Outline of DNE21+ Model

-Iron and Steel, Cement, Aluminum Sector-

August 20, 2008

1. Iron and Steel Sector

(1) Modeling of Iron and Steel Sector

○ The iron and steel sector is explicitly modeled focusing raw material processing steps such as coke oven and sintering furnace up to hot rolling steps.

○ Technological options are modeled by grouping several technique groups (routes). Four routes of basic oxygen furnace (BOF), three routes of scrap-based electric arc furnace (EAF) and two routes of direct reduction method are assumed.

○ Crude steel production scenario is exogenously assumed by region. Technology selection which minimizes total energy system costs is evaluated on the basis of the vintage of existing facilities, capital costs, energy costs (determined endogenously for the overall model) to meet the production scenario. (Figure 1).

○ The crude steel production scenario by scrap-based EAF methods was set exogenously by region as a lower limiting scenario and an upper limiting scenario (setting incorporates a level of freedom in the range).

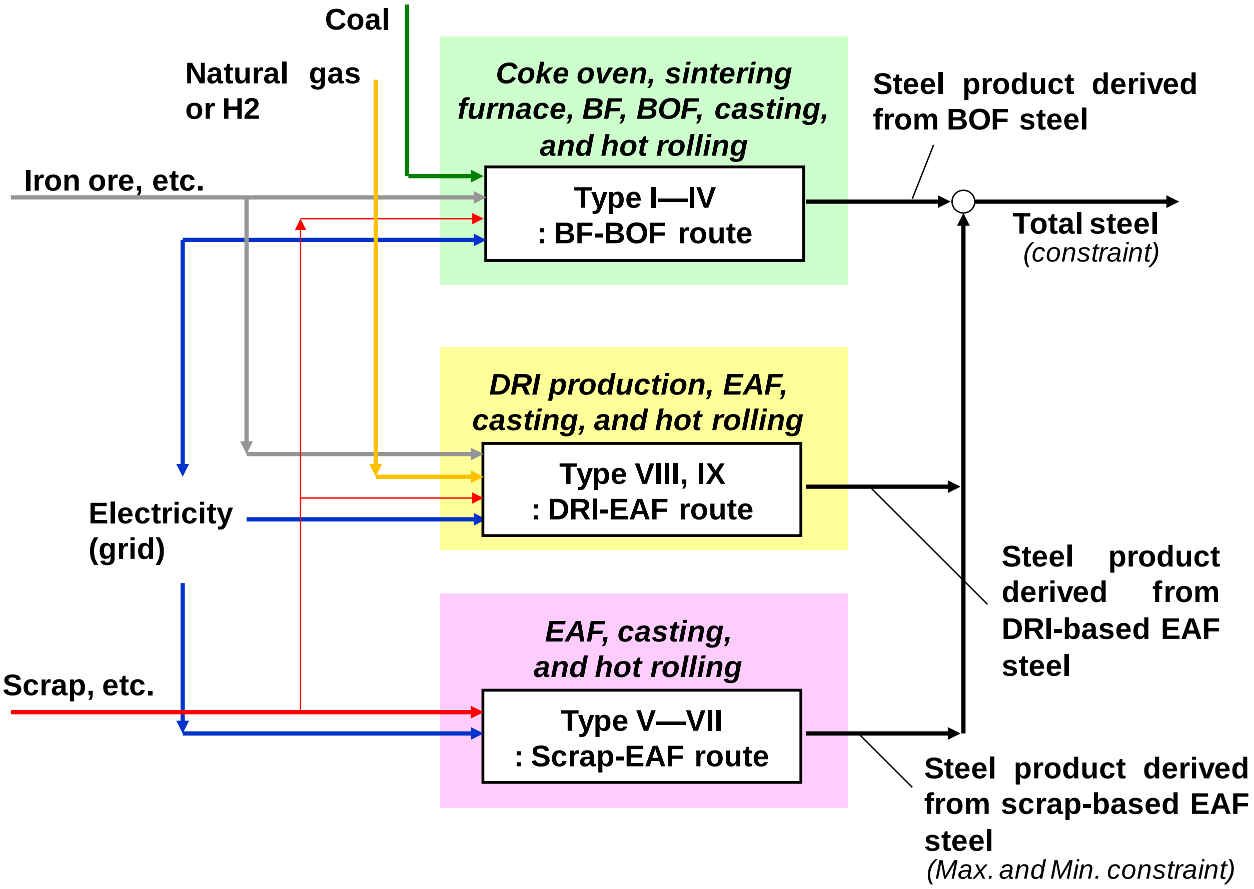

Fig.1 Model diagram of iron and steel sector

(2) Assumed Technology Options for Iron and Steel Sector

○ Overall energy efficiency at iron foundries is considered to depend not only on utilization level of various production technologies and energy saving technologies but also various factors such as scale of facilities and vintage, and properties of used raw materials.

○ Technology options are modeled as routes with grouped various technologies. The energy flow and assumed costs of each route are shown in Table 1.

Table 1 Capital cost of energy flow of supplementary technologies

	Energy Input and Recovery Amount (see note 1) (per t crude steel)	Capital Cost (US$/t rude steel/year)
BF-BOF		
Type I:Low Efficiency Facilities (including BOF open hearth furnace)	Coal 29.9GJ, heavy oil 1.2GJ, Electricity 490kWh	276.2
+ COG Recovery	Energy recovery 1.9GJ, other as above	+11.6
Type II:Medium Efficiency Facilities	Coal 26.9GJ, heavy oil 0.2GJ, Electricity 465kWh (net input)	295.4
+COG Recovery	Additional 2.2GJ energy recovery, others same as Type II	+9.3
+basic oxygen furnace gas recovery	Additional 0.9GJ energy recovery, others same as Type II	+16.2
+ coke dry quenching (CDQ)	Additional 63kWh power recovery, others same as Type II	+16.1
+ top pressure **r**ecovery turbine (TRT)	Additional 48kWh electricity recovery, others same as Type II	+13.6
Type III:High Efficiency	Coal 24.1GJ, electricity 364kWh (net input) Energy recovery:4.5GJ	386.5
+ Recycling facilities of waste plastics and tires	Coal 23.8GJ, others as above	+1.54
Type IV:High Efficiency Facilities (+ next generation coke oven)	Coal 22.5GJ, electricity 364kWh(net input) Energy recovery:4.5GJ	377.1
+carbon recovery and storage facilities (0.6tCO2/t crude steel)	Coal 22.5GJ, electricity 472–451kWh (see note 2) Energy recovery:3.5–4.1GJ (see note 2)	+30.0–25.8 (see note 2)

Scrap-EAF		
Type V:Low Efficiency Facilities (EAF and induction furnace)	Heavy oil 3.6GJ,electricity 623kWh	143.0
Type VI:Medium Efficiency Facilities	Heavy oil 2.5GJ, electricity 551kWh	174.0
Type VII:High Efficiency Facilities	Heavy oil 2.4GJ, electricity 513kWh	183.7
DRI-EAF		
Type VIII:Medium Efficiency Facilities	Natural gas 15.9GJ, electricity 705kWh	374.3
Type IX:High Efficiency Facilities	Natural gas or hydrogen 12.1GJ, electricity 695kWh	438.1

Note 1) Energy input figures do not include waste plastic or waste tires or biomass. Energy recovery is the total of by-product gases or steam.

Note 2) Capital costs and additional energy consumption of CO2 recovery and storage facilities will improve over time. 30.0–25.8(US$/(t crude steel/year)) corresponds to 66,900–57,600 (US$/(tC/day)).

○ For technological options, the considered technologies are shown in Table 2. The following individual technologies in the table, which correlate, should be modeled from a comprehensive perspective, as well as considered in detail.

Example 1: The more powdered coal is blown into, the less coke per ton of crude steel [t-coke/t-CS] is commonly consumed. Therefore, even when the energy saving effects of CDQ (coke dry quenching) in the coke making process stay constant, increase of blown powdered coal makes CDQ energy saving effects per one ton of crude steel smaller.

Example 2: High top pressure operation of blast furnace causes air heater to consume more energy, but also causes top pressure recovery turbine plants (TRT) to generate more electricity.

Table 2 Considered technologies in Iron & Steel Sector

A.	Coke making
1.	Use of waste plastic (alternative to coking coal)
2.	Use of waste tires (alternative to coking coal)
3.	Coal moisture control
4.	Recovery of COG (coke oven gas)
5.	Recovery of COG and sensible heat
6.	Traditional wet quenching of coke
7.	Low-efficient coke dry quenching of coke (traditional Russian type CDQ)
8.	High-efficient coke dry quenching (CDQ)
9.	Programmed heating [coke oven]
10.	Beehive coke oven
11.	Traditional coke oven
12.	Next-generation coke oven, e.g., SCOPE21 (Super Coke Oven for Productivity and Environmental enhancement toward the 21st century)
B	Sintering
13.	Improved blending of material segregation
14.	Conventional manual control of fueling
15.	Basic sintering furnace
16.	Waste heat recovery of main exhaust
17.	Waste heat recovery in the sinter cooler
C.	Iron Making
18.	Pulverized coal injection to a small volume of iron (PCI)
19.	Pulverized coal injection to a large volume of iron (PCI)
20.	Top pressure recovery turbine (wet type)
21.	Top pressure recovery turbine (dry type)
22.	Recovery of exhaust heat in the hot stove
23.	Small-scale blast furnace
24.	Middle-scale blast furnace
25.	Large-scale blast furnace
26.	Oxygen enrichment of the hot blast
D1.	Steelmaking – BOF (Basic Oxygen Furnace)
27.	Recovery of BOG (Basic Oxygen Gas)
28.	Recovery of BOG and the sensible heat

29. Recuperative burners of the ladle
30. Oxygen top blowing
31. Open hearth furnace (OHF)

D2 Steelmaking – Electric Arc furnace

32. Scrap preheating
33. Recuperative burners of the ladle
34. Direct current (DC) arc furnaces with water-cooled wall
35. Three phase alternating current AC arc furnaces
36. Small-scale electromagnetic induction furnaces

E. Casting and Rolling

37. Blooming/ingot making/rolling facilities
38. Low-efficient continuous casting
39. High-efficient continuous casting
40. Cold charging
41. Hot charging
42. Direct charging
43. Conventional burners
44. Recuperative burners
45. Low-efficient hot rolling
46. High-efficient hot rolling

F. Others, Cross-process Technologies

47. Hydrogen amplification and utilization of coke oven gas
48. Carbon capture and storage from blast furnaces (chemical absorption method)
49. Capture and utilization of sensible heat from blast furnace slag (energy use for carbon capture)
50. Direct reduction (improvements in natural gas vapor and CO2)

(3) Set-up of Vintage Data

○ A model was constructed allowing for selection of technology taking into account the vintage (year of construction) and durable years (40 years in the iron and steel sector) by region.

○ Figure 2 shows the energy efficiency by region at 2000 calculated using the vintage data.

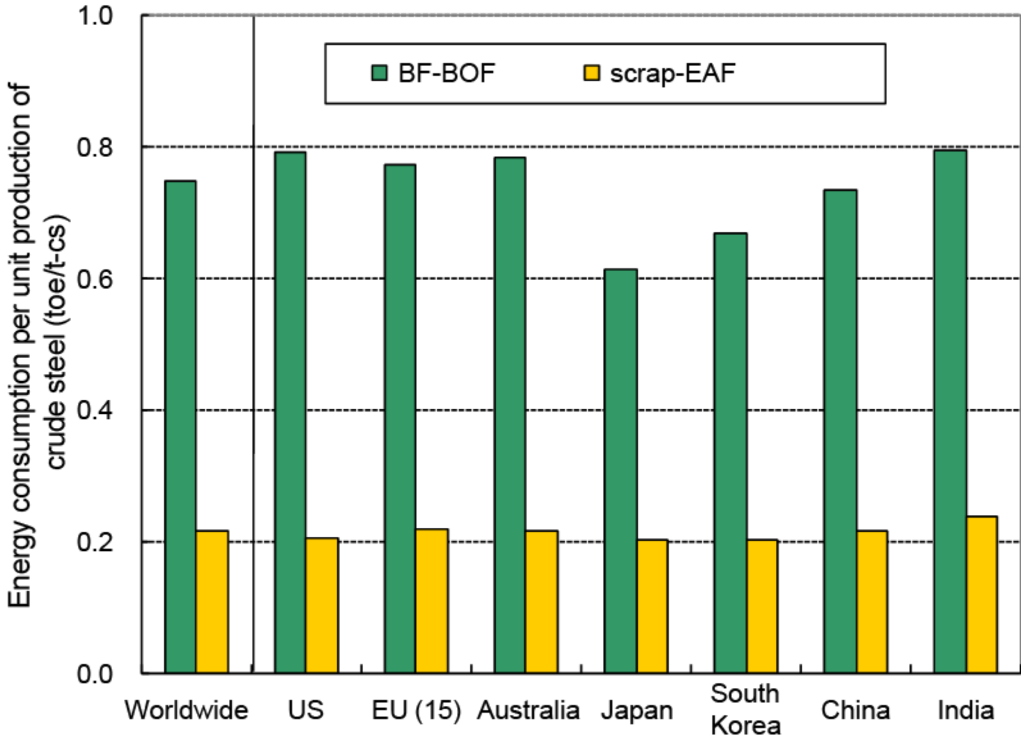

Fig.2 Estimated energy efficiency by region (2000)

Note 1) toe is a ton in terms of oil, 1 toe has an amount of energy equivalent to 1*10^7 kcal and 41.868 GJ. If 1 kg of metallurgical coal contains 6,904 kcal, 1 toe is equivalent to 1.448 t.

Note 2) Electricity is converted to primary energy (1 MWh = 0.086/0.33 toe).

(4) Regional Crude-Steel Production Scenario

○ Regional crude-steel production is assumed as an exogenous scenario (as discussed above). Figure 3 shows crude steel production for major countries.

○ Construction of scenarios takes into account the correlation between transition of per capita GDP and apparent per capita consumption of crude steel, trends in production structure by region and government planning reports.

○ Figure 4 shows actual figures and scenario for worldwide total crude steel production and production by scrap-based EAF. A lower limiting scenario and an upper limiting scenario for scrap-based EAF are assumed by region.

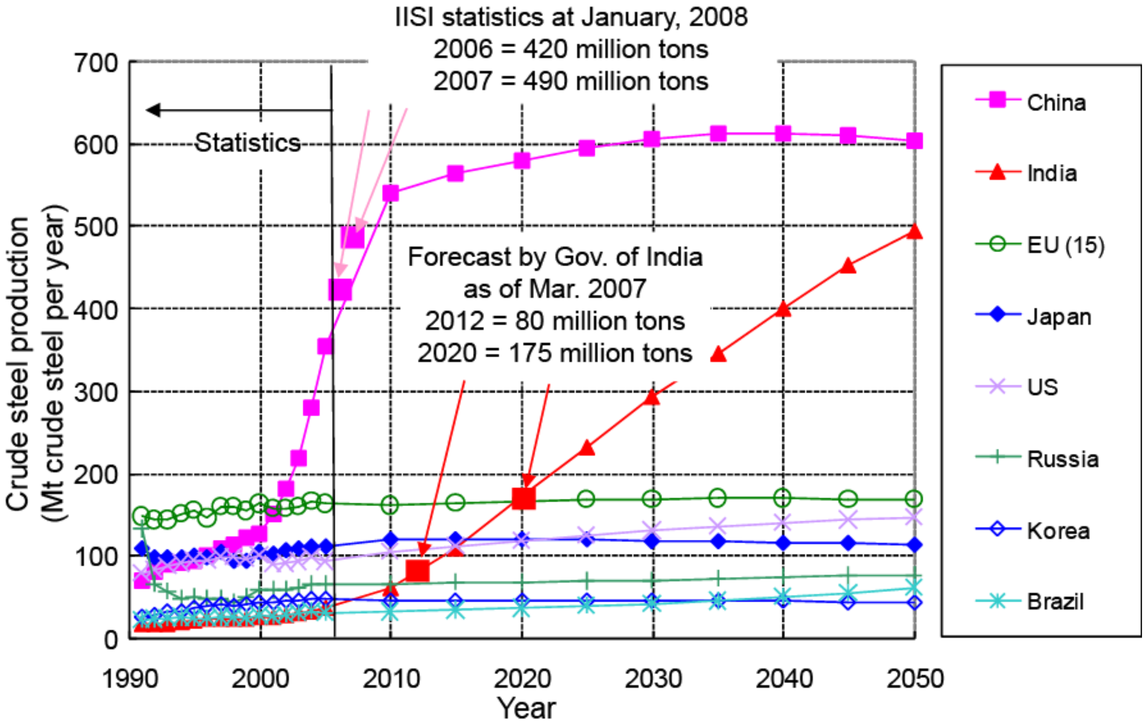

Fig.3 Crude-steel production of major regions (Statistics + Scenario)

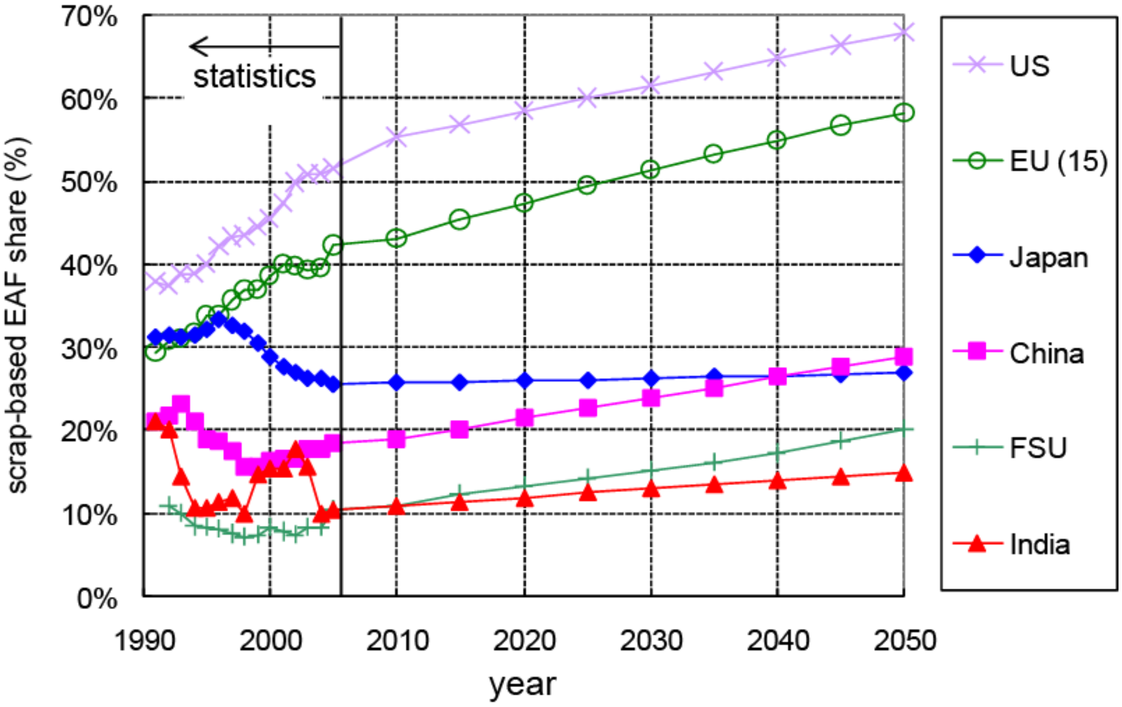

Fig.4 Scrap-based EAF shares by major regions (statistics, average of lower and upper limit scenarios)

2. Cement Sector

(1) Modeling of Cement Sector

- ○ The cement sector is modeled explicitly by taking into account each step from raw material preparation to finish grinding steps.
- ○ Since energy efficiencies and applicable technologies are different by production facility scales, selectable groups of technologies (routes) and production scenarios are assumed separately with respect small-scale facilities (1,000t-clinker/day or less) and large-scale facilities (1,000t-clinker/day or more).
- ○ Cement production and a clinker/cement ratio are exogenously assumed by region. Technology selection which minimizes costs is evaluated endogenously on the basis of the vintage of existing facilities, capital costs, energy costs (determined endogenously for the overall model).. (Figure 5).

(2) Assumed Technology Options for Cement Sector

- ○ The clinker production step accounts for more than half of fuel consumption during cement production. Energy efficiency largely depends on type of kiln for clinker production.
- ○ Technology groups characterized by clinker production are shown in Table 3.
- ○ Type IX (BAT: Best Available Technologies) incorporates all the most energy efficient facilities currently used at 2005. Since Type IX uses waste plastic and waste tires, there is a large difference in the fossil fuel consumption relative to Type VIII. Furthermore, the plant scale of Type IX is particularly large even when compared with large scale facilities and heat recovery power generation with clinker cooler and SP/NSP is large. As a result, there is a large difference between Type IX and Type VIII with respect to net electricity consumption.
- ○ Type IX is based on the premise of advantageous conditions for energy efficiency resulting from a loosening on raw material restrictions such as limestone or restrictions related to receipt of waste or byproducts. In this manner, it is stressed that Type IX is an (ideal) route which overcomes many current obstacles.
- ○ For technological options, the considered technologies are shown in Table 4.

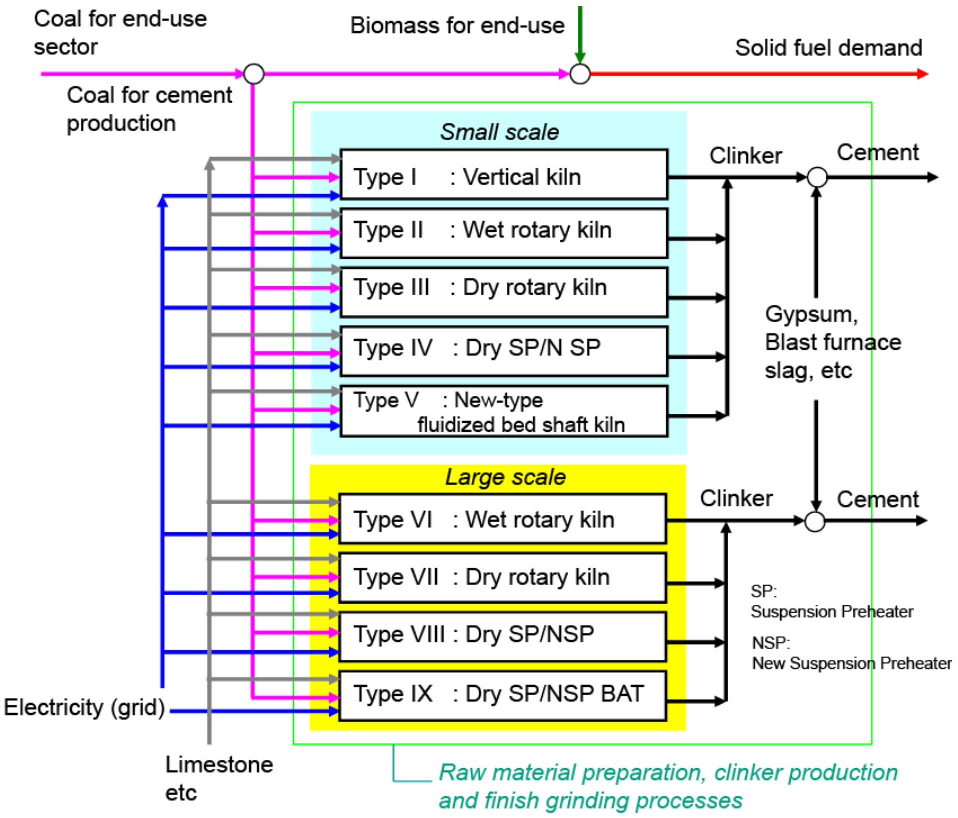

Fig.5 Model diagram of cement sector

Table 3 Capital costs and energy consumption for each route

	Energy Consumption		Capital Costs
	Fossil Fuel (GJ/t clinker)	Electricity (kWh/tclinker)	(US$/ (tclinker/year))
Small Scale Facilities			
Type I:Vertical Kiln	5.45	148	324.9
Type II:Wet Rotary Kiln	6.20	146	438.5
Type III:Dry Rotary Kiln	4.00	146	526.9
Type IV:Dry Rotary Kiln (SP/NSP)	3.50	141	501.7
Type V:New-type Fluidized Bed Shaft Kiln	2.99	110	473.3
Large Scale Facilities			
Type VI:Wet Rotary Kiln	4.95	146	409.1
Type VII:Dry Rotary Kiln	3.58	139	542.8
Type VIII:Dry Rotary Kiln (SP/NSP)	2.98	134	267.9
Type IX:Dry Rotary Kiln (SP/NSP) BAT	2.41	88	307.8

Table 4 Considered technologies

A.	Material grinding
1.	Ball mill (tube mill)
2.	Vertical roller mill
3.	Vertical roller mill with external material circulation system
4.	Vertical roller mill for blast furnace slag
B	Clinker production
5.	Manual vertical kiln (20~100t-cl/d)
6.	Mechanical vertical kiln (300t-cl/d)
7.	Small-scale wet rotary kiln (1,000t-cl/d)
8.	Large-scale wet rotary kiln (3,000t-cl/d)
9.	Wet rotary kiln with 1 or 2 stage preheaters
10.	Small-scale dry rotary kiln (1,000t-cl/d)
11.	Large-scale dry rotary kiln (3,000t-cl/d)
12.	Dry rotary kiln with 1 or 2 stage preheaters
13.	Dry rotary kiln induced 4 stage SP (suspension preheater)
14.	4 stage SP-type direct precalcination
15.	5 or 6 stage SP (advanced SP with 4 stages)
16.	Low pressure loss SP
17.	Advanced fluidized bed shaft furnace
18.	Utilization of used tires as fuel for calcinations
19.	Utilization of used plastics as fuel for calcinations
20.	Power generation with waste heat from suspension heater exhaust gas
21.	Highly efficient clinker cooler (full airbeam)
22.	New type clinker cooler (CCS)
C.	Finish grinding
23.	Inefficient ball mill (tube mill)
24.	Highly-efficient ball mill (tube mill)
25.	Vertical roller mill
26.	Clinker pre-crusher (roller press)
27.	Clinker pre-grinder
28.	Highly efficient cement separator

(3) Set-up of Vintage Data

○ A model was constructed allowing for selection of technology taking into account the vintage (year of construction) and durable years (40 years in the cement sector) by region.

○ Figure 6 shows consistent energy efficiency by region at 2000 with the vintage set up in the model.

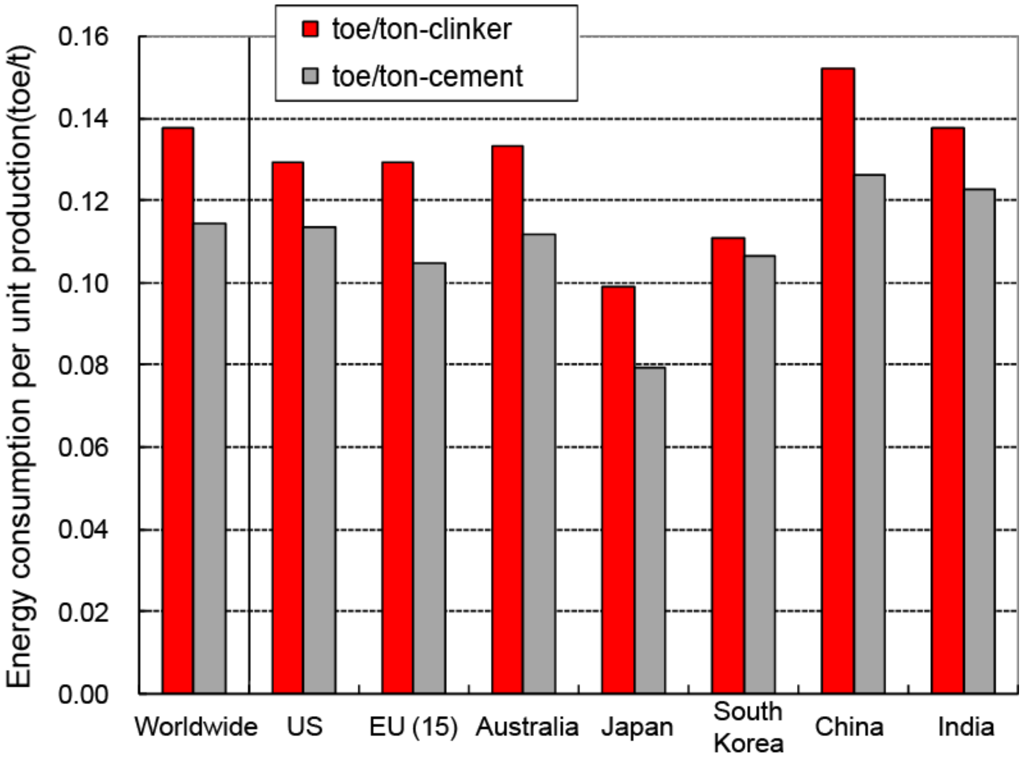

Fig.6 Estimated energy efficiency by region (2000)

Note 1) toe is a ton in terms of oil, 1 toe has an amount of energy equivalent to 1*10^7 kcal and 41.868 GJ. If 1 kg of metallurgical coal contains 6,904 kcal, 1 toe is equivalent to 1.448 t.

Note 2) Electricity is converted to primary energy (1 MWh = 0.086/0.33 toe).

(4) Regional Cement Production Scenario

○ Regional cement production and clinker/cement ratio are assumed as an exogenous scenario (as discussed above). Figure 7 shows cement production for major countries.

○ Cement production scenario is assumed from historical trends based on the assumptions that cement production depends on total GDP in regions and at times where and when per capita GDP is low and that the production depends on population size when per capita GDP increases.

○ The clinker/cement ratio is fixed across the timeframe of analysis.

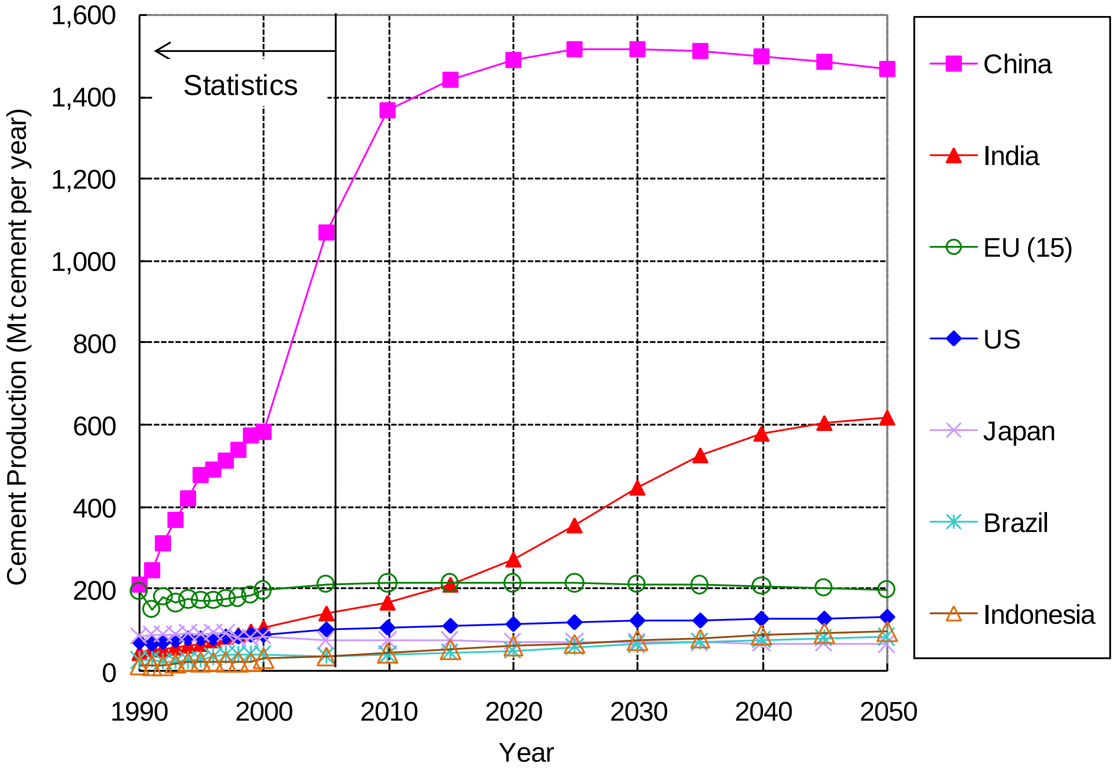

Fig.7 Cement production of major regions (statistics + scenario)

3. Aluminum Sector

(1) Modeling of Aluminum Sector

○ The aluminum sector was modeling focusing on primary aluminum processing. Reference: energy consumption in the aluminum sector consists of 1) fuel required in processes for producing aluminum from bauxite (2005 global average:11.6GJ/t alumina), 2) electricity required when producing primary aluminum by refining aluminum (approximately 15MWh/t primary aluminum), and 3) electricity required when producing aluminum by recycling urban scrap aluminum (approximately 0.45－0.75MWh/t recycled aluminum). The proportion of these energy consumption components is given by 2:25:1 per unit production amount (proportion when electricity taken as primary energy). In other words, 2) "energy consumption for production primary aluminum" accounts for the majority of energy consumption in the aluminum sector.

○ Primary aluminum production is exogenously assumed by region, given the recovered amount of urban aluminum scrap or the traded amount of each type.

○ A model is constructed for technology selection which minimizes costs while satisfying the primary aluminum production scenario.

(2) Assumed technology options

○ Commercially applied technologies for primary aluminum processing are shown below.

□Söderberg:
  1. Horizontal Stud Söderberg
  2. Vertical Stud Söderberg

□Prebake:
  1. Side Work Prebake
  2. Center Work Prebake
  3. Point Feeder Prebake

○ As shown by Figure 8, Type I Söderberg or Type II Prebake can be selected. The capital costs are shown in Table 5.

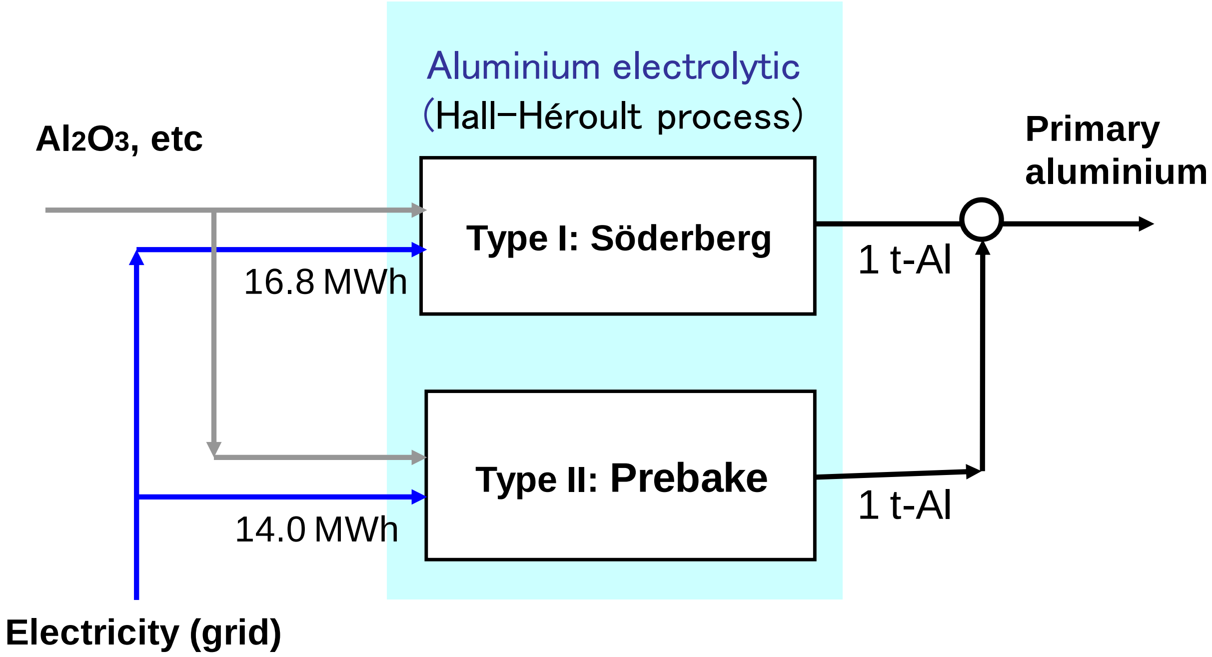

Fig.8 Model of primary aluminum production process

Table 5 Capital costs of each route

	Capital Cost (US$/(t primary aluminum/year))
Type I:Söderberg	1980
Type II:Söderberg	2640

(3) Regional primary aluminum production scenario

○ Figure 9 shows the primary aluminum production scenario by region. The primary aluminum production scenario has been constructed with reference to factors such as the outlook for urban scrap recovery amounts, worldwide demand for aluminum, electricity prices for each region and the outlook going forward for production.

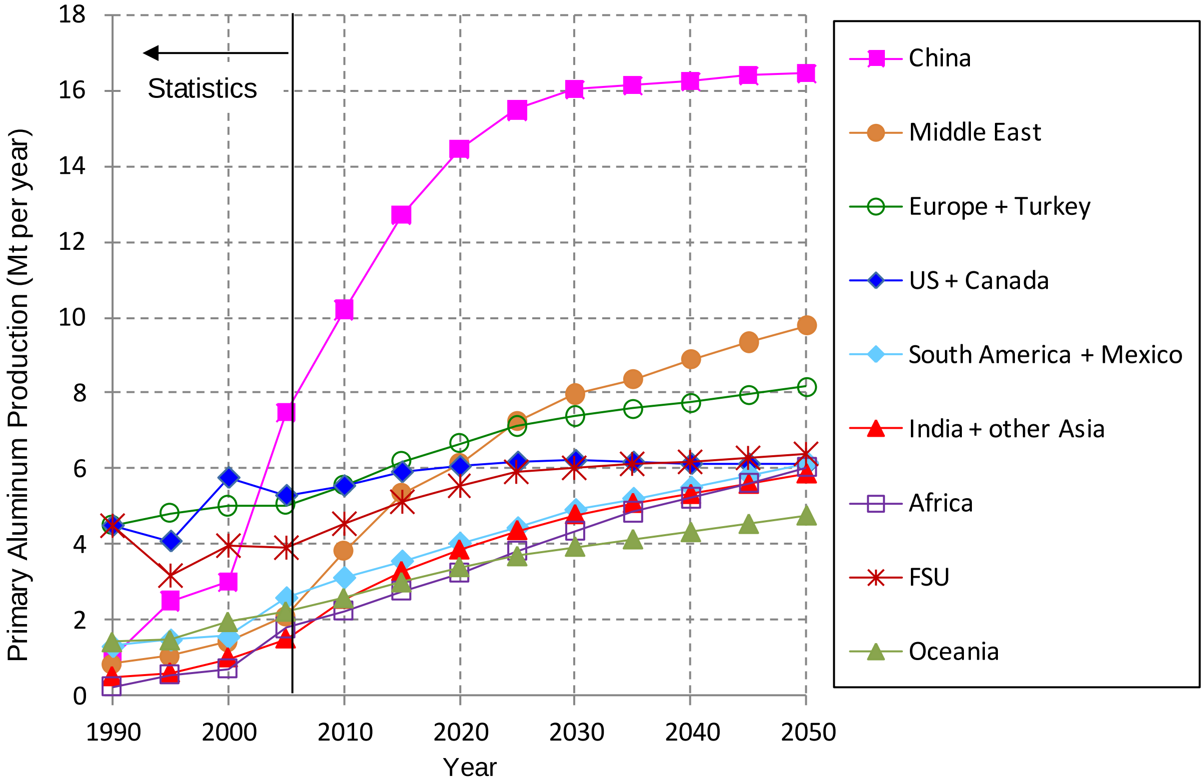

Fig.9 Primary aluminum production amount by region (statistics, scenario)