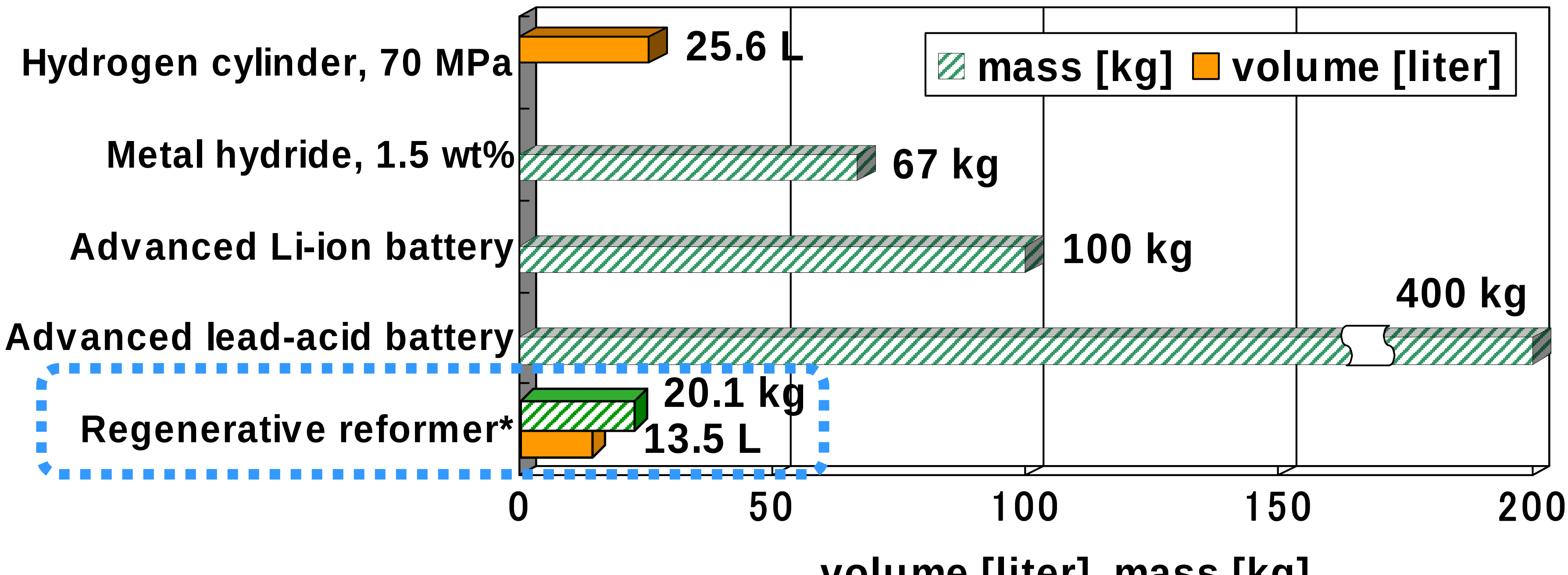
- $CaO+CH_4+2H_2O$ -> $4H_2+CaCO_3$: CO_2-free barge-mounted reforming
- Use of redundant output at off-peak from NPPs
- Safe, energy-efficient and compact H_2 carrier systems



Y. Kato, *Chem. Eng. Res. Design*, 83(A7), pp. 900-904 (2005)

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)



(*total reactant amount including CaO, H_2O and liquefied CH_4 assuming under 3.86 MPa and at -88^oC).

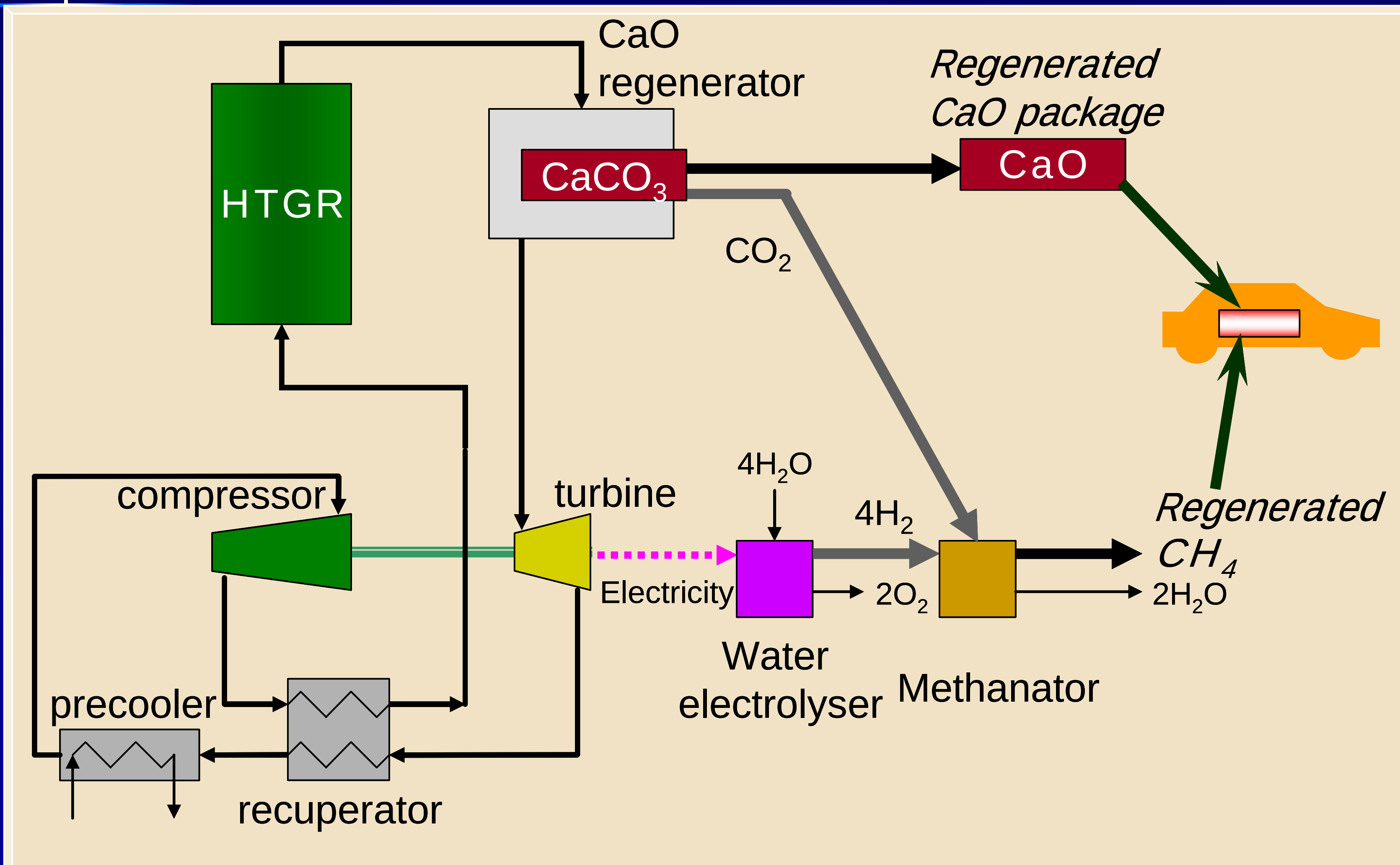
Merits of Carbon recycle type H_2 carrier system

$$\mathbf{CaO}(s)+\mathbf{CH_4}(g)+\mathbf{2H_2O}(g)\leftrightarrow\mathbf{4H_2}(g)+\mathbf{CaCO_3}(s),$$
$$\Delta H^\circ_4 = -13.3\ \mathrm{kJ/mol}$$

- CO_2 removing induces the reforming state into non-equilibrium
- Reaction enhancement by non-equilibrium
  - Enhancement of H_2 production yield
  - Reduction of reforming temperature
- Self heating
- CO_2 recoverable
- Elimination of compression work and explosion risk for hydrogen supply

The hydrogen carrier system with HTGR

Combination of the H_2 carrier system and HTGR



The H_2 carrier vs. H_2O electrolysis (2) HTGR system (GTHTR300)

	Proposed H_2 carrier system	Conventional water electrolysis system
HTGR thermal power[1]	600 MWt	
Outlet coolant temperature from HTGR	850 ^oC	
HTGR operation duration for hydrogen processes	8 h/day	
Inlet/outlet coolant temperature for CaO	850 / 835 ^oC	-
Inlet/outlet coolant temperature for gas-turbine	835 / 587 ^oC	850 / 587 ^oC
Power input for CaO regeneration	34.8 MWt	-
Plant power input for gas-turbine power	565.2 MWt	600.0 MWt
Gas-turbine power efficiency[2]	44.3 %	45.0 %
Water electrolysis efficiency (□*H* base)[3]	90 %	
Compression pressure	175 bar-CH_4	700 bar-H_2
Power for H2 electrolysis	245.8 MWe	247.1 MWe
Power for compression	3.8 MWe-CH_4	22.9 MWe-H_2
H2 production/equivalent	2.26E+07 H_2-mol equ	2.27E+07 H_2-mol
Number of FC vehicles for 100 km mileage each[4]	4.52E+04 -	4.54E+04 -

Based on GTHTR 300, (Kunitomi et al, JAESJ, 1(4), 352(2002))

Enthalpy balance of the H_2 carrier & H_2O electrolysis systems based on HTGR

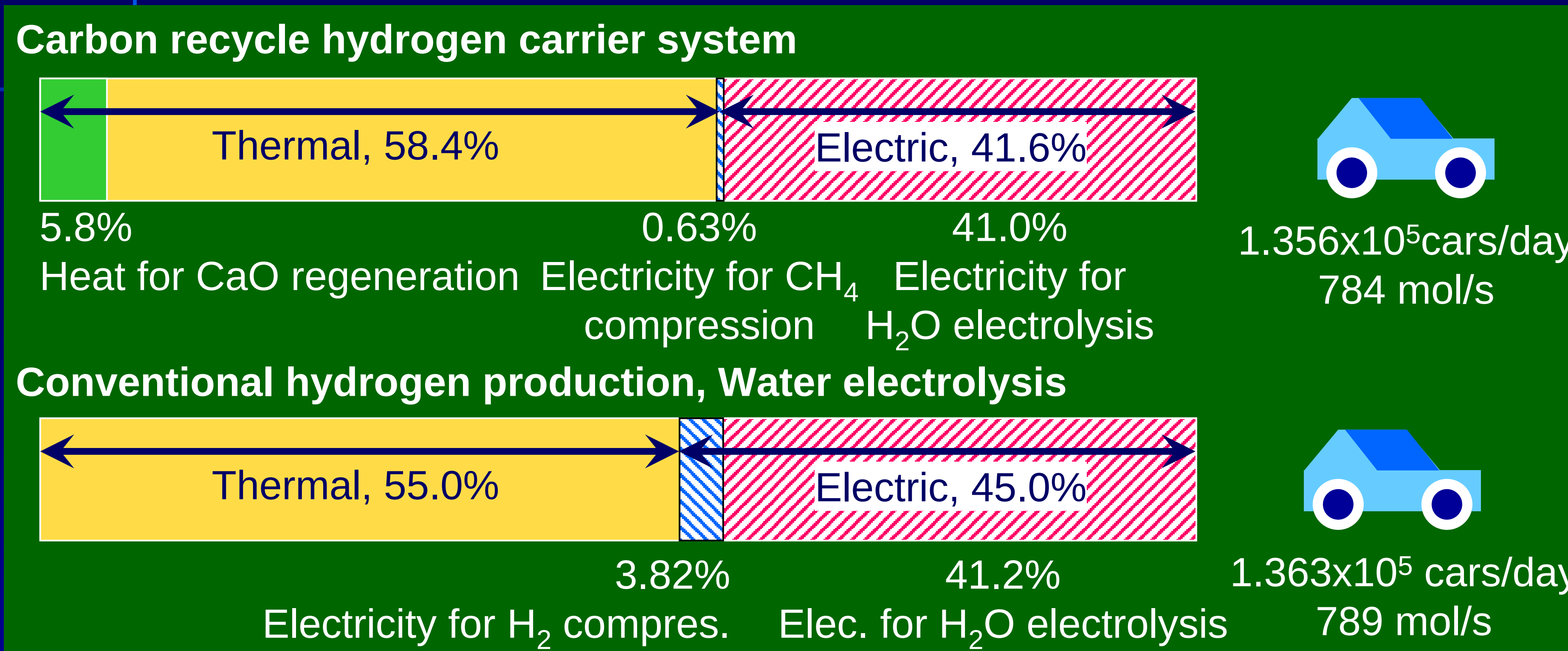


Fig. Enthalpy consumption ratio of HTGR output (600 MWt, 8h/day) for both systems

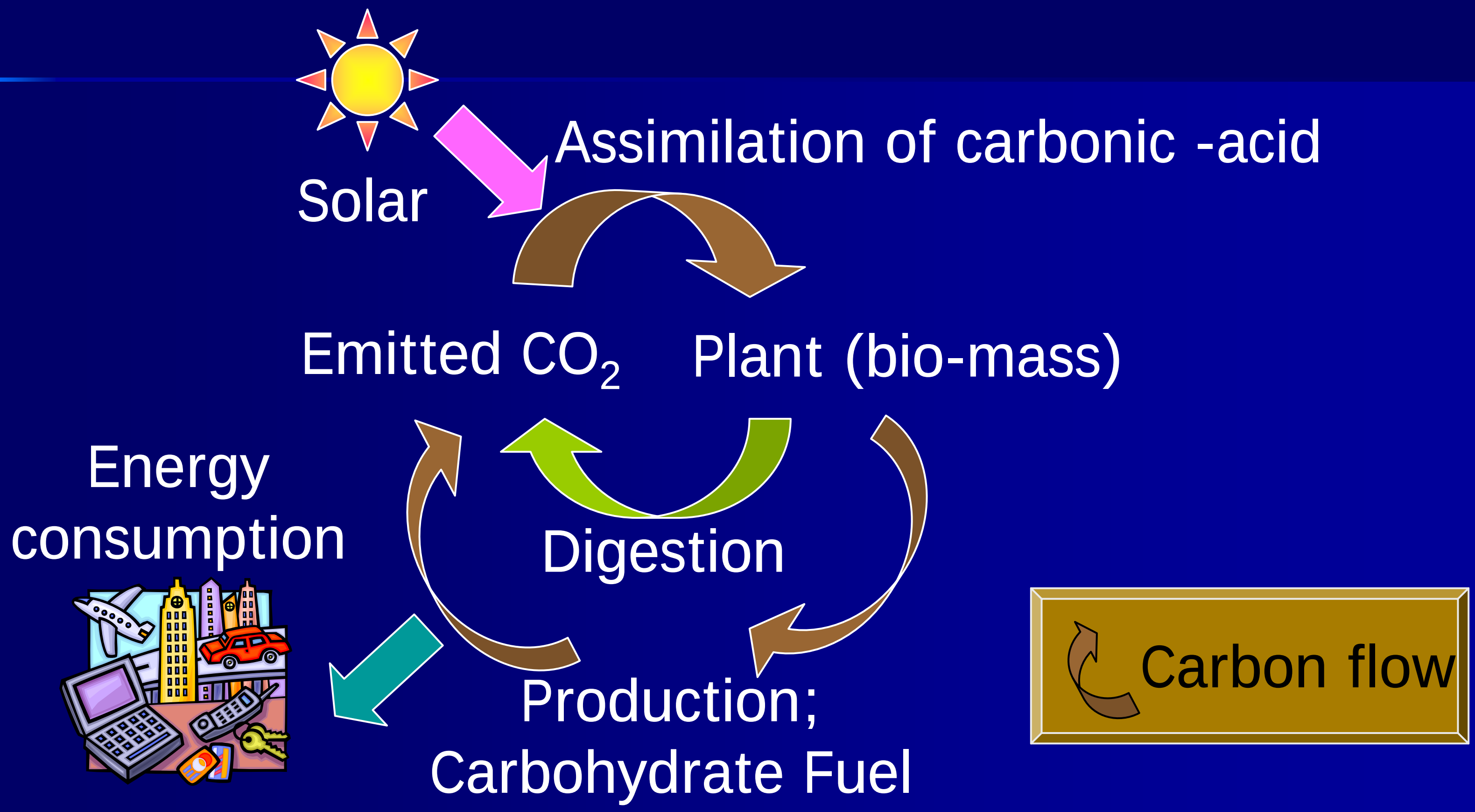
The carrier system : Reduction of compression pressure & work and transportation risk with consisting the same efficiency of conventional H_2 system
> Safe and compact H_2 carrier system

Application of the regenerative reforming to ethanol and bio-mass

- Fuel reforming for Ethanol
  - $C_2H_5OH(l) + 3H_2O(l) \rightarrow 6H_2(g) + 2CO_2(g)$
    $\Delta H^\circ_5 = + 341.7$ kJ/mol
- CaO carbonation
  - $CaO(s) + CO_2(g) \leftrightarrow CaCO_3(s)$,
    $\Delta H^\circ_3 = -178.3$ kJ/mol
- Regenerative reforming (CO_2 absorption reforming, self-heating)
  - $C_2H_5OH(l) + 3H_2O(l) + 2CaO(s) \rightarrow 6H_2(g) + 2CaCO_3(s)$ $\Delta H^\circ_6 = - 9.13$ kJ/mol

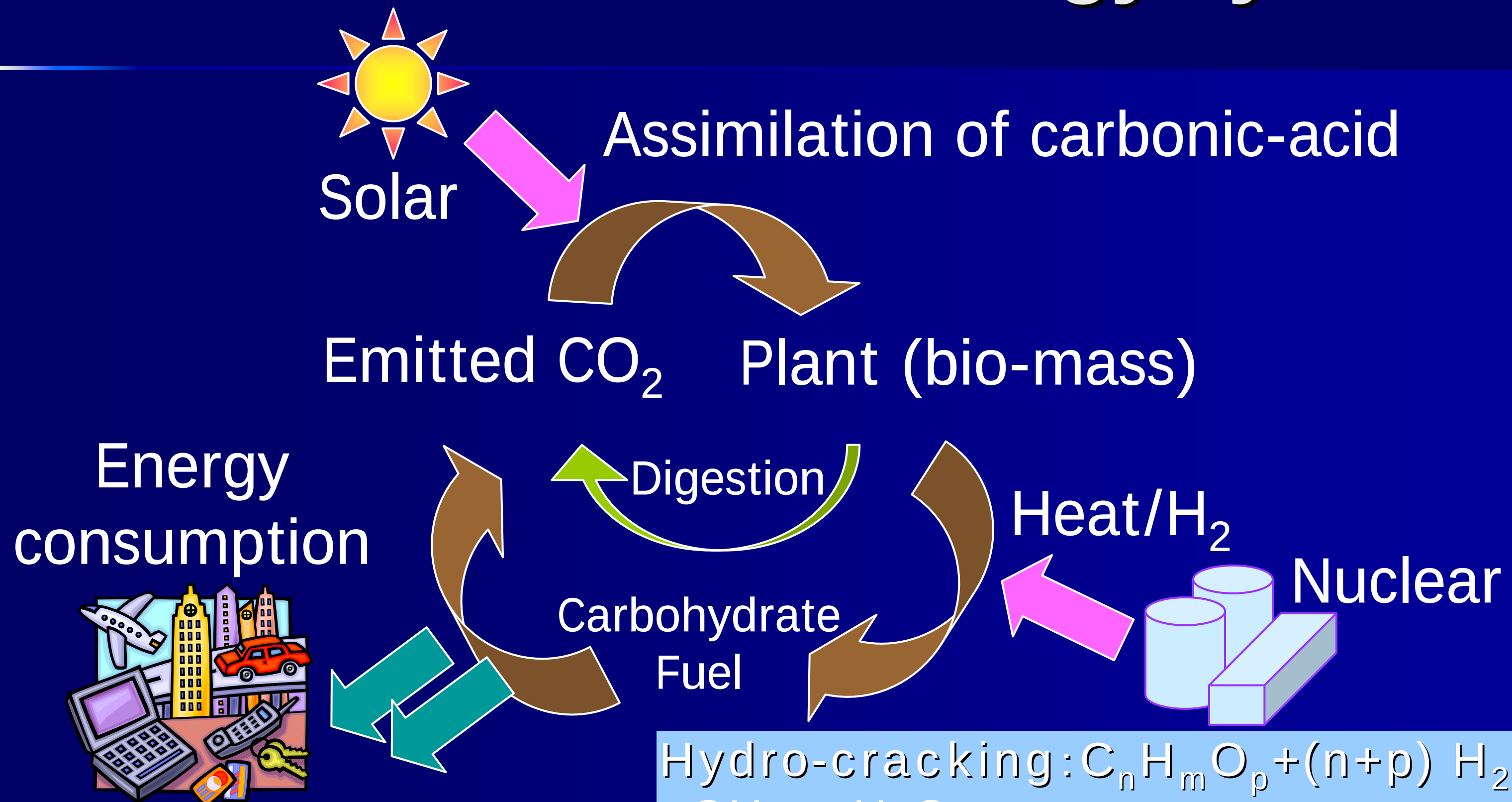
Synergy of bio-mass and nuclear for H_2 supply

Carbon neutral energy system



Forests and farms maintain air-borne CO_2 at constant by recycling in the carbon neutral cycle, while converting solar power to energy

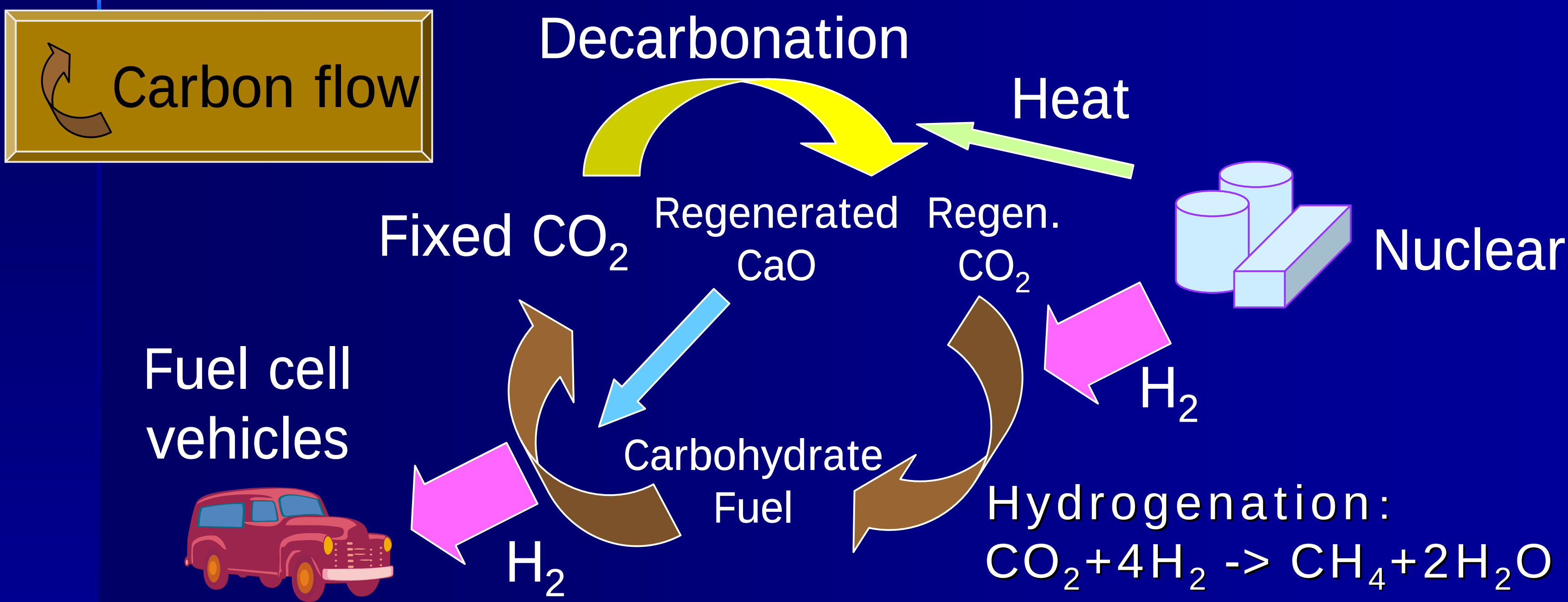
Synergistic system by carbon neutral and nuclear energy systems



Hydro-cracking: $C_nH_mO_p+(n+p)\ H_2 \rightarrow nCH_4+pH_2O$

- Increasing carbohydrate fuels by synergistic combination of carbon neutral and nuclear H_2 systems
- CO_2 and H_2 are recycled in the synergistic neutral system

Carbon Recycle Hydrogen Carrier System Using Nuclear Power



- Carbon as H_2 carrier media is recycled in the system by nuclear power
- Carbon is free from the restriction of bio-mass quantity

Conclusions

- Carbon recycle type H_2 carrier system has possibility to realize efficient H_2 transportation by reduction of storage compression work, storage volume and fuel explosion risk.
- Total energy consumption is similar with conventional H_2O electrolysis system.
- The carrier system have good compatibility with HTGR, and can utilize the top temperature part in the primary loop of HTGR
- Synergistic systems of carbon neutral and nuclear energy systems
- Choice of hydrogen source is limited by numbers of FC vehicles
  - First generation: Synergy of biomass and nuclear for hydrogen economy
  - Next generation: Carbon recycle H_2 carrier system using nuclear power

Thanks!

- E-mail: yukitaka@nr.titech.ac.jp
- URL: http://www.nr.titech.ac.jp/~yukitaka/

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. > 700^{o}C)

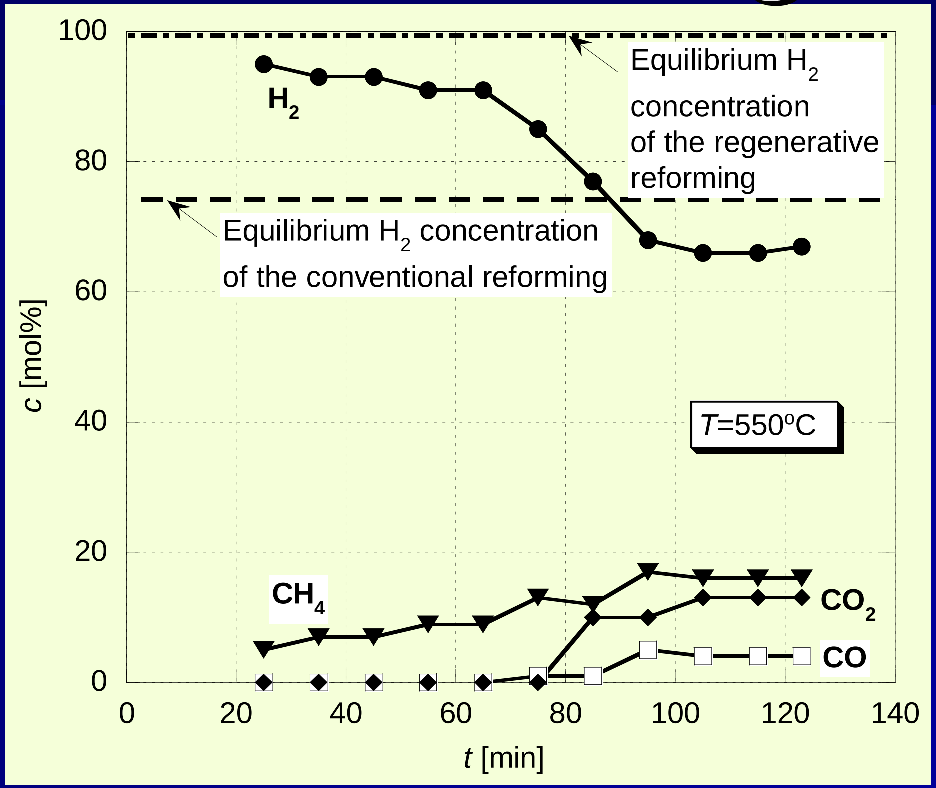


Fig. Temporal change of effluent composition of the regenerative reformer at 550°C