# Outline of DNE21+ Model
## -CO2 Capture & Storage (CCS)-

August 20, 2008

## 1. Introduction

- ○ $CO_2$ capture and storage (CCS) refers to the capture, transportation, storage and sequestration of $CO_2$. The main processes in each step are modeled in a DNE21+ model.
- ○ The modeling of the DNE21+ model enables transportation (by pipeline or by tanker in liquid form) of captured $CO_2$ in 77 regions. When only a portion of countries implement strict emission controls, it is theoretically possible that $CO_2$ will be transported to neighboring countries without such strict emission controls and released. However actually since such a possibility is not reasonable, such interpretations are excluded in the many analysis of DNE21+ models by analyzing on the condition that captured $CO_2$ cannot be transported across national borders. Regional $CO_2$ transportation which does not cross national borders is possible across the regional divisions of a single country.

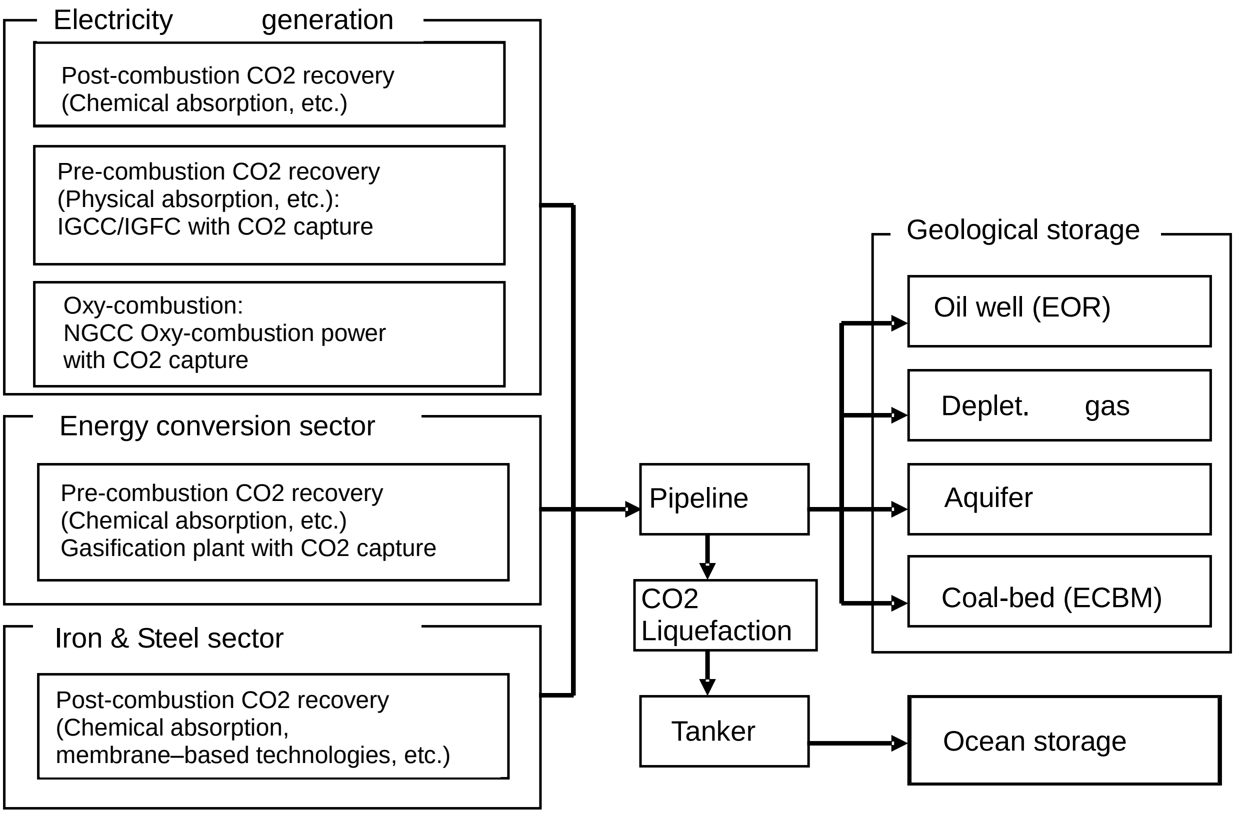


Fig.1 CCS modeling

## 2. CO2 Capture Technologies

- $CO_2$ capture technologies are assumed in power generation, other energy conversion sectors and iron and steel sector. Although discussion is found in the relevant sections above for each sector, Table 1 shows an overview of assumed $CO_2$ capture.
- Although $CO_2$ capture is being investigated in the cement and paper sectors, many applications will be at the smaller range of scale and in many cases, implementation will not be realistic. Therefore CCS is not assumed for these sectors in the DNE21+ model.

Table 1 Assumed capital cost, required power and $CO_2$ capture efficiency of various $CO_2$ capture plants.

| | Capital Cost [US$/kW] | Power generation efficiency [LHV %] | $CO_2$ Recovery Efficiency [%] |
|---|---|---|---|
| IGCC/IGFC with $CO_2$ Capture | 1,700 – 1,325 | 34.0 – 51.0 | 90 – 99 |
| Natural Gas Oxy-fuel Combustion Power Generation | 1,495 – 1,245 | 40.7 – 50.7 | 90 – 95 |
| | Capital Cost [US$/(tC/day)] | Required Power [MWh/tC] | |
| Post-combustion $CO_2$Recovery in Coal Power Generation | 59,100 – 52,000 | 0.792 – 0.350 | 90 |
| Post-combustion $CO_2$Recovery in Natural Gas Power Generation | 112,500 – 100,000 | 0.927 – 0.719 | 90 |
| $CO_2$ Recovery from Biomass Power Generation | 112,500 – 100,000 | 2.588 – 1.144 | 90 |
| $CO_2$ Recovery from gas reforming plant | 14,500 | 0.801 | 90 – 95 |
| $CO_2$ Recovery from iron foundry blast furnace gases $CO_2$ | 70,620 – 57,600 | 0.730 – 0.550 | 90 |

## 3. $CO_2$ storage and sequestration

- $CO_2$ storage and sequestration options can be broadly divided into geological storage (including under the sea floor) and ocean sequestration.
- Geological storage may be further divided into several options and the DNE21+ model explicitly considers four options: oil wells (enhanced oil recovery), gas wells, deep aquifers, coal beds (enhanced methane recovery).

(1) Oil Wells (enhanced oil recovery)

- ○ A method of enhancing oil recovery by injecting $CO_2$ into oil wells is already used for the purpose of increasing oil recovery. Since the $CO_2$ is stored in the oil well, it can be viewed as a $CO_2$ storage option.
- ○ Figure 2 shows $CO_2$ storage potential in oil wells by region.
- ○ If a 1 tC amount of $CO_2$ is injected, it is assumed that oil recovery will be enhanced by 1.12 toe. It is assumed that the recovered oil can be used for energy in the same manner as normal oil.
- ○ It is assumed that the worldwide storage potential is 30.7 GtC (112.4 $GtCO_2$).

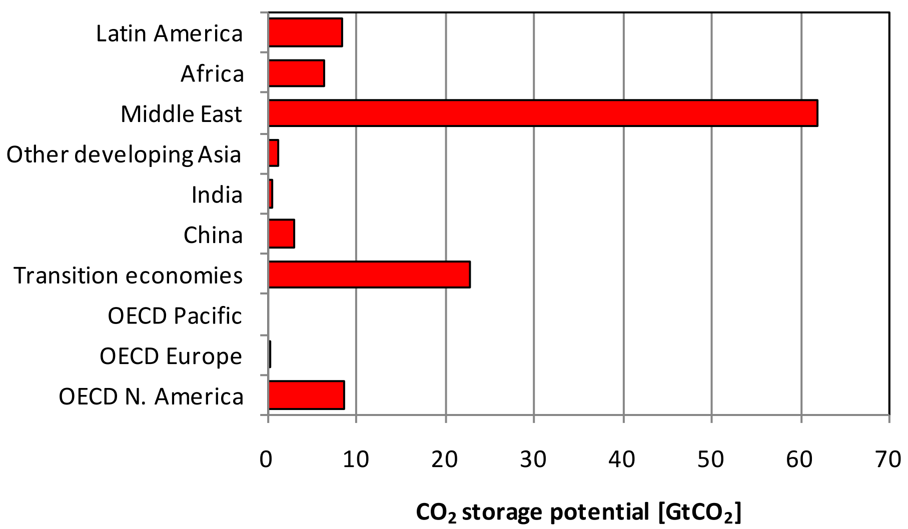


Fig.2 Assumed $CO_2$ storage potential in oil wells (enhanced oil recovery)

(2) Gas Wells

- ○ Gas wells in which natural gas was originally present are thought to be appropriate geological structures for the storage of $CO_2$. This option is available for the storage of $CO_2$ when natural gas extraction has been completed.
- ○ Figure 2 shows $CO_2$ storage potential in gas wells in 2000 by region. This potential has been calculated using historical cumulative natural gas production amounts.
- ○ It is assumed that the worldwide storage potential at 2000 is 40.2 GtC (147.3 $GtCO_2$).

- Since the number of gas wells will increase together with development of gas production, the $CO_2$ storage potential in gas wells will display a corresponding increase. If 1 toe of natural gas is produced, it is assumed that the $CO_2$ storage potential will increase by 0.83 tC.
- When all gas wells are utilized, a storage potential of 181.5 GtC (665.5 $GtCO_2$) is assumed.

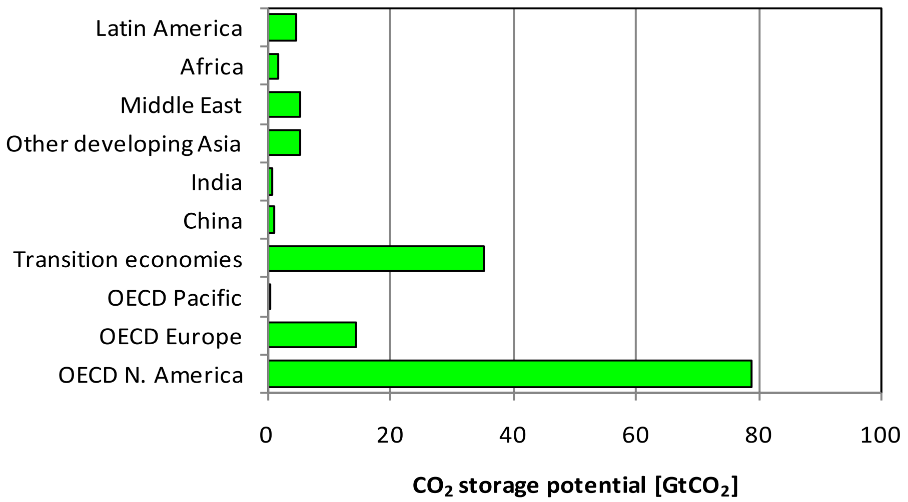


Fig.3 Assumptions regarding $CO_2$ storage potential of gas wells at 2000

(3) Deep Aquifers

- The theoretical $CO_2$ storage potential in deep aquifers is estimated based on GIS data for sedimentary basins of the US Geological Survey (USGS). However the entire theoretical potential will not actually be able to be used for $CO_2$ storage due to limitations resulting from faults or above-ground buildings. Therefore actual potential has been premised on 10% of the terrestrial theoretical potential and 20% of the marine theoretical potential in the DNE21+ model. (Akimoto et al., 2004, “Role of $CO_2$ Sequestration by Country for Global Warming Mitigation after 2013,” GHGT7)
- Figure 4 shows the estimated regional distribution of theoretical potential of $CO_2$ storage in deep aquifers.
- Figure 5 shows the actual potential $CO_2$ storage in deep aquifers by region.
- The actual storage potential in deep aquifers worldwide is assumed to be 856.4 GtC (3140.1 $GtCO_2$).

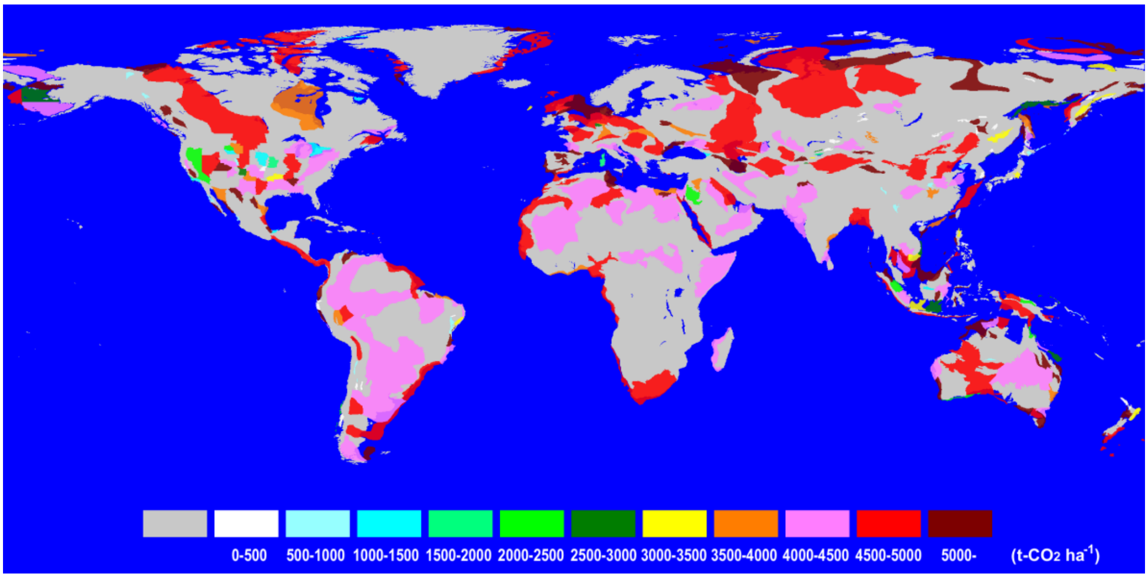


Fig.4 $CO_2$ storage potential in deep aquifers (theoretical potential)

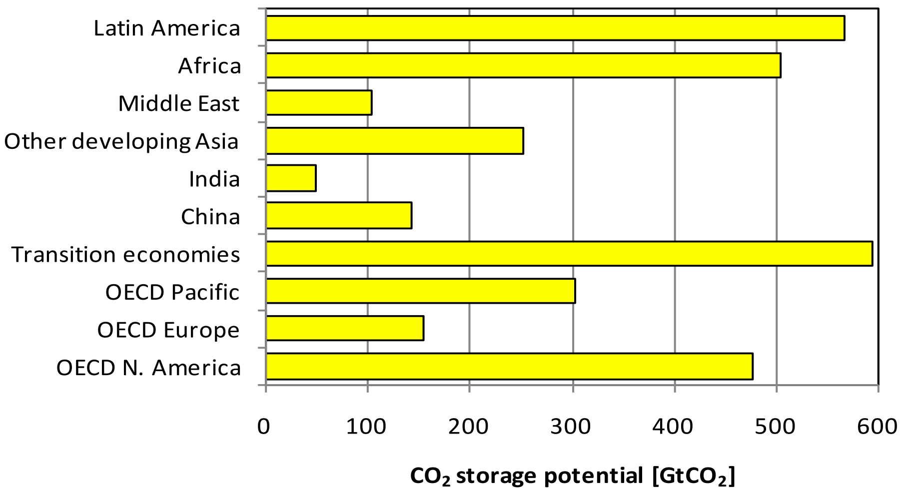


Fig.5 Assumed $CO_2$ storage potential in deep aquifers (actual potential)

(4) Coal Bed (Enhanced methane recovery)

- ○ $CO_2$ displays a greater absorption capacity to coal beds than methane and therefore this technique contemplates the recovery of methane by injecting $CO_2$ into a coal bed.
- ○ The $CO_2$ storage potential in coal beds by region was calculated based on "Enhanced Coal Bed Methane Recovery with $CO_2$ Sequestration," Report Number

PH3/3, 1998, IEA GHG and used as a assumption in the DNE21+ model. Figure 6 shows storage potential by region.

- ○ When 1 ton of $CO_2$ is injected, it is assumed that enhanced recovery will correspond to 0.717 toe of methane. Methane recovered by enhancing technology is assumed to be used as energy in the same manner as normal natural gas.
- ○ It is assumed that the worldwide storage potential is 40.4 GtC (148.2 $GtCO_2$).

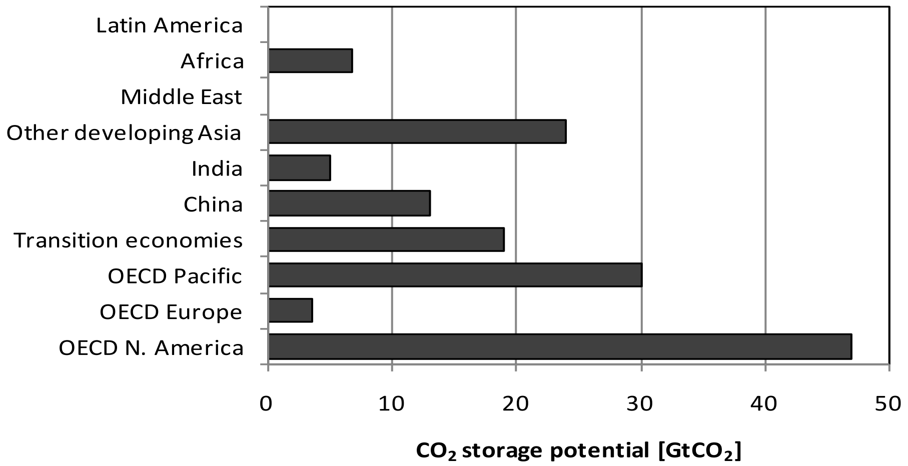


Fig.6 Assumed $CO_2$ storage potential in coal beds (enhanced methane recovery)

(5) Ocean Sequestration

- ○ $CO_2$ sequestration in the ocean is being broadly investigated along two lines: release as effluent into middle layers at a depth of approximately 2000m and sequestration at a depth in excess of 3000m. Since there is not a large cost differential between the techniques, both techniques have been equally evaluated in the DNE21+ model.
- ○ Actual ocean sequestration is assumed to be performed by liquefaction of $CO_2$ and injection of $CO_2$ from a liquid carrying tanker.

- ○ TableTable 2 shows costs associated with liquefaction of $CO_2$. Costs associated with injection of $CO_2$ are assumed to be 30.4 $/tC.
- ○ However although $CO_2$ ocean sequestration is assumed in the DNE21+ model and no large technical problems are seen in the application of the technology, at the present time, grave international apprehensions remain regarding the environmental impact on the ocean and therefore the outlook regarding possible

applications is surrounded by uncertainly. As a result, it is assumed that ocean sequestration will not be used an option and it is not evaluated in the present analysis.

Table 2: Assumed capital costs and required power for $CO_2$ liquefaction plant

| | Capital Cost [US$/(tC/day)] | Required Power [MWh/tC] |
|---|---|---|
| $CO_2$ Liquefaction | 28,100 | 0.543 |

(6) Summary

○ Table 3 shows an overview of the assumption regarding storage costs and $CO_2$ storage potential worldwide according to the discussion above. Table 4 shows the $CO_2$ geological storage potential in comparison with figures from the IPCC Special Report related to $CO_2$ Capture and Storage (SRCCS).

Table 3 Assumed storage costs and worldwide $CO_2$ storage potential

| | Storage Potential (GtC) | Storage Cost ($/tC) ‡ |
|---|---|---|
| Geological Storage | | |
| Oil Well (Enhanced Oil Recovery) | 30.7 | 209 – 252†† |
| Gas Well | 40.2–181.5 | 34 – 215 |
| Deep Aquifer | 856.4 | 18 – 139 |
| Coal Bed (Enhanced Methane Recovery) | 40.4 | 99 – 447†† |
| Ocean Sequestration† | – | 106‡‡ |

† Although incorporated into the model, it is assumed in the normal analysis that this technology option will not be used.
‡ $CO_2$ recovery costs are not included in these figures. Separate treatment.
†† The benefit of oil and gas is not included in these figures. Separate treatment.
‡‡ Overall figure including $CO_2$ liquefaction facility costs and required electricity (when electricity costs are assumed to be 10 cent/kWh).

Table 4 Comparison of assumption for worldwide $CO_2$ storage potential and figures reported in IPCC Special Report

| | Assumed $CO_2$ Storage Potential under DNE21+ | | IPCC SRCCS |
|---|---|---|---|
| | (GtC) | ($GtCO_2$) | ($GtCO_2$) |
| Oil Well・Gas Well | 70.9 – 212.2 | 260– 778 | 675–900 |
| Deep Aquifer | 856.4 | 3140 | $10^3$–～$10^4$ |
| Coal Bed (Enhanced Methane Recovery) | 40.4 | 148 | 3–200 |