http://www-iam.nies.go.jp/aim/publications/report/2010/cge_4.5W.pdf
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Analysis of 4.5 W/m2 stabilization scenarios with renewable energies and advanced technologies using AIM/CGE[Global] model

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1. Introduction

In order to reduce the greenhouse gas (GHG) emissions to avoid the climate change, many countermeasures are proposed. The energy efficiency improvement can contribute to the reduction of energy demand. On the energy supply side, introduction of renewable energies is recognized as an important countermeasure to reduce the fossil fuel demand. Moreover, CCS (carbon capture and storage) is regarded as a key technology for the long-term countermeasure.

In this paper, in order to stabilize 4.5 W/m2 of radiative forcing, the contribution of renewable energies and the advanced technologies such as CCS is assessed using a global model named AIM/CGE[Global].

2. Model

The AIM (Asia-Pacific Integrated Model) has been developed to assess mitigation options to reduce the GHG emissions. The AIM/Enduse model is a partial equilibrium model of energy system, and it can assess the GHG emission reduction by introduction of specific technologies based on the assumption of the future energy service demands. On the other hand, the AIM/CGE model can show consistent economic activity by introducing the countermeasures to reduce the GHG emissions. In this paper, introduction of renewable energies and new technologies to stabilize 4.5 W/m2 of radiative forcing is assessed by using AIM/CGE[Global], a variant of AIM/CGE model.

The AIM/CGE[Global] is a global computable general equilibrium model with recursive dynamics. The world is divided into 24 regions as shown in Table 2.1. The benchmark economic dataset follows the GTAP6. That is to say, the benchmark year is 2001. The simulation years are 2005, 2010, and every 10 years up to 2100. The classification of commodities is shown in Table 2.2. The electricity is produced by many sub-sectors; thermal power plants (based on coal, crude oil, oil products and natural gas), hydro, nuclear, solar, wind, geothermal, biomass, and others. It is assumed that the CCS technology can be installed in the thermal and biomass power plants. The biomass energy can be transformed into bio-fuel or bio-gas.

Table 2.1 Regional definition in AIM/CGE [Global]

JPN	Japan	USA	USA
CHN	China	XE15	EU-15 in Western Europe
KOR	Korea	XE10	EU-10 in Eastern Europe
IDN	India	RUS	Russia
IND	Indonesia	XRE	Rest of Europe
THA	Thailand	ARG	Argentine
XSE	Other South-east Asia	BRA	Brazil
XSA	Other South Asia	MEX	Mexico
AUS	Australia	XLM	Other Latin America
NZL	New Zealand	XME	Middle East
XRA	Rest of Asia-Pacific	ZAF	South Africa
CAN	Canada	XAF	Other Africa

Table 2.2 Classification of commodities

AGR	Agriculture	(1)	TRT	transport	(3)
LVK	Livestock	(1)	CMN	communication	(3)
FRS	Forestry	(1)	OSG	public service	(3)
FSH	Fishing	(2)	SER	other service	(3)
OMN	mining (except fossil fuels)	(2)	COA	coal	(4)
EIS	energy intensive products	(3)	OIL	crude oil	(4)
M_M	metal and machinery	(3)	P_C	petroleum products	(5)
OMF	other manufactures	(3)	GAS	natural gas	(4)
WTR	water	(3)	GDT	gas manufacture distribution	(6)
CNS	construction	(3)	ELY	electricity	(7)

(1)-(7) correspond to the classification of production structure in Appendix.

Figure 2.1 shows the overall model structure. Each region has the production sectors as shown in Table 2.2 and the final demand sector. The final demand sector consists of household and government. The final demand sector has capital, labor, resources, and land as endowments, and receives income by supplying these endowments to the production sectors. Each production sector produces the corresponding commodity by taking inputs of production factors, raw materials and energies. The land is input in agriculture, livestock, and forestry sectors, and can be shared among these three sectors. In order to produce commodities in the fishing, mining, crude oil, coal and natural gas sectors, rent is taken into account as a production factor. The depletion of these fossil fuels is represented by increase in the fuel extraction cost. The model assumes a relationship between the fuel extraction cost and the accumulated fuel extraction. The detailed production structures are depicted in the Appendix.

The produced commodities are supplied to the international market and/or domestic market. In the domestic market in each region, the goods produced in that region and the imported goods are added. A uniform international market for the crude oil, coal and natural is assumed. Bilateral trades for other goods are considered based on the Armington assumption. In each domestic market, the supplied commodities are consumed as intermediate goods in the production sectors, or final consumption goods or investment goods in the final demand sector.

The total investment in each region in a period follows the expected future economic growth rate defined exogenously. In the production sectors, the existing capital and the new capital are distinguished. The existing capital cannot move among the sectors, whereas the new capital can. When the new capital is installed in a specific sector, it cannot move to other sectors later. The technology changes such as energy efficiency improvement are represented through the new capital. For the existing capital, the efficiency change is assumed in proportion to the new capital installed in the previous years. This means that the more new capital is installed, the more rapid efficiency change will be. The sectors in which the new investment is not introduced do not exhibit efficiency improvement.

The GHG emissions treated in the model are CO2, CH4 and N2O. Other GHGs are treated exogenously. The air pollutants such as SO2 and NOx are calculated in the model. The GHG and other gas emissions from the fossil fuel combustion and production process are distinguished.

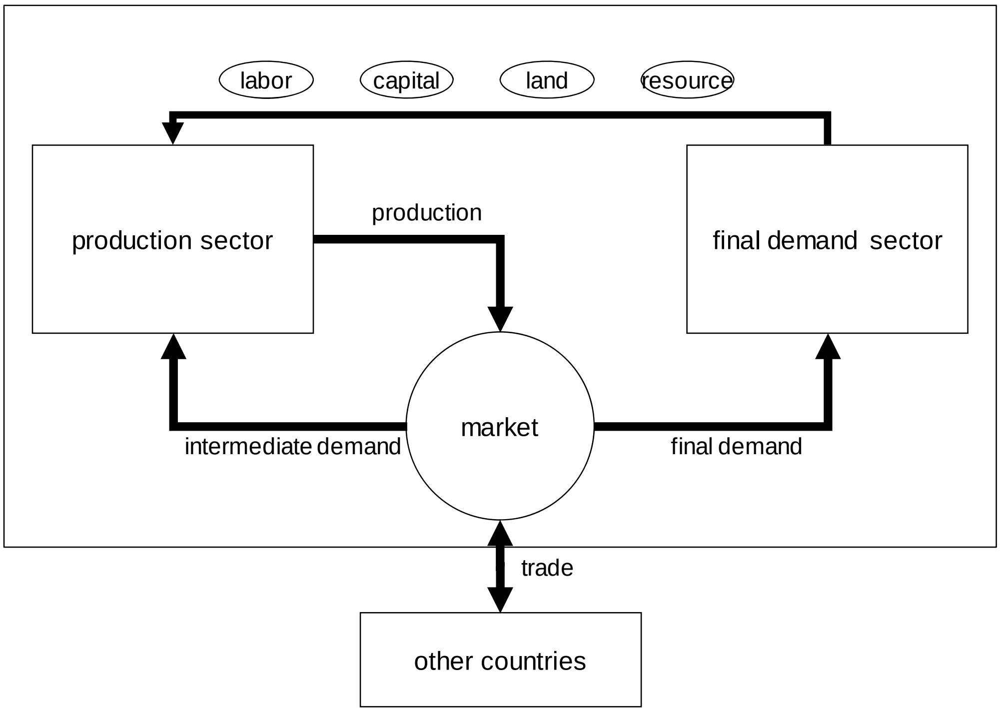

Figure 2.1 Overall structure of AIM/CGE[Global]

3. Renewable energy potential

The model includes five types of renewable energy: (1) Solar, (2) Wind, (3) Biomass, (4) Hydro, and (5) Geothermal. Future potentials for hydro and geothermal have been set based on 2007 survey of energy resources by World Energy Council, and estimation by International Geothermal Association, respectively.

3.1 Solar power

The potentials are determined based on SeaWiFS Surface Solar Irradiance data[1] and Global Land Cover Characterization data[2].

The SeaWiFS Surface Solar Irradiance data includes monthly-averaged solar intensity (unit: 10,000 W/m^2) on the global surface (onshore and offshore) from July 1983 to June 1991. The global surface is represented by 2.5^o x 2.5^o mesh.

The Global Land Cover Characteristic data is represented by 0.5^{o}x0.5^o mesh and its land use is classified into 17 types of covers as shown in Table 3.1.

Table 3.1 Legend of land use type in the global land cover characteristic data

Value	**Description**
1	Evergreen Needleleaf Forest
2	Evergreen Broadleaf Forest
3	Deciduous Needleleaf Forest
4	Deciduous Broadleaf Forest
5	Mixed Forest
6	Closed Shrublands
7	Open Shrublands
8	Woody Savannas
9	Savannas
10	Grasslands
11	Permanent Wetlands
12	Croplands
13	Urban and Built-Up
14	Cropland/Natural Vegetation Mosaic
15	Snow and Ice
16	Barren or Sparsely Vegetated
17	Water Bodies
99	Interrupted Areas (Goodes Homolosine Projection)
100	Missing Data

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[1] The NASA Goddard Institute for Space Studies (GISS), (1991). “Surface solar irradiance: Datasets produced for SeaWiFS”, http://data.giss.nasa.gov/seawifs/.

[2] 2) The U.S. Geological Survey (USGS), (1997). “Global Land Cover Characterization”, http://edc2.usgs.gov/glcc/glcc.php

3.1.1 Methodology of evaluation

Utilization of solar power can be classified into two categories; generation of electricity and direct heat use. The model focused on only electricity generation potentials by photovoltaics.

Solar potentials have been estimated by four steps: (1) Grouping of land use, (2) Determination and grading of solar intensity (3) Estimation of solar energy's physical and technological potentials by country, and (4) Calculation of solar energy's economic potentials by country.

(1) Grouping of land use

The type of land use impacts construction of photovoltaic systems. We aggregated land use types in the Global Land Cover Characteristic data into four types: (1) Forests, (2) Grasslands, (3) Urban, and (4) Others, and assumed the space availability for setting up photovoltaics of 5% in forests, 20% in grasslands, 20% in urban areas. No photovoltaic is available for 'other' types of lands. In table 2.1, Nos. 1, 2, 3, 4, 5, 6, 8, 14 are grouped as Forests, Nos. 7, 9, 10, 15, 16 are Grasslands, and No. 13 is Urban land.

(2) Determination and grading of solar intensity

We used the data from January 1984 to December 1990 of the SeaWiFS Surface Solar Irradiance data. By averaging monthly data during that period, representative monthly averaged solar intensity has been set by each mesh (25^{o} x 25^{o}).

Each mesh is classified into six grades based on its solar intensity, as shown in Table 3.2.

Table 3.2 Definition of solar intensity grades

Grade	Explanation
Grade 1	> 280 W/m^2
Grade 2	210-280 W/m^2
Grade 3	170-210 W/m^2
Grade 4	40-170 W/m^2
Grade 5	120-140 W/m^2
Grade 6	< 120 W/m^2

(3) Estimation of solar energy's physical and technological potentials by country

Physical potential of solar energy for a country can be calculated by:

$$R_k = \int_{i \in Country\ k} \left(rad_i \times \eta_i \times A_i \right) di \qquad (3.1)$$

where, k is country number, i is mesh number, R_k is total solar energy in country k [W], rad_i is total solar intensity in mesh i [W/m^2], η_i is availability factor by land use type in mesh i (Forests: 0.05, Grasslands: 0.2, Urban: 0.2), A_i is the area in mesh i [m^2].

Technological potentials could be obtained from physical potentials by multiplying with efficiency of photovoltaic system. In our study the efficiency was assumed as 8%.

(4) Calculation of economic potentials by country

Economic potentials are determined by the model analysis. Here, we calculated cost data as an input for the model, which is one of the major drivers of economic potential.

Generation cost of the photovoltaic system is:

$$Cst = (crf + ins) \times (1 + IND) \times \frac{(MOD + BOS + PC \times SP \times EPV)}{SYR \times EPV \times EPC} + OMC \qquad (3.2)$$

where Cst is generation cost [\$/MWh], crf is capital recovery factor (determined by equation (3.3)) [-], ins is insurance [-], IND is indirect cost [-], MOD is module cost of photovoltaic system [\$/MW], BOS is non-module cost [\$/MW], PC is ancillary cost for power output [\$/MWh], SP is maximum solar intensity [kW/m^2], EPV is efficiency of photovoltaic system [-], EPC is efficiency of power control [-], SYR is annual solar radiation [MWh/m^2/yr] and OMC is operation and maintenance cost [\$/MWh].

$$crf = \frac{r}{1-(1+r)^N} \qquad (3.3)$$

where r is discount rate and N is depreciation year.

Figure 3.1 represents the summary of solar power energy potential by grade and model region.

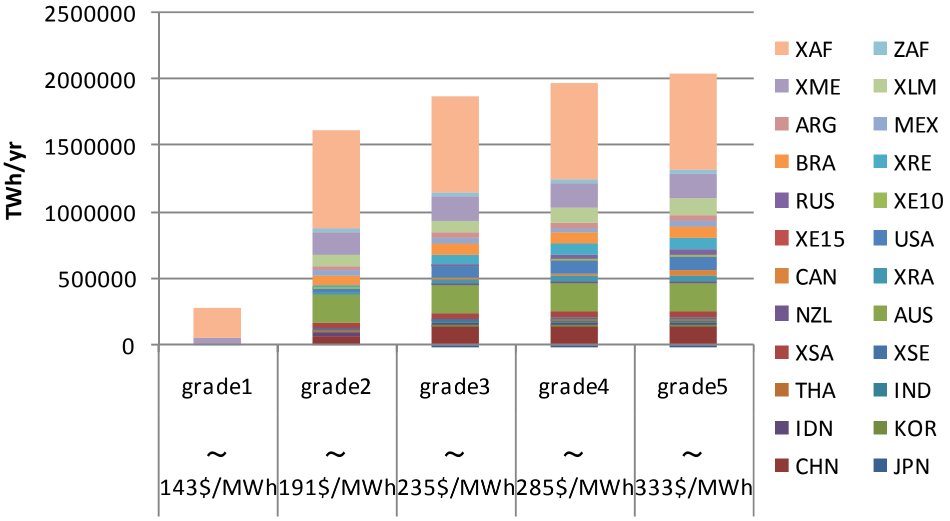

Figure 3.1 summarized cost of solar energy by region.

3.2 Wind energy potentials

The potentials of wind energy are determined based on the Climatic Research Unit Global Climate Dataset[3] and the Global Land Cover Characterization data[2)] (same as section 3.1).

The Climatic Research Unit Global Climate Dataset includes monthly-averaged wind speed (Unit: 10 m/s) on the global surface (onshore) from 1961 to 1991. The global surface is represented

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[3] IPCC Data Distribution Center (IPCC/DDC), (2009). "The Climatic Research Unit Global Climate Dataset", http://www.ipcc-data.org/obs/cru_climatologies.html

by 0.5° x 0.5° mesh.

Wind potentials have been calculated by seven steps: (1) Grouping of land use, (2) Assumption for typical wind generator (3) Estimation of average wind speed over the available altitude for the wind turbine (>30 meter), (4) Estimation of annual average generation from wind turbine, (5) Grading of physical potentials of wind energy, (6) Estimation of physical and technological potentials by country, (7) Calculation of economic potentials by country.

(1) Grouping of land use

Installation of wind turbine is constrained by land use type. We aggregated Land use types in the Global Land Cover Characteristic data into three types: (1) Forests, (2) Grasslands, and (3) Others. In Table 3.1, Nos. 1, 2, 3, 4, 5, 6, 8, 14 are grouped as Forests, and Nos. 7, 9, 10, 15, 16 are Grasslands.

(2) Assumption for typical wind generator

In order to evaluate wind energy potentials at the global scale, a virtual wind turbine is assumed. Capacity of wind turbine is 500 kW, diameter is 40 m, and cut-in (V_{in}) and cut-out (V_{out}) wind speed is 5.5 m/s and 24 m/s. Rated wind speed is 12.5 m/s. The characteristic curve for the wind turbine can be drawn as shown in Figure 3.2.

For installation of multiple wind turbines, in order to avoid rear turbulence, each wind turbine is assumed to keep 10 times of diameter clearance, thus, one wind turbine occupies 160,000 m^2.

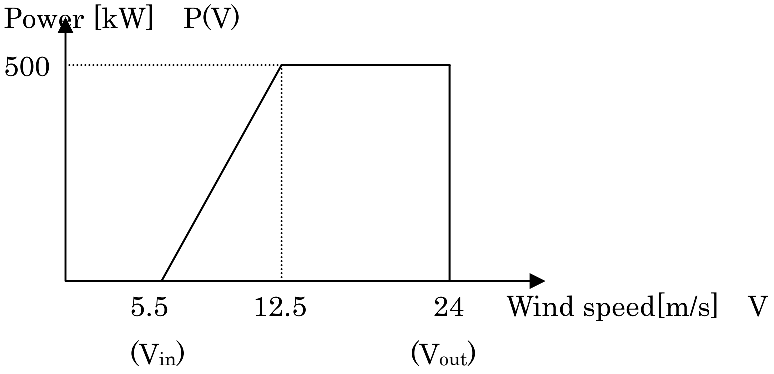


Figure 3.2 Characteristic curve for virtual wind turbine

(3) Estimation of average wind speed over the available altitude for the wind turbine (>30 meter)

The data includes varying observation altitude, however, in the research we assume all data at 10 m height.

By averaging all data by mesh, total monthly average wind speed is derived. It is well known that wind speed follows power law of altitude as shown in equation (3.4). By using this equation, wind speed at 30 meter altitude is calculated in each mesh.

$$V = V_h \times \left(\frac{z}{h}\right)^{\frac{1}{n}} \qquad (3.4)$$

where V is wind speed at altitude z, V_h is observed wind speed at altitude h, and n is landform-dependent parameter (4.8 in the research).

(4) Estimation of annual average generation from wind turbine

Probability distribution of wind speed follows the Rayleigh distribution as shown in equation (3.5).

$$f(V;V_z) = \frac{\pi}{2} \times \frac{V}{V_z} \times \exp\left\{ -\frac{\pi}{4} \cdot \left(\frac{V}{V_z} \right)^2 \right\} \qquad (3.5)$$

Then, annual generation from wind turbine at wind speed V can be calculated by:

$$G(V) = P(V) \times f(V;V_z) \times 8760 \qquad (3.6)$$

where $G(V)$ is generation at wind speed V [Wh]

By integration from cut-in speed to cut-off speed, annual generation from wind power can be estimated.

$$WYP_i = \int_{V_{in}}^{V_{out}} G(V)\, dV = \int_{V_{in}}^{V_{out}} P(V) \times f(V;V_z) \times 8760\, dV \qquad (3.7)$$

where WYP_i is yearly wind power generation at mesh i.

Figure 3.3 shows results of annual generation by wind speed.

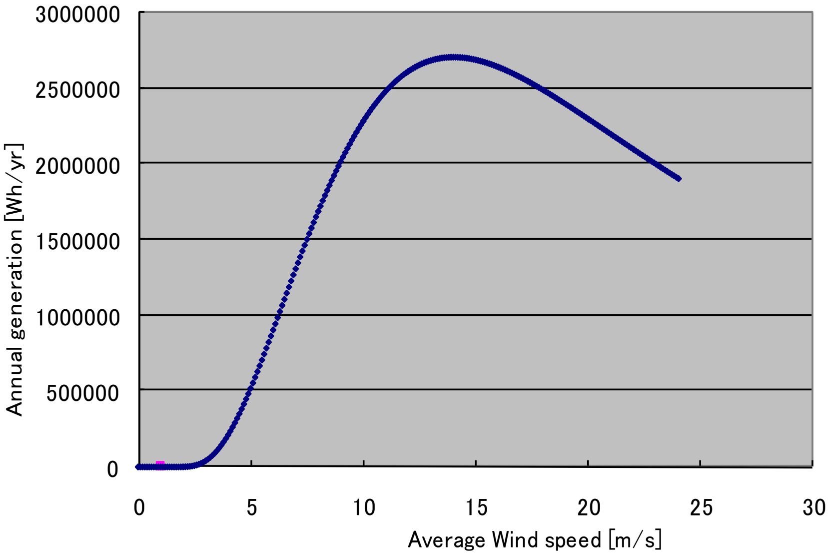


Figure 3.3 Annual generation by wind speed

(5) Grading of physical potentials of wind energy

Wind energy has been classified into 5 grades based on annual utilization rate as shown in Table 3.3. Annual utilization rate in each mesh (U_i) is determined by equation (3.8).

$$U_i = \frac{WYP_i}{Capacity \times 8760} \quad \text{(Capacity is 500 kW)} \qquad (3.8)$$

Table 3.3 Grading for wind power

Grade	Utilization rate
Grade 1	> 0.30
Grade 2	0.25-0.30
Grade 3	0.20-0.25
Grade 4	0.15-0.20
Grade 5	< 0.15

(6) Estimation of physical and technological potentials by country

Physical potentials from wind power by country can be calculated by multiplying maximum number of wind turbines with the results of equation (3.7). Maximum number of wind turbines is set based on the area available in each mesh and the area required by a turbine (160,000 m2)..

(7) Calculation of economic potentials by country

Economic potentials are determined by the model analysis. Here, we calculated cost data as an input for the model.

Generation cost of the wind turbine is:

$$Cst = \left(\frac{crf \times C_c + C_m}{WYP} \right) \times (N \times 500) \qquad (3.9)$$

where Cst is generation cost [\$/kWh], crf is capital recovery factor as shown in equation 3.3, C_c is Capital cost [\$/kW], C_m is maintenance cost [\$/kW], and N is number of wind turbines in a country.

Figure 3.4 shows the summary results of wind energy potential by the model regions.

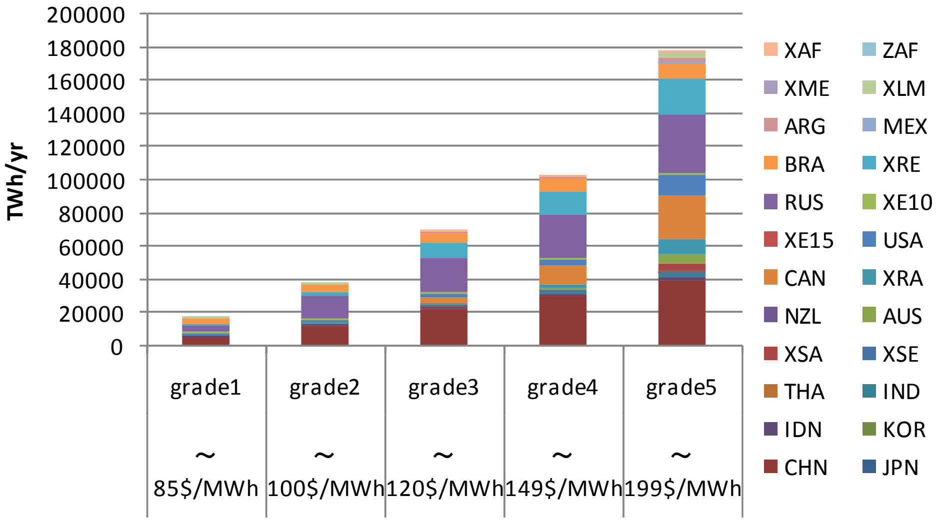


Figure 3.4 Summary of wind energy potential

3.3 Biomass potential

Biomass energy can be classified into three categories: (1) Traditional fuelwood, (2) Plantation bioenergy, and (3) Residue bioenergy. In this section, only the residual bio energy is explained. Plantation bioenergy is calculated in the model taking into account the land.

Source of bioenergy is a wide variety even of biomass production and utilization processes. The model addresses residue bioenergy through the following steps:

(1) Assumption for incidence rate of residue bioenergy from biomass production/utilization process
(2) Determination of production/utilization quantity of biomass
(3) Estimation of cost for utilization of residue bioenergy

Table 3.4 shows a part of the data set we prepared for incidence rate of residue bioenergy for the model. Figure 3.5 shows its potential .

Table 3.4 Incidence rate of residue bioenergy

Process	Incidence rate [dry-t/dry-t]	Energy production rate [GJ-HHV/dry-t]
Rice production	1.4	16.3
Straw production	1.3	17.5
Corn production	1.0	17.7
Rootstock production	0.4	6.0
Sugarcane production	0.28	17.33
Bagasse	0.15	17.33
Cow	1.10 [t/yr/animal]	15.0
Grunter	0.22[t/yr/animal]	17.0
Chicken	0.037[t/yr/animal]	13.5
Horse	0.55[t/yr/animal]	14.9
Buffalo, Camel	1.46[t/yr/animal]	14.9
Sheep, Goat	0.18[t/yr/animal]	17.8
Log stock for industrial use	1.17	16.0
Log stock for fuel woods	0.67	16.0
Lumber residue	0.784	16.0

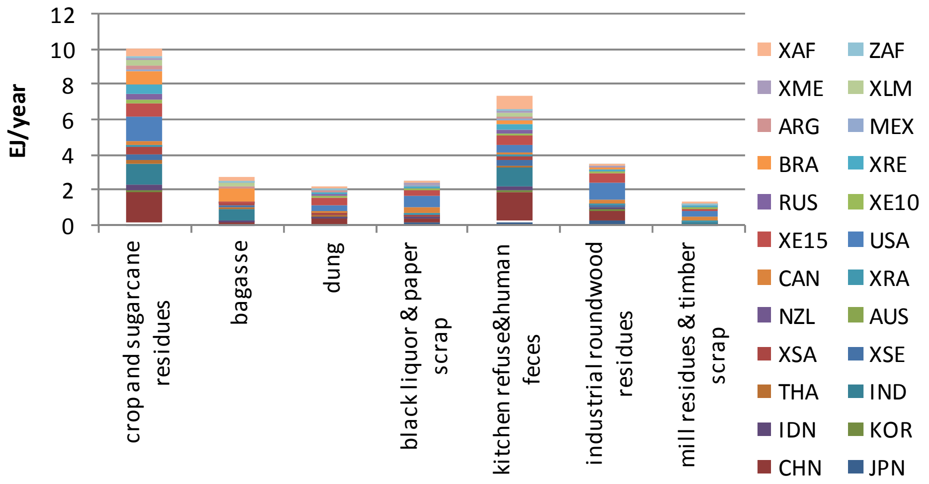


Figure 3.5 Summary of residue bioenergy by model regions

4. Future Scenarios and simulation results

The following three scenarios are considered for analysis.

1) The reference scenario

2) Stabilization of 4.5W/m2 with CCS technologies

3) Stabilization of 4.5W/m2 without CCS technologies

These scenarios use common assumptions about population change, expected GDP growth, efficiency changes, and renewable energy potential. The renewable energy potential in the future is explained in the previous section.

The future population changes up to 2050 follow the medium variant estimated in “World Population Prospects, The 2008 Revision”, and after 2050, the growth rates of population follow the medium scenario estimated by “World Population to 2300”. The economic growth follows the Sustainability First scenario of UNEP/GEO4. The energy efficiency improvement is set to reproduce the primary and final energy demands in SRES B2 for the reference scenario. The land productivity is assumed to follow the past trend with an upper limit.

Figure 4.1 shows the global CO2 emissions in each scenario. In the reference scenario, CO2 emissions will increase throughout 2100. On the other hand, in the 4.5W/m2 stabilization scenarios, CO2 emissions will peak in 2050, and then decrease. In the reference scenario, the radiative forcing in 2100 will reach about 6.3 W/m2 as shown in Figure 4.2.

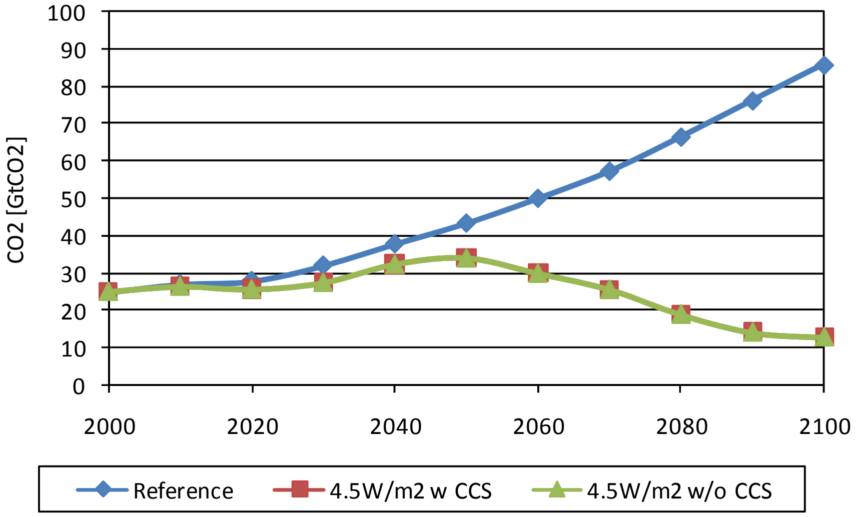


Figure 4.1 Global CO2 emissions results

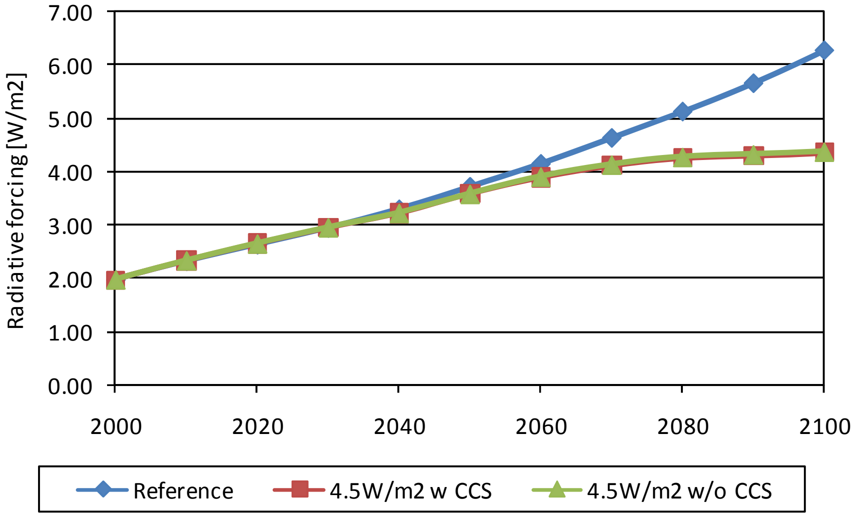


Figure 4.2 Total radiative forcing

In order to reduce the GHG emissions, many countermeasures are introduced. Figures 4.3 and 4.4 represent the global primary energy and the global final energy change in each scenario. In the reference scenario, the global primary energy in 2100 will exceed 1000 EJ. On the other hand, the global primary energy in the stabilization scenarios in 2100 will be about 700 EJ. In the stabilization scenarios, the primary energy supply in the scenario with CCS will be more than that in the scenario without CCS, because the CCS can reduce the CO2 emissions from the large scale fossil fuels combustion plants as shown in Figure 4.5. The CCS capital will be installed after 2050. In the stabilization scenario without CCS, more renewable energy will have to be introduced instead of fossil fuels. Figure 4.6 represents the mix of the primary energy supply. In the stabilization scenario with CCS, the share of renewable energy will be expanded, especially in wind and bioenergy. In the stabilization scenario without CCS, increase of the renewable energy share will be more intense. As a result, the price of CO2 in the stabilization scenario without CCS will be more expensive than that with CCS, as shown in Figure 4.7. The GDP change in 2100 compared to the reference scenario will be -4.6% and -7.0% in the stabilization scenarios with CCS and without CCS, respectively.

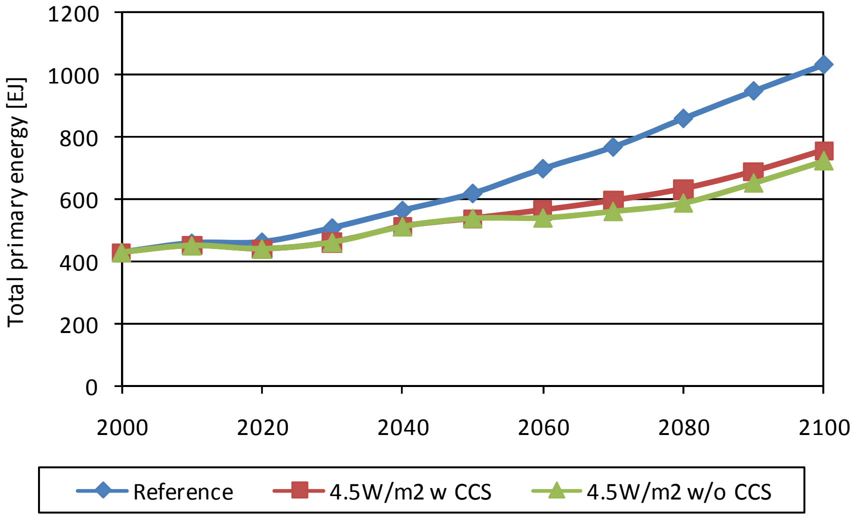


Figure 4.3 Global primary energy supply

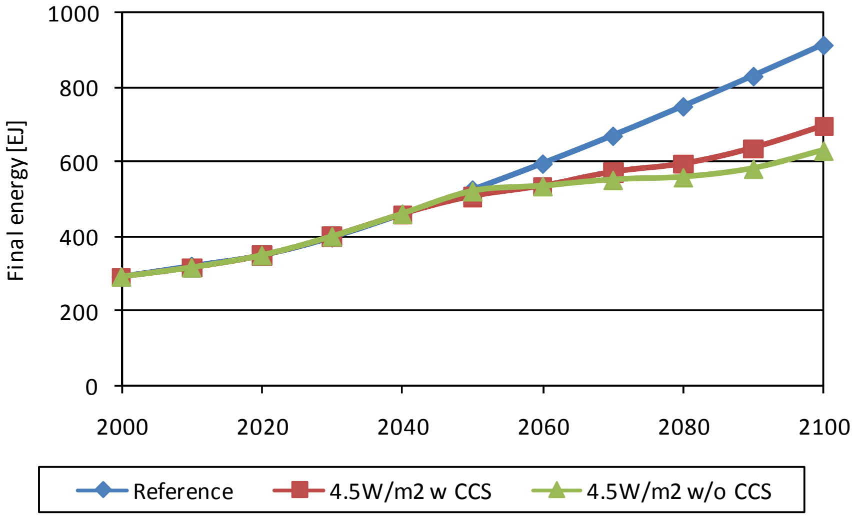


Figure 4.4 Global final energy demand

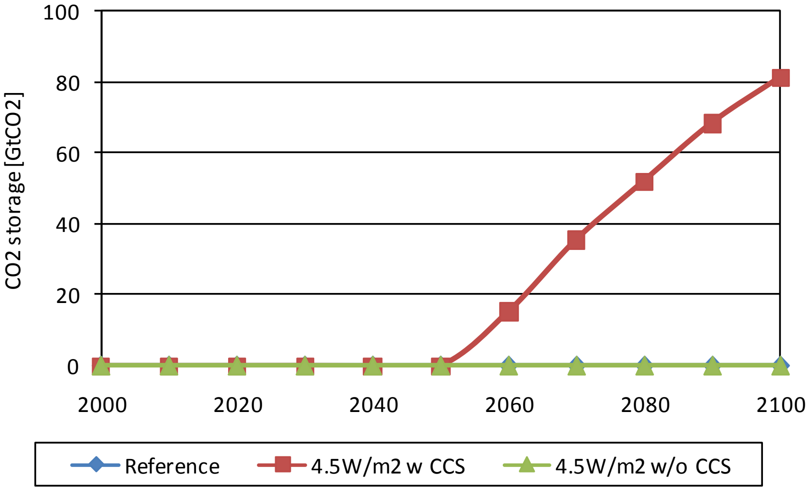


Figure 4.5 Captured CO2 in the world

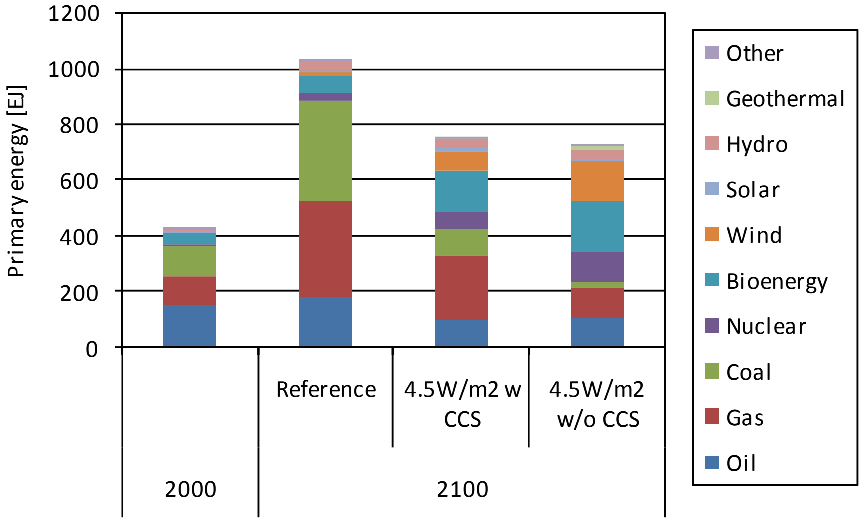


Figure 4.6 Mix of primary energy supply in the world

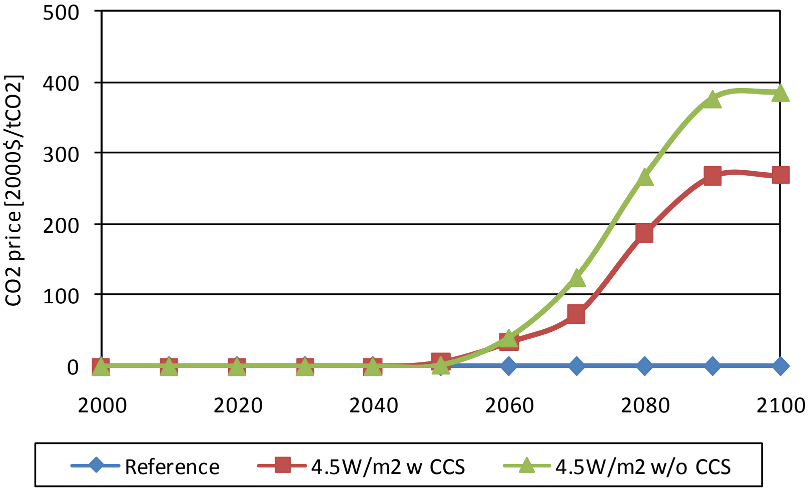


Figure 4.7 Price of CO2

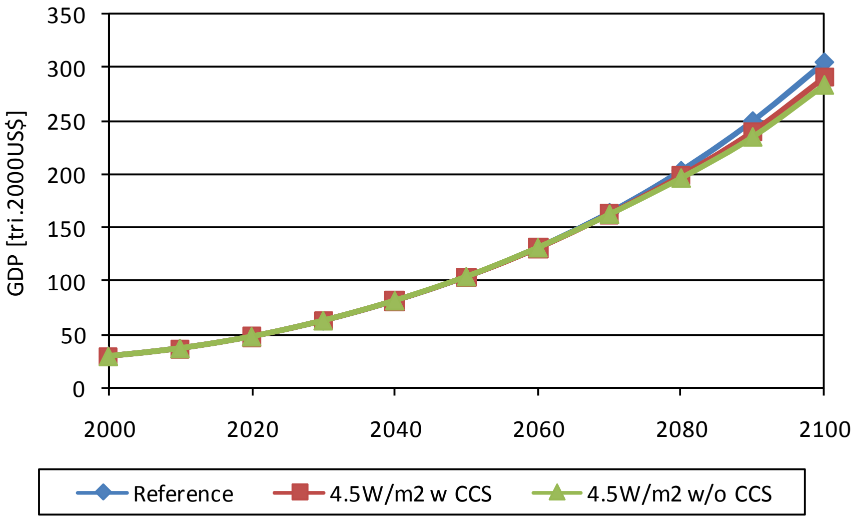


Figure 4.8 Global GDP change

The GDP losses in non-Annex I countries in the stabilization cases will be larger than those in Annex I countries as shown in Figure 4.9, because a global emission market is assumed in these simulations. Although allocations of CO2 emissions in Annex I countries will be smaller than those in non-Annex I countries, the real CO2 emissions in Annex I countries will be more because of purchase of emission rights. If the global emission market is not assumed, the carbon price in Annex I countries will increase, and consequently, the GDP loss in these countries will be more severe.

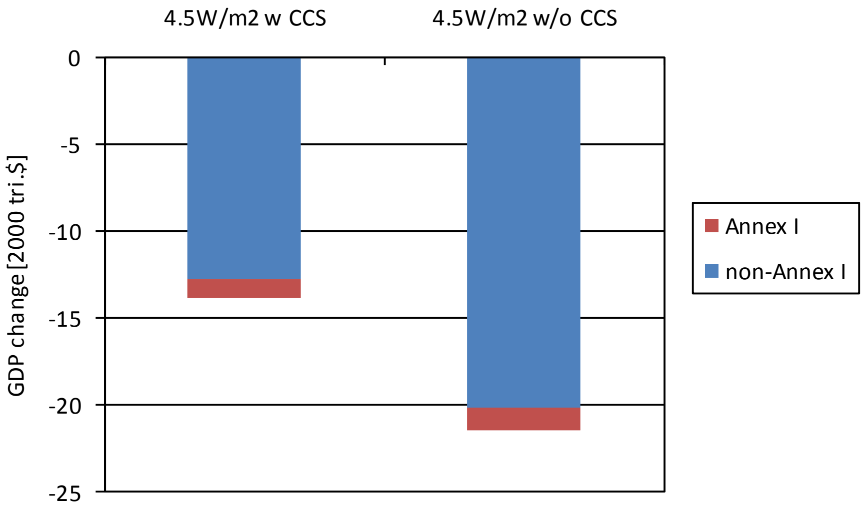


Figure 4.9 Breakdown of GDP change by regions

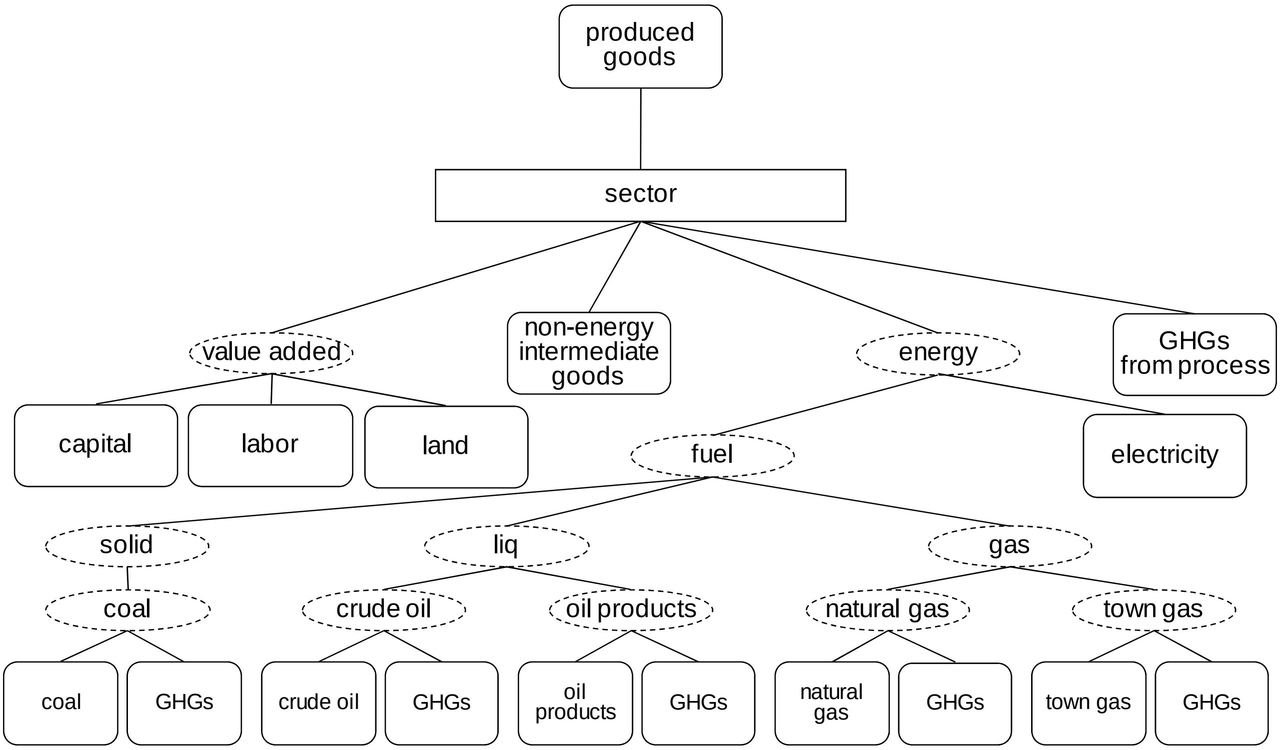
5. Conclusion

In this paper, the stabilization scenarios at 4.5 W/m2 of radiative forcing are examined. Compared to the reference scenario, the stabilization scenarios will require more renewable energies. If the

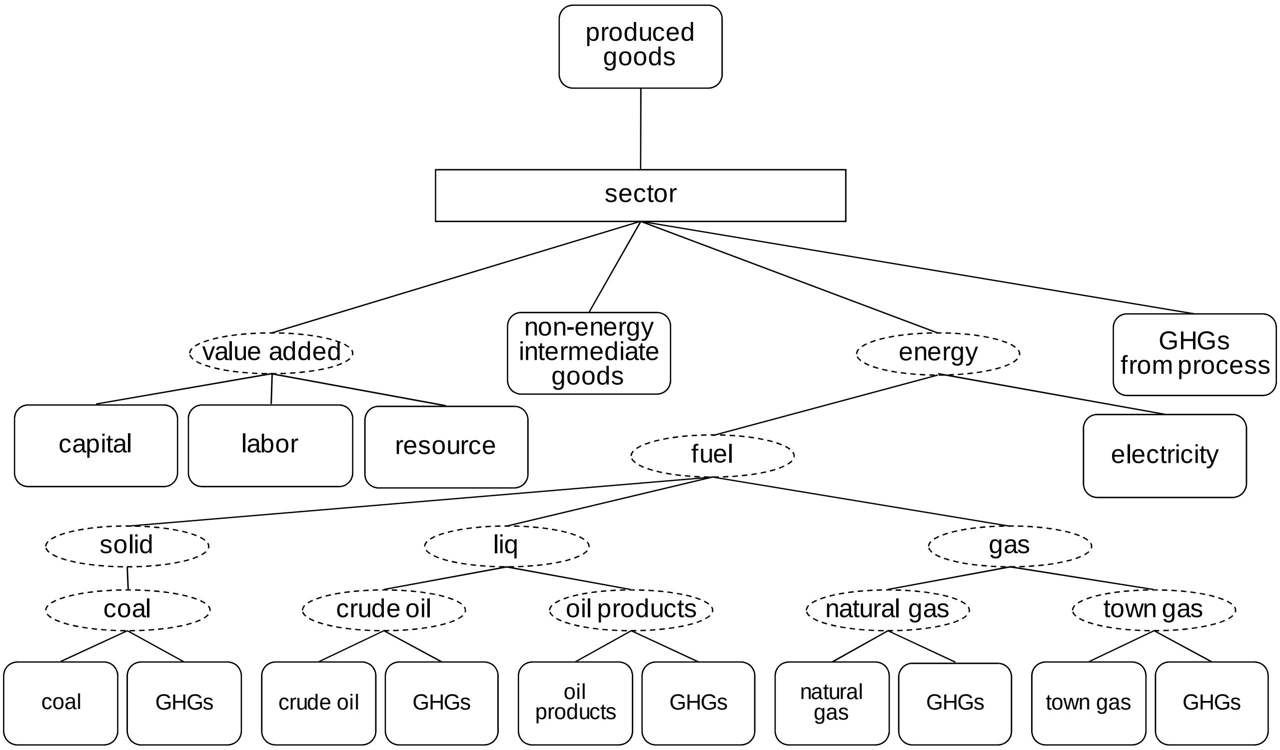
CCS technologies are not introduced, furthermore renewable energies will have to be introduced to achieve the stabilization target. As a result, the economic impacts will be more severe. In order to avoid severe economic impacts, all possible countermeasures will have to be prepared. In this case, involvement of the developing countries in mitigation will become necessary, as they have a starting disadvantage of technologies and requirement of more rapid economic growth as compared with the developed countries.

Appendix: Production structure in AIM/CGE[Global]

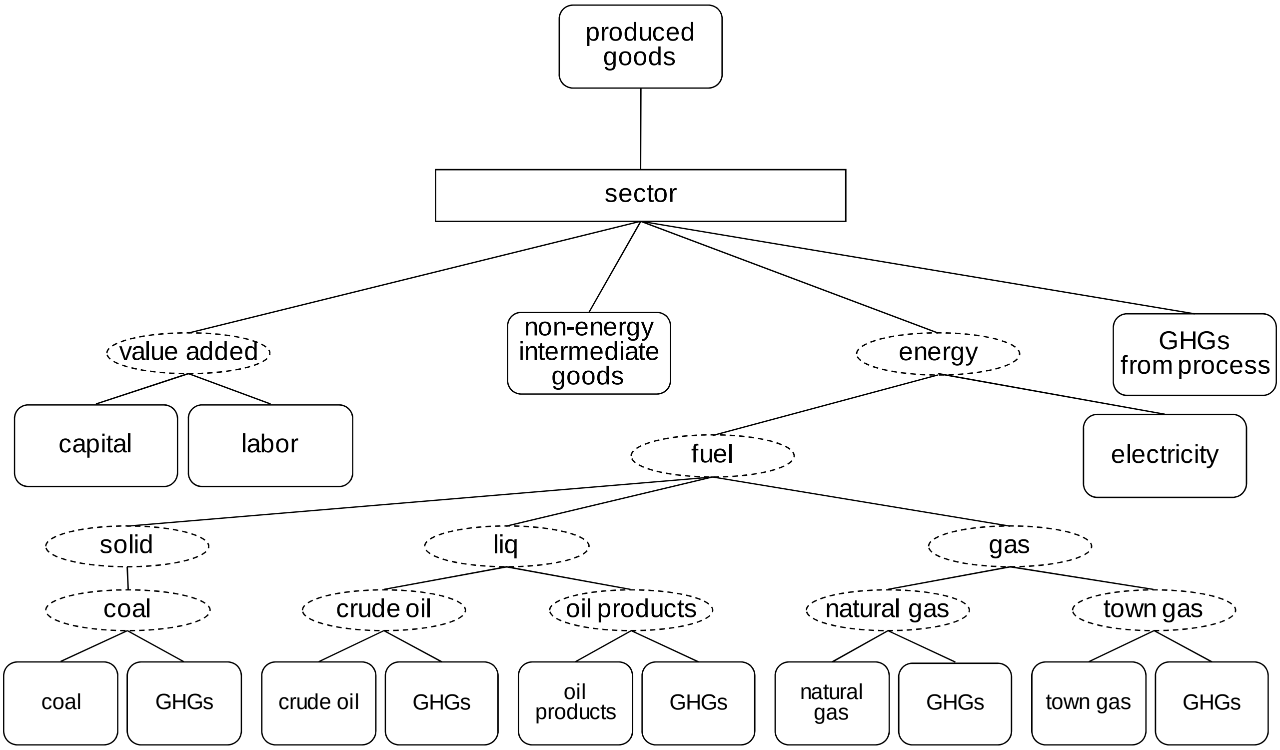
(1) Production structure using land



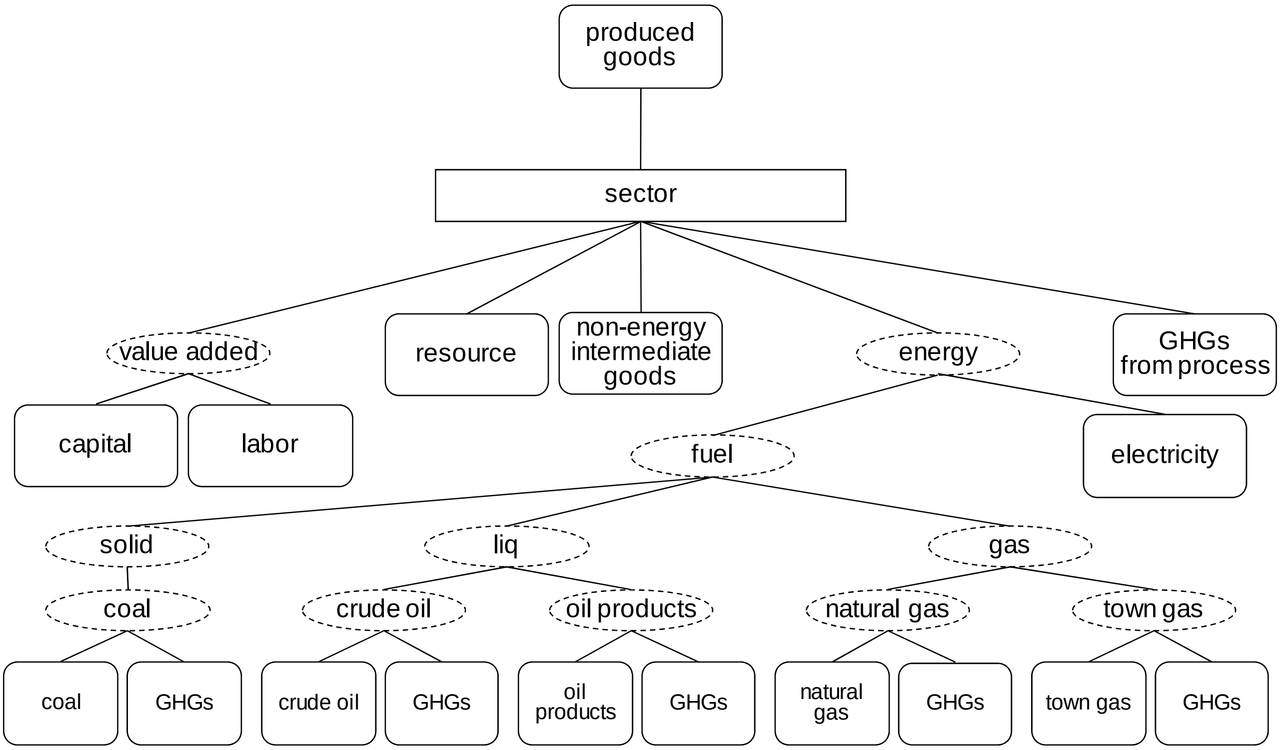
(2) Production structure using non-fossil resources



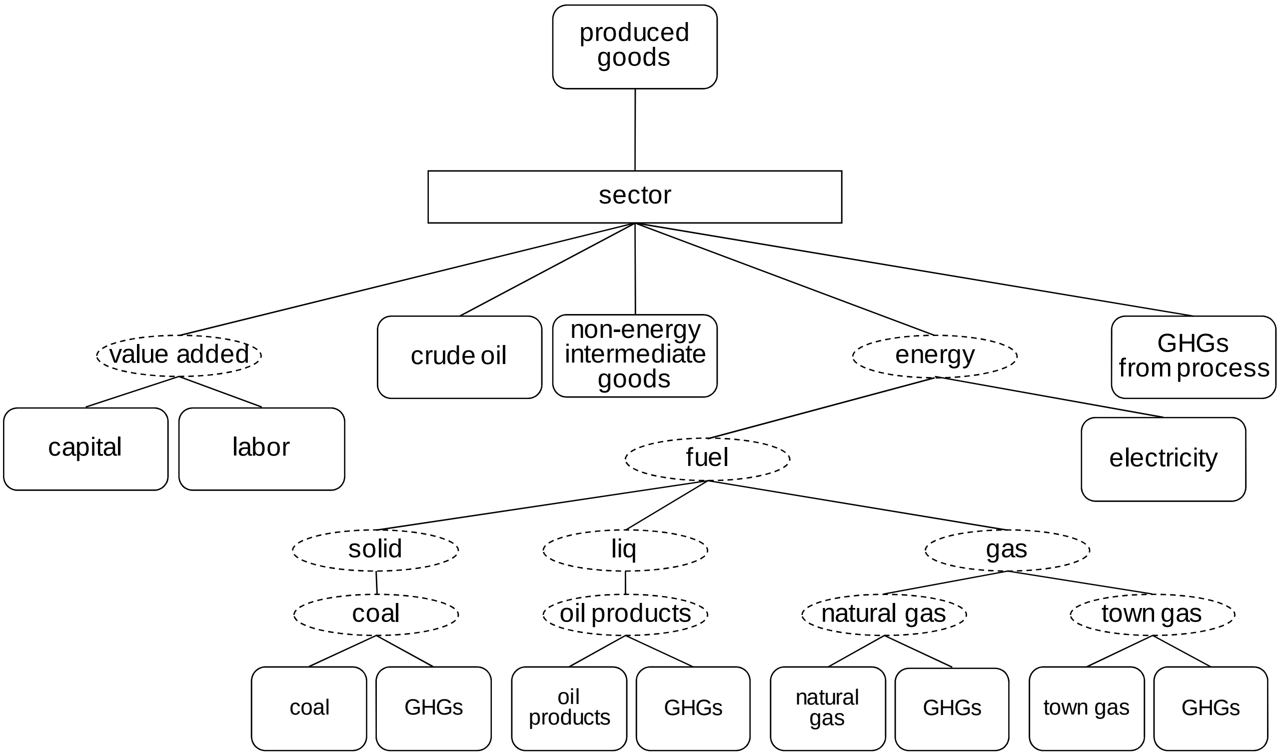
(3) Production structure in manufacturing and service sectors



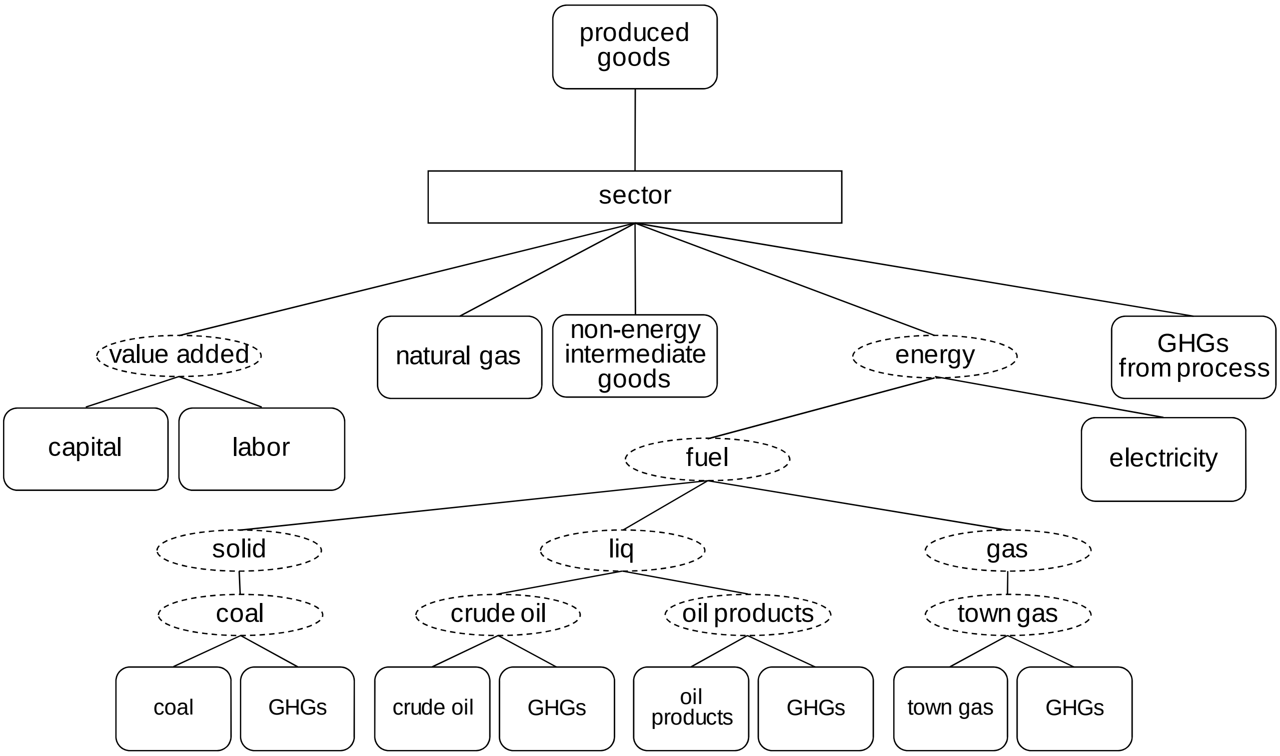
(4) Production structure in fossil fuels extraction



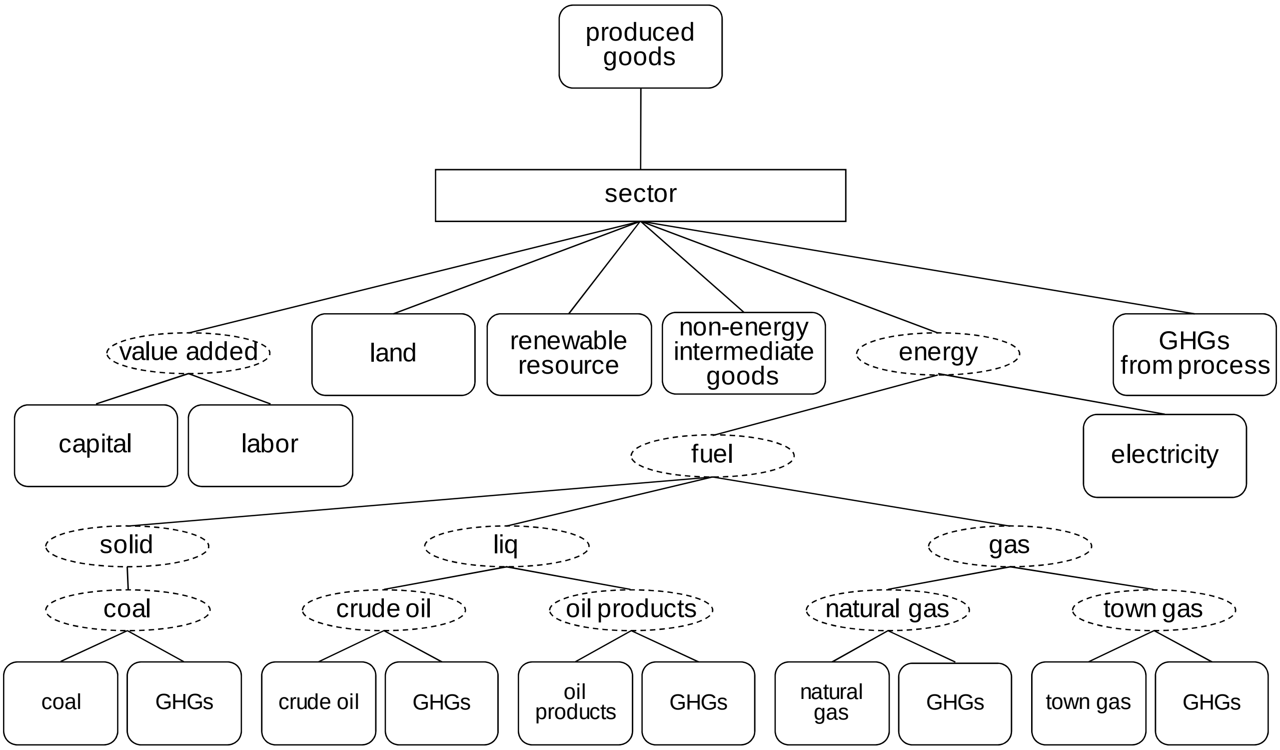
(5) Production structure in petroleum products



(6) Production structure in gas production and distribution



(7) Production structure in power sectors



notes: Individual power sectors have different structures.

Biomass power sector takes land as an input.

Other renewable sectors take the input of corresponding renewable resources.

A thermal power sector takes corresponding fossil fuel as input.