# CARBON RECYCLE HYDROGEN CARRIER SYSTEM USING NUCLEAR POWER

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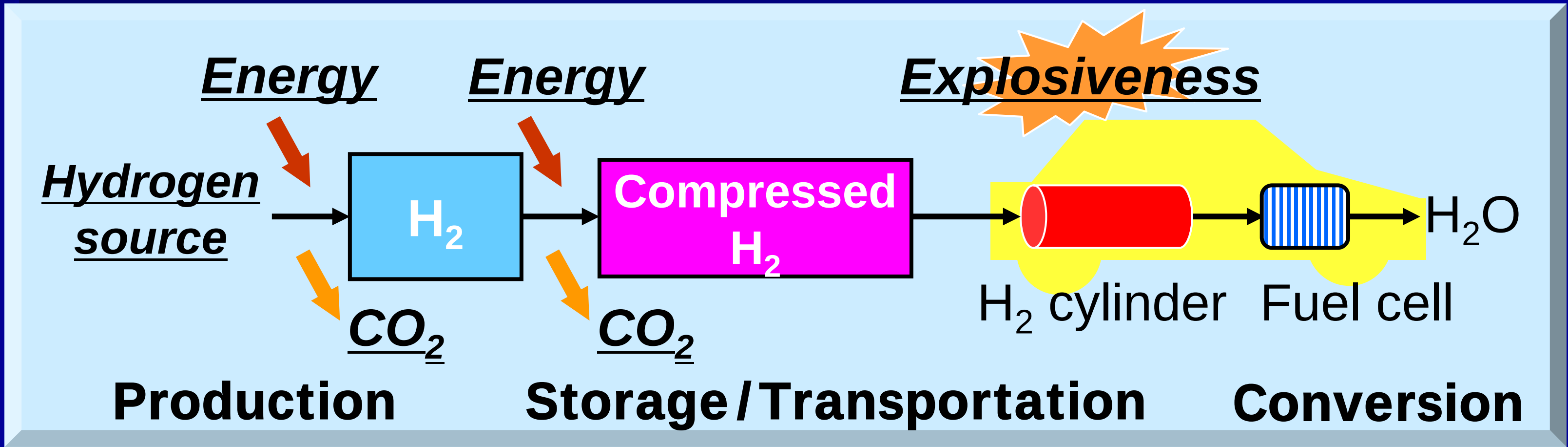
# Contents

# 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 : $C_nH_m + nH_2$ -> $n CH_4$
- 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

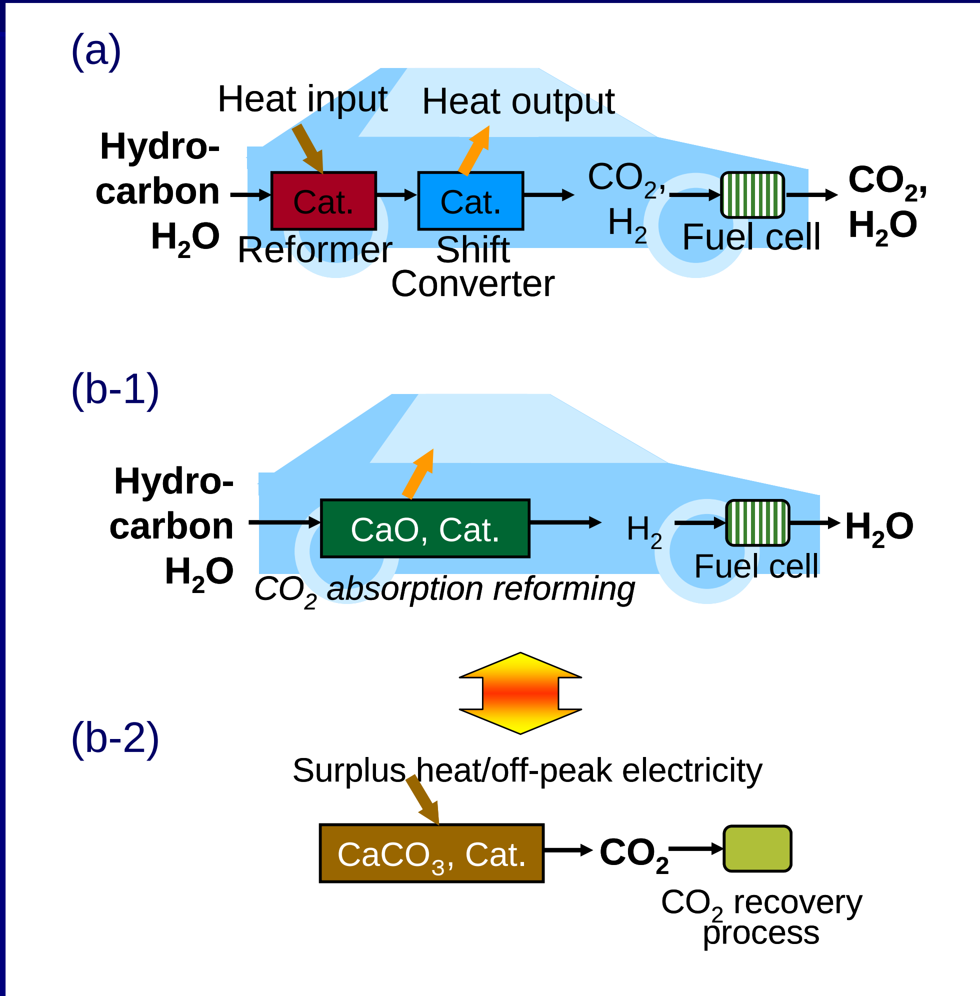
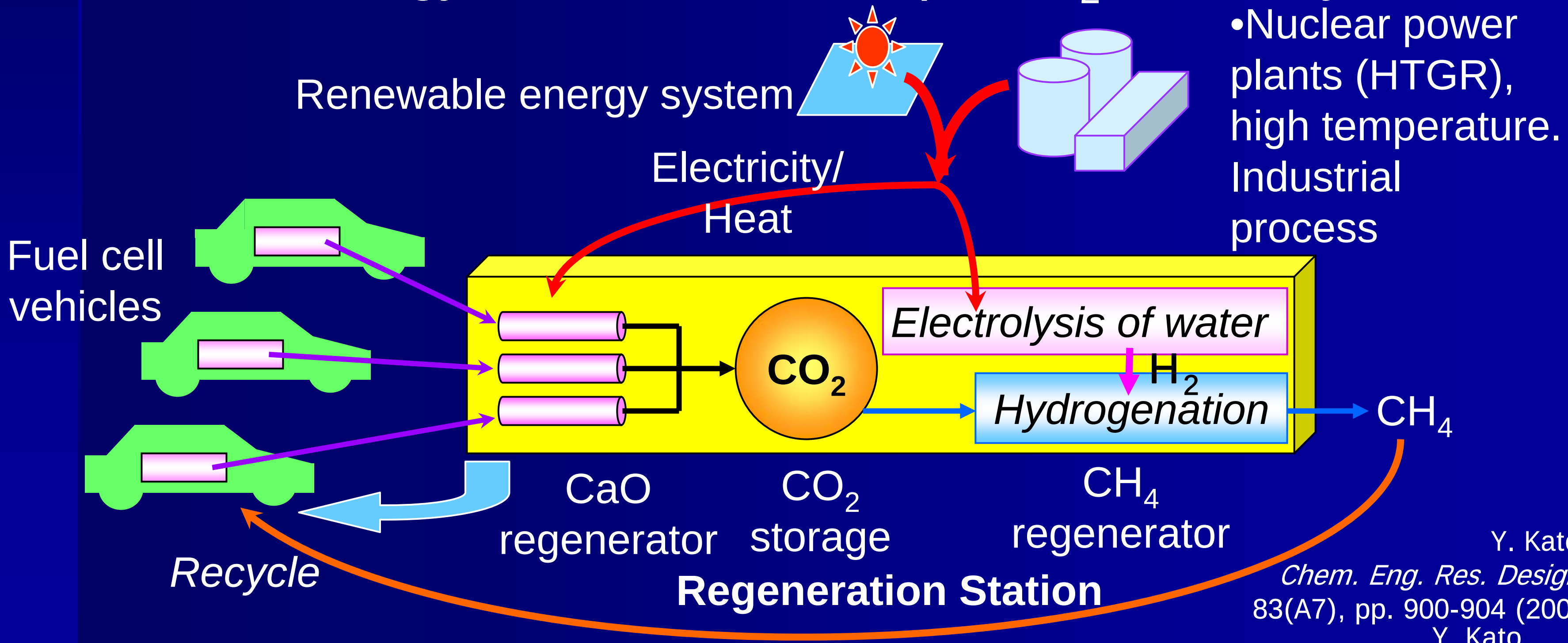



Figure 1. Concept of a zero $CO_2$ emission FC vehicle using a thermally regenerative reformer; (a) conventional reforming, (b-1,2) proposed thermally regenerative reforming, (b-1) reforming mode, (b-2) regenerating and $CO_2$ recovering mode

# Carbon recycle type nuclear hydrogen carrier system

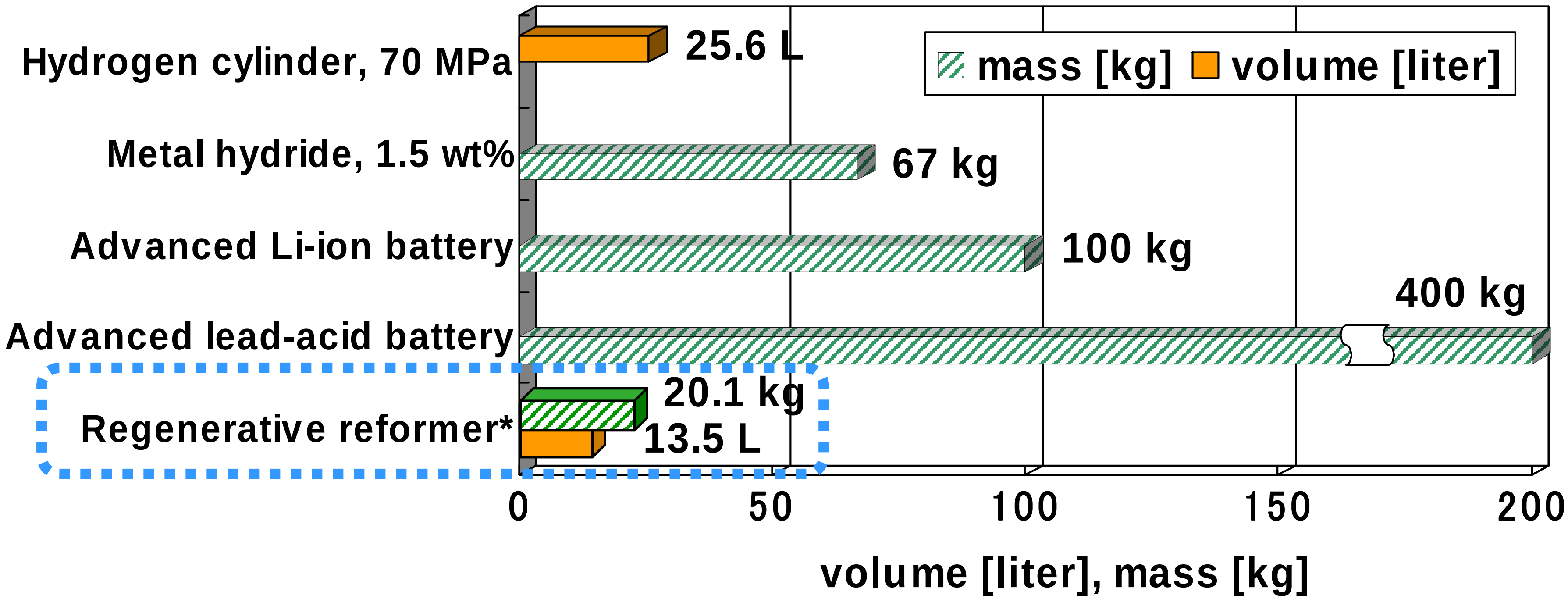
- $CaO+CH_4+2H_2O$ -> $4H_2+CaCO_3$: $CO_2$-free barge-mounted reforming
- Use of redundant output at off-peak from NPPs
- Safe, energy-efficient and compact $H_2$ carrier systems




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°C).

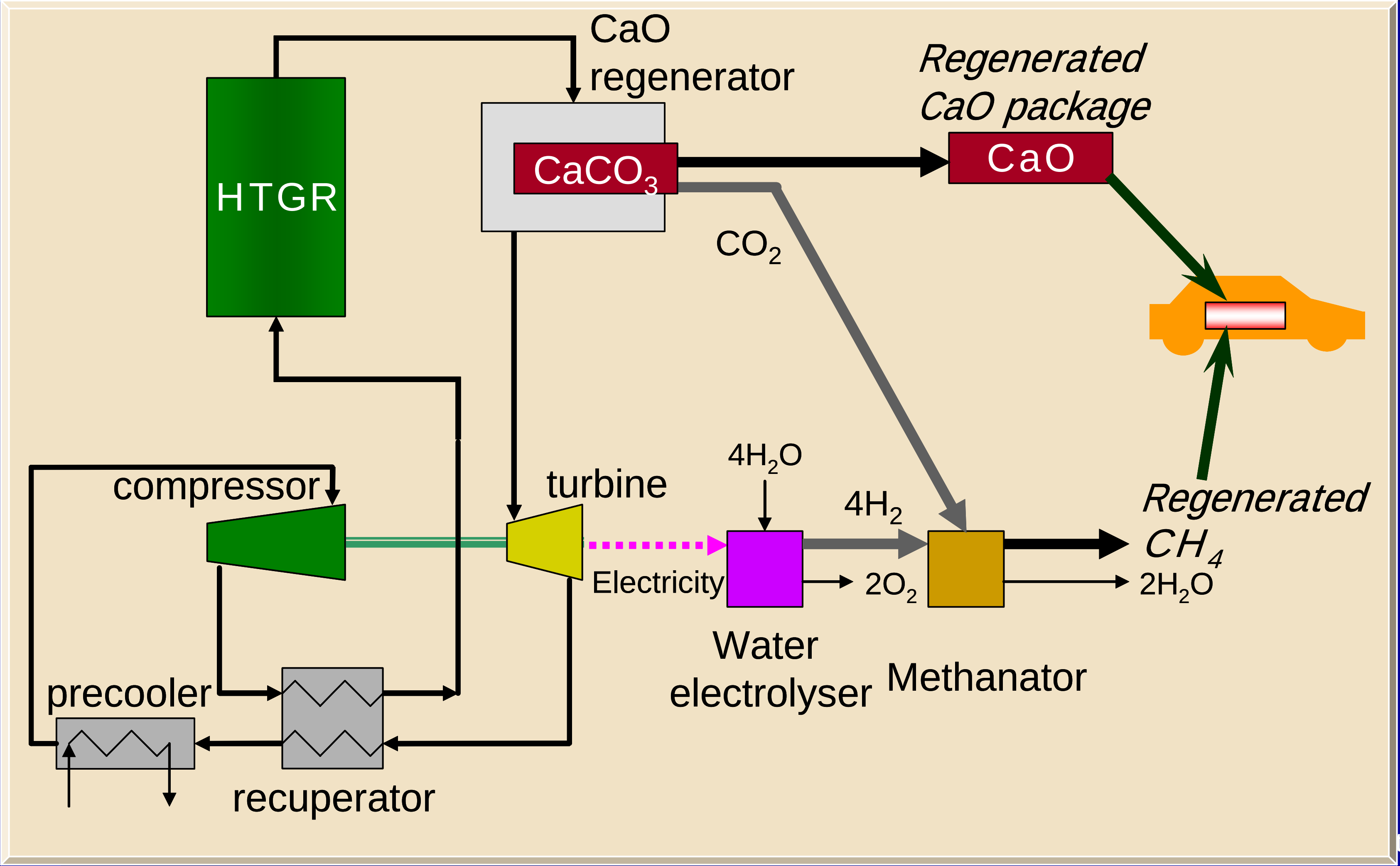
# Merits of Carbon recycle type $H_2$ carrier system

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

- $CO_2$ 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 °C | |
| HTGR operation duration for hydrogen processes | 8 h/day | |
| Inlet/outlet coolant temperature for CaO | 850 / 835 °C | - |
| Inlet/outlet coolant temperature for gas-turbine | 835 / 587 °C | 850 / 587 °C |
| 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

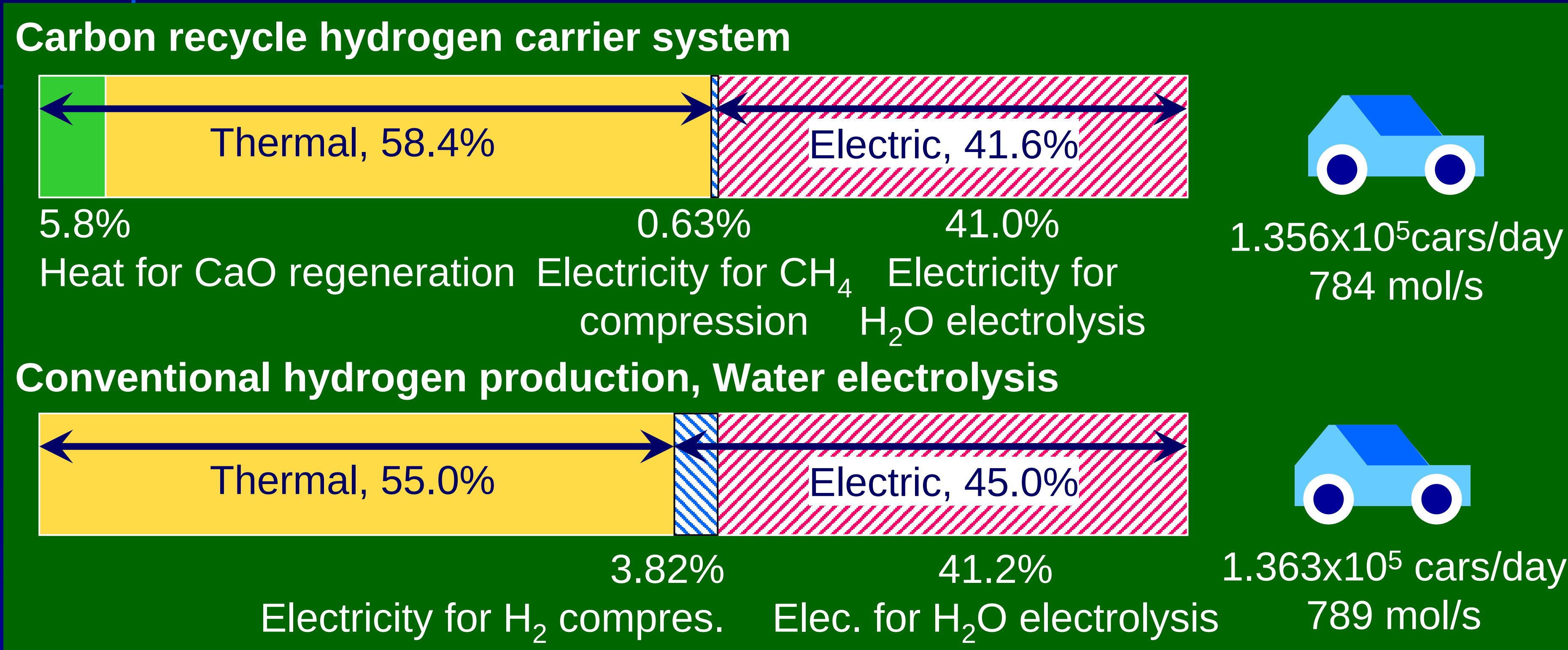



**Fig. Enthalpy consumption ratio of HTGR output (600 MWt, 8h/day) for both systems**

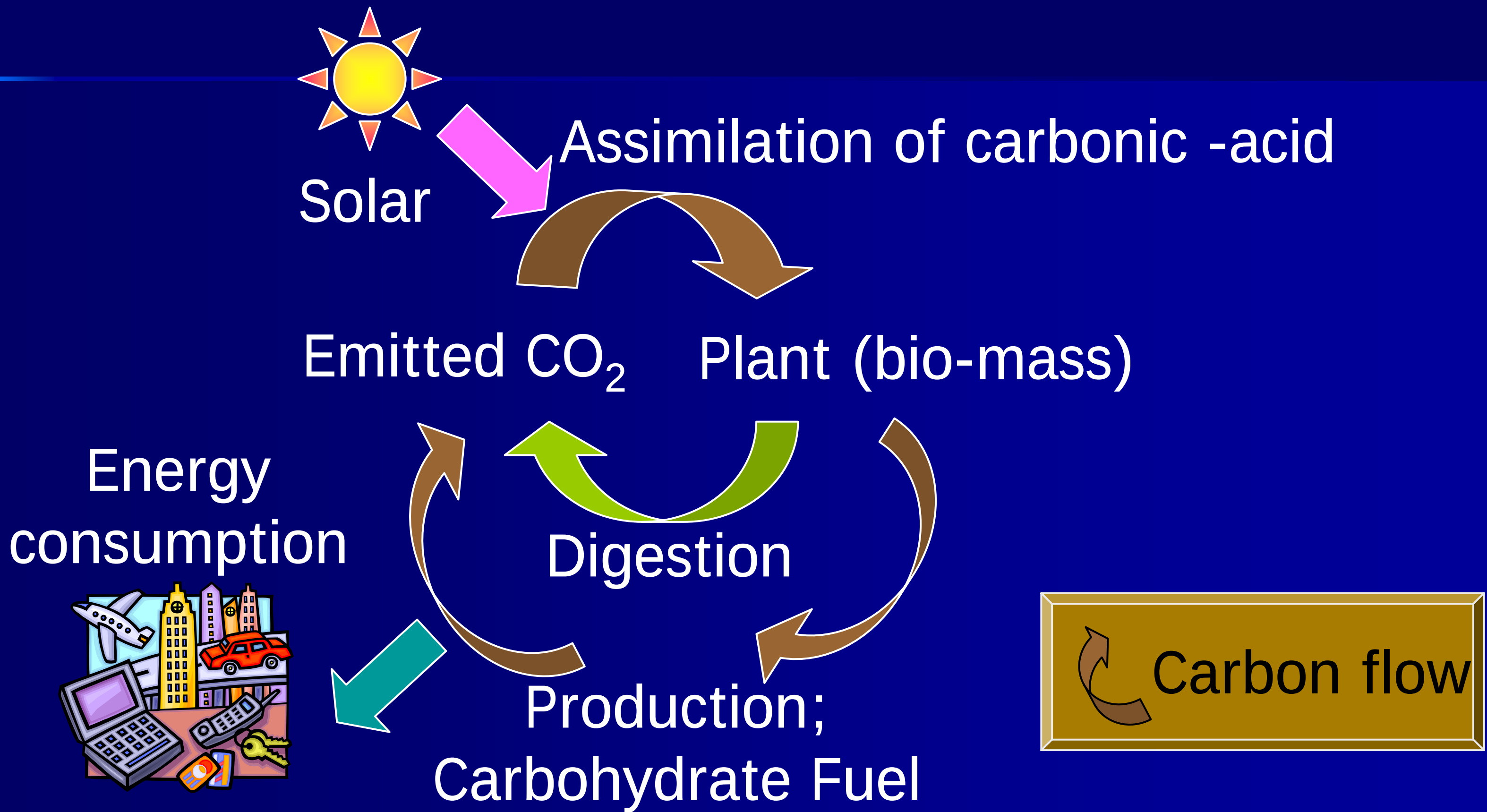
The carrier system : Reduction of compression pressure & work and transportation risk with consisting the same efficiency of conventional $H_2$ system
> Safe and compact $H_2$ carrier system

# 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

# 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!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