RITE GHG Mitigation Assessment Model DNE21+

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Systems Analysis Group

Research Institute of Innovative Technology for the Earth (RITE)

1. Model scope and methods DNE21+

1.1. Model concept, solver and details

RITE's integrated assessment framework consists of 3 modules; 1) Key Assessment Model DNE21+ for energy-related CO_2, 2) Non-energy CO_2 emission scenario, which assumes specific non-energy CO_2 emissions separately from mitigation levels of energy-related CO_2 emissions 3) Non-CO_2 GHG Assessment Model, for mitigation of the five non-CO_2 greenhouse gases emissions of the Kyoto Protocol, based on the United States Environmental Protection Agency (US EPA) assessments.

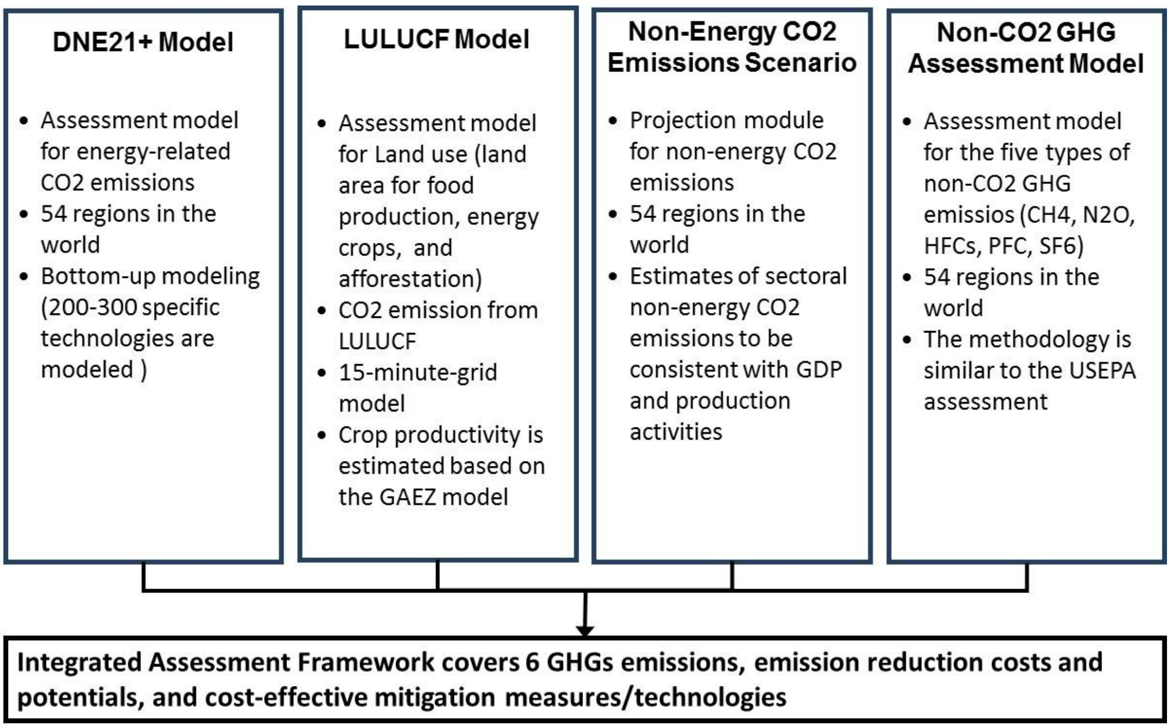

Figure 1 Integrated Assessment Framework

DNE21+ is an intertemporal linear programming model for assessing global energy systems and global warming mitigation options. It represents energy systems (e.g., energy flows, capacities of energy related facilities) consistently in which the sum of the discounted total energy systems costs are minimized. The model represents regional differences and assesses detailed energy-related CO_2 emission reduction technologies up to 2050. The energy supply sectors are hard-linked with energy end-use sectors, including energy exporting/importing; working lifetimes of facilities are taken into account so that assessments maintain complete consistency over energy systems and over time periods.

The base year of the model is 2000, and the GHG emissions are completely consistent with the historical data. The historical data on total GHG emissions for Annex I and non-Annex I parties are based on the GHG inventories of the UNFCCC and IEA statistics respectively. Energy-related CO_2 emissions are based on the IEA statistics for all the countries. Whereas the statistical data for energy-related CO_2 emissions differ between the UNFCCC and IEA in some countries, non-CO_2 GHG emissions for Annex I parties are defined by subtracting the energy-related CO_2 emissions reported by the IEA and the non-energy use CO_2 emissions inventory of the UNFCCC from the total GHG emissions of the UNFCCC, thus, giving priority to the total GHG emission consistency with the UNFCCC inventory.

Technological costs and energy efficiency of technologies (various type of power generation technologies, oil refinery, coal gasification technology, etc.) and carbon dioxide capture, storage and sequestration are explicitly modeled. Energy intensive industries such as steel, cement, paper & pulp, aluminum, some groups of the chemical industry (ethylene, propylene production in the petrochemical industry and ammonia production), transportation (automobiles) and several groups of residential & commercial sector are also explicitly modeled ("Bottom-up approach"). The amounts of activities of these sectors (industry: outputs, automobiles: transportation demands, groups of residential & commercial sector: time periods of equipment utilization) are estimated exogenously and kept fixed in this model regardless of emissions constraints, while technological options are endogenously determined in the model. Other sectors, whose technological characteristics and future evolutions vary widely, are modeled in a top-down fashion.

(Reference)

Akimoto, Keigo, et al. "Comparison of marginal abatement cost curves for 2020 and 2030: longer perspectives for effective global GHG emission reductions." Sustainability

Science 7.2 (2012): 157-168.
Akimoto, Keigo, et al. "Estimates of GHG emission reduction potential by country, sector, and cost." Energy Policy 38.7 (2010): 3384-3393.

1.2. Spatial process

DNE21+ has global coverage and divides the world into 54 regions (America, Canada, Australia, China, India, Russia are divided into further small regions, making a total of 77 regions).

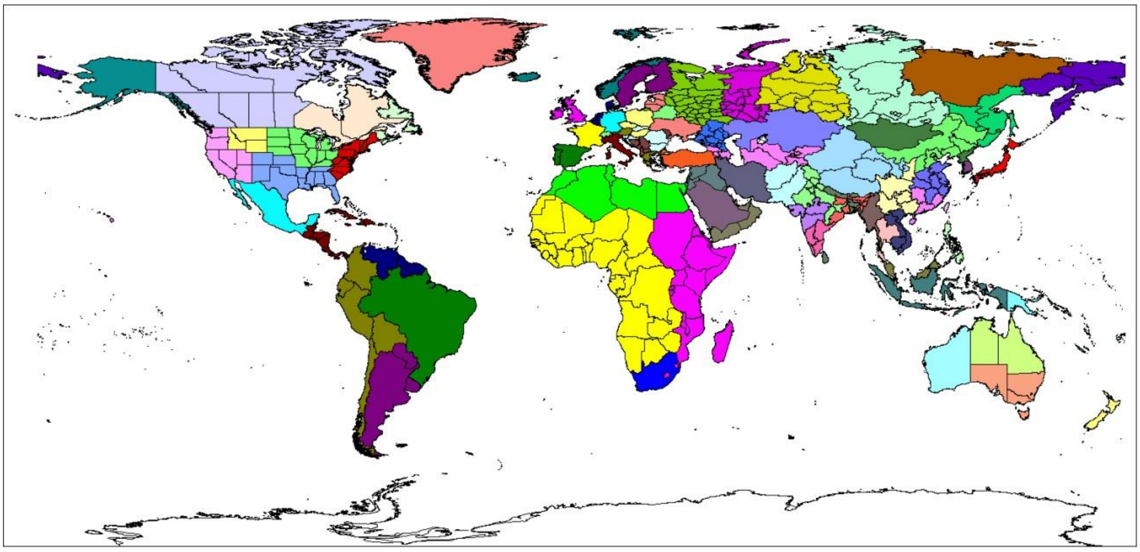

Figure 2 DNE21+ 77 regions

Table 1 List of DNE21+ regions

DNE21+ Region	**Country**
United States	United States, United States Virgin Islands Guam, Puerto Rico
Canada	Canada
United Kingdom	United Kingdom
France	France, Monaco
Germany	Germany
Italy	Italy, San Marino, Vatican City
Spain, Portugal	Spain, Portugal, Azores (Port.)
Belgium, Netherlands, Denmark	Belgium, Netherlands, Denmark
North Europe	Sweden, Finland
Other EU	Austria, Ireland, Greece, Luxembourg

Norway, Iceland	Norway, Iceland
Greenland (Denmark)	Greenland
Other Western Europe	Switzerland, Liechtenstein, Malta, Andorra Faeroe Islands, Gibraltar, Cyprus
Japan	Japan
Australia	Australia
New Zealand	New Zealand
Other Oceania	Papua New Guinea, Fiji, French Polynesia, Kiribati, Nauru, New Caledonia, Solomon Islands, Tonga, American Samoa, Vanuatu
China	China, Hong Kong
North Korea, Mongolia	Democratic People's Republic of Korea, Mongolia
Viet Nam, Cambodia, Laos	Viet Nam, Cambodia, Lao People's Democratic Republic
Korea	Korea
Malaysia, Singapore	Malaysia, Singapore
Indonesia	Indonesia, East Timor
Thailand	Thailand
Philippines	Philippines
Brunei	Brunei Darussalam
Chinese Taipei	Taiwan Province of China
India	India
Pakistan, Afghanistan	Pakistan, Afghanistan
Myanmar	Myanmar
Other Asia	Bangladesh, Nepal, Bhutan, Sri Lanka, Maldives
Iran	Iran
Saudi Arabia	Saudi Arabia
Bahrain, Oman, Qatar, UAE, Yemen	Bahrain, Oman, Qatar, United Arab Emirates Yemen
Other Middle East	Iraq, Kuwait, Jordan, Israel, Lebanon, Syrian Arab Republic
Turky	Turkey

North Africa	Egypt, Libyan Arab Jamahiriya, Tunisia, Algeria, Morocco
South Africa	South Africa
South East Africa	Sudan, Eritrea, Djibouti, Ethiopia, Somalia, Kenya, Uganda, Rwanda, Burundi, United Republic of Tanzania, Malawi, Mozambique, Swaziland, Lesotho, Madagascar, Seychelles Comoros, Mauritius, Reunion
Other S.S.Africa	Angola, Benin, Botswana, Burkina Faso, Cameroon, Cape Verde, Central African Republic, Chad, Congo, Cote d'Ivoire, Democratic Republic of the Congo, Equatorial Guinea, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Liberia, Mali, Mauritania, Namibia, Niger, Nigeria, Sao Tome and Principe, Senegal, Sierra Leone, Togo, Zaire, Zambia, Zimbabwe, Western Sahara
Mexico	Mexico
Other Central America	Bahamas, Bermuda, Cuba, Jamaica, Haiti, El Salvador, Guadeloupe, Saint Vincent and the Grenadines, Grenada, Dominica, Dominican Republic, Saint Lucia, Saint Kitts and Nevis, Barbados, Antigua & Barbuda, Netherlands Antilles, Trinidad and Tobago, Guatemala, Belize, Honduras, Nicaragua, Costa Rica, Panama
Brazil	Brazil
Venezuela, Guyana, Suriname	Venezuela, Guyana, Suriname, French Guiana
Paraguay, Uruguay, Argentina	Paraguay, Uruguay, Argentina
Other South America	Colombia, Ecuador, Peru, Bolivia, Chile
Russia	Russian Federation
Other Annex I of FUSSR	Ukraine, Estonia, Latvia, Lithuania
Belarus	Belarus
Kazakhstan	Kazakhstan

Other FUSSR	Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan, Armenia, Azerbaijan, Georgia
OECD E.Europe	Hungary, Poland, Czech Republic
Other Annex I of East Europe	Bulgaria, Romania, Slovakia, Croatia, Slovenia
Other E.Europe	Yugoslavia, Albania, Bosnia And Herzegovina Republic Of Moldova, The former Yugoslav Republic of Macedonia

1.3. Temporal process

DNE21+ is an inter-temporal optimization perfect foresight model with the time horizon 2005 to 2050 in 5- and 10 year time steps where the first 6 periods (2005, 2010, 2015, 2020, 2025 and 2030) are 5-year periods and the remaining 2 periods are 10-year periods(2040 and 2050). 2005 represents the period from 2003 to 2007, 2010 represents the period from 2008 to 2012, 2015 represents the period from 2013 to 2017 and so on.

1.4. Policy

Based on the scenario setup, energy- and climate-related policies are explicitly represented in DNE21+. This includes carbon pricing, emission cap and trade system, carbon tax, preferred tax on specific energy sources, fuel subsidies, fuel standards and energy standards. In general, these policies are implemented via constraints or a price mark-up on energy sources.

When any emission restrictions (e.g., upper limit of emissions, emissions reduction targets, specific unit improvement goals, carbon taxes) are applied, the model finds out the energy systems whose costs are minimized, meeting all the assumed requirements, given the sectoral amounts of production activities (e.g., crude steel and cement), the amount of service activities (e.g., the traffic amount in the transportation sector), the final energy demand in other sectors and the performances and the facility costs of various technologies.

2. Economy and demand drivers

2.1. Population and GDP

The primary drivers of future energy demand in DNE21+ are projections of population and GDP at market exchange rate (MER). We developed two different prospects as they may more or less likely take place in the future as macroeconomic trends, considering from the past statistics. In Scenario A, slow economic growth slows down after the miraculous past growth mainly in developed countries In Scenario B, technological advances keep ongoing as in the past and per capita GDP continues to grow quite rapidly. As a reference case, we usually refer to Scenario A, but it depends on scope and purpose of analysis.

The world population scenarios were developed with reference to The UN Population Division; World Population Prospects (The 2008 Revision) which have been used worldwide. UN scenarios of the world population are developed every two years and have been revised downward for every update. Therefore, in this scenario, even after taking account of the future population increase in developing countries such as in Asia or Africa, we assume it very unlikely that the future world population will be substantially over 10 billion. Historical statistics explicitly show the trends that the fertility and population growth rates become lower with growing GDP per capita. Our population scenario is developed, assuming this trend to keep in the future, by replacing the relationship between fertility and per capita GDP by the relationship between annual change rate of population and per capita GDP. The population growth in Scenario B is assumed to be smaller than that in Scenario A, as per capita GDP is larger in Scenario B.

Figure 3 shows the world population scenarios. In Scenario A, the world population is assumed to have a medium growth rate and the UN medium variant scenario of the world population, the 2008 Revision is adopted. After growing to 9.1 billion in 2050, the world population grows steadily to 9.3 billion by the year 2100. In Scenario B, the world population is assumed to have a low growth rate. This scenario is roughly equivalent to the average of UN medium variant and low variant scenarios of the world population, the 2008 Revision. The world population grows slowly from 6.1 billion in 2000. After peaking at 8.6 billion around 2050, it declines to 7.4 billion by the year 2100.

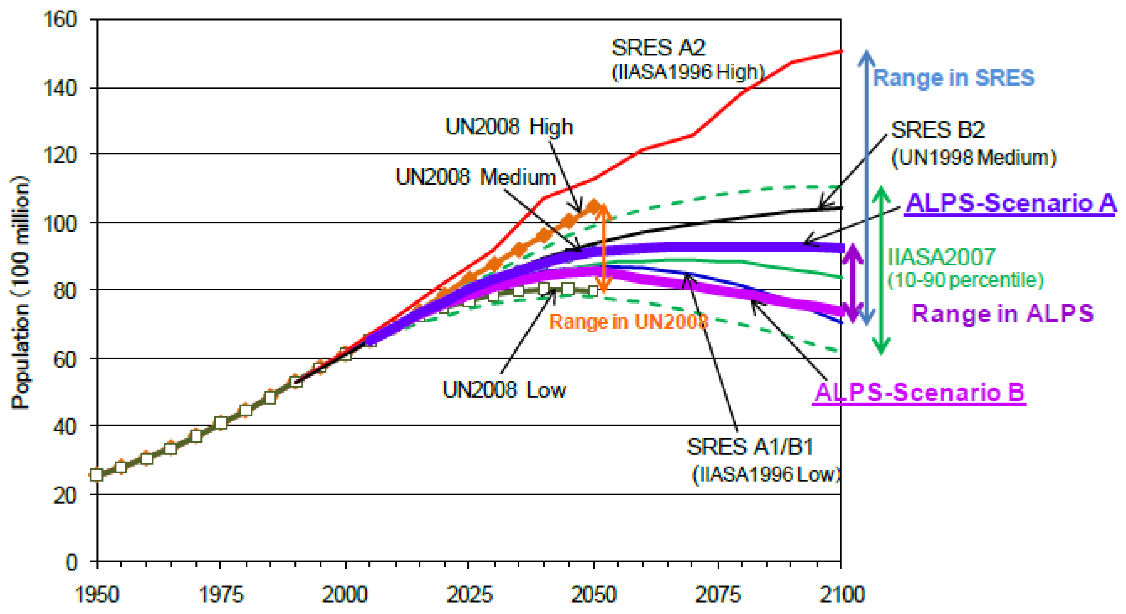

Figure 3 Population Scenario

In terms of GDP per capita, the following distinct trends are observed historically.

- The growth rate of GDP per capita is low in the least developed countries (LDCs).
- When GDP per capita is between a few hundred dollars and a thousand dollars, the growth rate of GDP per capita tends to become high.
- For the higher GDP per capita, the growth rate tends to decrease gradually, shifting toward moderate economic growth.
- The industrial structure has three big trends; in the first period the structure centers in primary industry, in high economic growth period heavy industry develops starting from light industry, and in gradual growth period the tertiary industry starts to grow such as service and information industries.

Based on these observations, GDP (MER) per capita scenarios are developed as shown Figure 4. In Scenario A, the current developed countries slow down the GDP per capita growth until 2100 and the growth rate converges to 0.5% per year in 2100. Developing countries continue to grow steadily. The current emerging economies and least developed countries have the per capita GDP growth rates of around 1%/year and around 2%/year in 2100, respectively. The global average growth rate from 2000 to 2100 is 1.5% per year.

In Scenario B, the current developed countries continue to increase GDP per capita by 1.0%/year in 2100. Developing countries continue to grow rapidly. The current emerging economies and least developed countries grow at the rate of around 2%/year and around 3%/year even in 2100, respectively. The global average growth rate from 2000 to 2100 is 2.1% per year.

Both in Scenario A and B, economic gaps between developed and developing countries narrow steadily until 2100. Yet, the gaps in Scenario B are still bigger than in Scenario A. The GDP per capita ratio of OECD90 to Africa is 38.5 in 2000, and in 2100 6.4 in Scenario A and 6.7 in Scenario B.

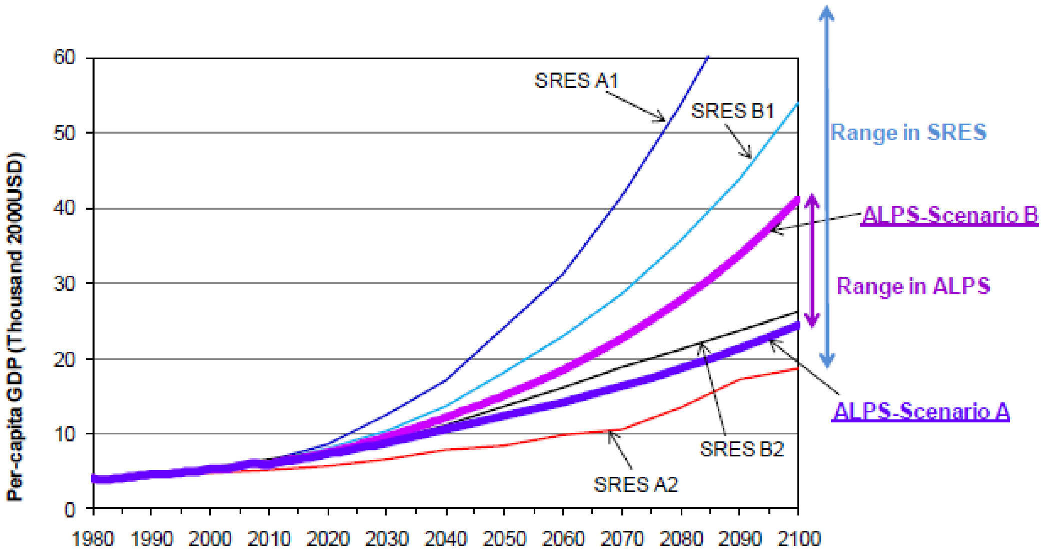

Figure 4 per capita GDP Scenario

GDP scenarios are formulated by combination population scenario and per capita GDP scenario. Figure 8 shows the world GDP scenarios. The potential world GDP grows at a higher rate in Scenario B than in Scenario A. As mentioned above, GDP per capita growth at a higher rate in Scenario B makes the population smaller than the population in Scenario A, so that GDP difference between the two scenarios shrinks. The world average of GDP annual growth is assumed to be 2.0% per year in Scenario A and 2.3% per year in Scenario B from 2000 to 2100.

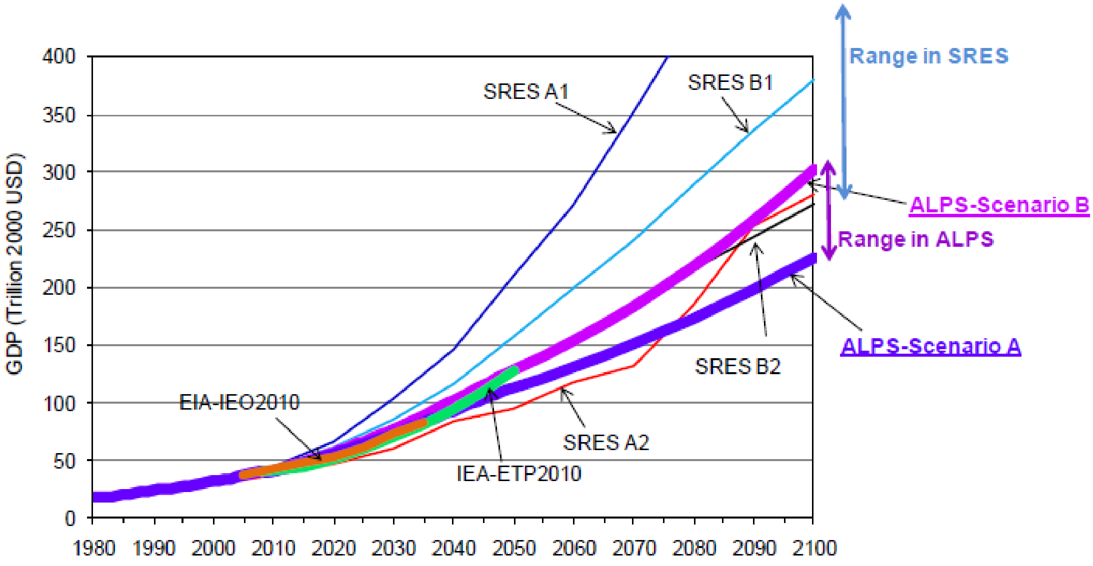

Figure 5 GDP (MER) Scenarios

(Reference) Systems Analysis Group, RITE, Development of Long-term Socioeconomic Scenarios -Population, GDP-, August 15, 2011
http://www.rite.or.jp/English/lab/syslab/research/alps/baselinescenario/E-ScenarioOutline_POPGDP_20110815.pdf

2.2. Demand

Population and GDP are not directly utilized to project future energy system, rather to assume the level of production or extent of service activity for individual sectors. The projected level of production or service activity is consistently satisfied by the optimal combination of various bottom-up technologies for the sectors that are explicitly modeled. For the other sectors, baseline amounts of final energy demands are assumed together with their long-term price elasticity using top-down modeling without explicitly describing bottom-up technologies.

The rest of final energy demands are estimated in a top-down manner, represented by four type of energy careers, which include solid energy, liquid energy (gasoline, light oil, and heavy oil), gaseous fuel and electrical energy, are assumed for aggregated three sectors: industry, transportation and residential and commercial.

2.3. Macro-economy

(see Population and GDP)

2.4. Technological change

Technological change is generally treated exogenously.

2.5. Behavioural change

DNE21+ is a least-cost optimization model that provides a detailed representation of energy supply and energy technology, modeling technology choice behavior of investors or consumers in a bottom up manner. Payback period, operation and maintenance cost, energy prices, technology costs and performance parameters determine the least-cost energy-equipment combination that meets a specific energy need in the model.

The payback period is a key parameter in determining their behavior, affected by numerous kinds of factors observed in the society such as interest rate, the depreciation rate, the price change rate of capital goods, income, subjective preference for risk and prospective profit rate of stockholders. A number of study reveals that payback period varies widely among technologies, countries, and sectors.

In business behavior, the return on investment (ROI) is generally 10–20%, and this means that payback period has to be 5–10 years. Most of large Japanese companies in industrial and commercial sectors make investment decisions in energy-saving technologies with 3–5 years payback periods (Energy Conservation Center, Japan [ECCJ] 2004). The payback period for the purchase of light-duty vehicles is 1.8–5 years (US EPA 2005). The payback period of consumer durable goods, such as space-heating systems, air conditioning, and refrigerators is generally 1-3 years or shorter (Wada et al. 2012; Train 1985; Dubin 1992).

Furthermore, the payback periods in developing countries are shorter than those in developed countries, and those in the residential and commercial sectors are shorter than those in industrial sectors.

Table 2 shows the payback periods of DNE21+, which come close to matching the observed payback periods in the real world, although the observed payback periods in different countries, sectors, and technologies are limited and uncertain. The model assumes different payback periods based on economic stages across countries. The periods become longer in accordance with the growth of economic level.

The selections of energy technologies and CO_2 emissions for 2005 determined within the model are roughly calibrated with the historical data by adjusting the assumptions of payback periods.

Table 2 Payback period and implicit discount rate

	Payback period (Implicit discount rate)	
	Upper limit	Lower limit
Electricity generation sector	11.9 (8%)	5 (20%)
Other energy conversion sector	6.6 (15%)	4 (25%)
Industrial sector (energy-intensive industry)	6.6 (15%)	4 (25%)
Transportation sector	3.3 (30%)	2.2 (45%)
(Purchase of environment-conscious products)	10 (10%)	
Residential & commercial	3.3 (30%)	1.8 (55%)

3. Energy

DNE21+ includes a detailed description of energy carriers and conversion technologies. It includes eight types of primary energy sources; coal, oil (conventional and unconventional), natural gas (conventional and unconventional), hydro power and geothermal, nuclear, wind power, photovoltaics and biomass). Interregional transportation of energy (coal, oil natural gas, synthetic oil, ethanol, electrical power and hydrogen) and CO_2 are incorporated in the model. As technological options, various types of energy-conversion technologies are explicitly modeled, such as electricity generation, oil refinery, natural gas liquefaction, coal gasification, and water electrolysis, methanol synthesis. The end-use sector are disaggregated into four types of secondary energy carriers: 1) solid fuel, 2) liquid fuel, 3) gaseous fuel, and 4) electricity. The demands for these energy carriers are endogenously calculated in a top-down fashion using long-term price elasticity in other cases than the reference case.

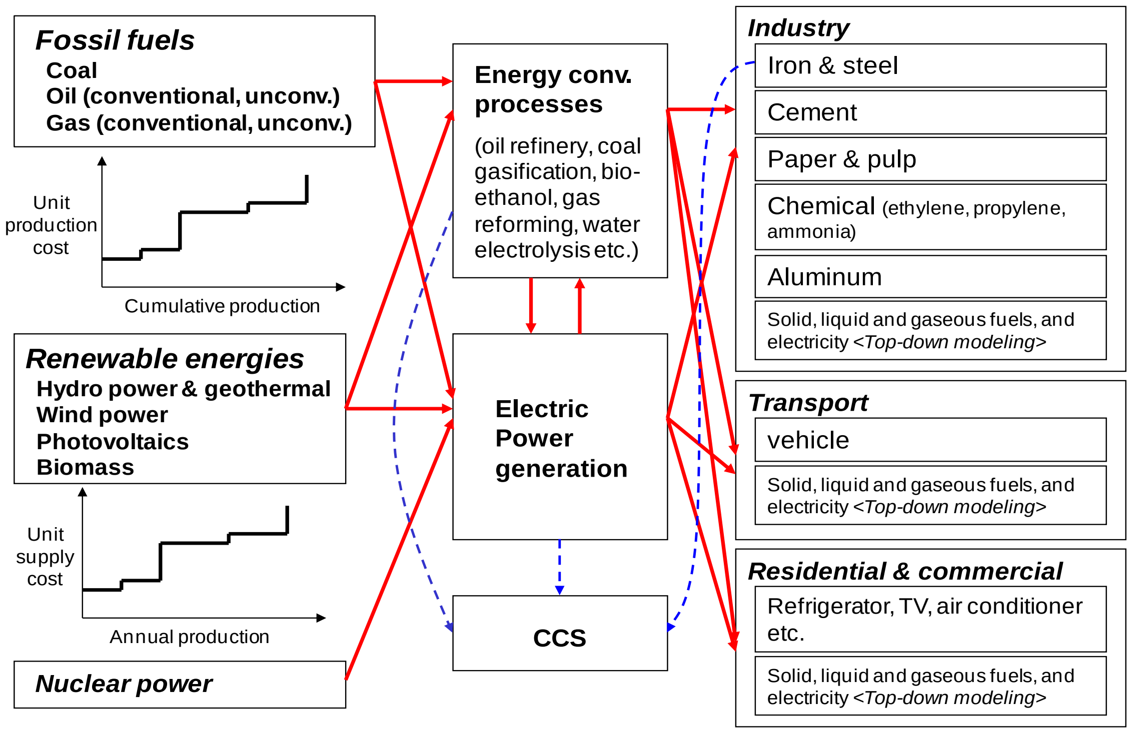

Figure 6 Outline of energy flows in DNE21+

3.1. Energy resource endowments

3.1.1. Fossil Reserves and Resources

Estimation of fossil fuel reserves refers to a number of studies, and supply cost curves for each resources are made based on economic and technological assumptions. For coal resource assessment "Survey of Energy Resources" by the World Energy Council (WEC) is mainly referred to. The USGS 1995 National Assessment of United States Oil and Gas Resources, the USGS Survey world petroleum assessment 2000: Description and results, and Rogner (1997) were used for conventional/non-conventional coal and gas reserve estimation.

The resource potentials are modeled using region-specific potentials, and they are classified into different grades. With IEA World Energy Outlook and Rogner (1997), fossil fuel supply curves are created as shown below. This grade structure with royalty and transportation costs allows to calculate supply chain optimization of global energy systems.

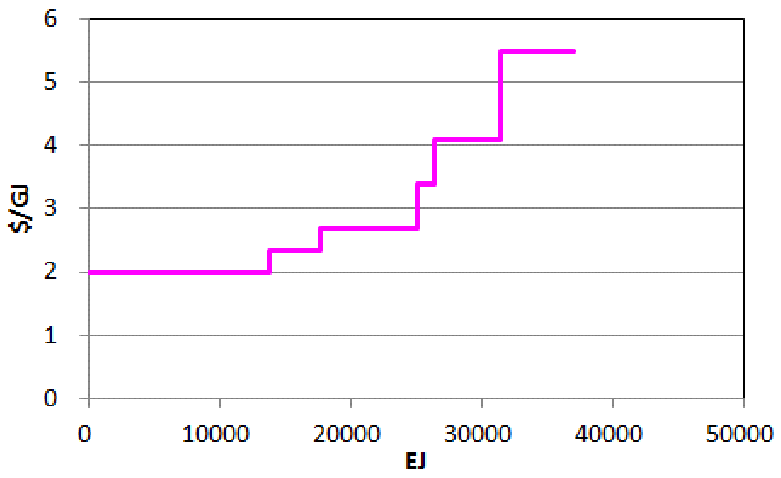

Figure 7 Cumulative Global Coal Supply Curve

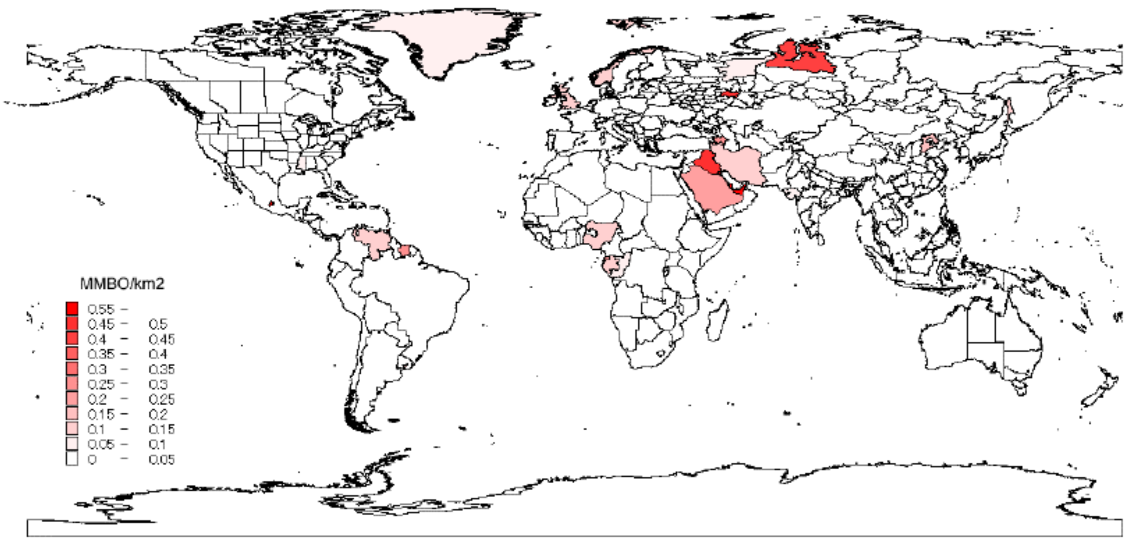

Figure 8 Distribution of Conventional Oil Resources (Source) USGS

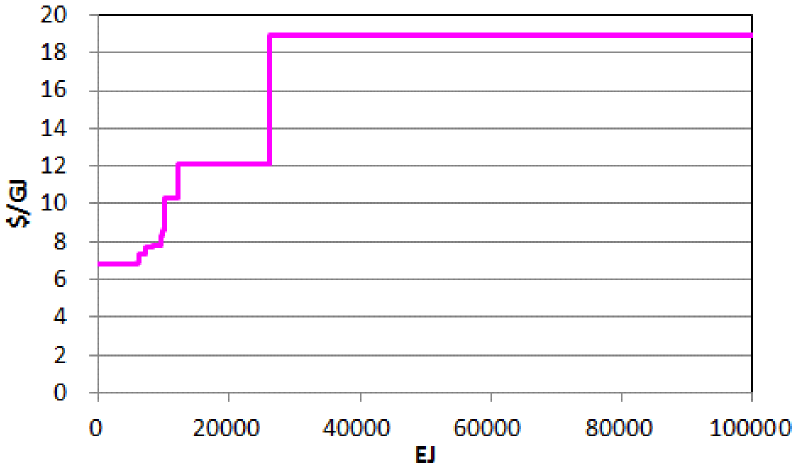

Figure 9 Cumulative Global Oil Supply Curve (incl. Non-conventional)

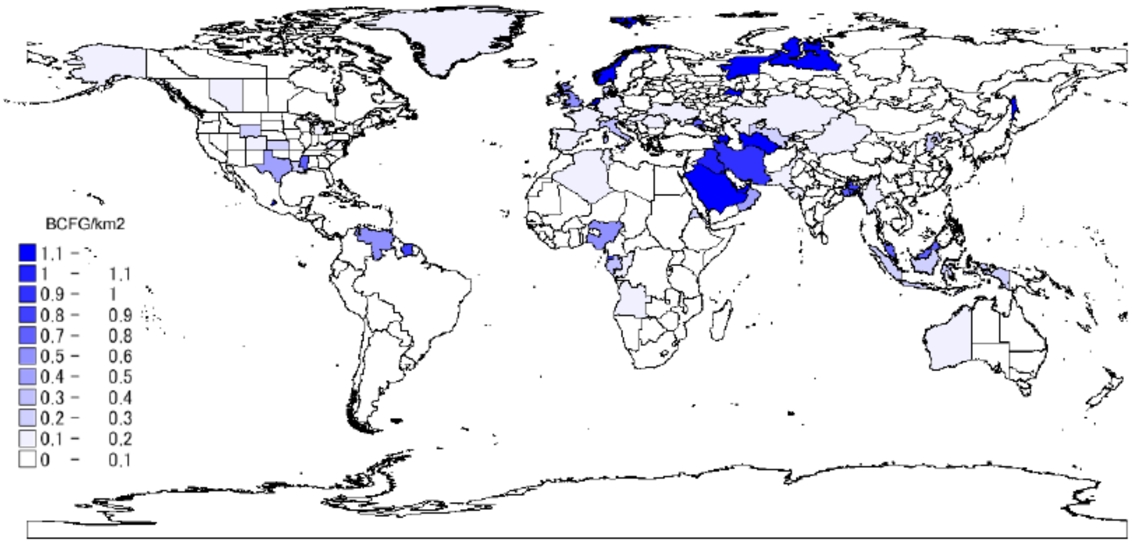

Figure 10 Distribution of Conventional Natural Gas Resources (Source) USGS

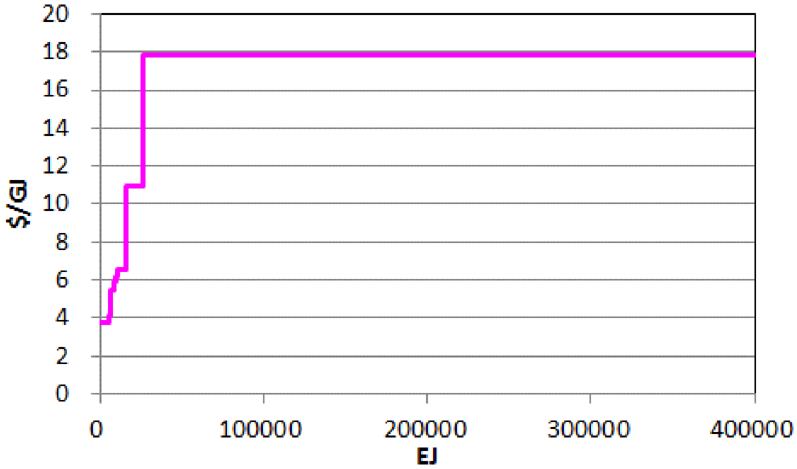

Figure 11 Cumulative Global Gas Supply Curve (incl. Non-conventional)

In DNE21+, emissions from fossil fuel combustion can be curbed by deploying carbon capture and storage (CCS). Storage potential was estimated based on a sedimentary basin map of USGS. The "ideal" potential of aquifer sequestration is shown in Figure 12.

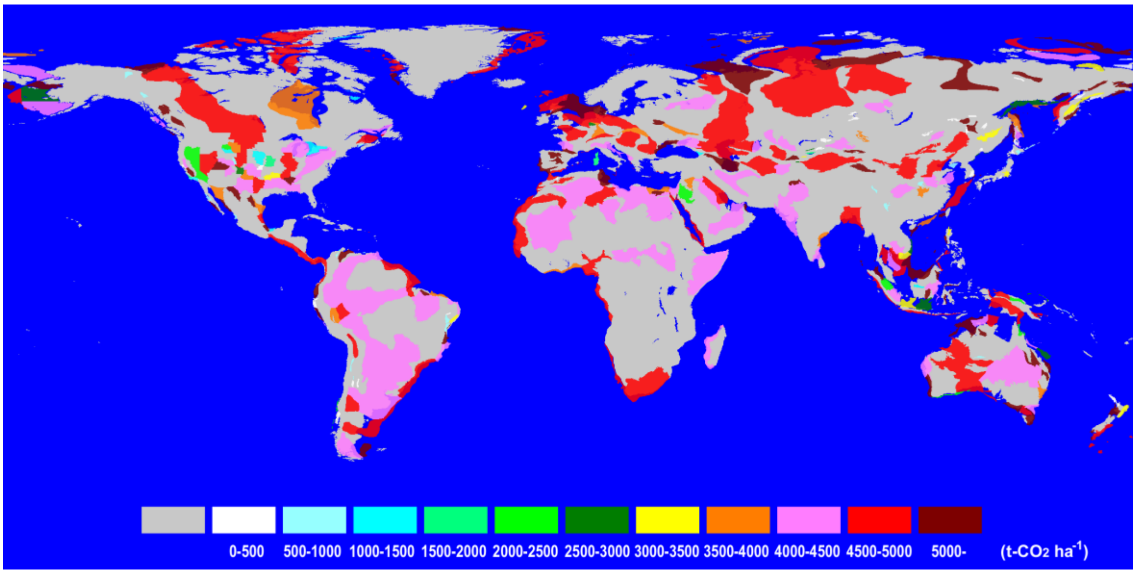

Figure 12 CO_2 Sequestration Potential into Aquifer

3.1.2. Renewable Resources

The resource potentials for solar and wind are estimated by using physical data combined with global land cover data developed by Chiba University. With globally gridded wind speed data provided by the National Oceanic and Atmospheric

Administration (NOAA) National Climatic Data Center (NCDC) and land use/cover GIS data, wind potentials are estimated as shown in Figure 13. The region-specific potentials are classified into five grades, and the technical potentials for wind power amount to 13,750 TWh/yr. Potentials of photovoltaics are estimated by solar radiation data offered by the National Aeronautics and Space Administration, Sea-viewing Wide Field-of-view Sensor (SeaWiFS) Project, and land-use data. Figure 15 overlays solar radiation intensity on a global map. In total, the solar potentials amount to 1,270,000 TWh/yr.

Wind power and photovoltaics is assumed to have an annual costs decrease rate of 1.0% and 3.4%, respectively. In 2000, the unit costs of wind power is 56– 118$/MWh and photovoltaics 209–720$/MWh, depending on wind velocity and solar radiation etc. In 2050, the unit costs of wind power and photovoltaics are assumed to become 34–71$/MWh and 37–128$/MWh, respectively.

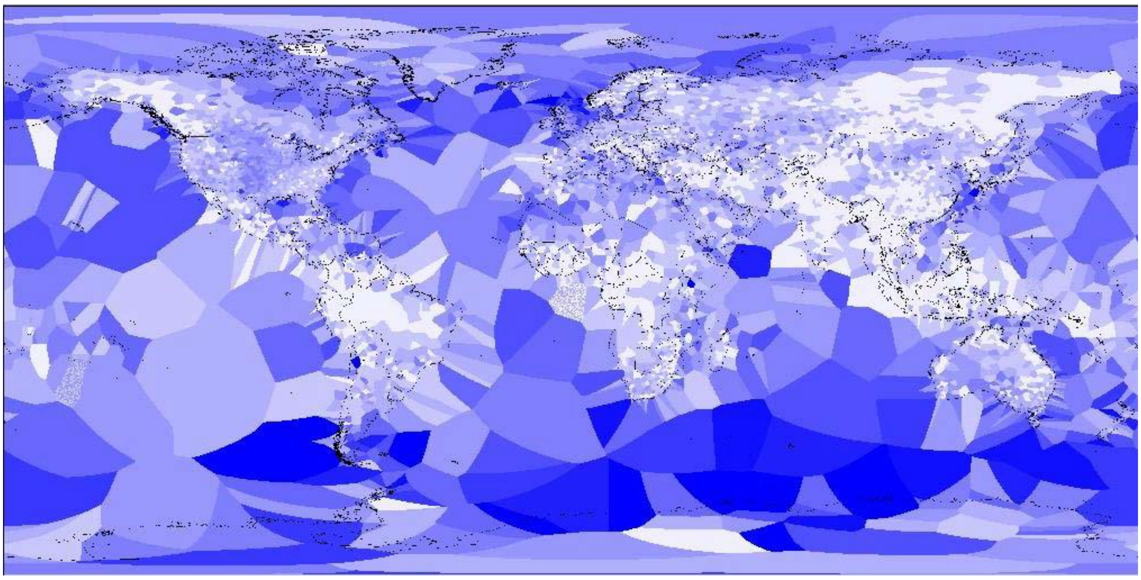

Figure 13 Resources of wind power

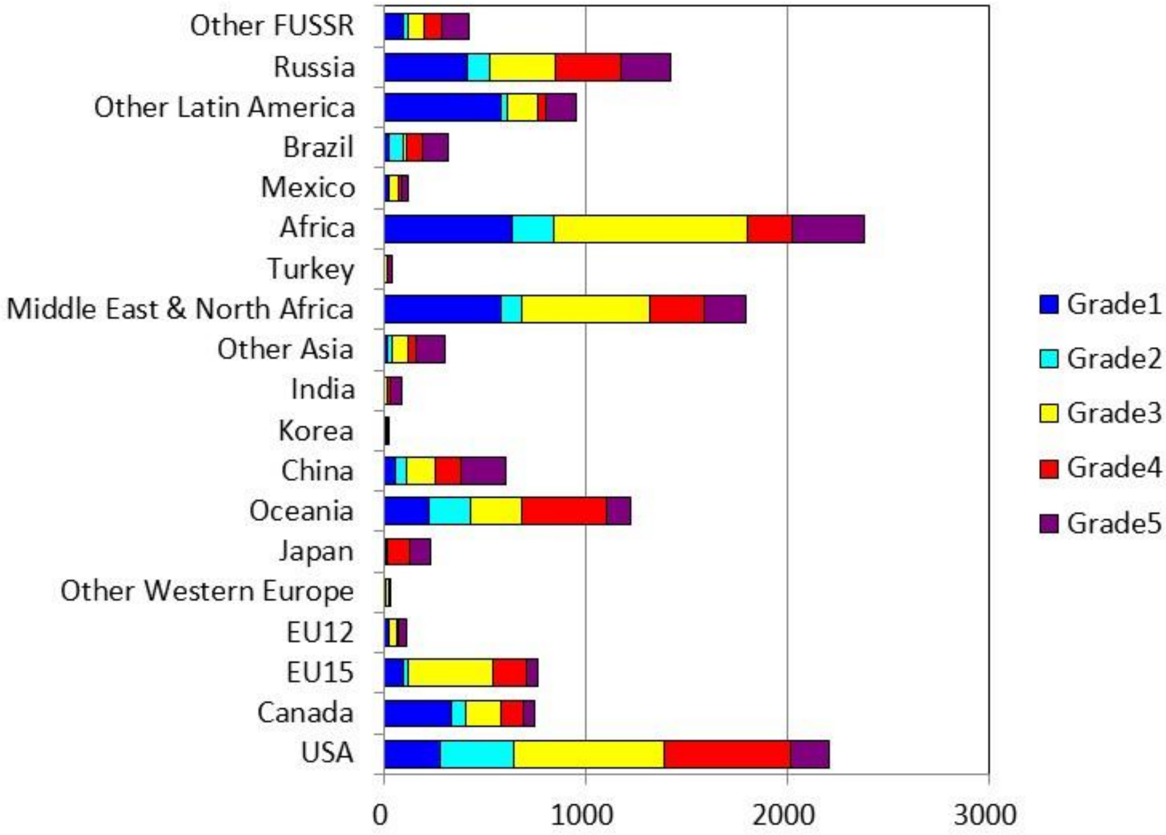

Figure 14 Regional supply potential for wind power (TWh/yr)

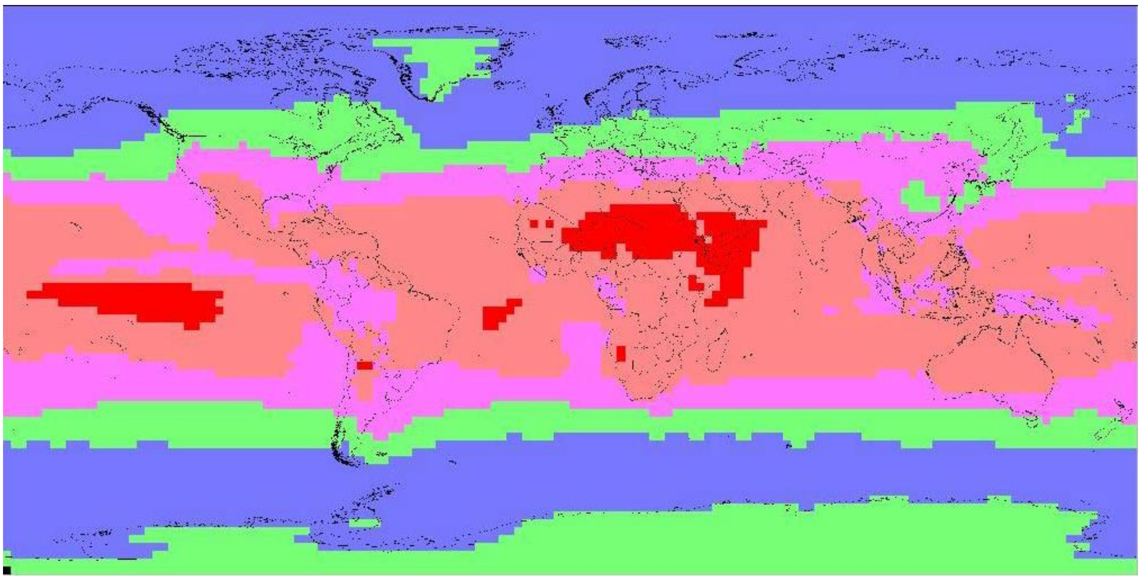

Figure 15 Solar radiation intensity (Annual Average)

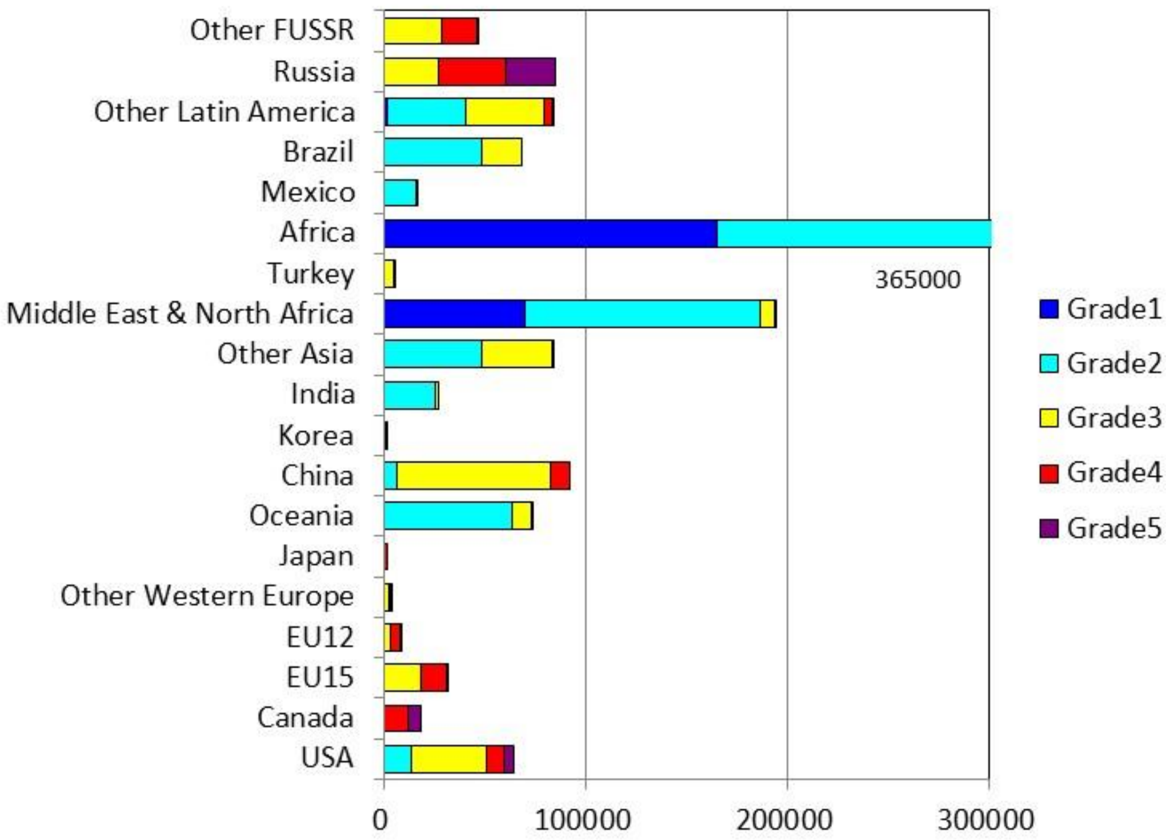

Figure 16 Regional supply potential for solar power (PV) (TWh/yr)

Currently hydropower plays an important part in global power generation and is the most common form of renewable energy. The overall technical potential for hydropower is estimated to 25,000 TWh/yr, using the WEC's "Survey of Energy Resources" as a reference.

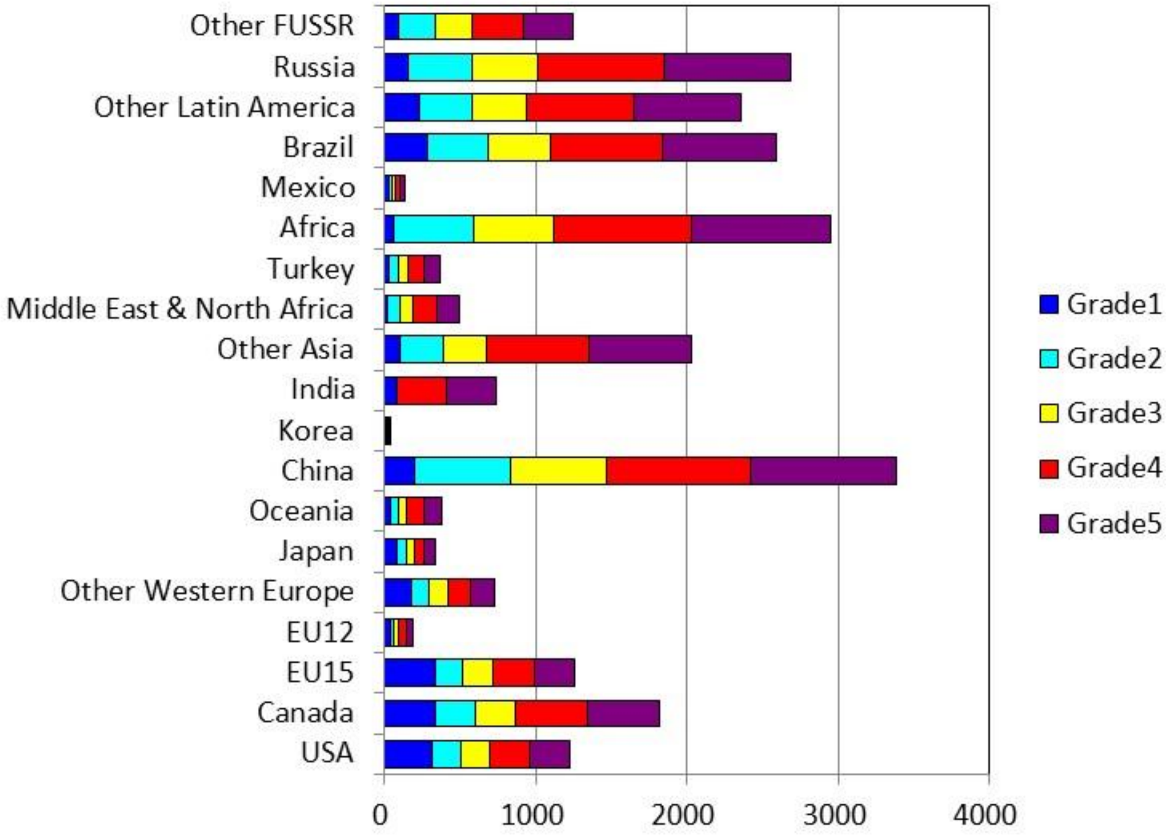

Figure 17 Regional supply potential of Hydro and Geothermal (TWh/yr)

For biomass resource assessment, DNE21+ employs the LULUCF model results on available land area for biomass production and afforestation, and land are productivity. Waste-based biomass potentials are also taken into calculation as a constraint of the DNE21+ model. Exogenous scenario is given for the future traditional biomass.

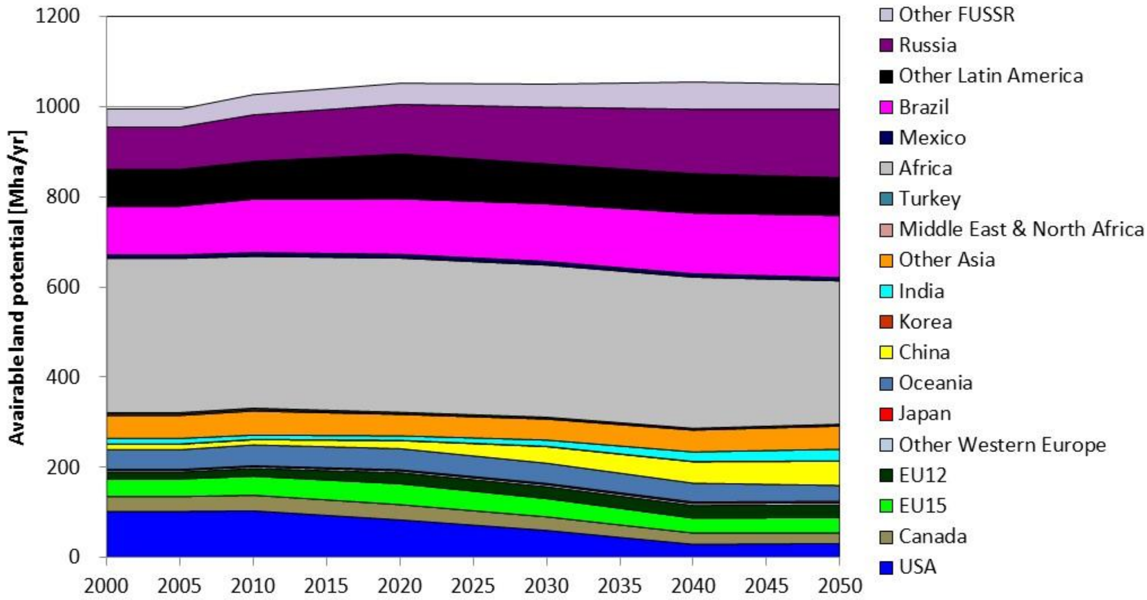

Figure 18 Available land potential for cellulosic biomass or afforestation

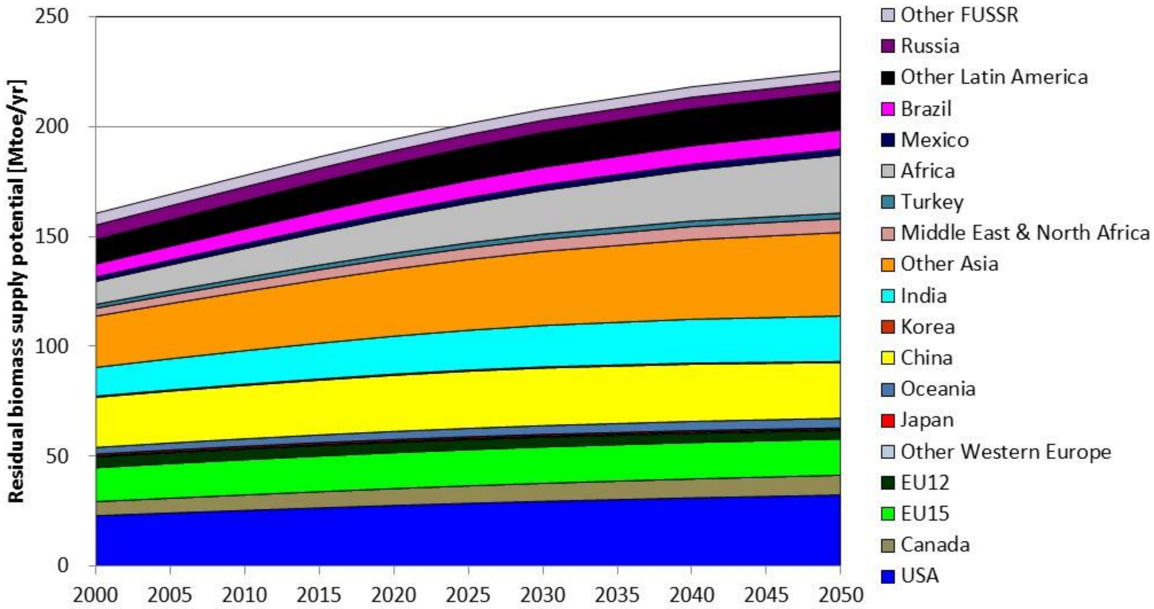

Figure 19 Available land potential for Biomass Residues

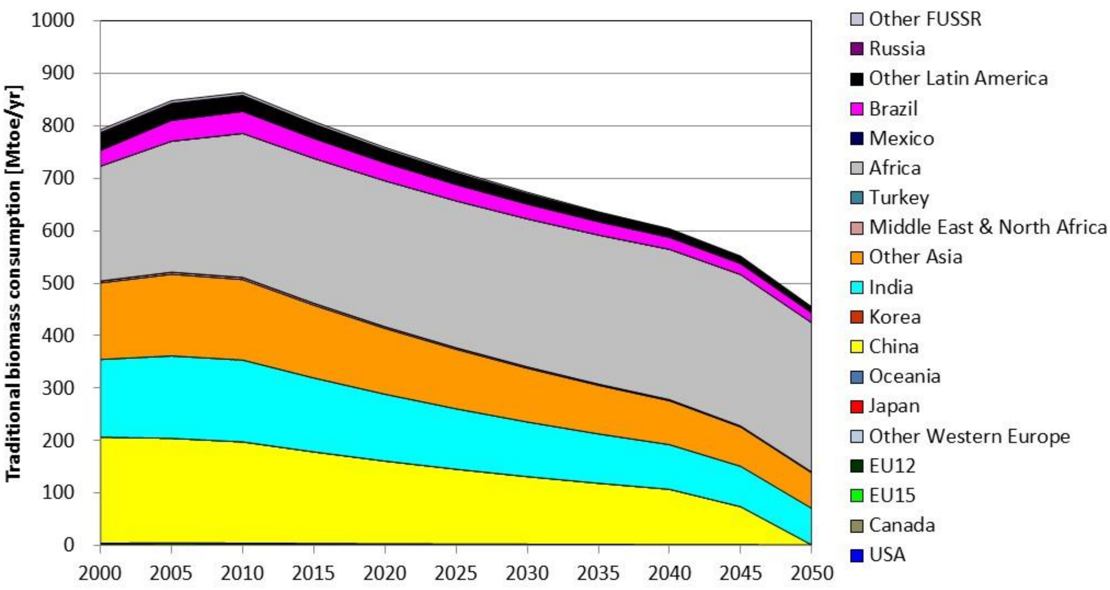

Figure 20 Available land potential for Traditional Biomass

3.2. Energy conversion

DNE21+ model covers various type of energy conversion technologies, including electricity generation, coal gasification and liquefaction, natural gas reforming, and carbon dioxide capture, storage and sequestration (CCS) for energy conversion process.

3.2.1. Electricity

The modeled electricity generation options include: Coal power {low efficiency (subcriticality), mid-efficiency (supercriticality), high efficiency (extra supercriticality–IGCC/IGFC), and IGCC with pre-combustion CO_2 capture}, Oil power {low efficiency (diesel generator, etc.), mid-efficiency (subcriticality), high efficiency (supercriticality), and CHP}, Synthetic oil power {mid efficiency, and high efficiency}, Natural gas power {low efficiency (steam turbine), mid-efficiency (conventional NGCC), high efficiency (high temperature NGCC), CHP, and oxy-fuel combustion}, Biomass power {low efficiency, and high efficiency}, Nuclear power {conventional, and next-generation (Generation IV, etc.)}, Hydro/geothermal power, Wind power, and Photovoltaics. In association with generation technologies, Power storage system for wind/PV, Hydrogen power, Electrical cable {conventional, superconducting high efficiency}, and CCS {post-combustion capture; applicable for coal, oil, synthetic oil, natural gas, biomass power} are also represented in DNE21+.

As shown above, each type of power generation technology has is classified according to level of energy efficiencies and facilities costs are differentiated corresponding to the level of efficiency. The different levels of generation efficiencies are assumed in order to represent the broader ranges in current generation efficiency levels in different countries (see Oda et al. 2012). Their technological progresses are assumed exogenously. Table 3 shows the assumptions on capital costs and the efficiency of electricity generation. Fossil fuel prices are endogenously determined within the model by using the relationship between the cumulative production of fossil fuels and production costs. However, the fossil fuel prices will be dominated not only by production prices, but also by speculation, etc. Therefore, the baseline fossil fuel prices are calibrated to meet the prices of the reference scenarios of the IEA WEO 2010 (IEA 2010b) over the assessment time periods, while the prices in the mitigation scenarios are endogenously determined by the cumulative amounts of production induced by levels of emission reductions or the MAC. DNE21+ also tracks investments by vintage capital stock.

Table 3 Capital costs and generation efficiency

	Capital cost ($/kW in 2007 price)	Generation efficiency (LHV %)
Coal power		
Low efficiency (e.g., sub-critical)	1,250	22.0–27.0
Middle efficiency (e.g., critical in the present; super-critical (SC) in the future)	1,875	36.0–45.0
High efficiency (e.g., SC, ultra SC in the present; IGCC and IGFC are included in the future)	2,125	42.0–55.0
IGCC/IGFC with CO_2 capture	3,500–2,625	33.0–51.0
Oil power		
Low efficiency (e.g., diesel)	313	22.0–27.0
Middle efficiency (sub-critical)	813	37.0–45.0
High efficiency (critical)	1,375	50.0–60.0
Combined heat and power (CHP)	875	37.0–47.0[a]
Gas power		
Low efficiency (steam turbine)	375	26.0–32.0
Middle efficiency (combined cycle)	813	38.0–47.0
High efficiency (combined cycle with high temperature)	1,375	52.0–62.0
Combined heat and power (CHP)	875	38.0–48.0[a]
Oxy-blown combined cycle with CO_2 capture	2,375–1,750	40.7–50.7
Biomass power		
Low efficiency (steam turbine)	1,500–1,125	18.0–28.0
High efficiency (combined cycle)	2,750–2,000	36.0–46.0
Nuclear power		
Conventional	3,000	–
Advanced	2,625	–
Hydrogen power (FC/GT)	1,375	52.0–64.5
Electricity storage		
Pumping-up	1,250	70.0–75.0
Battery for PV and wind power	1,612– 42 ($/kWh)	100.0
	Generation cost (cent/kWh in 2007 price)	
Hydro and geothermal power	3–23	
	Year 2005	Cost reduction (% p.a.)
Wind power	7–14	1.0
Photovoltaics	22–76	3.4

*Some of capital costs and efficiency are shown in a range because they change over time.

Electricity demand is modeled in a way that demand-supply is balanced. The demand is expressed by the load duration curves, representing four time periods, instantaneous peak, peak, intermediate, and off peak time periods, in accordance with the level of electricity demand. This enables appropriate evaluation of electricity system corresponding to the characteristics of individual power generation technologies such as the base power load power plants and the peak load power plants.

For nuclear power generation, exogenous scenarios are assumed for nuclear power generation up to 2030. Some constraints are assumed that the power generation of nuclear would be capped at 50% of the total power generation amount and that an annual expansion of conventional nuclear power generation would be 0.33%, and the expansion rate of advanced nuclear power generation would be 1%. As long as the constraints are obeyed, costs-efficient options are selected by the model.

(Source) Akimoto, Keigo, et al. "Comparison of marginal abatement cost curves for 2020 and 2030: longer perspectives for effective global GHG emission reductions." Sustainability Science 7.2 (2012): 157-168.

3.2.2. Other conversion processes

Besides electricity and heat generation there are three further subsectors of the conversion sector represented in DNE21+, such as oil refinery, natural gas liquefaction, coal gasification, and water electrolysis, methanol synthesis.

3.2.3. Grid and infrastructure

Inter-regional energy transmission infrastructure, such as pipelines for liquid and gas, such as oil, natural gas, synthetic oil, ethanol, hydrogen and CO_2, and power grids, are represented in the DNE21+ model.

In terms of systems integration, wind power and solar PV are represented in the DNE21+ model as follows:

(1) Capacity credit:

There are some literatures that evaluate capacity credits of wind power in the United States and Europe (e.g., Milligan and Poter 2008, Holttinen et al. 2009). The estimated capacity credits of wind power vary widely from approximately a few percent to 40% by region. It is also observed that there is a correlation between the capacity credit and the level of technology penetration: the capacity credit becomes lower in higher wind power penetration. When the share of wind power capacity in peak load is 30%, the capacity credits of wind power range from 5% to 25% (Holttinen et al. 2009). In addition, the methods used for the evaluation of the capacity credit exist widely by region, such as capacity factor in peak period and equivalent load carrying capacity.

For solar PV, GE Energy (2010) reported that the capacity credit of solar PV is higher than that of wind power according to the study by the WestConnect group in the United States. In Japan, the capacity credit of solar PV in summer is considered as 16% (Japanese government committee on electricity supply and demand 2013). However, available studies that evaluate the capacity credit of solar PV are limited compared with wind power.

In the DNE21+ model, capacity credit is defined as potential power supplies from wind power and solar PV without electricity storage at the instantaneous peak. Since the peak of these generation does not always match the instantaneous peak time period of power demand, the output of wind power generation at instantaneous peak time is constrained in the model. The capacity credit of wind power is assumed to be 10% in all regions. Although the physical situation for solar and wind energy is different, the same assumption with wind power is applied to solar PV in this paper.

(2) Grid stability
Capacities of wind power and solar PV without electricity storage are limited for the grid stability. In DNE21+, maximum shares in the total electricity supply are 10% both for wind power and PV without electricity storage. Electricity storage systems on the demand side are required for wind power and solar PV to be installed over that shares. If wind power and solar PV are deployed with electricity storage, further 20% of the total electricity supply are available from wind power and solar PV as additional capacities. The capital cost of electricity storage is exogenously assumed to be 1600$/kWh (2005) – 40$/kWh (2050), presuming rapid technology progress for electricity storage.

Theoretically, the maximum share of wind power and solar PV together in the total electricity generation reaches 60% (10% for wind power without storage, 20% for wind power with storage, 10% for solar PV without storage and 20% for solar PV with storage). The recent large regional wind integration studies in the United States (Milligan et al. 2009) have evaluated wind energy generates up to 30% of annual energy demand. The outlook of electricity generation shares of wind power and solar PV is16% and 20% in 2020 and 2030, respectively, in EU according to the EC communication (EC 2010). The assumed total maximum share is suitable level for energy system assessment until 2050 considering these targets.

The water electrolysis for hydrogen production by photovoltaics has no upper limit, (naturally restrictions on supply of natural resources should be treated separately).

(Reference) Impacts of different diffusion scenarios for mitigation technology options and of model representations regarding renewables intermittency on evaluations of CO_2 emissions reductions, Fuminori Sano, Keigo Akimoto, Kenichi Wada

3.3. Transport

DNE21+ represents road transportation sector in two way. One is vehicle type and the other is technological category. The type of vehicle includes small passenger car, large passenger car, bus, small truck, and large truck. Vehicle technologies are categorized into internal combustion engines, electric cars, fuel-cell cars, and alternative fuel vehicles, including bioethanol mixed with gasoline, biodiesel mixed with diesel, and CNG. The gasoline and diesel combustion engines for gasoline/diesel are further classified into conventional internal combustion cars (low/high efficiency), hybrid cars, and plug-in hybrid cars.

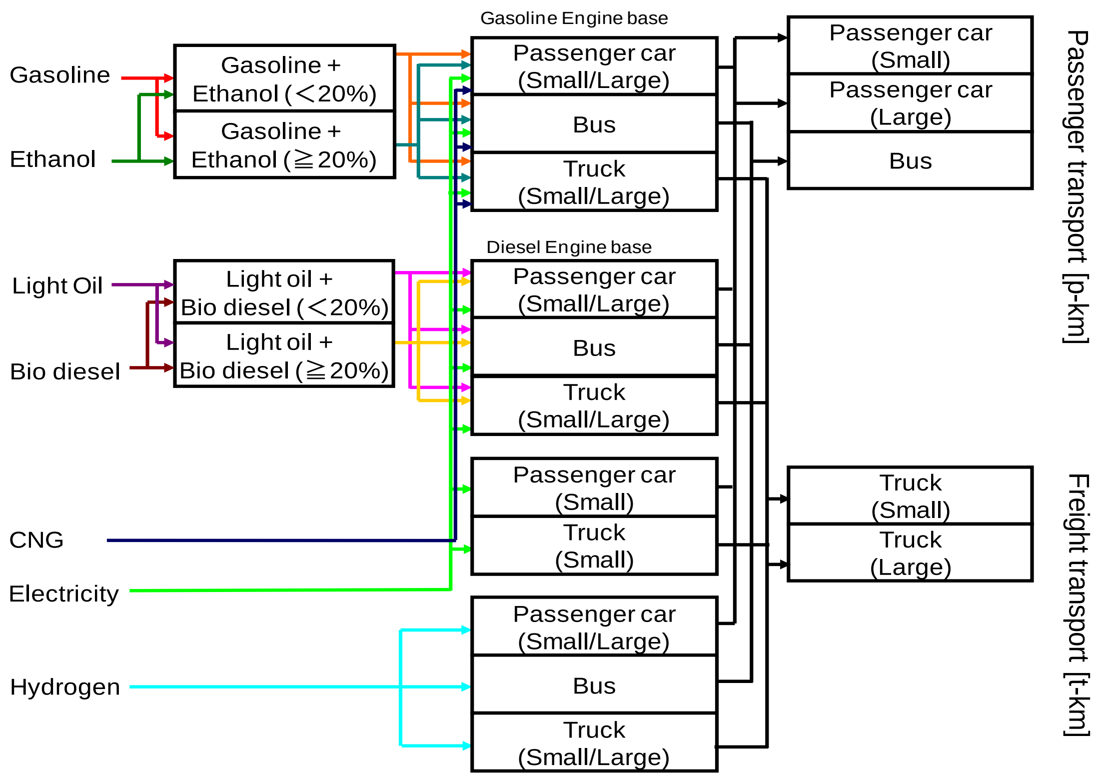

Figure 21 Schematic diagram of transportation service demand in DNE21+

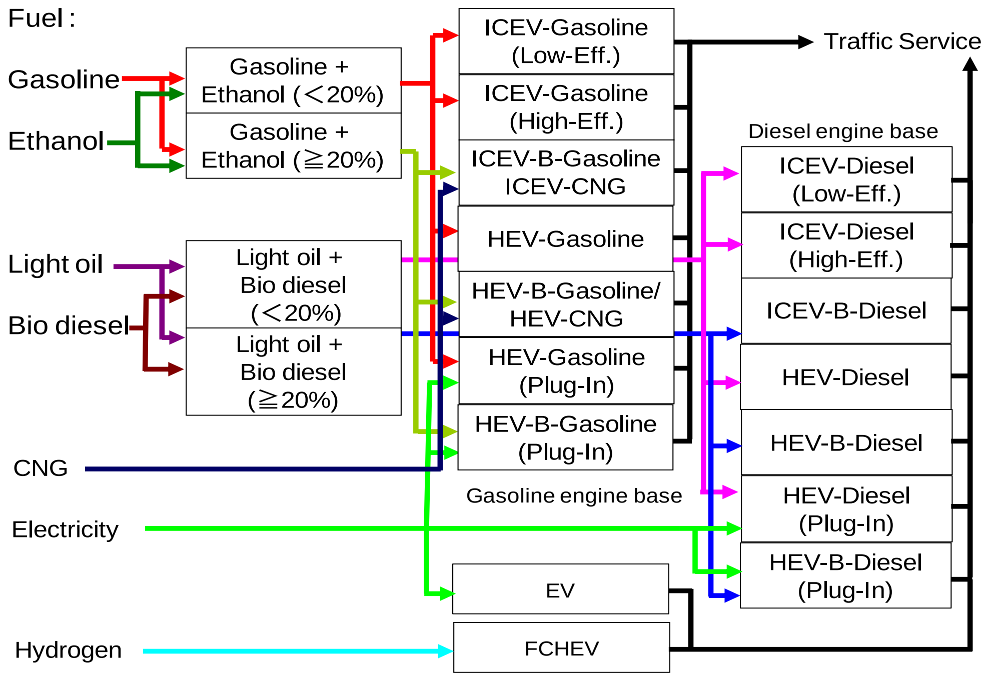

Figure 22 Taxonomy of passenger cars in DNE21+

Scenarios on service demand of road transportations are developed for passenger cars and buses separately based on per-capita GDP and the historical trends. As for road freight transport (t-km) scenarios of cargo trucks, overall cargo service per-capita is estimated by the GDP size, and then the transition of modal share is assumed.

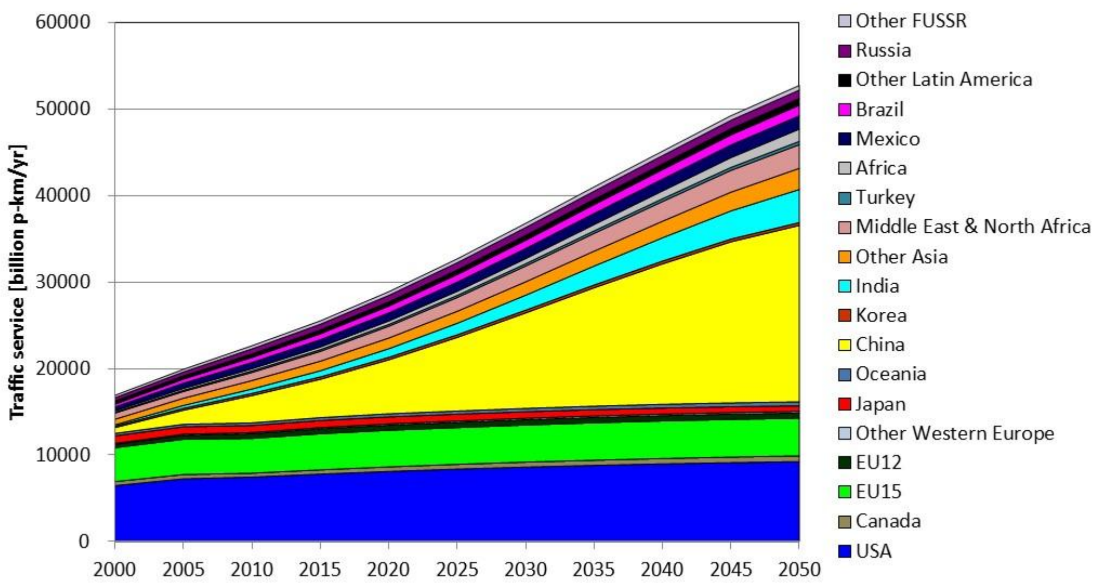

Figure 23 Traffic service of passenger car by region

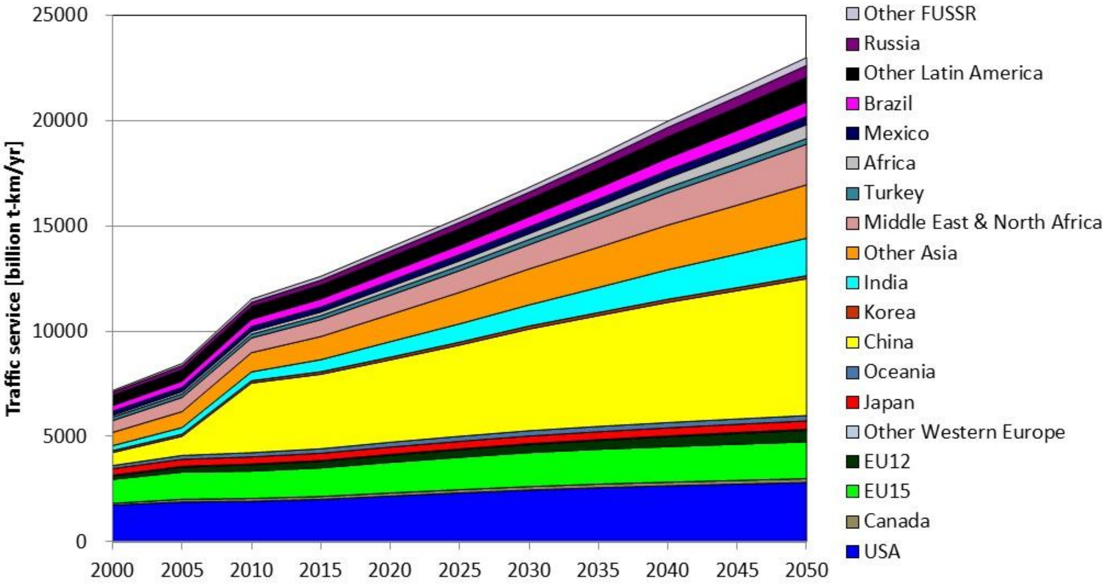

Figure 24 Traffic service of cargo truck by region

3.4. Residential and commercial sectors

DNE21+ has detailed technology representation for residential and commercial sectors. The modeled technologies include, refrigerator, lighting, television, air conditioner, and gas cooking stove. Each of above technology are segmented into several product category according to size and efficiency as shown in Table 4. The other technologies in the residential and commercial sectors are aggregated and modeled in a top-down manner.

Table 4 Product category of appliances

Appliance		Product category	Energy consumption (kWh/d.u./y)	Lifetime (years)	Price ($/d.u.)
Refrigerator		Low-Efficiency	1318	15.0	443
		Mid-Efficiency	842	15.0	758
		High-Efficiency	408	15.0	1525
Television	Small	Low-Efficiency	259	15.0	300
		High-Efficiency	138	15.0	358
	Large	Low-Efficiency	412	15.0	3514
		High-Efficiency	276	15.0	3639
Lighting[a]	Small	Incandescent	21.9	2.7	0.8
		CFL, fluorescent	5.8	11.0	8
	Middle	Mid-Eff. fluorescent	134.8	3.1	4
		High-Eff. fluorescent	97.3	4.1	10
	Large	Mid-Eff. HID	821.3	3.7	40
		High-Eff. HID	657.0	3.7	90
Air Conditioner[b]		Low-Eff. (COP 2.1)	1.412	15.0	960
		Mid-Eff. (COP 3.9)	0.798	15.0	1020
		High-Eff. (COP 6.5)	0.498	15.0	1080

Acronyms: d.u. = device unit, CFL = compact fluorescent light, HID = High-Intensity Discharge, COP = coefficient of performance.

[a] Lighting usage pattern is differentiated by size: 1 h for Small, 8 h for Middle, and 9 h for Large per day.

[b] Energy consumption of air conditioners is shown on an hourly basis.

3.5. Industrial Sector

DNE21+ explicitly models technologies for industry subsector, such as iron and steel, cement, pulp and paper, aluminum, petrochemical and ammonia. The other subsector are aggregated and modeled in a top-down manner. Each subsector includes following technology options:

Iron and steel; Blast Furnace (BF) - Basic Oxygen Furnace (BOF) {low efficiency (small scale), mid-efficiency (large scale), high efficiency (large scale, equipped with Coke Dry Quenching (CDQ), Top-pressure Recovery Turbine (TRT), recovery of by-product gases), next-generation (super coke oven, eg. SCOPE 21, utilizing plastic wastes and tire wastes, as well as highly efficient equipments), iron making by hydrogen reduction}, coke oven gas (COG) recovery {externally attachable to low/mid-efficient BF-BOF}, basic oxygen furnace gas (LDG) recovery, CDQ/TRT {externally attachable to mid-efficient BF-BOF}, Direct reduction {natural gas base (mid/high efficiency), hydrogen gasification base}, Scrap- Electric Arc Furnace (EAF) {low efficiency (small scale), mid-efficiency (tri-phase electric arc furnace), high efficiency (DC water-cooled walls arc furnace equipped with scrap preheating)}, CCS {applicable for BF-BOF}

Cement; [Small scale facilities] Vertical kiln, Wet rotary kiln, Dry rotary kiln, SP/NSP dry rotary kiln {equipped with suspensionpreheaters (SP), or new SP (NSP) meaning precalciner}, Advanced fluidized bed shaft furnace {equipped with SP/NSP, efficient clinker coolers}, [Large scale facilities (more efficient than small scale)] Wet-process rotary kiln, Dry-process rotary kiln, SP/NSP dry-process rotary kiln, SP/NSP dry-process rotary kiln (BAT) {equipped with efficient clinker coolers, SP with 5 or 6 levels, efficient waste heat recovery}

Pulp and Paper; Chemical pulp {low efficiency, mid-efficiency, high efficiency, next-generation}, Paper recycling {low efficiency, mid-efficiency, high efficiency}, Milling paper {low efficiency, mid-efficiency, high efficiency, Next-generation}, Black liquid recovery&use {low efficiency, high efficiency}, Paper sludge boilers, Steam turbine power systems

Aluminum; Söderberg aluminum production, Prebake aluminum production
Chemical; Ethylene/propylene: Naptha cracking {low efficiency, mid-efficiency, high efficiency, next-generation}, Other production {ethane cracker etc. low efficiency, mid-efficiency, high efficiency}

Ammonia: from Coal {low efficiency, mid-efficiency, high efficiency}, from Oil {low efficiency, mid-efficiency, high efficiency}, from Natural gas {low efficiency, mid-efficiency, high efficiency}

As an illustration how these technological options are model in DNE21+, the outline of the modeling framework for the iron and steel sector is shown below:

1. Nine types of steelmaking routes having different levels of energy efficiency are modeled. These routes include four types of BOF steelmaking, three types of scrap-based EAF steelmaking and two types of DRI-based EAF steelmaking.
2. In the BOF steelmaking routes, retrofit measures of the facilities for CDQ, TRT, waste plastics and tires recycling, and COG and LDG recovery are explicitly modeled.
3. The lifetime of all the facilities in the steel sector described above is assumed to be 40 years. The model considers the historical installation of the facilities.
4. Scenarios of crude steel production by region are assumed exogenously. In addition,

the maximum and minimum scrap-based EAF steel production scenarios are also assumed. These assumptions are kept fixed regardless of the simulation cases.

Figure 25 shows the concept of energy flows in steelmaking process modelling. These nine steelmaking routes encompass processes from raw materials input to coke oven and sintering furnace and from scrap input to EAF and BOF, to hot rolling. The processes of downstream, such as cold rolling, thin coating, special steel making, and ferroalloy making are not considered.

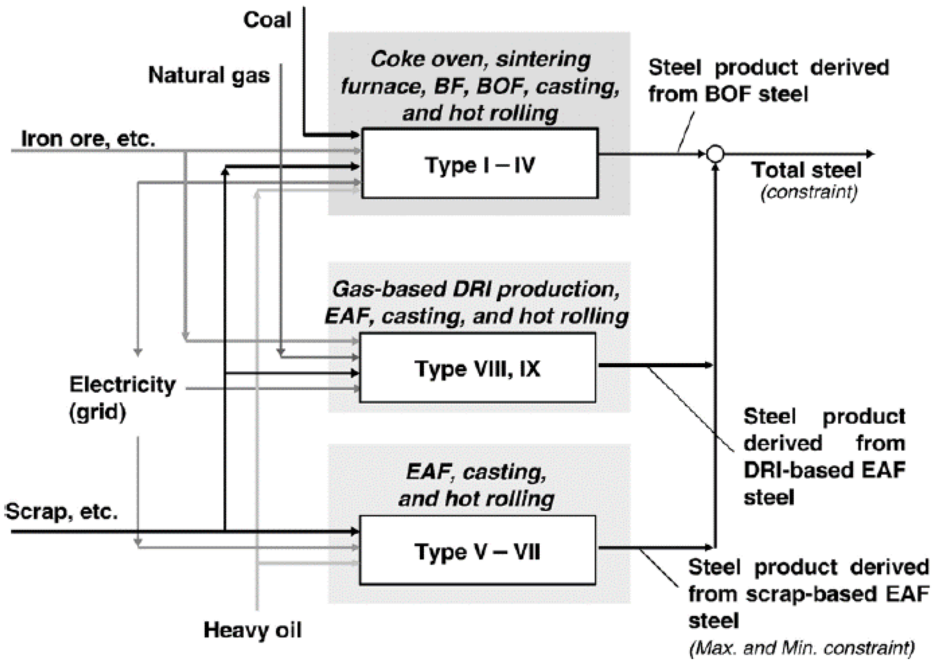

Figure 25 Modeling of energy use of the steel sector in DNE21+.

As shown in Figure **26**, DNE21+ assumed that the low-efficiency basic oxygen furnace (BOF) steelmaking route (type I) has a smaller scale capacity, partly including ingot making and some classical processes such as beehive coke oven and open hearth furnace (OHF). Type I is allowed to retrofit coke oven gas (COG) recovery in the model.

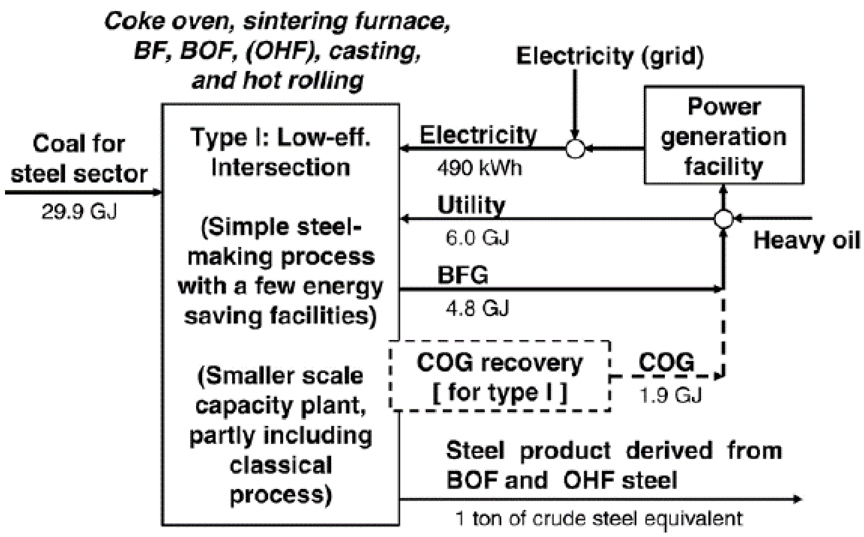

Figure 26 Type I energy use of low-efficiency BOF steelmaking (

Fig. 19 shows the Type II energy use for middle-efficiency BOF steelmaking route. Type II is a large-scale facility with modern steelmaking processes including pulverized coal injection (PCI) and continuous casting facilities. The average coal injection ratio in the type II is 88 kg/t-pig iron (2.3 GJ/t-pig iron), which can bring a net energy saving of 1.0–1.4 GJ/t-pig iron. The model allows some retrofit measures for COG recovery, basic oxygen furnace gas (LDG) recovery, effective utilization facility of COG and LDG, CDQ, and TRT to the type II.

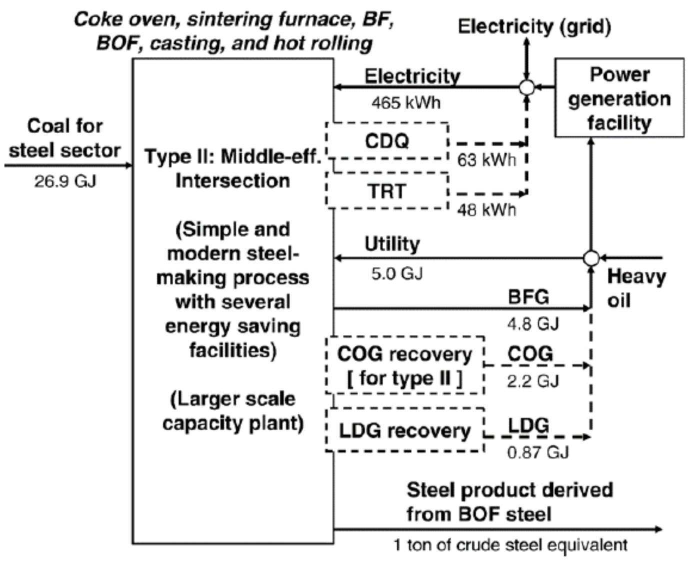

Figure 27 Type II energy use of middle-efficiency BOF steelmaking

The high-efficiency BOF steelmaking route (type III) shown in Figure 28 is for a large-scale facility with sophisticated steelmaking processes including CDQ, TRT and COG, BFG, and LDG recovery and effective utilization facilities of the gases and sensible heat. The average coal injection ratio in the type III is 151 kg/t-pig iron (4.0 GJ/t-pig iron), which can bring a net energy saving of 1.5 GJ/t-pig iron. Energy input data in the figures takes into consideration the net energy saving effects derived from these energy efficient facilities. Type IV is the steelmaking process with the next-generation coke oven added to type III. Type IV is assumed to be available only after 2011. All the steelmaking routes (type I–IV) are assumed to use scrap of 161 kg-scrap/t-crude steel in BOFs.

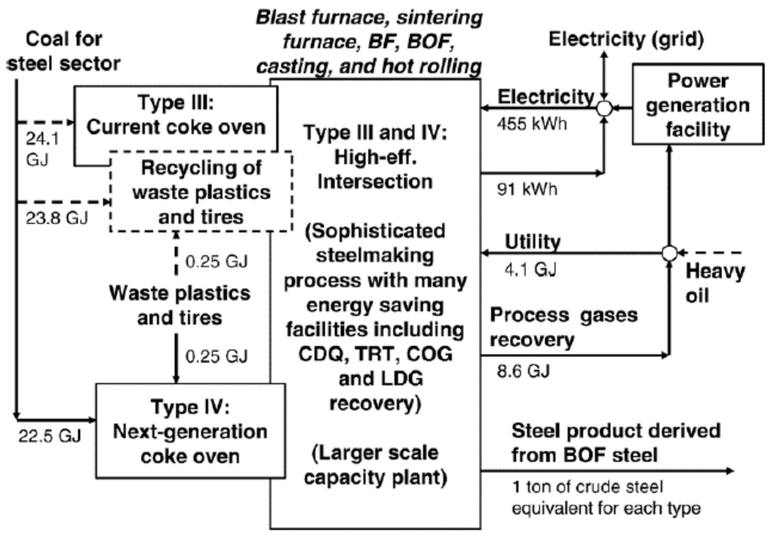

Figure 28 Type III and IV energy use of high-efficiency BOF steelmaking

Figure 29 shows the energy flow for the electric arc furnace (EAF) steel production. The low efficient electric steelmaking route (type V) consists of a small-scale EAF and induction furnace that is widely utilized in India. The mid-efficient EAF steelmaking route (type VI) assumes an alternate current (AC) arc furnace that is widely used in the US, Europe, and Japan. The highly efficient EAF steelmaking route (type VII) consists of a direct current (DC) arc furnace and many types of energy saving facilities such as scrap preheating and recuperative burner ladle preheating.

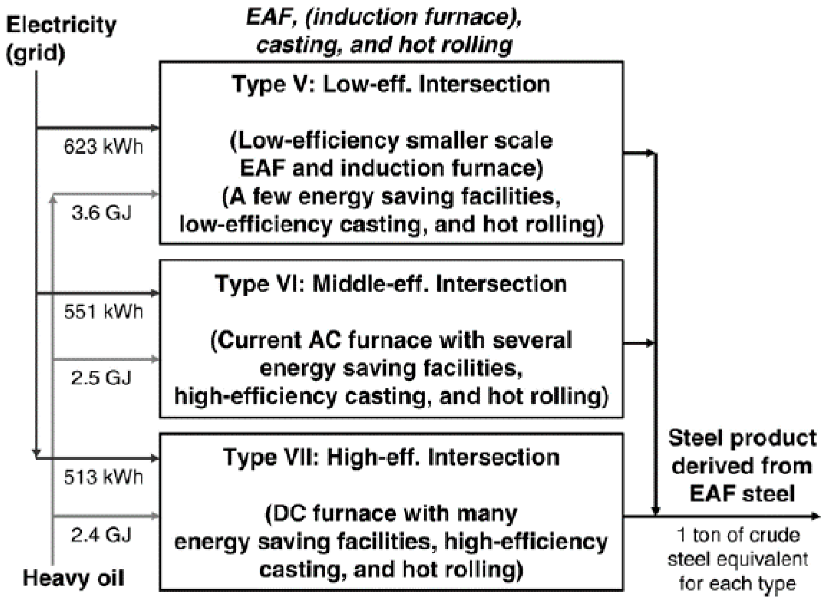

Figure 29 Modeling of three types of EAF steelmaking (type V, VI, and VII).

The correlation between evolution of per-capita GDP and per-capita apparent consumption of crude steel, trends in industry structure change by region, government planning reports etc. were taken into account in the scenario shown in Figure 30. The crude steel production is modeled by sorting out the processes into three routes; basic oxygen furnace (BF-BOF), scrap-based electric arc furnace (EAF) and DRI-based electric arc furnace (DRI-EAF) where the estimation on the historical installation of the facilities are conducted and their results are taken into account; installation year, energy efficiency and capacity.

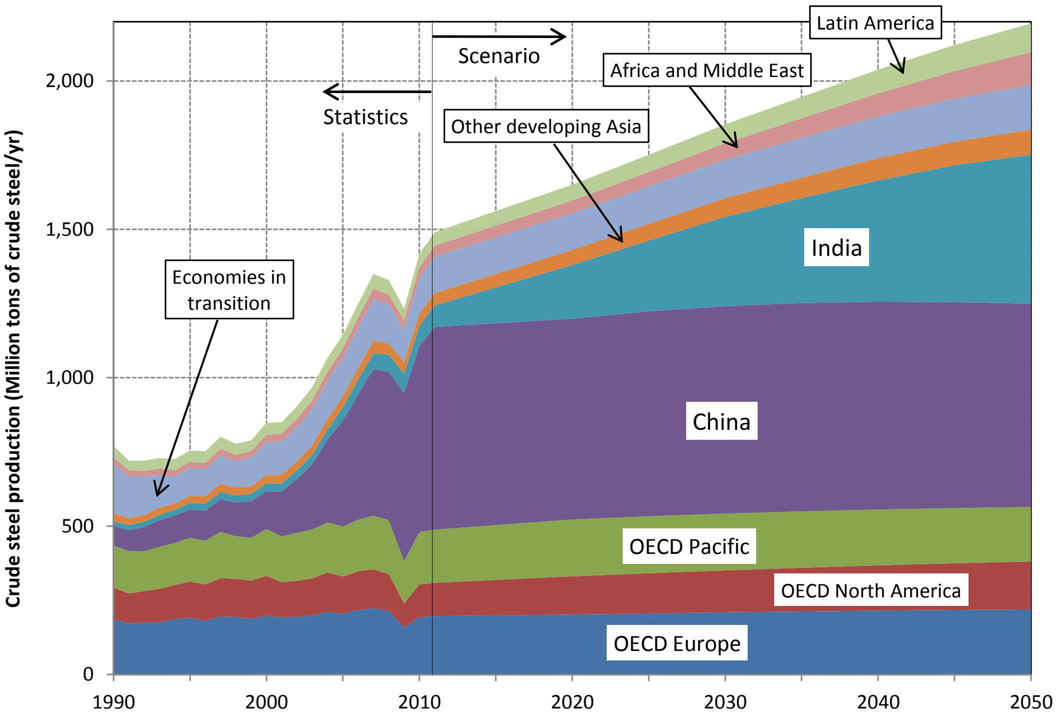

Figure 30 Crude-steel production of major regions (statistics and future scenario)

4. Land Use

Potentially available land area for energy crop production and afforestation, which is one of the input data of DNE21+ model, is evaluated by using a land-use model to maintain consistency with the land area required for food crop production and forest conservation and water-stressed basins. The land-use mode is basically a 15-minute-grid model, for every decade from 2000 to 2050, and at time points for 2070 and 2100. It is integrated with the water-use model; therefore, the water-stressed basins are estimated under the same scenario regarding socioeconomic development, climate change, and land use for food crop production.

a) Land area required for food crop production

Food crop types include wheat, rice, maize, sugar cane, soybeans, oil palm fruit, rapeseed and others, in consideration of their importance in terms of principal food, favorite food, vegetable oil and feed considerations. The available land area for food crop production are allocated in order to meet the regional food demands. If there is a shortage of food crop production due to a lack of available land, production is reallocated to regions where land is still available and any shortage is fulfilled by means of trade.

Impacts due to climate change and adaptations for planting can be taken into account through changes in the potential production, which can be calculated using the information on crop characteristics and soil types provided in the in the Global Agro-Ecological Zones (GAEZ) model (Fischer et al. 2002) for both rain-fed and irrigated conditions. Impacts on crop productivity due to technological progress associated with economic growth and production adjustments to avoid falling crop prices and so on are taken into account through a scenario of 'yield (or management) factor' for each of crops and for each of the 32 regions. For all crops, a greater growth of the 'yield factor' is expected in developing regions than in developed regions. The grids available for irrigation are based on an irrigation map for the year 2000 (Siebert et al. 2007). The regional areas for irrigation maintain the consistency with those of the original map, although the share of irrigation area for each of grids is simplified to be either 0 or 100%. No expansion of the irrigation available grids is allowed in the future according to the assumptions by Alcamo et al. (2007). For details of the land-use model, please refer to Hayashi et al. (2013).

(Reference) Hayashi, Ayami, et al. "Global evaluation of the effects of agriculture and water management adaptations on the water-stressed population." Mitigation and Adaptation Strategies for Global Change (2013): 1-28.

b) Available land area for energy crop production and afforestation

The agro-land use model is equipped with a land cover map for eight major land-cover categories (i.e., rainforest, other forests, arable land, grassland, pasture, barren, built-up, and water), which was constructed by reference to data from around 2000 (Fischer et al. 2008, PBL 2009, USGS 2000). Fallow land is estimated by subtracting the land required for food crop production from arable land. Then, fallow land and grassland are treated as candidate land for energy crop production and afforestation. They don't include either cropland or pasture; therefore, there is no worrying about competition with food production technically. Furthermore, they don't include rainforests and other forests; therefore, concerns regarding CO_2 emissions and biodiversity loss through the use of land for energy crop production are minimal. In the next step, water-stressed basins are excluded from the candidate land. Water-stressed basins are estimated based on a criterion ($0.4 \leq$ the annual water withdrawal-to-availability ratio) while maintaining consistency in terms of agricultural water use for irrigation, domestic and industrial water use, and water availability. Data for the river basins are derived from the Total Runoff Integrating Pathways (TRIP) database (Oki 2001).

We focus on land satisfying conditions for energy crop yield and land accessibility of the candidate land, and we calculate the available energy from the energy crop production on the land by level of conditions for yield and land accessibility. Energy crop types include cereals (wheat, rice, or maize), sugar cane, oil palm fruit, other oil crops (soybeans, or rapeseed), and lignocellulosic crops.

c) CO_2 emissions from LULUCF

Four types of CO_2 emission/fixation are taken into account; (1) CO_2 emissions due to expansions of crop land for food crop production, (2) CO_2 fixation by forests planted and naturally-regenerated before 2010, (3) CO_2 fixation by afforestation after 2010, and (4) CO_2 emissions by other sources (i.e., emission abandoned land after deforestation).

CO_2 emission due to expansions of crop land for food crop production is estimated by multiplying the land area converted to crop land from other types of land, by CO_2 emission coefficients. The former is evaluated by using the land-use model, and the latter was constructed by reference to Houghton's studies (1999, 2001) for each of the 32 regions.

Land area for forests planted and naturally-regenerated during the last 60 years were estimated based on the FRA 2010 report (FAO, 2010) for each of the 54 regions. The amount of CO_2 fixation by the forests were calculated based on the estimated forest area and the NPP (Net Primary Production) for each of the regions. CO_2 fixation by afforestation after 2010 is one of the mitigation options in the DNE21+ model.

CO_2 emissions by the other sources in 2005 were estimated so that the total CO_2 emission to consists to the amount for the year by RCP database (IIASA database). After that, it was assumed to decrease associated with increase in per capita GDP.

5. Non-energy CO_2 emissions

CO_2 emissions from industrial processes, such as cement production, are accounted for based on the cement production scenario.

6. Non-CO_2 GHGs

The non-CO_2 GHG assessment model, one of the DNE21+ model group, disaggregates the world into the 54 regions, consistent with the regional definition in the DNE21+ model (Akimoto et al.(2009), Akimoto et al.(2009)). The model converts bottom-up assessments of mitigation technologies performed by the USEPA (2002) to a proxy model using elasticity (Dowaki et al., 2006). The historical emission of non-CO_2 GHGs was adjusted using the UNFCCC inventory (UNFCCC, 2009) and the IEA statistics (IEA, 2007) for Annex I countries and non-Annex I countries, respectively. The emission mitigation costs and potentials were modified using new technology assessments performed by the USEPA (2006b).

Equation (1) indicates the relationship between the individual non-CO_2 GHG mitigation ratio and marginal abatement costs evaluated by using the elasticities. In the model, the non-CO_2 GHG mitigation in 54 regions is estimated when the non-CO_2 GHG abatement costs are equalized to the CO_2 marginal abatement costs. The elasticities are determined such that the marginal abatement cost curves correspond to the USEPA estimates obtained separately for each sector and type of gas. The estimates are calculated using a technology database for non-CO_2 GHG measures. Thus, the model used here is not a direct bottom-up model; however, marginal costs and potentials of non-CO_2 GHG mitigation are essentially based on the bottom-up analysis of the USEPA.

Basically the elasticities in the model developed by Hyman et al. (2003) are applied to the model, but the elasticities are adjusted to be consistent with the result of analysis for a 20%/year discount rate which are close to the rate usually observed in decision makings of socio-economic activities, taking into consideration the results of sensitivity analysis for the discount rate (payback period) carried out by the USEPA (2002). The elasticities are also partially adjusted on the basis of the mitigation effect report of the USEPA (2006b). The elasticities of gases and the mitigation potentials in the model are estimated to be less than those reported by Hyman et al (2003).

$$\mathrm{Red}(g, h, n, t) = 1 - \left(\frac{1}{P(g, h, n, t)} \right)^{\sigma(g,h,n)} \qquad (1)$$

where g represents the gas; h, the sector; n, the region; and t, the year. Red is the reduction rate for the total emission, P is the marginal abatement cost, and σ is the elasticity derived on the basis of studies by the USEPA (2002, 2006b) and Hyman et al. (2003).

The baseline emissions were estimated using the above assumptions for population and GDP adopted in the model. The model considers five types of emissions: CH_4 in seven sectors, N_2O in six sectors, hydrofluorocarbons (HFCs) in one sector, perfluorocarbons (PFCs) in one sector, and SF_6 in one sector for 54 regions.

CH_4 emissions were considered in seven sectors: agriculture, oil, coal, natural gas, residential, transportation, and energy intensive industries. N_2O emissions were considered in six sectors: agriculture, oil, natural gas, residential, transportation, and energy-intensive industries. HFCs, PFCs, and SF_6 emissions were considered for one macro-sector each. The baseline HFCs, PFCs, and SF_6 emissions were basically estimated using the SRES B2 scenario for each of the four regions the world was divided into.

(Reference)

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