1. What is global environmental problems?

- Global warming due to a huge amount of CO2 emission
  Japan: 1.3 Gton-CO2/year, World: 25 Gton-CO2/year
- Depletion of fossil fuel resources

Any countermeasure should have a **net and quantitative** contribution to solve those problems as a total system.
2. OVERVIEW - A realistic scenario for sustainable development

Long term prospect of fossil fuel consumption
(Source: Clean Coal Science Handbook, 1996 CCUJ)

**FutureGen (US)**
- Gasification
- CO + H₂
- Shift reaction
- CO₂ + H₂
- Steam reforming
- Energy system

Hydrogen Energy System
(Fuel Cell, Hydrogen Turbine, ..)

- CO₂ Recovery
- CO₂ Separation and Recovery (MEA, ..)
- CO₂ Sequestration (Ocean, Geological, ..)

[Short term]
- CO₂ recovery and sequestration
- Integration of fossil fuel, hydrogen and CO₂ mitigation

<Okazaki, J. Energy, 2004>

[Medium term]
- Hydrogen production from natural energies

But, still many problems ...

Semi-commercialized FC vehicles and buses

Toyota FCHV  Nissann X-TRAIL FCV  Honda FCX  Mitsubishi FCV

Daihatsu Move FCV  Suzuki MR Wagon FCV  GM/OPEL HydroGen3  Daimler F-Cell

Ford Focus FCV  Toyota/Hino FCHV- BUS2  Daimler FC Bus  MAN FC Bus

Present status of hydrogen energy technologies

Hydrogen energy has been used only for some special purpose such as a launch of space shuttle.

Hydrogen energy is now spreading widely to various public use such as transportation, stationary energy sources as a countermeasure to solve environmental issues.

Launch of Space Shuttle
(combustion of hydrogen with oxygen)

Hydrogen energy has been used only for some special purpose such as a launch of space shuttle.

Hydrogen energy is now spreading widely to various public use such as transportation, stationary energy sources as a countermeasure to solve environmental issues.

But, still many problems ...

Present status of hydrogen energy technologies
Hydrogen refueling stations for commercialization

Los Angeles Air Port water electrolysis self-service
Washington DC Hydrogen station with GS liquid-hydrogen storage
HF-150, moving type hydrogen refueling station (150kg, 35MPa)

CEP Berlin, self-service liquid-hydrogen storage water electrolysis
H-CUTE Berlin, Self-service liquid-hydrogen storage LPG reforming
Burbank low-cost PEM electrolysis self-service

Opening ceremony of hydrogen station at UC-Davis, April 4, 2004
California Hydrogen Highway Network (CaH₂Net) plan was presented by the governor Arnold Schwarzenegger in April, 2004.

California Hydrogen Highway Network Program in California

<table>
<thead>
<tr>
<th>Hydrogen stations in northern California</th>
<th>Target presented in 2004</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen station: 250 sites</td>
<td></td>
</tr>
<tr>
<td>Hydrogen vehicles: 20,000</td>
<td></td>
</tr>
<tr>
<td>Reduction of GHG emission: 30%</td>
<td></td>
</tr>
</tbody>
</table>

- Hydrogen stations in northern California
- Hydrogen stations in southern California
- 18 stations connecting big cities

Source: Homepage of Hydrogen highway

Hydrogen Highway Program

British Columbia, Canada

Hydrogen Highway Program
In Norway (HyNor)
Japanese Projects for Mitigation of Global Warming

- **Coal Technologies for CO₂ Recovery**
  - CO₂/O₂ (Oxy-firing) Coal Combustion (NEDO-CCL; 1996-2000)
  - IGCC+CO₂ Recovery and Hydrogen-rich Gasification, Hydrogen Turbine
  - IGFC+ CO₂ Recovery and SOFC, Co-production
  - HyPr-RING: New Hydrogen Production Process with CO₂ Recovery

- **CO₂ Sequestration Technologies**
  - Geological Sequestration

- **Hydrogen related Technologies**
  - WE-NET (World Energy Network Project)

- **Fuel Cell Vehicles and Hydrogen Refueling Stations**
  - JHFC (Japan Hydrogen and Fuel Cell Development Project)
    (METI-JARI(JEVA); Phase-I: 2002-2005, Phase-II: 2006- )
**Project Integration and World Collaboration**

**Coal Utilization with CO₂ Recovery**
- JCOAL
  - O₂/CO₂ Coal Combustion
  - CO₂ Capture from IGCC
  - HyPr-RING for Hydrogen Production

**CO₂ Sequestration**
- RITE
  - Ocean Sequestration
  - Geological Sequestration

**Hydrogen Energy System**
- ENAA, IAE
  - JARI-JHFC
  - FC-Vehicles and H₂ Stations
  - Distributed Co-generation System

(Annual Budget: 1.2 billion yen, M$ 300/year for FY2005)

**US** (Hydrogen Initiative, FutureGen), Europe, etc.

**to improve our global environment for future generations**

---

**OVERVIEW**

**FutureGen (US)**
- CO₂ + H₂ → CO₂ Recovery
- O₂/CO₂ Combustion → CO₂ Separation and Recovery
- CO₂ Sequestration

**Renewable Energy**
- (Wind, PV ..)

**Electricity**
- H₂ + O₂ → H₂O

---

**Present Status of Clean Coal Technology**

**Emissions of NOx and SOx from Fossil Fuel-Fired Power Stations**

**Acid Rain**
- technology transfer from Japan

**CO₂ Problems**
- only increase of eff. is not enough, and new strategies are definitely necessary.

---

**O₂/CO₂ (Oxy-firing) Coal Combustion**

**Conventional pulverized coal combustion**
- CO₂ concentration in flue gas is about 13 %
- Great energy consumption to separate CO₂

**O₂/CO₂ pulverized coal combustion**
- CO₂ concentration in flue gas is enriched up to 95 %
- Easy and efficient CO₂ recovery

Practically realized by Ishikawajima-Harima Co., Ltd.
Drastic Reduction of CR* (Fuel-N to NOx) by Oxy-firing

![Graph showing comparison between Conventional coal combustion and Oxy-fuel combustion with heat recirculation.]

Base case
Conventional
O₂: 21%
H.R.: 0%

Oxy-fuel
O₂: 30%
H.R.: 0%

Oxy-fuel
O₂: 21%
H.R.: 0%

Oxy-fuel
O₂: 15%
H.R.: 40%

Decreased to one-seventh

Case 1 Case 2 Case 3 Case 4

Various cases for CR estimation

<table>
<thead>
<tr>
<th>Cases</th>
<th>System</th>
<th>O₂ concentration (%)</th>
<th>Gas recirculation ratio according to chemical stoichiometry</th>
<th>A in volatile matter combustion zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>Conventional pulverized coal combustion</td>
<td>21</td>
<td>0.0</td>
<td>0.7</td>
</tr>
<tr>
<td>Case 2</td>
<td>O₂/CO₂, pulverized coal combustion</td>
<td>20</td>
<td>0.21</td>
<td>0.7</td>
</tr>
<tr>
<td>Case 3</td>
<td>O₂/CO₂, pulverized coal combustion with heat recirculation</td>
<td>21</td>
<td>0.84</td>
<td>0.7</td>
</tr>
<tr>
<td>Case 4</td>
<td>O₂/CO₂, pulverized coal combustion with heat recirculation</td>
<td>15</td>
<td>0.39</td>
<td>0.7</td>
</tr>
</tbody>
</table>

<Liu & Okazaki, FUEL, 2003>

Australia/Japan Oxy-firing Project

Site map

Power Plant site
*Callide-A Power Station of CS Energy

Sequestration site

Scheme

Australia
Coal 21
Project manager
Electric companies
Coal suppliers
Research Gr.

Japan
NEDO: New Energy and Industrial Technology Development Organization

Advisory Group:
*Tokyo Institute of Technology
*National Institute of Advanced Industrial Science and Technology
*Electric Power Development Co., Ltd.
*Central Research Institute of Electric Power Industry
*Nippon Sanso Corporation
*Research Institute of Innovative Technology for the Earth

CCUJ (JCOAL)
Application study of Oxy-firing technology in other region

IHI
Study of boiler conversion to Oxy-firing

Australia/Japan Oxy-firing Project

Air separation units
Oxygen
Oxygen pre-heater
Stack
Compressors
CO₂
Injection
Tank

Sequestration
(Direct gas injection)

Transportation
(truck or railway or pipeline)

Storage
(gas or liquid)
OVERVIEW

**CO2 + H2**

**Fossil Fuel** (Coal, Oil ..)

**O2/CO2**

**Combustion**

**Steam reforming**

**Gasification**

**CO2 Recovery**

**CO2 Recovery and Recovery** (MEA ..)

**Air-blown**

**Combustion**

**FutureGen (US)**

**Renewable Energy** (Wind, PV ..)

**Electricity**

**Hydrogen Energy System** (Fuel Cell, Hydrogen Turbine ..)

**CO2 Sequestration** (Ocean, Geological ..)

[Short term]

CO2 recovery and sequestration

Integration of fossil fuel, hydrogen and CO2 mitigation

*Okazaki, J. Energy, 2004*

[Medium term]

CO2 recovery and sequestration

Short, medium and long term scenario for CO2 mitigation and introducing hydrogen

**[Far future]**

Hydrogen production from natural energies

---

**CO2 Sequestration Projects in Japan**

**Ocean Sequestration** by moving ship

**direct dissolution type**

**CO2 droplet dissolution must finish before reaching to sea surface**

Control of released liquid CO2 droplet size

Fundamental understanding of liquid CO2 injection behavior with hydrate

We have almost developed this technology without additional effect on marine environment

**Atmospheric CO2 peak shaving** by artificial dissolution of CO2 into ocean

---

**CO2 Sequestration technologies for a vast amount of CO2**

Sequestration technologies for a vast amount of CO2

Displacement/collection sequestration method

Stationary type ( Pipelines, Subsea injection ..)

Variable type (Shrimp ship, Inflation/Deflation ..)

Deep ocean storage and subsequent recovery method

---

**CO2 discharge:** 23.8 Gt CO2/year (World)

1.2 Gt CO2/year (Japan)

---

*Figures compiled by METI & JETI*
Sleipner Project - aquifer
Statoil – Norway
1MtCO₂/year

CO₂ Injection Experiment in Niigata Prefecture

OVERVIEW

**FutureGen (US)**

- CO₂ + H₂
- Gasification
- Steam Reforming
- Energy Enhancement
- **Air-blown Combustion**
- **O₂/CO₂ Combustion**
- **CO₂ Recovery**
- **CO₂ Separation and Recovery (MEA ..)**
- **CO₂ Sequestration (Ocean, Geological ..)**

**Renewable Energy**

- (Wind, PV ..)

**Hydrogen Energy System**

- (Fuel Cell, Hydrogen Turbine ..)

**Electricity**

- **H₂ + O₂ → H₂O**

**[Far future]**

- Hydrogen production from natural energies

**[Short term]**

- Integration of fossil fuel, hydrogen and CO₂ mitigation
- <Okazaki, J. Energy, 2004>

**[Medium term]**

- CO₂ recovery and sequestration

**[Far future]**

- Hydrogen production from natural energies

**JHFC: Japan Hydrogen and Fuel Cell Demonstration Project**

<table>
<thead>
<tr>
<th>YEAR (FY)</th>
<th>2002</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Facility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Garage Showroom</td>
<td>Construction</td>
<td>Opening</td>
<td>Expansion</td>
<td>Operation</td>
</tr>
<tr>
<td>Hydrogen Station</td>
<td>Construction</td>
<td>Extension</td>
<td>Extension</td>
<td>Operation</td>
</tr>
<tr>
<td>Test</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Test</td>
<td>Test Method</td>
<td>Demo. Test, Data Acquisition, Validation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen Station Test</td>
<td>Test Method</td>
<td>Operation &amp; Demo. Test, Validation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Public Relation</td>
<td>Seminar</td>
<td>Seminar</td>
<td>Seminar</td>
<td>Seminar</td>
</tr>
</tbody>
</table>

**JHFC Project**

- **Vehicle Test**
- **Hydrogen Station Test**
- **Public Relation**
Overall efficiency (fuel production eff. × running eff.)

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Running (%)</th>
<th>Total efficiency (fuel eff. × running eff.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gasoline ICV</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Gasoline HV</td>
<td>88</td>
<td></td>
</tr>
<tr>
<td>Comp. H2 FCV</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>Comp. H2 FCHV</td>
<td>58</td>
<td></td>
</tr>
<tr>
<td>FCHV target</td>
<td>70</td>
<td></td>
</tr>
</tbody>
</table>

HV: Hybrid Vehicle  
FCV: Fuel Cell Vehicle  
FCHV: Fuel Cell Hybrid Vehicle  
(source: Toyota)

JHFC Demonstration FCVs

- Nissan X-TRAIL
- Honda FCX
- Toyota FCHV
- Toyota/ Hino FCHV-BUS2
- Suzuki wagonR-FCV
- General Motors Hydrogen3
- MITSUBISHI FCV

JHFC Park (Garage・Showroom, Hydrogen Station)

Opening: March 12, 2003

Hydrogen Stations in Metropolitan Area near Tokyo

- Garage-Showroom
- Yokohama-Daikoku Hydrogen Station
- Yokohama-Asahi Hydrogen Station
- Senju Hydrogen Station
- Ariake Hydrogen Station
- Kawasaki Hydrogen Station
- Relocatable Hydrogen Station
- Hadano Hydrogen Station
- Sagamihara Hydrogen Station
- Ome Hydrogen Station
- Yokohama-Tsurumi Hydrogen Station
**Total Efficiency**

Outline of Total efficiency estimation

**Well to Wheel**

- Ingredient → Fuel → Hydrogen
- Well to Charge Tank → Fuel Tank → Fuel Tank to Wheel

**Estimation from references**

- Data from hydrogen refueling station operation
- Data from FCV demo test

Total efficiency using “real world data” will be shown.

---

**Driving Test Result - Energy Consumption (1)**

Compared with ICV and HEV, FCV showed better energy consumption rate per vehicle weight.

Test Route: Designated

Air Conditioner: ON

**FCV-ICV-HEV Comparison Result (with Vehicle Weight Modification)**

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Energy Consumption Rate (km/L gasoline equivalent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HEV</td>
<td></td>
</tr>
<tr>
<td>ICV</td>
<td></td>
</tr>
<tr>
<td>FCV</td>
<td></td>
</tr>
</tbody>
</table>

**Scenario to introduce FCVs, Stations and Stationary FCs (Japan’s target)**

By Dr. Takenaka (AIST)

**Number of FCVs**

- **2006** <Introduction> 50,000 Official vehicles, Buses
- **2010** <popularization> 5 million Freight trucks, Business cars
- **2020** <full-popularization> 15 million Public cars

**Vehicle Types**

- Hydrogen Stations (Hydrogen Demand)
  - 500 sites (40 k ton)
  - 3500 sites (580 k ton)
  - 8500 sites (1510 k ton)

**Stationary Fuel Cell**

- Commercialization 2.2 GW
- 10 GW
- 12.5 GW

**Spread of Micro Grids**

- Durability Target
  - 3,000 hrs (FC vehicle)
  - 30,000 start & stop (FC vehicle)
  - 40,000 hrs (stationary)

- Cost Target
  - Millions JP¥/kW (Stack cost for FC vehicle)
  - Millions JP¥ (System price for stationary FC)

**Needed Innovations for PEFC**

- **Reliability** --- longer duration time
  (back to the basic: mechanism of degradation)

- **Much lower cost** (--- 1/100)

- **Higher efficiency** --- less energy loss
  (in the membrane and on the catalytic surface)

- **High efficiency catalyst**
  (less platinum or alternative materials)
4. Another important feature of hydrogen is exergy enhancement using hydrogen as an energy carrier

Exergy enhancement of low quality thermal energy by steam reforming of methanol

$$\text{CH}_3\text{OH} + \text{H}_2\text{O} = \text{CO}_2 + 3\text{H}_2$$

Heat value: endothermic

$$727 \text{ kJ/mol} \times 3 = 286 \times 3 = 858 \text{ kJ/mol}$$

Low quality thermal energy (waste heat)

$$\eta = \frac{\Delta G}{\Delta H} = 6 \%$$

(corresponding to 100 °C)
Multi-Path Hydrogen Production System from Coal or Biomass with Exergy Enhancement using Waste Heat on Site

Quality enhancement and reuse of low quality waste heat

5. Visions for the future prospect of hydrogen energy

**Long term strategy**
- Introducing a large amount of natural energy (x 100-1000)
- World hydrogen energy network

**Realistic intermediate scenario** (time scale, spatial scale)
- Even if the net contribution is very small at present
  - Hydrogen vehicle (PEFC)
  - Infrastructure, refueling station, hydrogen community
  - Advanced system of multilateral utilization of hydrogen combined with CCS (Carbon Capture and Sequestration)
  - Exergy enhancement of low temperature waste heat using hydrogen as an energy carrier
  - Optimization of distributed energy system (PEFC, MGT)
  - Efficient hydrogen production from fossil fuels and biomass
  - Lower cost and longer lifetime of PEFC
  - Establishing safety and public acceptance

Technology development for system integration based on advanced utilization of hydrogen
- Interface, matching of quantity and rate
- Inter-industry collaboration
- Co-production

System integration as a realistic intermediate scenario toward hydrogen society