Long-Term Global Energy Strategy for Stabilizing Atmospheric CO_2 Concentration with Focus on the Potential Role of Hydrogen

T. Takeshita, K. Yamaji, and Y. Fujii

The University of Tokyo, Japan

Phone & FAX: +81-3-5841-6740

E-mail: taka@yamaji.t.u-tokyo.ac.jp

Presented at the 24th USAEE/IAEE North American Conference

Capital Hilton Hotel, Washington D.C., July 8-10, 2004

Outline of the Presentation

- **Introduction**
  - Background
  - Research objective
- **Methodology**
  - Model structure
  - Data set
- **Results and Discussion**
  - Simulation results
  - Discussion
- **Summary**

Background and Research Objective

- **Background**
  - Increasing contribution of the transportation sector to the problems of oil resource dependence and CO_2 emissions
  - Various ideas raised to address this issue, e.g., H_2 fuel cell vehicles
  - Very few global energy model analyses on the potential role of various options in the transportation sector under the atmospheric CO_2 concentration constraint
- **Research objective**
  - To examine the optimal global energy strategy for stabilizing the atmospheric CO_2 concentration at 550ppm by 2100 with focus on a potential role of hydrogen using a regionally disaggregated global energy model with a detailed transportation sector
  - Furthermore, the following issues are addressed under the same CO_2 constraint:

    (1) Optimal combination of the technological options in the transport sector

    (2) Optimal patterns of the production, transportation, and use of hydrogen,

Overview of the REDGET

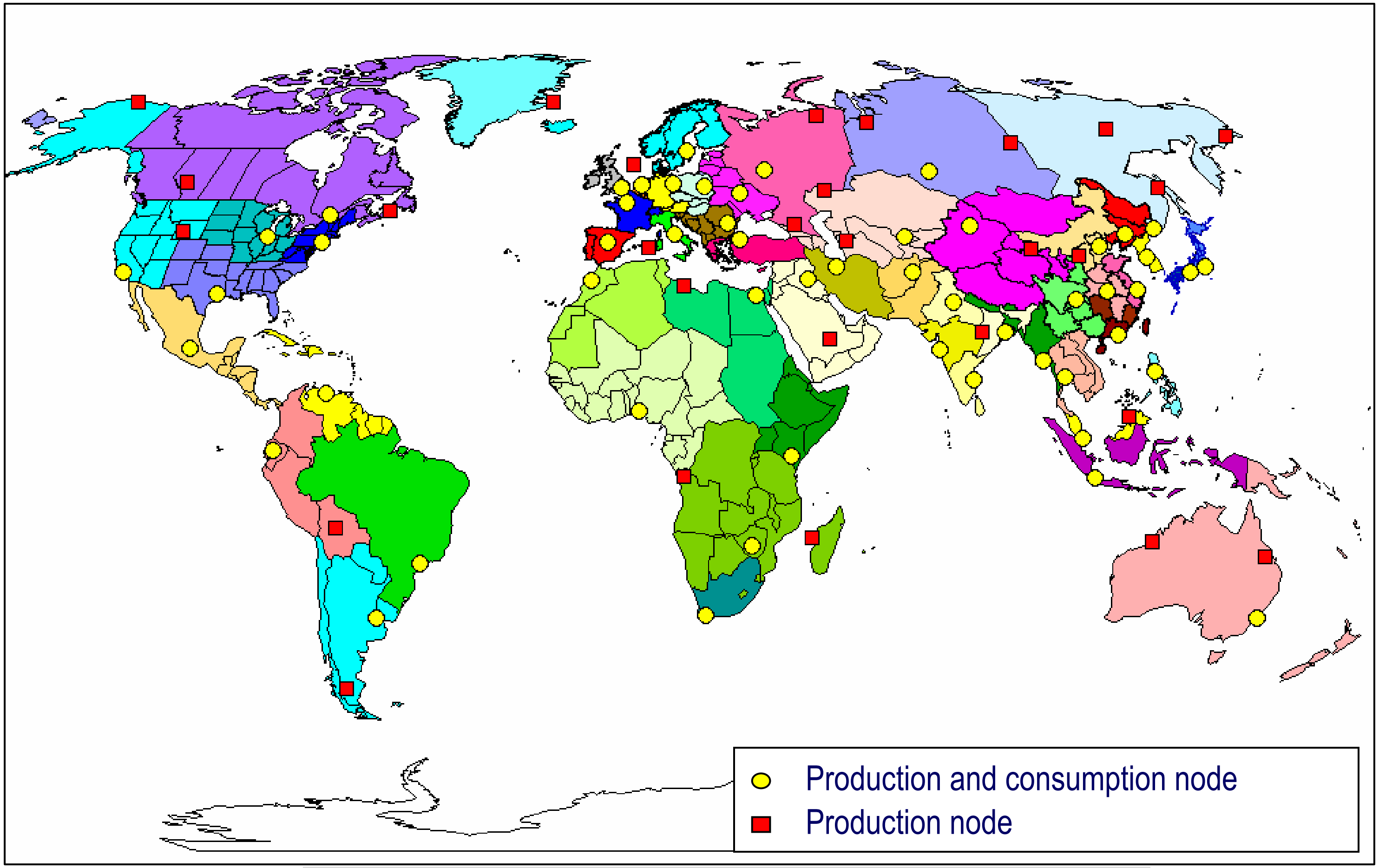
- **Fundamental characteristics of the REDGET**
  (**RE**gionally **D**isaggregated **G**lobal **E**nergy model with a detailed **T**ransportation sector)
  - Bottom-up type global energy system model formulated on the basis of the linear programming (LP) technique
  - One that is designed to determine the optimal growth path of the global energy system (i.e., the optimal combination of the technological options over time) that minimizes the total discounted cost under several constraints
  - Time horizon: 2000-2100 at 10-year intervals
  - Discount rate: 5%
  - Final energy demand: IIASA/WEC B scenario

- **Notable features of the REDGET**
  - Explicit consideration of various technological options
  - Ability to determine the optimal energy transportation patterns
    (Detailed regional breakdown and treatment of various energy transportation options)
  - Detailed specifications of the transportation sector and the fuel supply for this sector

Regional Disaggregation

Detailed regional disaggregation (82 regions)

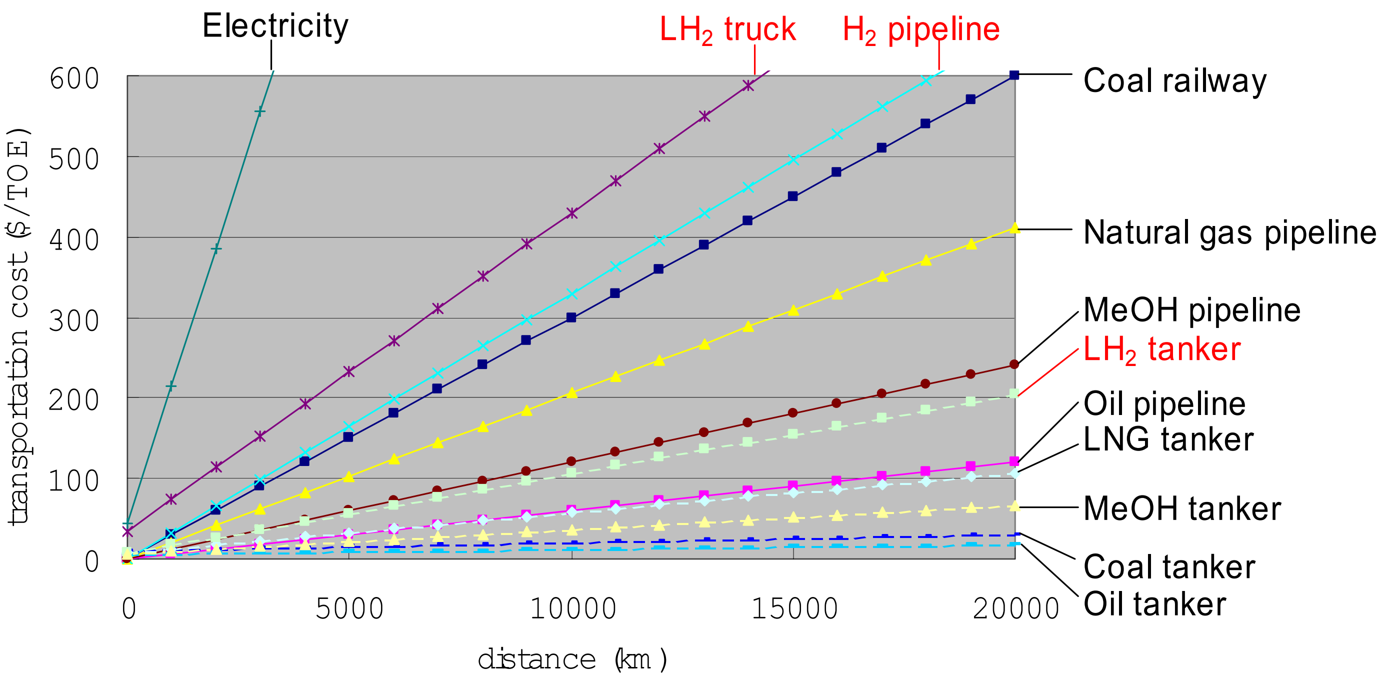
- an ability to determine the concrete picture of energy transportation



Regional breakdown of the REDGET

Modeling of Energy Transportation

- **Modeling of various energy transportation options in the REDGET**
  - Possible transportation routes defined in advance of model simulations
    - Land transport routes are given to the couple of nodes that are close to each other, and sea transport routes are given to every couple of the nodes with sea ports.
    - Concrete paths and their distances are set for each transport route by solving the shortest-path problem taking into consideration land use condition and land height.
    - Distances of the possible routes are calculated assuming the earth as a complete globe.
  - Separate treatment of fixed capital cost ($/(TOE/yr)) and variable cost ($/TOE)

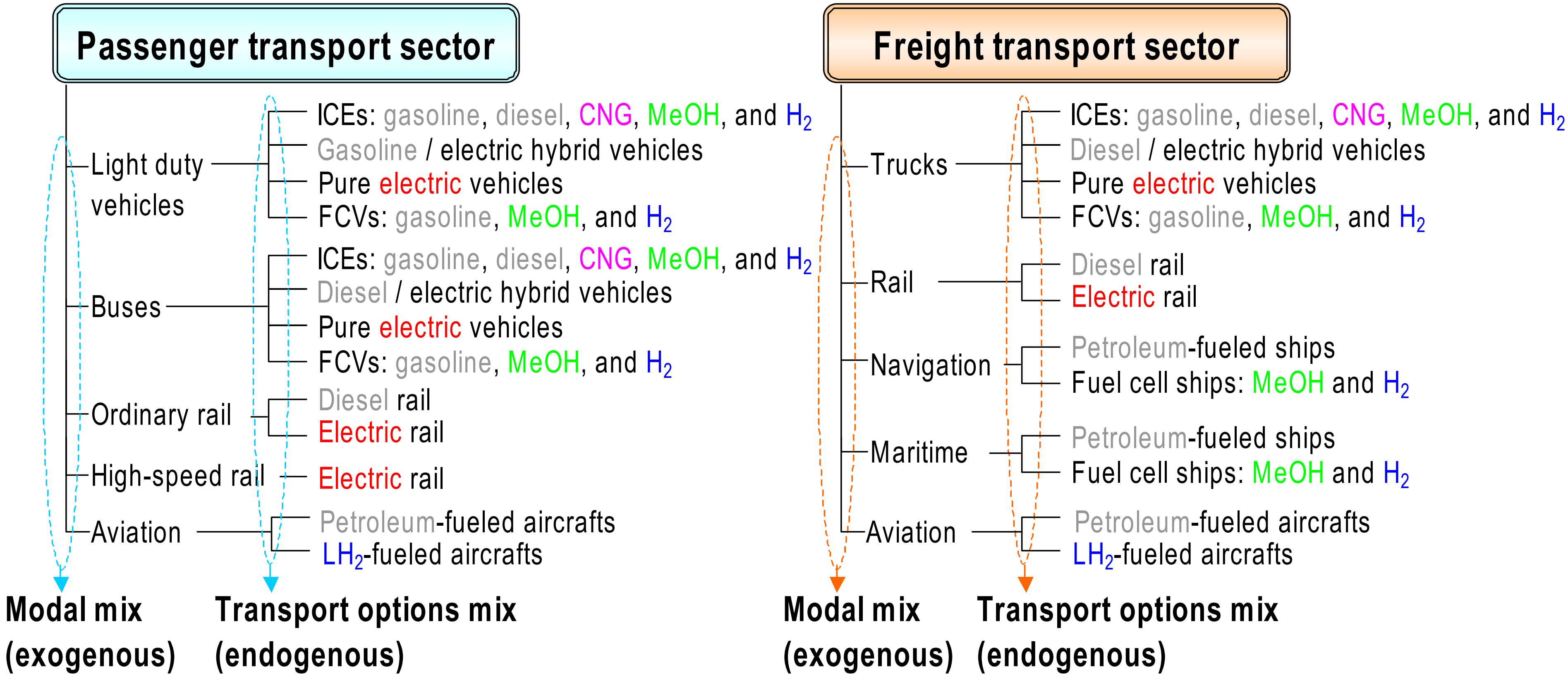


Unit transportation cost data in the REDGET

Modeling of the Transportation Sector

Detailed specification of the transportation sector

- an ability to determine the optimal combination of transport options to develop a sustainable transport sector that can mitigate oil shortage and climate change

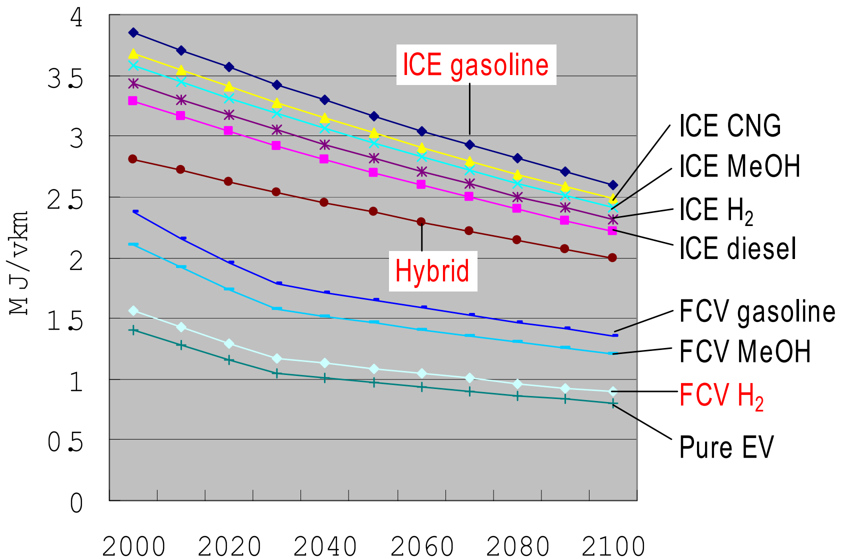


Specification of the transportation sector in the REDGET

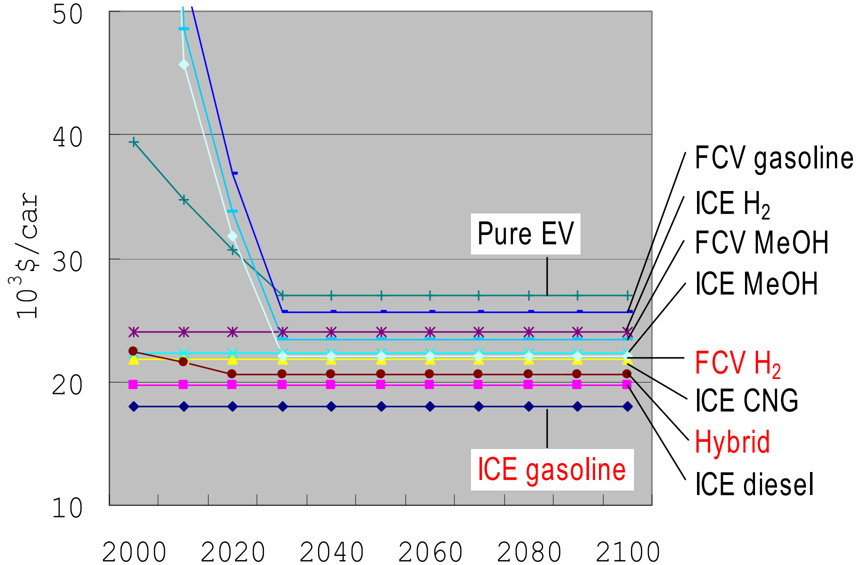
The optimal mix of options determined to minimize the total cost of the transport sector (capital, fuel, and distribution cost) under a given activity and constraints.

Data Set for the Transportation Sector

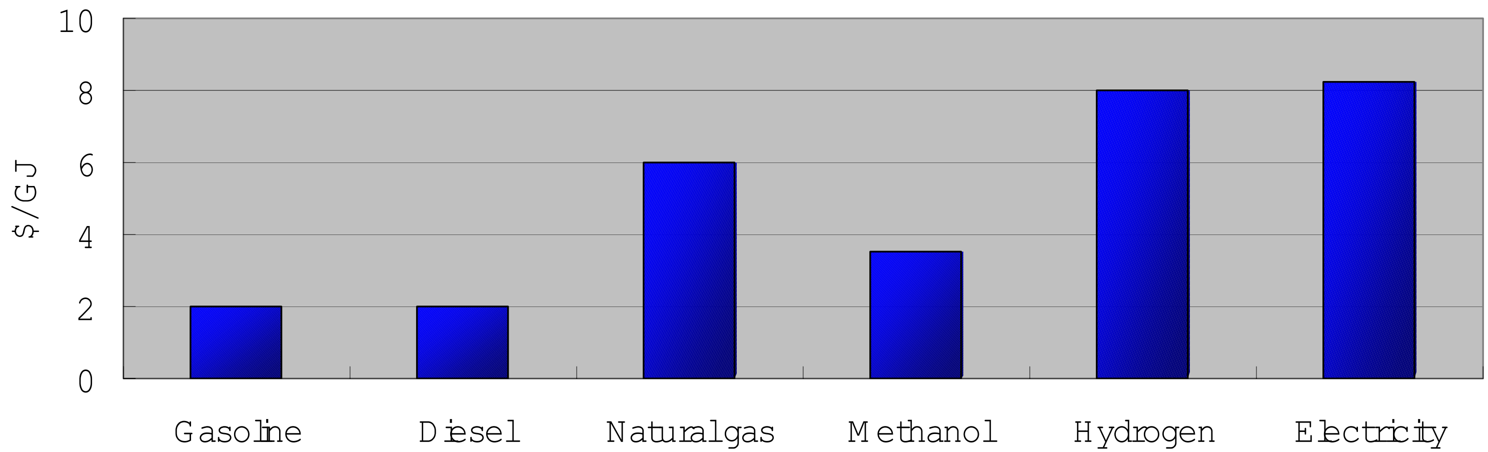
- Example of the data sets for the transportation sector



Estimated on-road fleet average fuel economy of LDVs for each drivetrain type



Estimated capital cost of LDVs for each drivetrain type

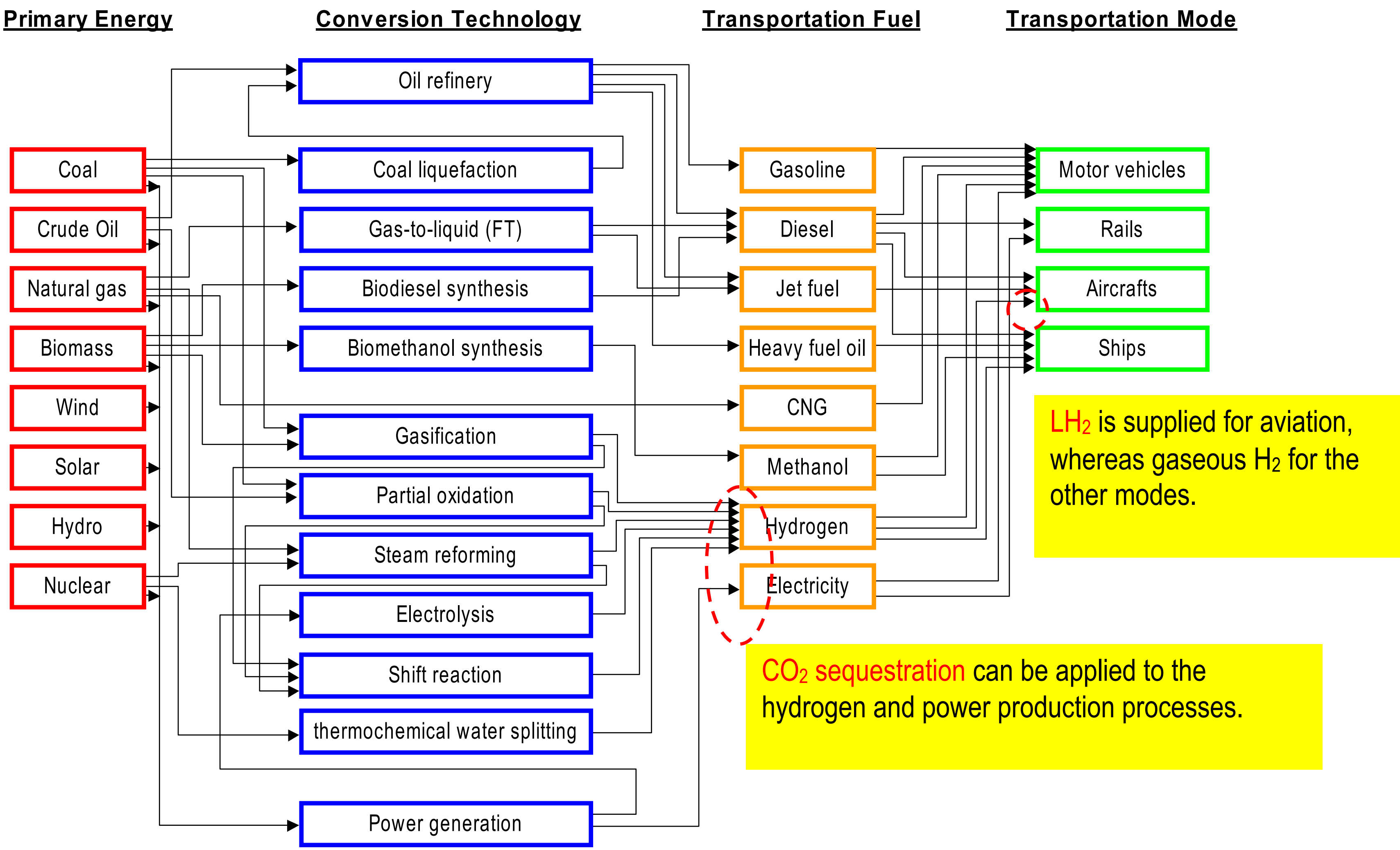


Estimated local distribution and refueling cost for each fuel

Modeling of Fuel Supply for Transportation

Detailed specification of the fuel supply for the transport sector

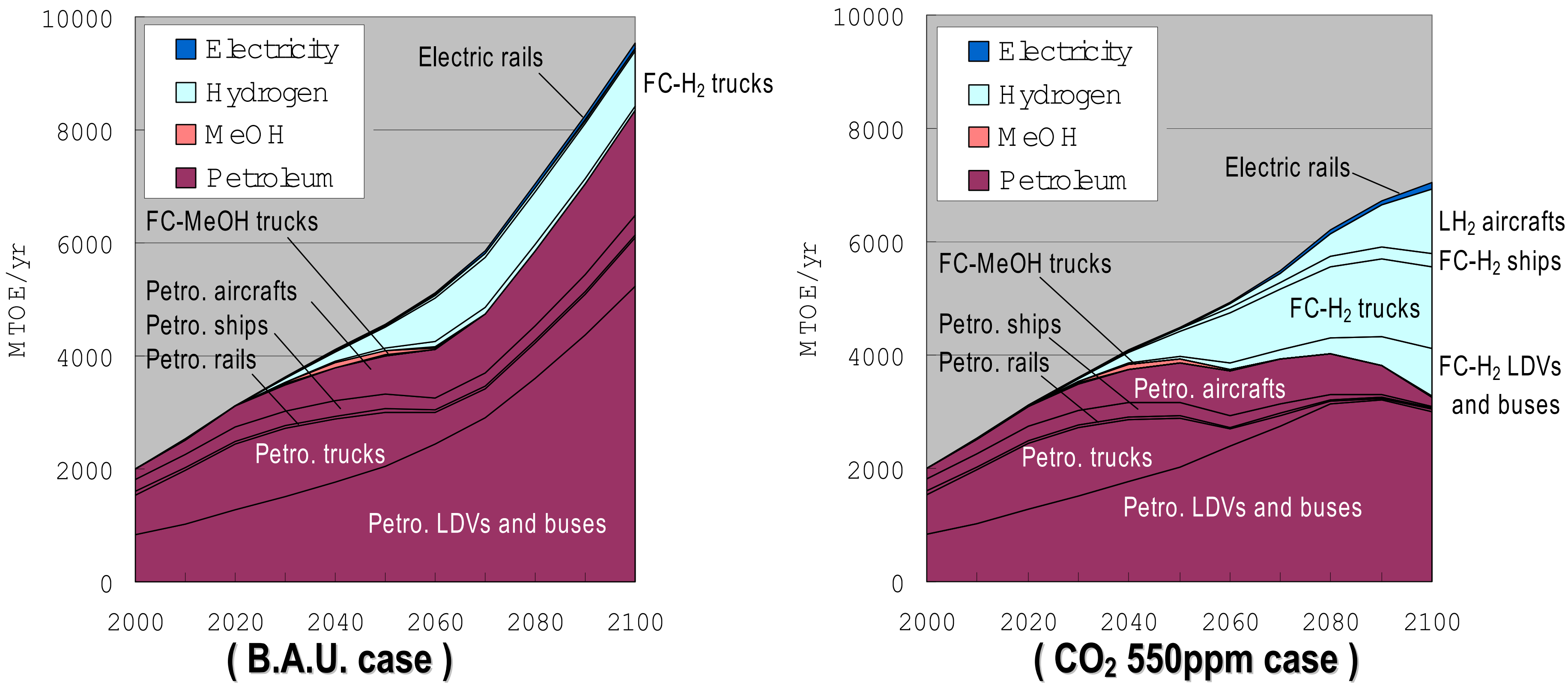
- an ability to determine the optimal fuel supply pattern for a sustainable transport sector



Specification of the fuel supply for the transportation sector in the REDGET

Optimal Mix of Transport Options

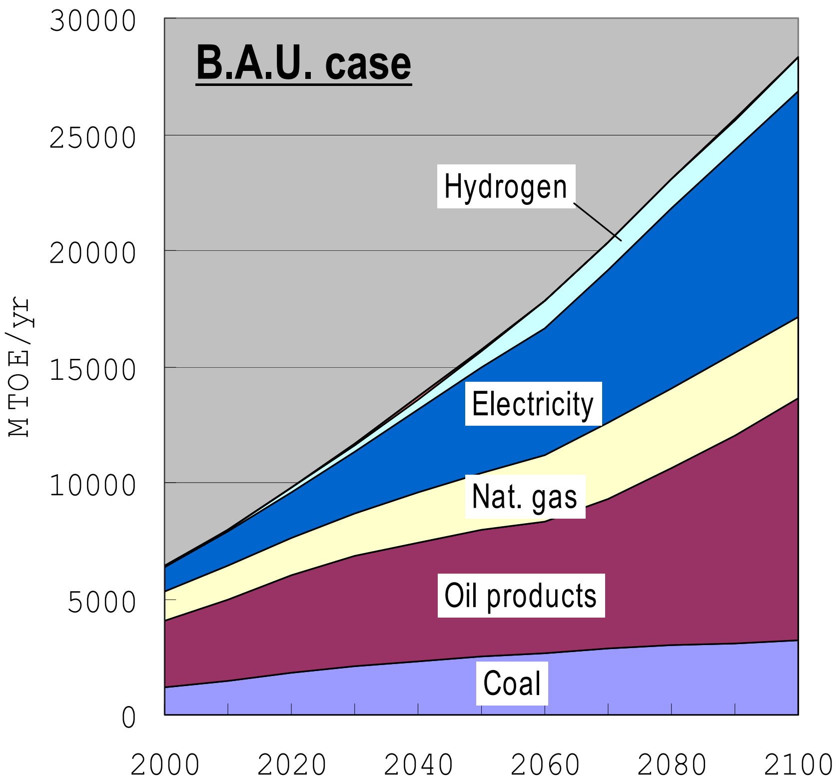
- Utilization of hydrogen and electricity in place of petroleum products is promoted to stabilize the atmospheric CO_2 concentration, which also leads to a significant improvement in the energy efficiency in the transportation sector.
- Introduction of hydrogen FCV is more attractive for freight trucks than for LDVs because of the larger share of fuel costs in the total life-cycle costs of truck utilization.

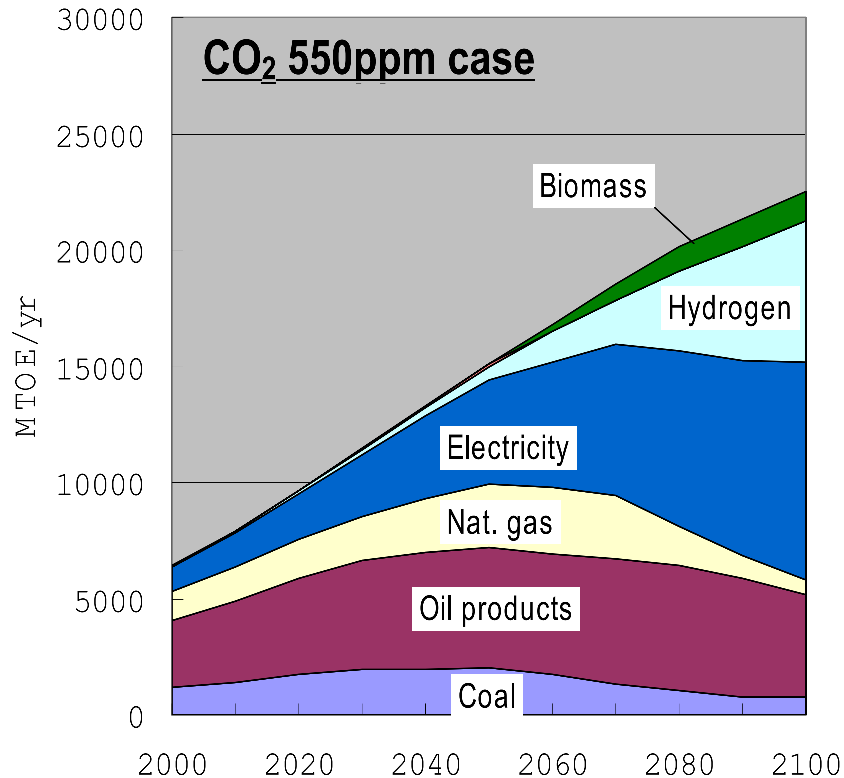


Global energy consumption in the transportation sector in the B.A.U. and CO_2 550 ppm cases

Optimal Mix of Final Energy

- Hydrogen plays an important role in the desirable future global energy system that can stabilize the global atmospheric CO_2 concentration, which replaces the roles of oil products and natural gas.
- Hydrogen begins to make a visible contribution from the latter half of this century.

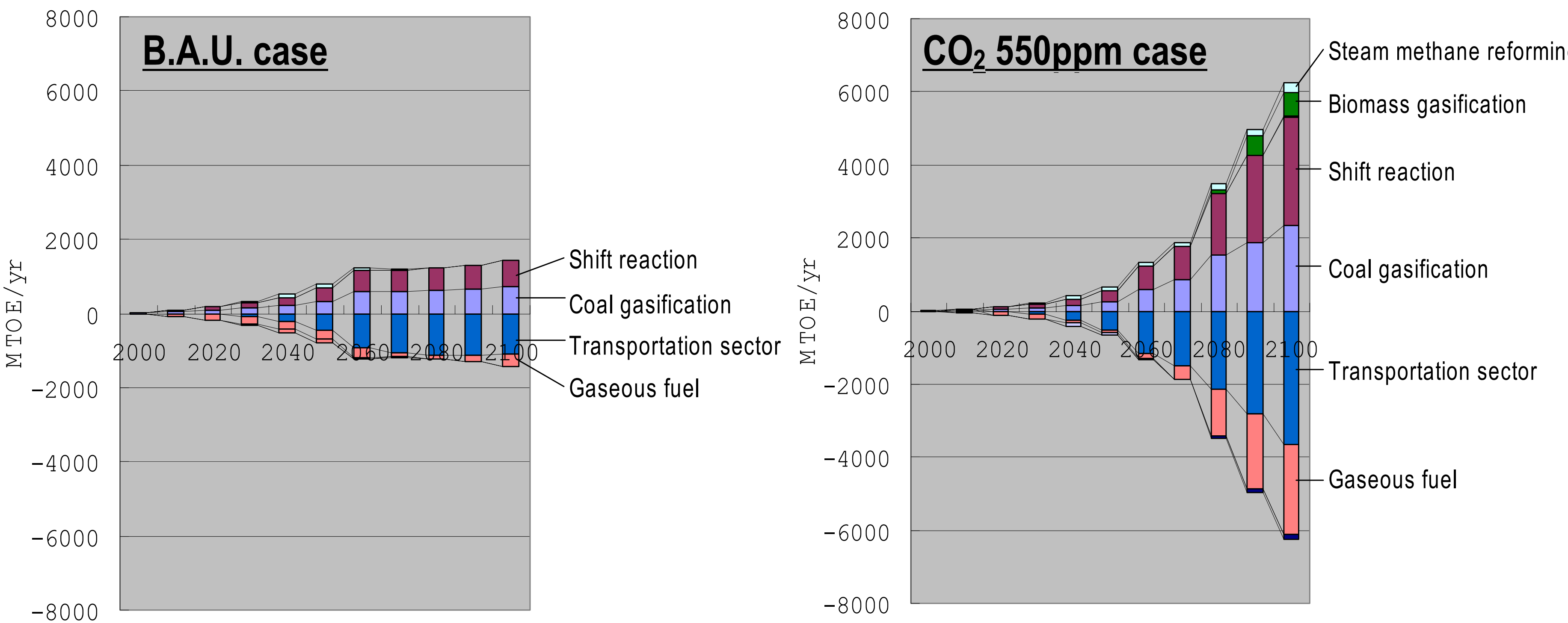




Optimal composition of global final energy consumption in the B.A.U. and CO_2 550 ppm cases

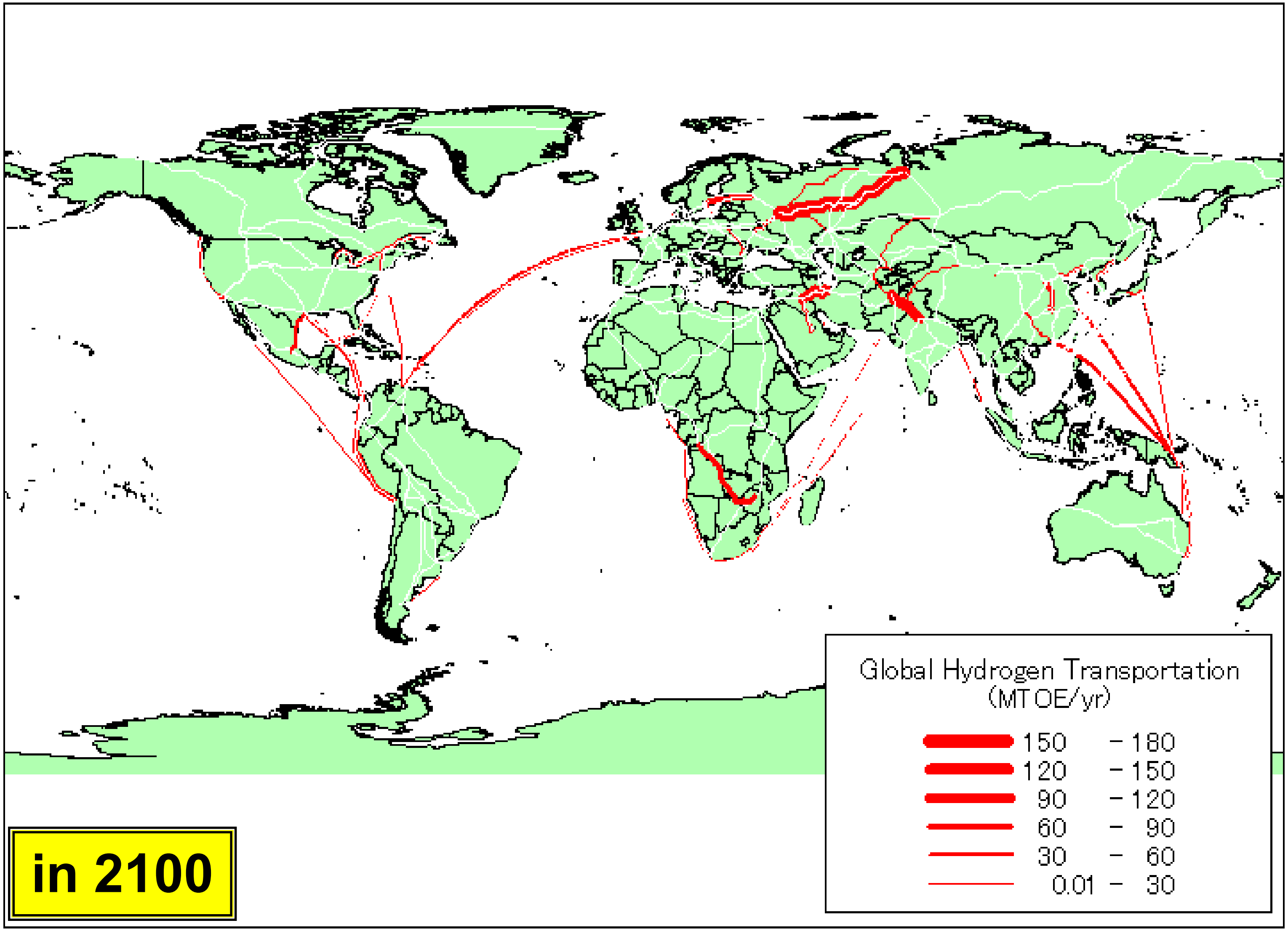
Optimal Production and Use of Hydrogen

- Despite of its high capital cost, not natural gas but coal (with CO_2 sequestration in the CO_2 550 ppm case) is the most promising hydrogen production option due to its low fuel and transportation costs.
  (implying that the economics of energy transportation significantly affects the economic competitiveness of feedstocks for hydrogen production)
- Transportation sector generates a very large demand for hydrogen, compared with other end-use sectors.



Optimal global hydrogen supply-demand balance in the B.A.U. and CO_2 550 ppm cases

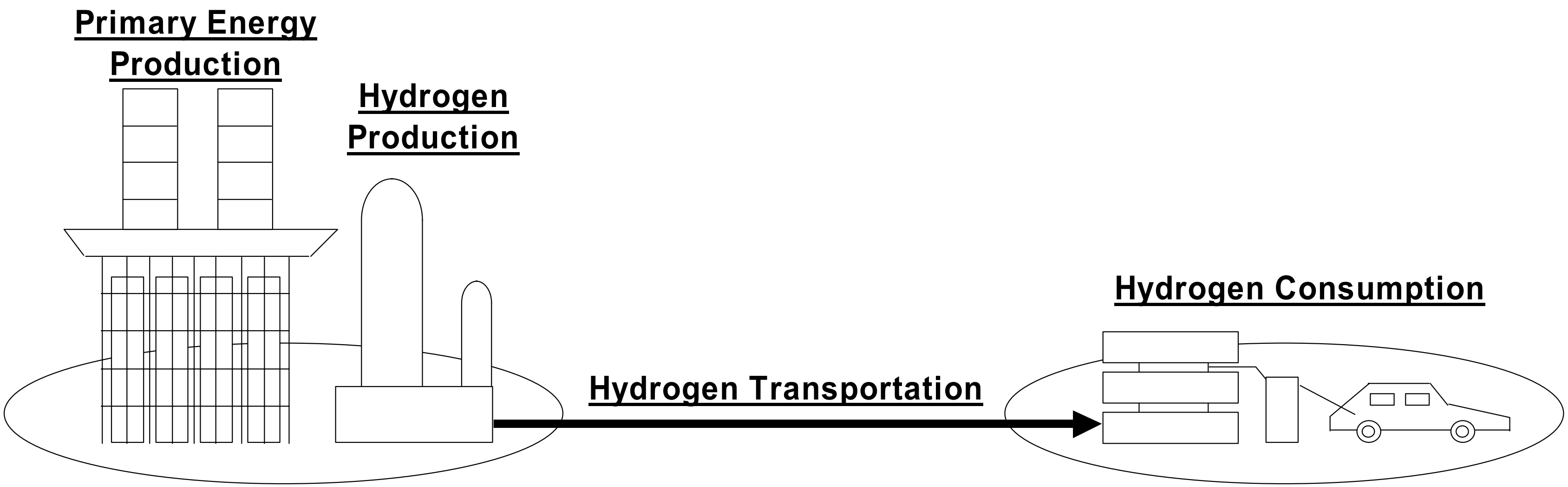
Optimal Hydrogen Transportation Pattern



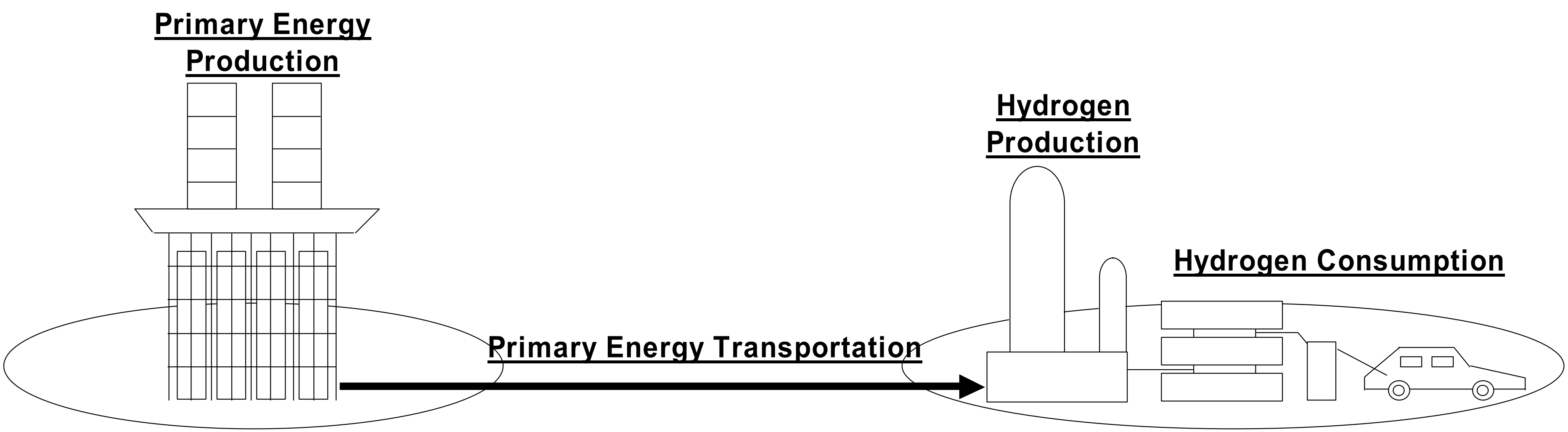
Optimal pattern of global hydrogen transportation in the CO_2 550 ppm case

Transport of Hydrogen or Its Feedstock (1)

(Option 1) H_2 production at primary energy production sites and long-distance H_2 transportation



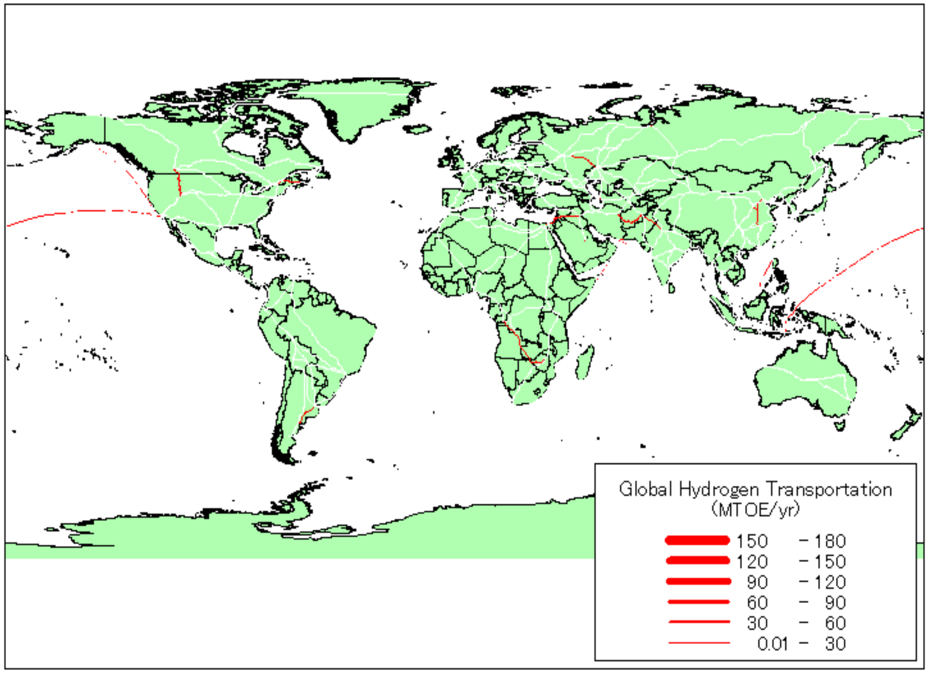
(Option 2) Long-distance primary energy transportation and local H_2 production



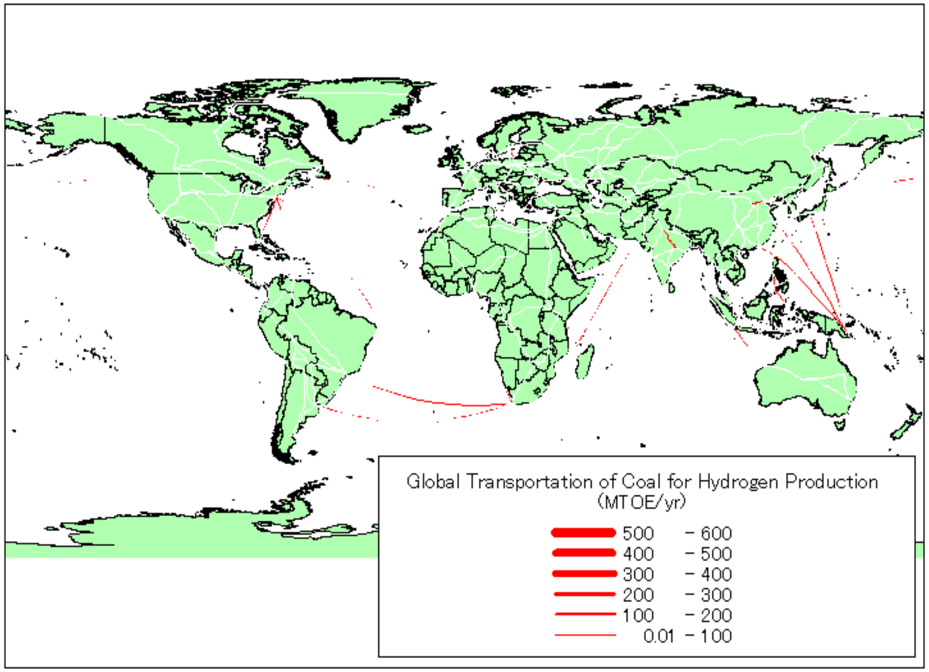
Transport of Hydrogen or Its Feedstock (2)

CASE 1. Period of very small (or even no) LH_2 demand

- Appropriate role of each transportation option can be identified:
  - Hydrogen transportation preferable for short-distance pipeline transportation by land
  - Coal transportation preferable for long-distance transportation by sea
- The reason is that although sea transportation is necessary for a long-distance transportation, liquefaction and regasification is required for LH_2 sea transportation.



Optimal pattern of hydrogen transportation in 2050 in the CO_2 550 ppm case

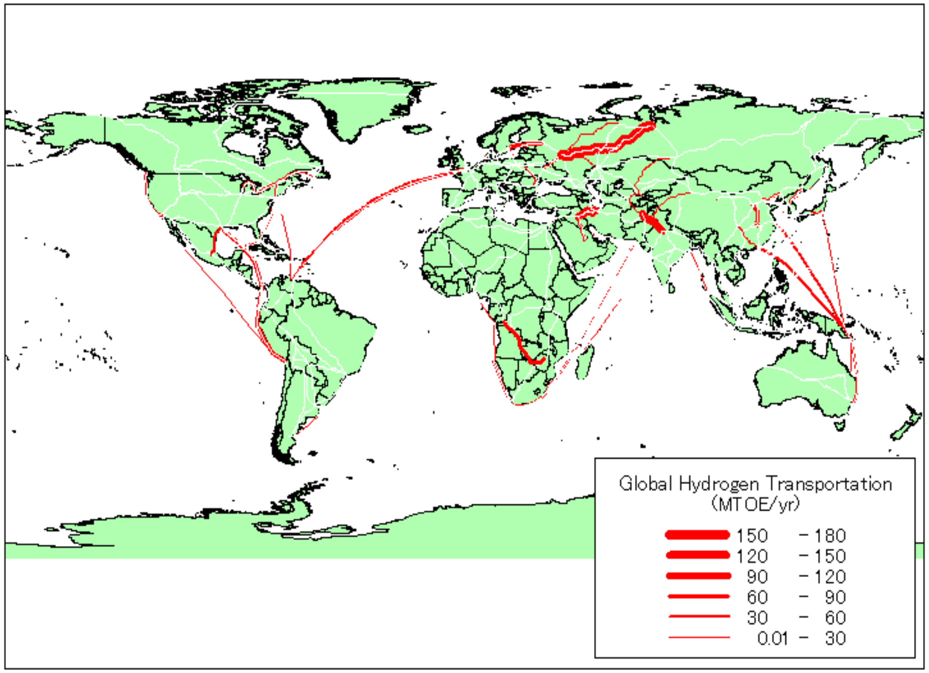


Optimal pattern of coal transportation for H_2 production in 2050 in the CO_2 550 ppm case

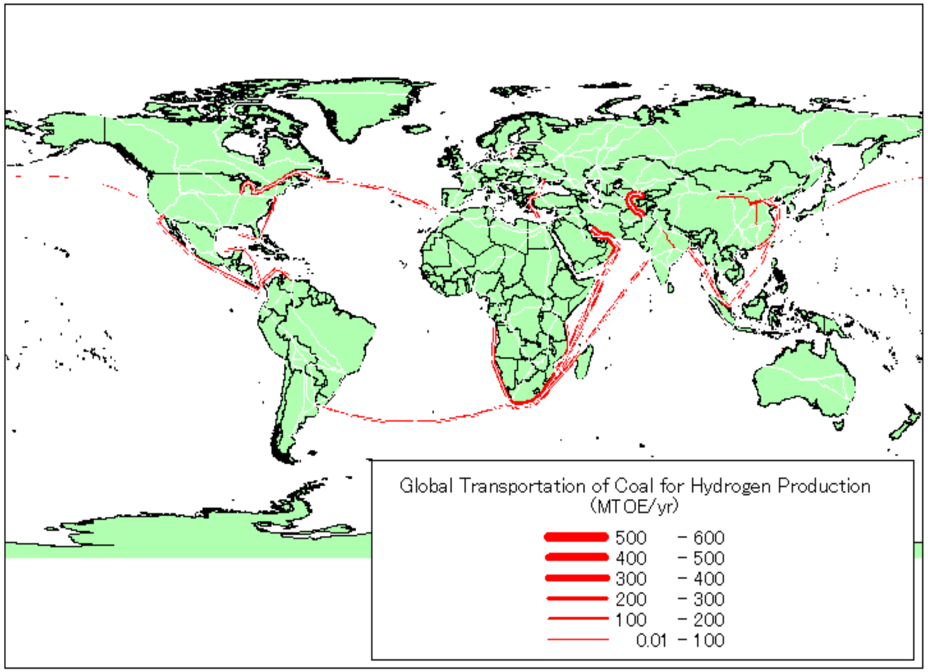
Transport of Hydrogen or Its Feedstock (3)

CASE 2. Period of very large LH_2 demand

- LH_2 sea transportation becomes more attractive
  - Amount of LH_2 sea transportation is always less than its demand by aviation
  - Previous finding holds for gaseous hydrogen supply: hydrogen transportation for a short-distance one by land; and coal transportation for a long-distance one by sea
- The reason is the increasing LH_2 demand by the aviation sector



Optimal pattern of hydrogen transportation in 2100 in the CO_2 550 ppm case



Optimal pattern of coal transportation for H_2 production in 2100 in the CO_2 550 ppm case

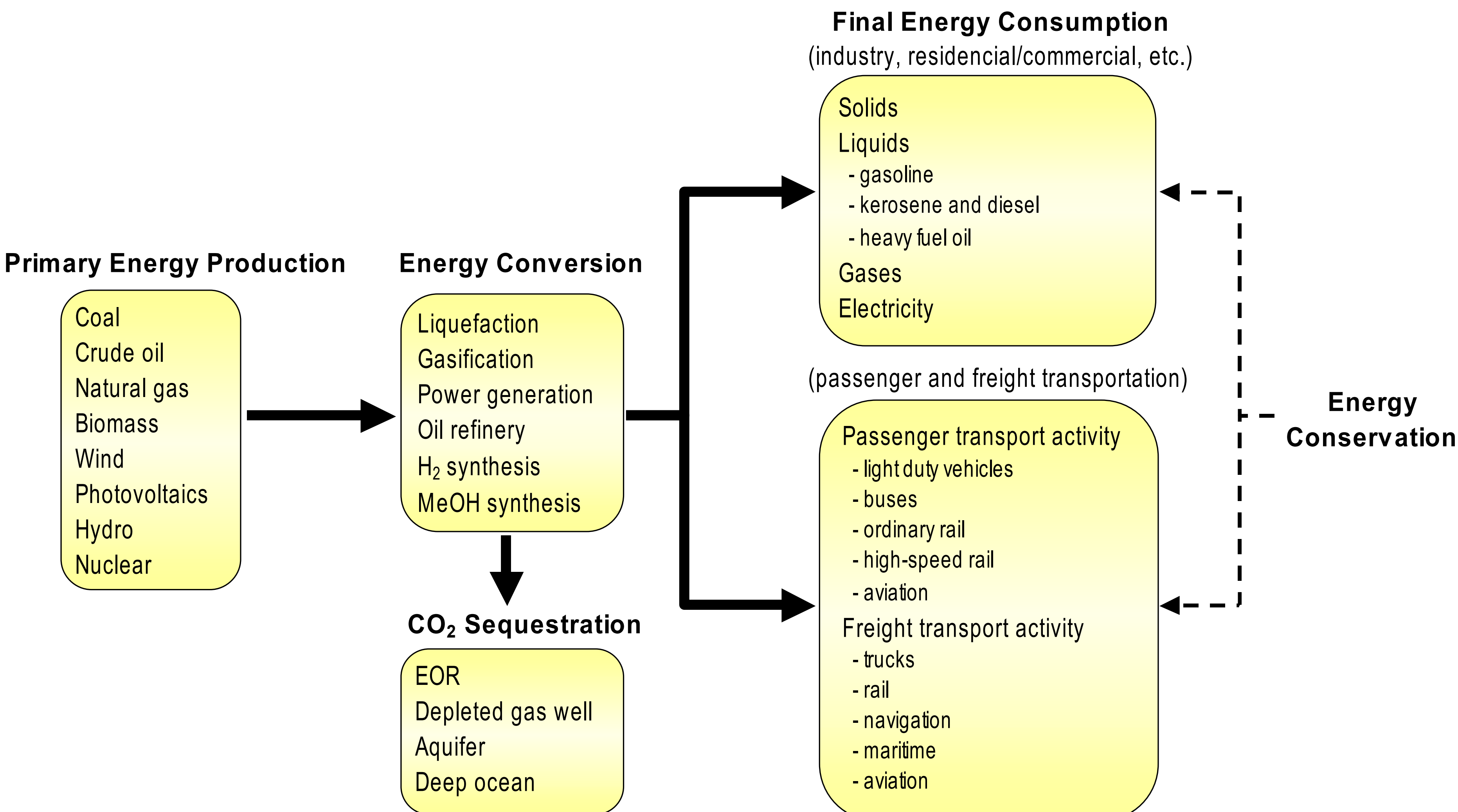
Summary

- **Hydrogen's potential role**: from the latter half of this century, hydrogen can play an important role in the desirable future global energy system that can stabilize the global atmospheric CO_2 concentration.
- **Hydrogen production**: coal is the most promising hydrogen production option due to its low fuel and transportation costs. Coal remains important even under the CO_2 constraint on condition that the CO_2 resulting from coal conversion processes is properly captured.
- **Hydrogen utilization**: a large-scale hydrogen utilization in the transportation sector instead of petroleum products is effective and efficient to stabilize the atmospheric CO_2 concentration, which also leads to a significant improvement in the energy efficiency in this sector.
- **Hydrogen transportation**:
  - In the period of very small LH_2 demand, hydrogen transportation is preferable for a short-distance pipeline transportation by land, and coal transportation is preferable for a long-distance transportation by sea.
  - As the LH_2 demand by the aviation sector increases over time, LH_2 sea transportation becomes more attractive. A long-distance LH_2 transportation option is superior to the on-site H_2 liquefaction, where hydrogen is liquefied for both the purposes of a long-distance sea transportation and LH_2 consumption by the aviation sector.
- **A detailed analysis of hydrogen transportation on a global basis is a new contribution of this model study**.

Structure of the REDGET

Consideration of various technological options

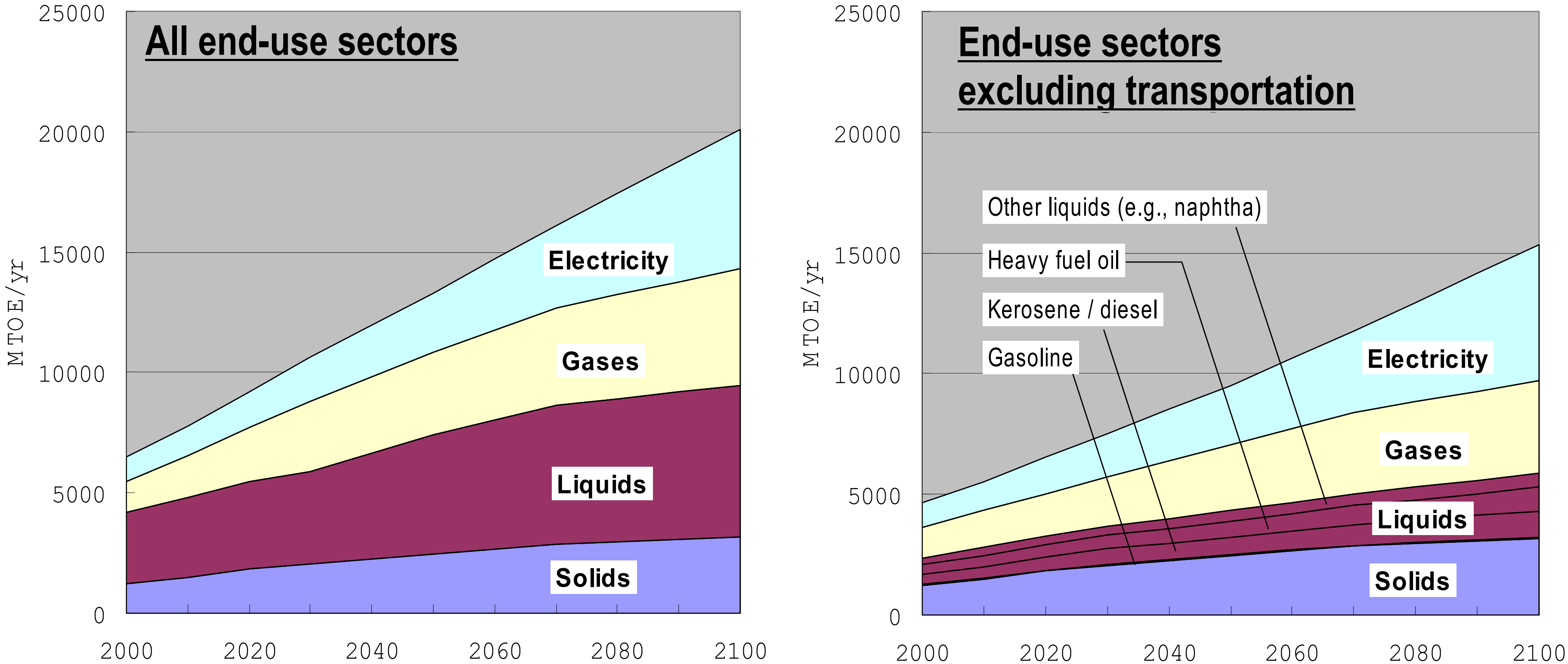
an ability to conduct a detailed technology assessment



Schematic diagram of the REDGET

Final Energy Demand Estimation

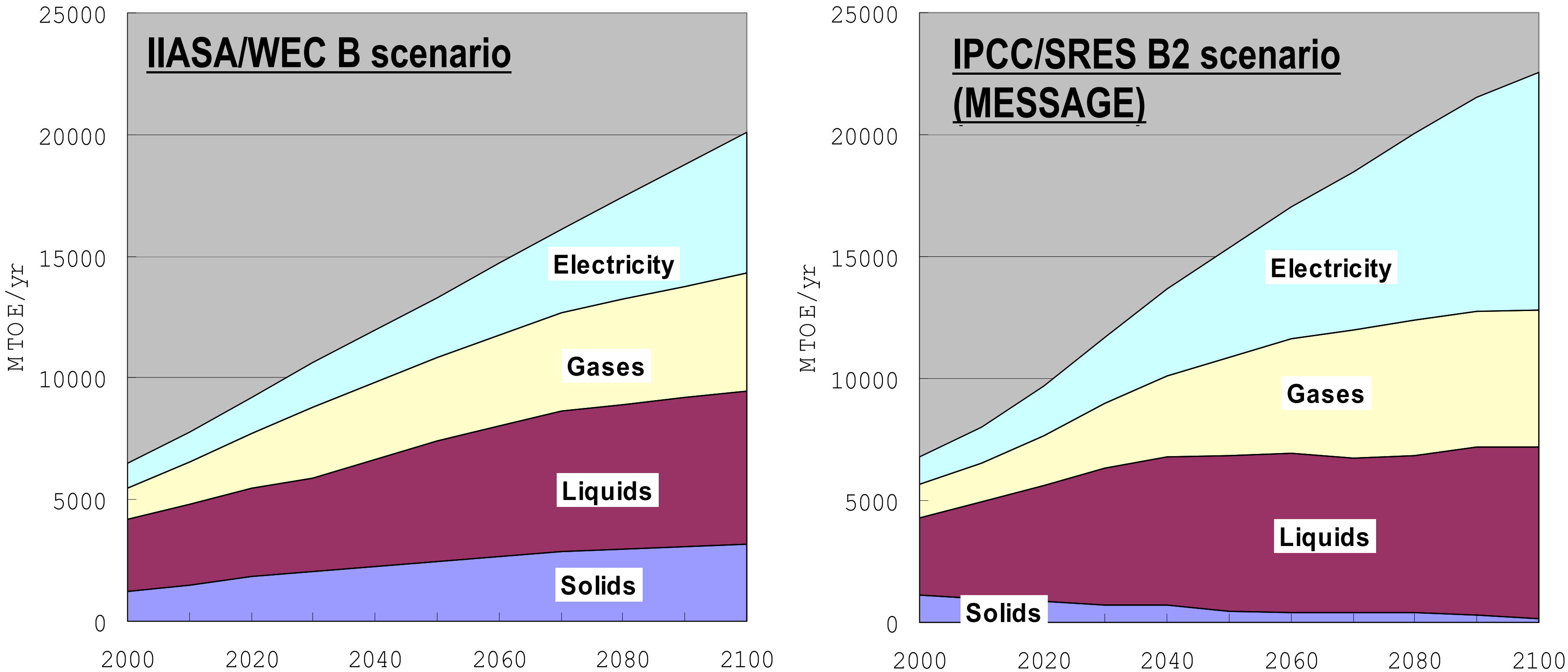
- Final energy demand data are set in line with the IIASA/WEC B scenario. (http://www.iiasa.ac.at/cgi-bin/ecs/book_dyn/bookcnt.py)
- Final energy demand excluding the transportation sector is set by subtracting the final energy demand in transportation (derived from the above source) for each of 11 regions from the total final energy demand and by assuming that the transportation sector is fueled by oil products, methanol, hydrogen, electricity, and (only slightly) natural gas.



Global final energy demand trajectory in the REDGET

Final Energy Demand Comparison

- Although the IIASA/WEC B scenario is pointed out to be consistent with the IPCC/SRES B2 scenario, there is a large difference between them. Why?

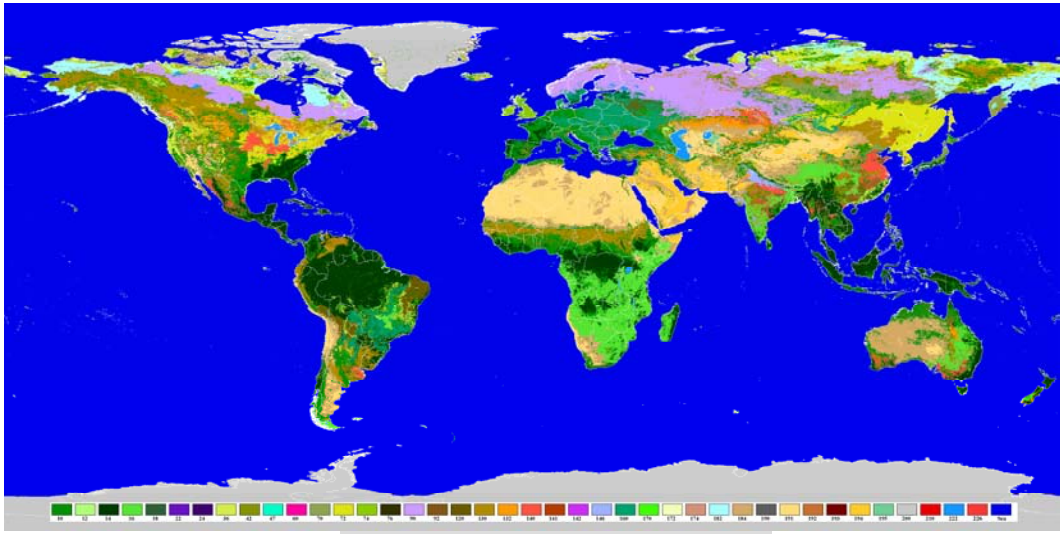


Comparison of well-known global final energy demand trajectories

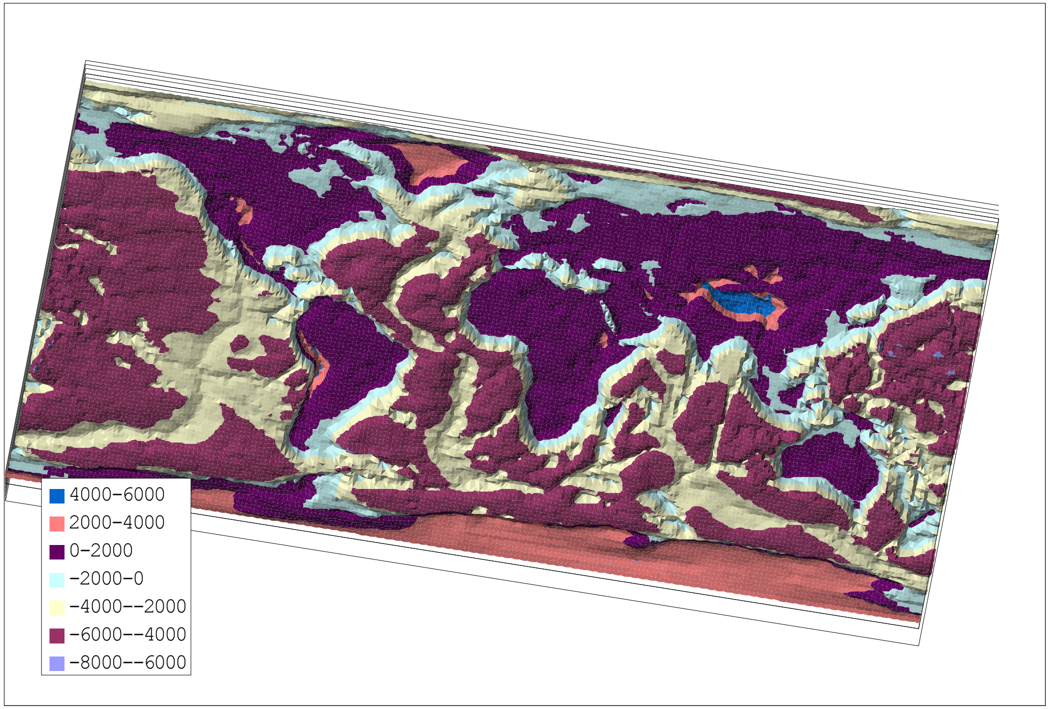
Penalty set according to land condition and height

- Routes across icebound areas: distance *5
- Undersea pipeline routes: distance*6 (distance*10 for undersea electricity transmission)

- height difference of 2m: distance+1km (no penalty for electricity transmission)



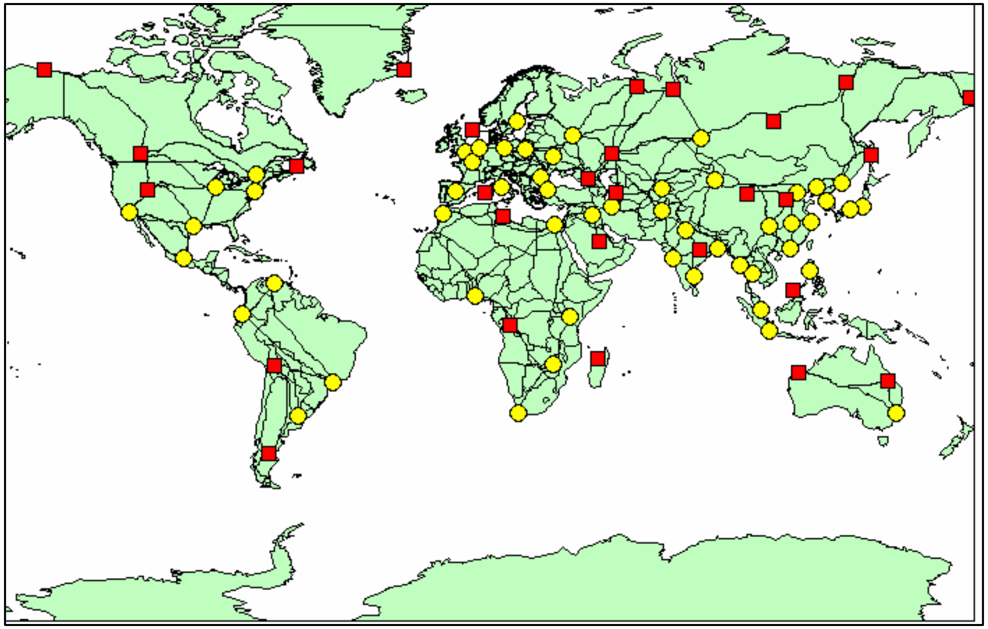
GIS land use data



Land height data

Possible land transport routes

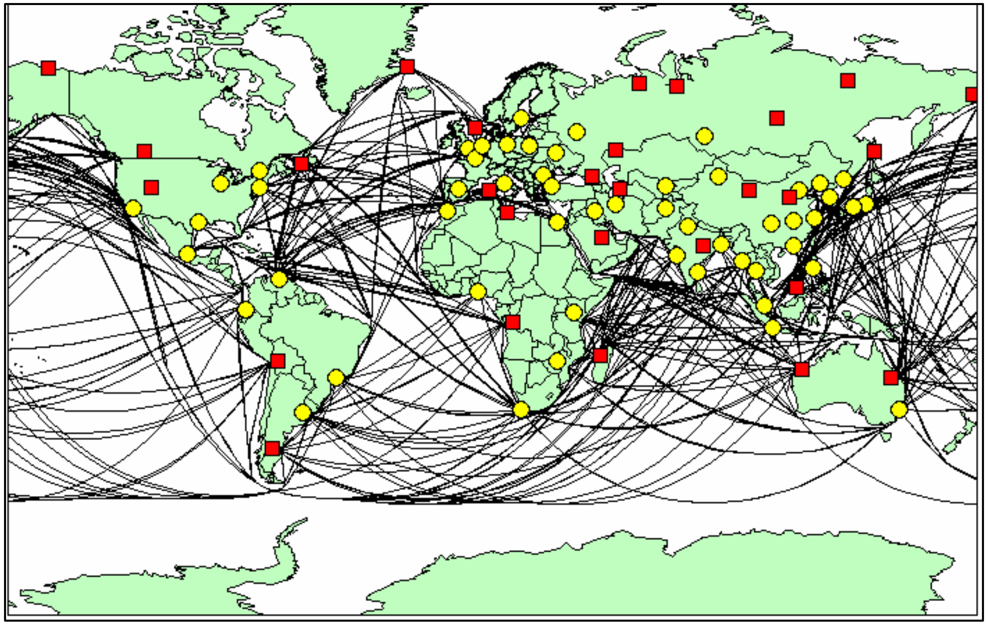
- It is first determined for each couple of nodes whether a transportation route should be given in the light of geographical characteristics.
- A concrete path and its distance are then determined for each couple of nodes with a transportation route by solving a shortest-path problem.
- Different penalty rules are applied to electricity transmission.



Possible routes for land transportation

Possible sea transport routes

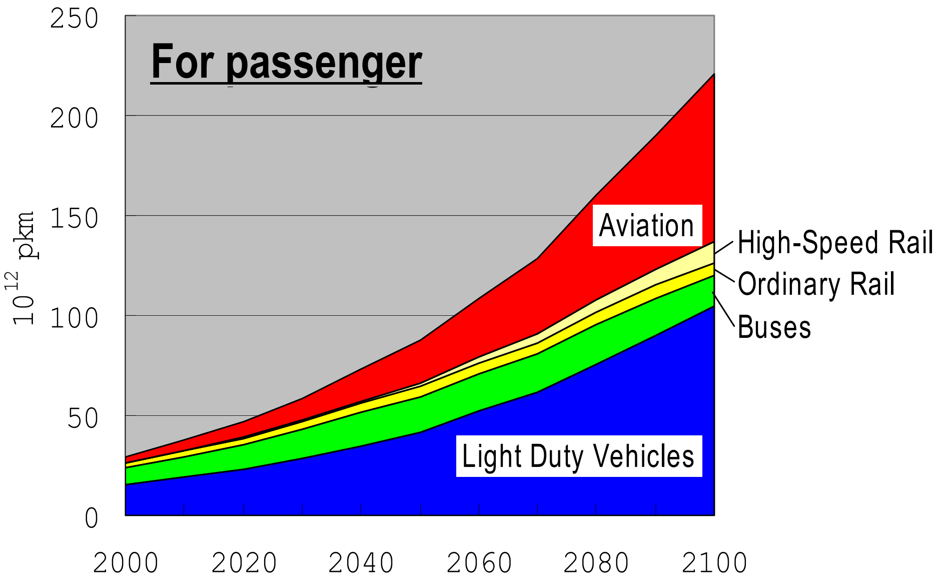
- It is assumed that a transportation route exists for every couple of nodes with sea ports.
- A concrete path and its distance are then determined for each couple by solving a shortest-path problem.

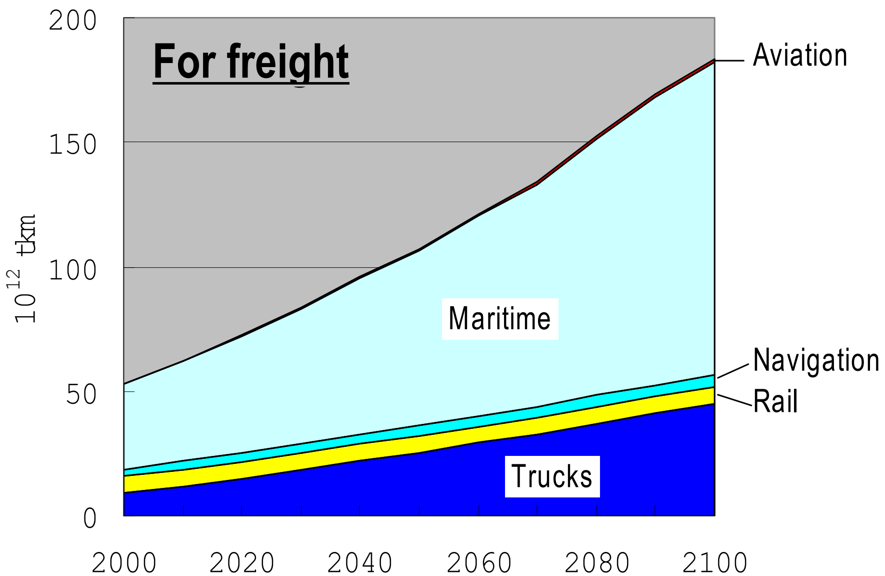


Possible routes for sea transportation

Future Transportation Activities

- **Transportation activity projections for passenger and freight**
  - 11-region projection for passenger using the method by Schafer and Victor (2000)
    - Future per capita mobility as a function of per capita GDP_{ppp}
    - Modal shares projected using two anthropological invariants, path dependence, and land-use characteristics (as the total mobility rises, people shift to faster modes)
  - 11-region projection for freight based on WEC (1998), Azar et al. (2000), etc.
    - Future freight activity derived from activity intensities (tkm/GDP_{ppp}) and GDP_{ppp}
  - 11-region activity allocated to 54 regions based on their current GDP_{ppp} and activities

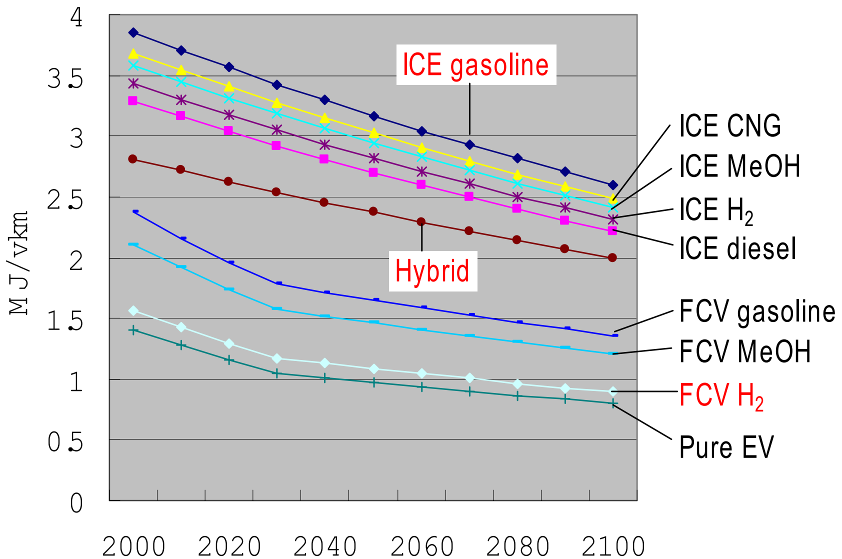




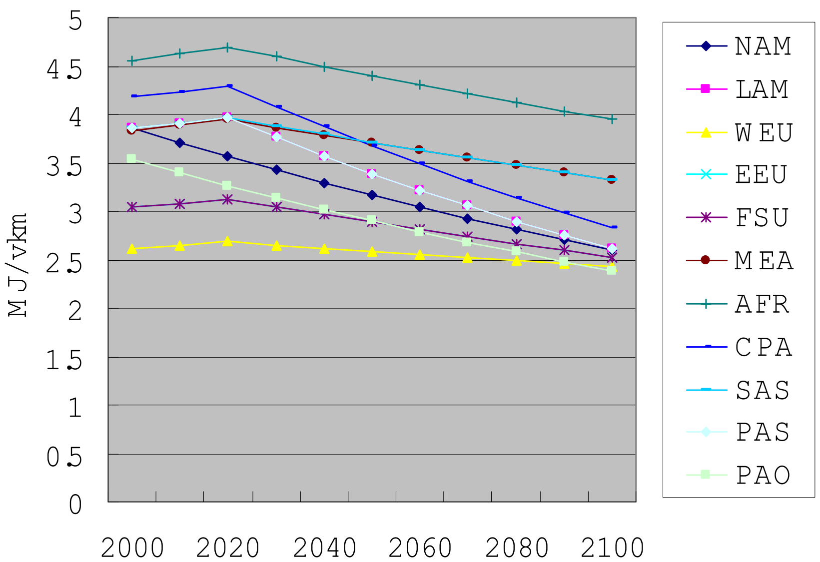
Estimated global passenger and freight transportation activities from 2000 to 2100

Energy Intensity for Passenger

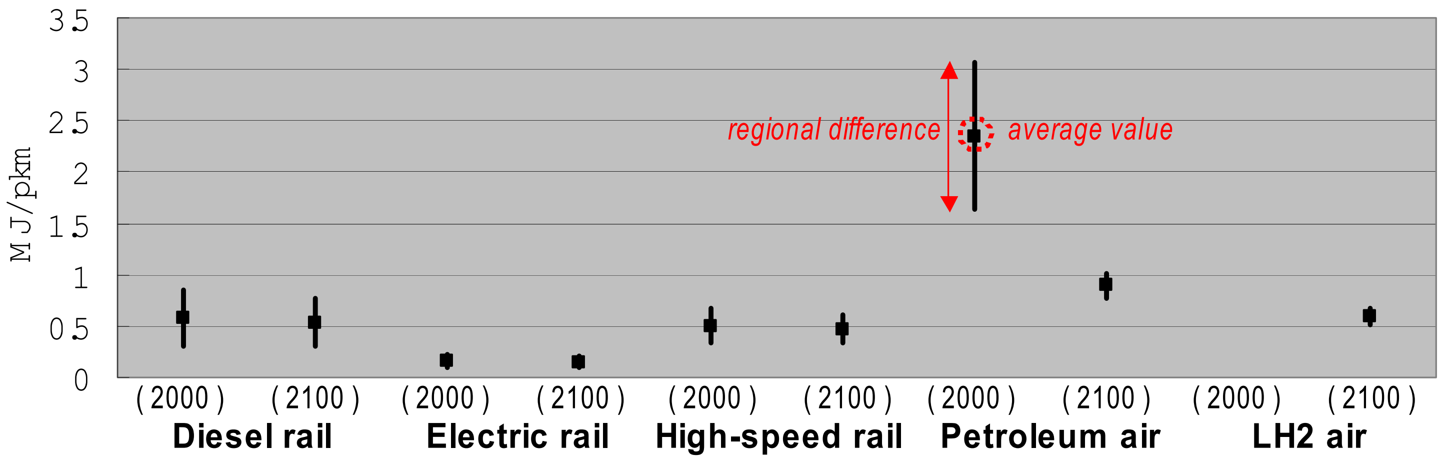
- Energy intensity projections for each mode and for each region



Estimated on-road fleet average fuel economy of LDVs for each drivetrain type



Estimated on-road fleet average fuel economy of ICE gasoline cars for each region



Estimated energy intensity for each passenger transportation mode

Change in test fuel economy of new cars
(sales weighted average in a base year)

decreasing factor
(technological improvement)

X

Change in average vehicle weight and power

increasing factor

X

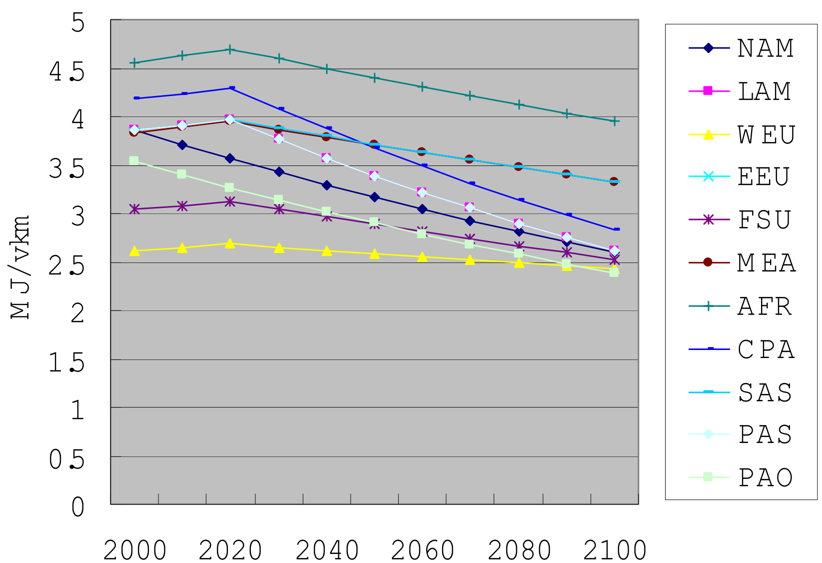
Change in stock turnover rate and maintenance

decreasing factor
(especially, developing world)

X

Change in test/on-road fuel economy gap
(real driving conditions, on-board devices, etc.)

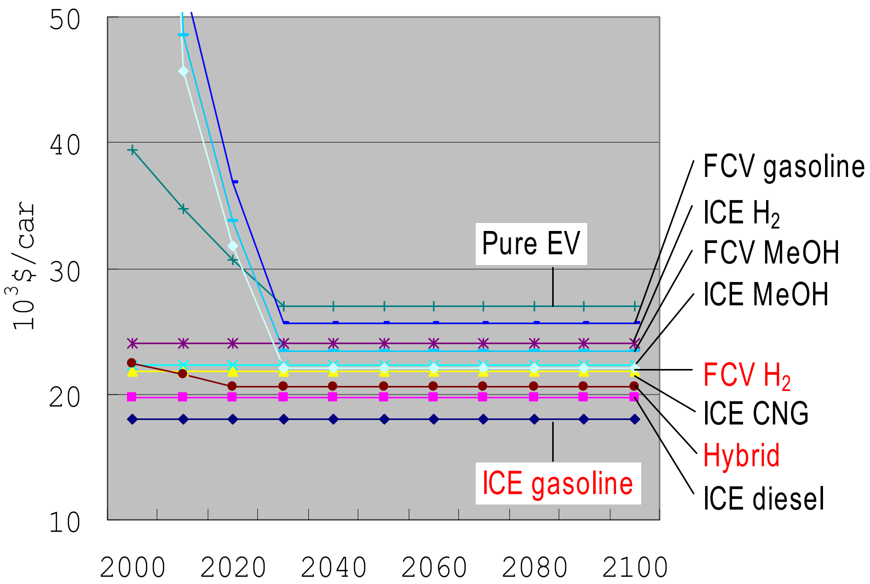
increasing factor



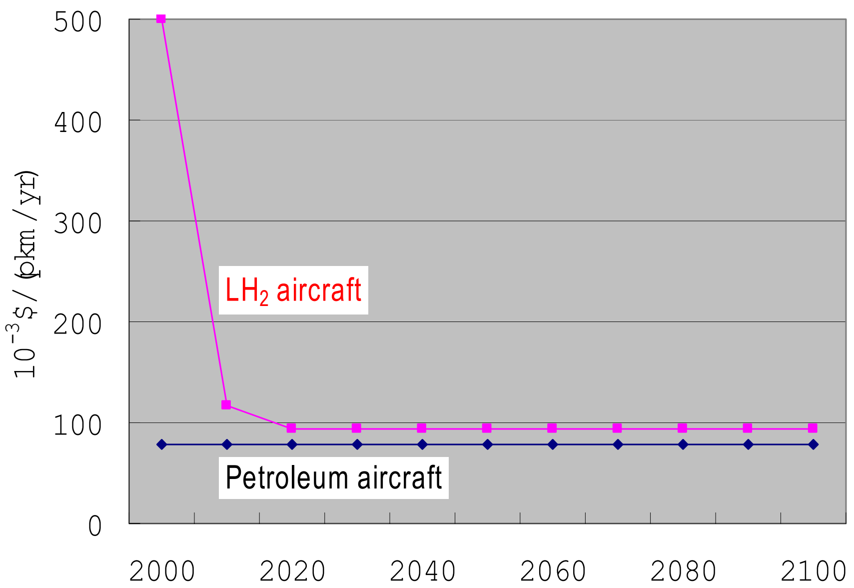
Estimated on-road fleet average fuel economy of ICE gasoline cars for each region

Cost Estimations for Passenger

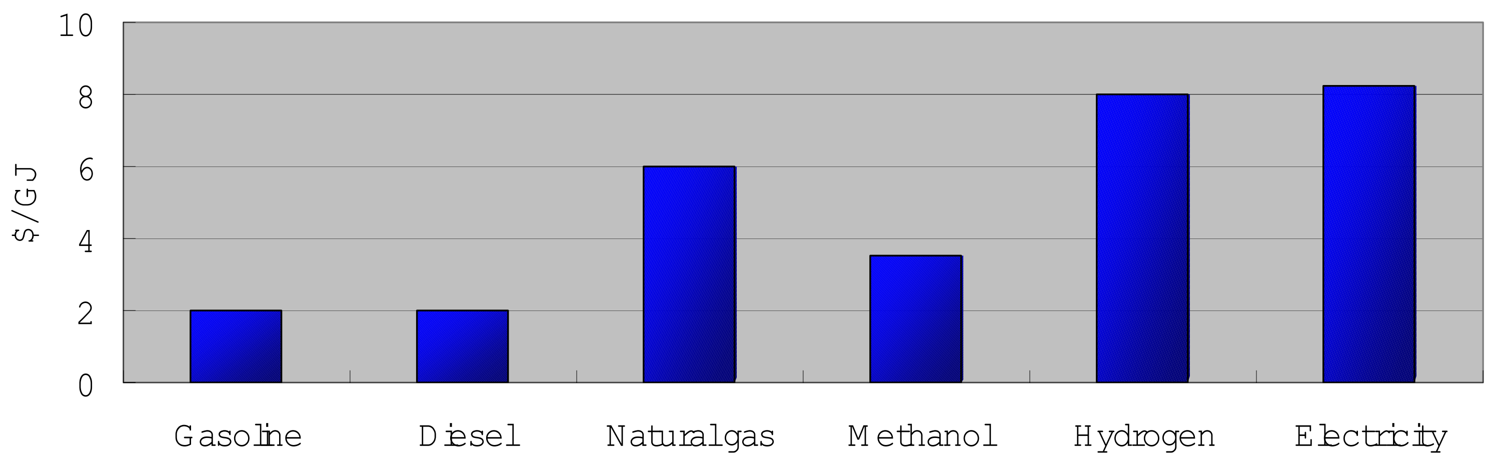
- **Cost estimations for each mode**



Estimated capital cost of LDVs for each drivetrain type



Estimated capital cost for each aircraft type



Estimated local distribution and refueling cost for each fuel

- **Data set for the hydrogen production technological options**

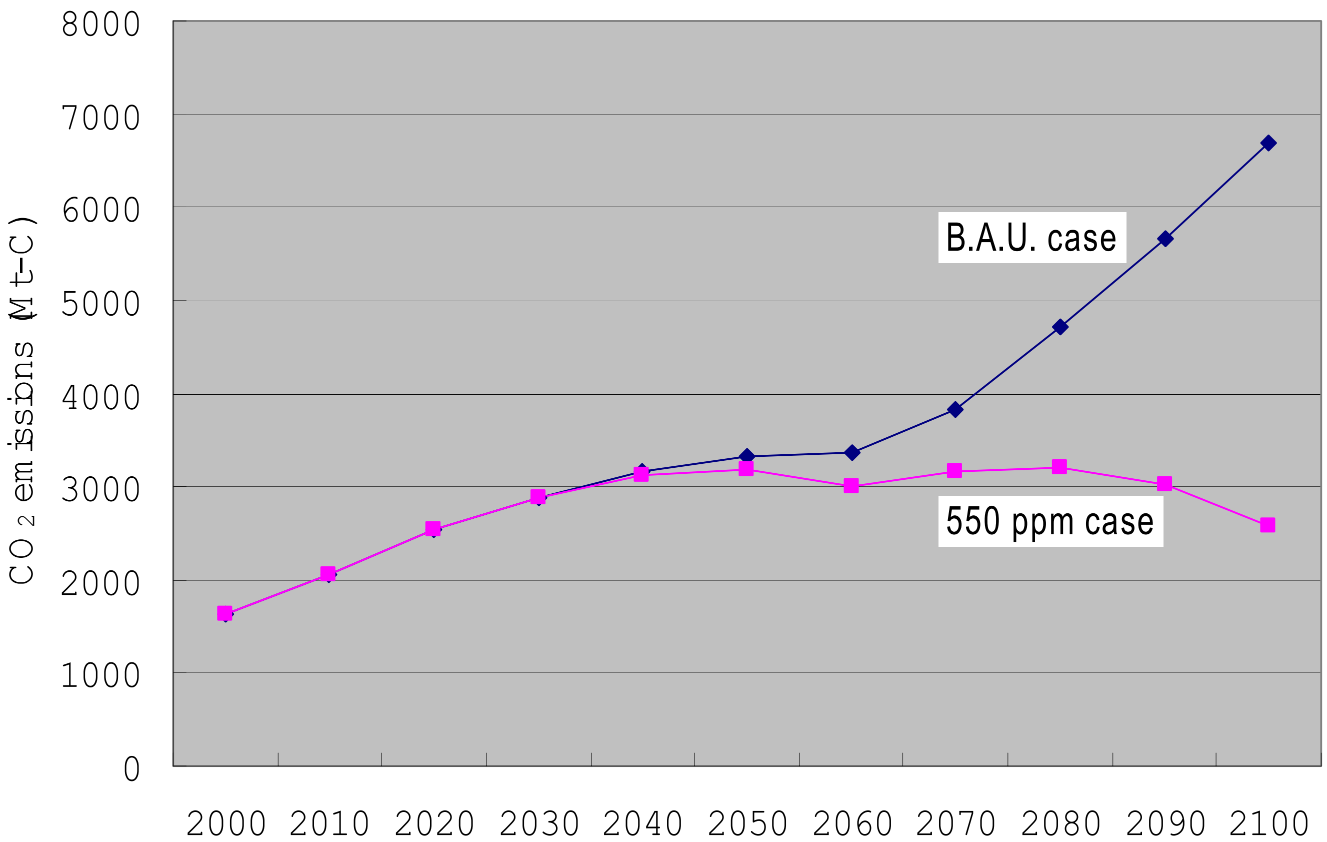
	Input (TOE)	H_2 output (TOE)	CO_2 output (t-C)	Energy required (TOE)	Capital cost ($/TOE/yr)
Coal gasification	Coal: 1	0.338	0.308	Elec.: 0.028	1010
Oil partial oxidation	Oil: 1	0.419	0.049	Elec.: 0.024	684
Steam methane reforming	Nat. gas: 1	0.467	0.171	Elec.: 0.023	419
Biomass gasification	Biomass: 1	0.302	(0.440)	Elec.: 0.026	903
Water-gas shift reaction	CO: 1	0.846	1.775	Elec.: 0.010	45
Water electrolysis	-	0.900	0	Elec.: 1	809
Steam methane reforming by nuclear heat	Nat. gas: 1	0.991	0.435	Elec.: 0.079 Heat: 0.645	702
Thermochemical water splitting by nuclear heat	-	0.355	0	Elec.: $1.836*10^{-4}$ Heat: 1	1060

- **Data set for the hydrogen conversion technological options**

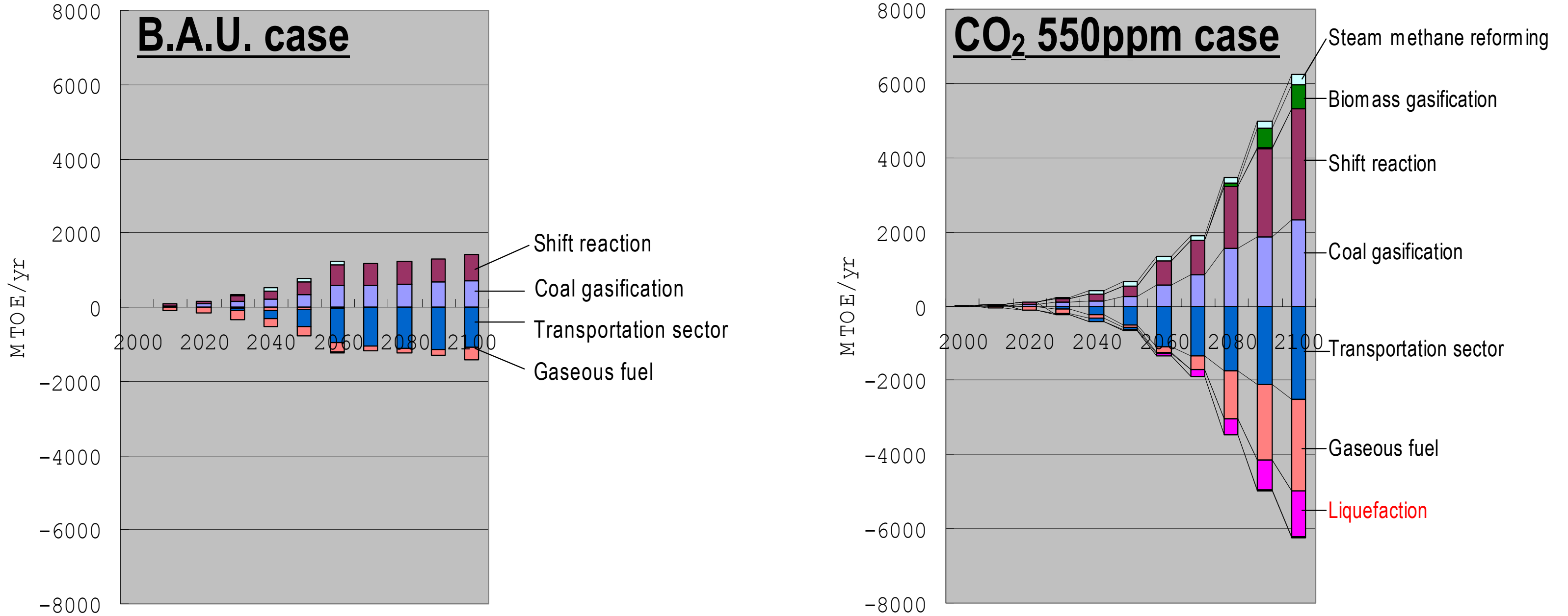
	Energy required per unit input (TOE)	Capital cost ($/TOE/yr)
Hydrogen liquefaction	Elec.: 0.284	601
Hydrogen regasification	-	448

CO_2 from the Transportation Sector

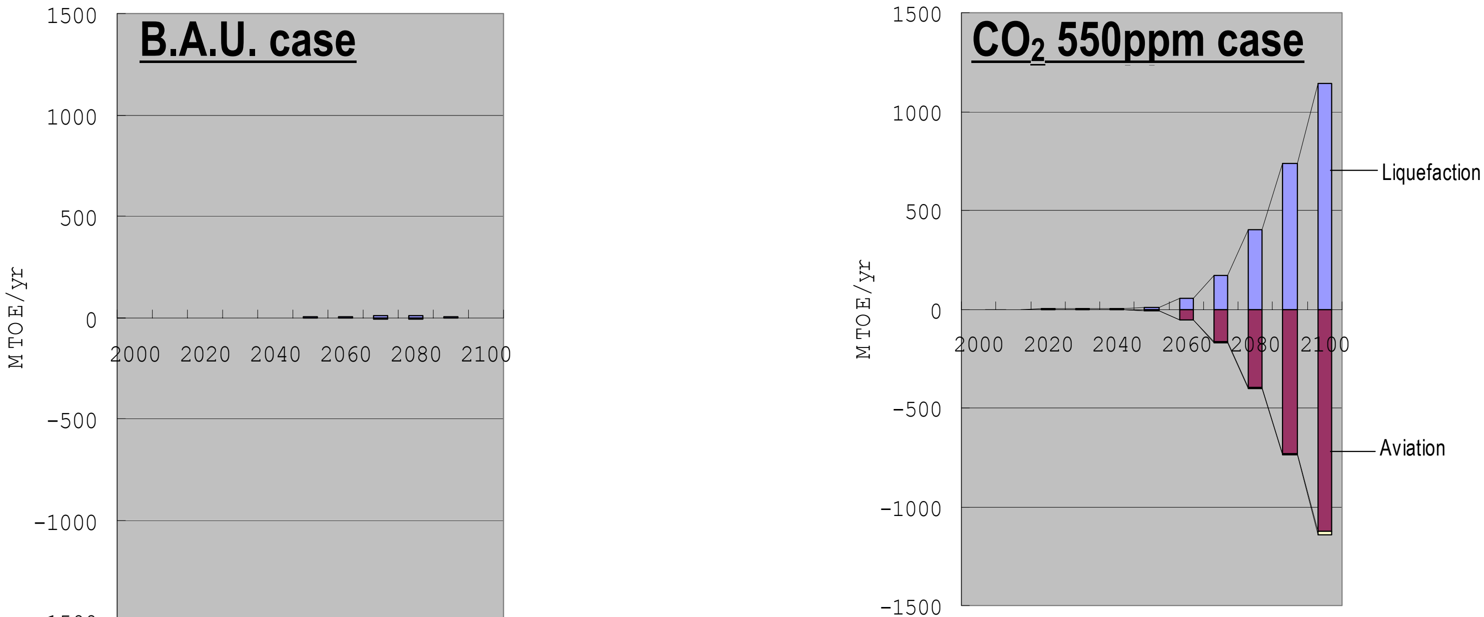
- Promotion of hydrogen utilization in the transportation sector contributes to the CO_2 emissions reduction from this sector.
- CO_2 emissions reduction in the transportation sector can be seen from the latter half of this century.



Global gross CO_2 emissions from the transportation sector in the B.A.U. and CO_2 550 ppm cases



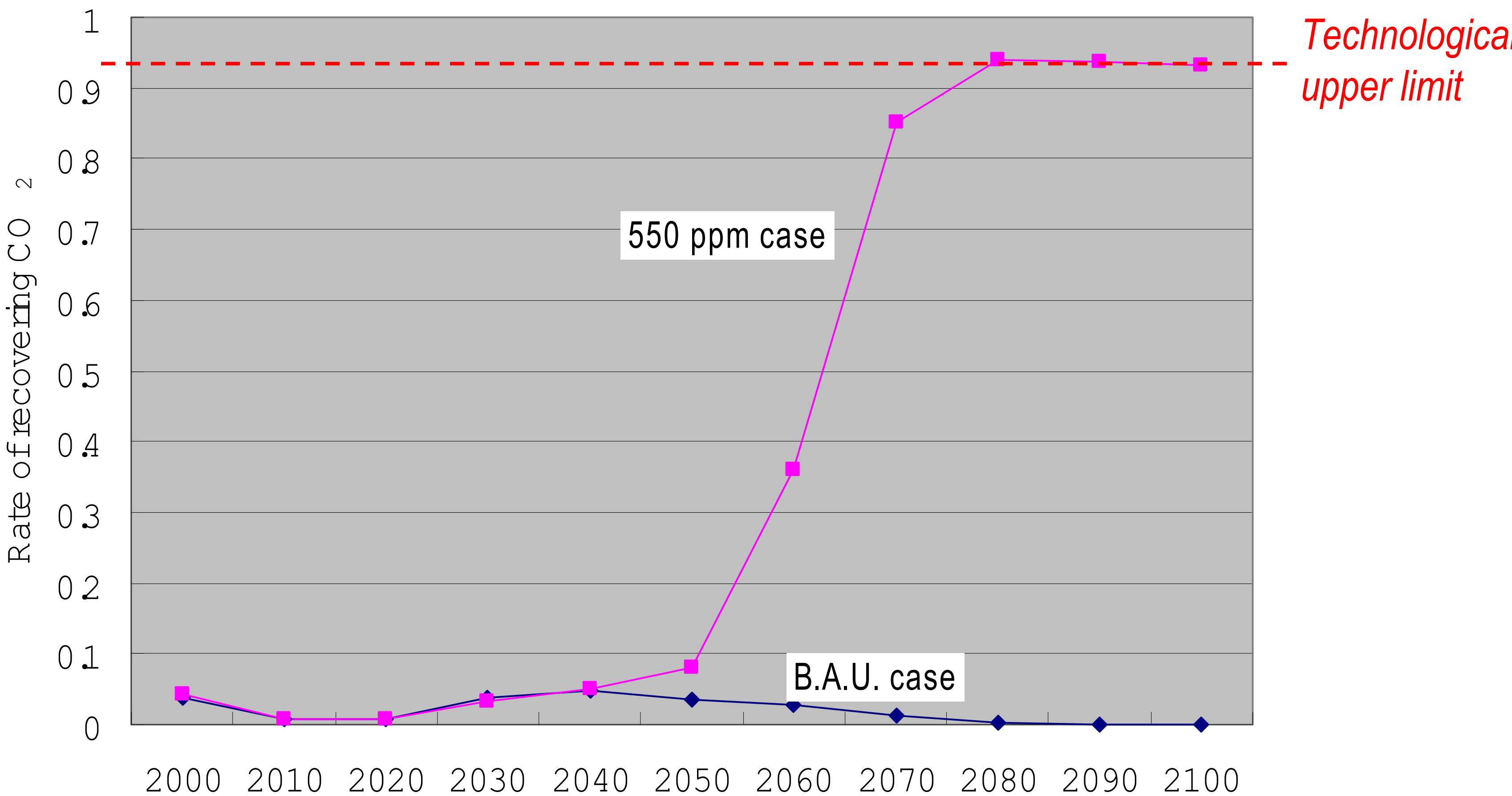
Optimal global gaseous hydrogen supply-demand balance



Optimal global liquid hydrogen supply-demand balance

Why Coal under CO_2 Constraint?

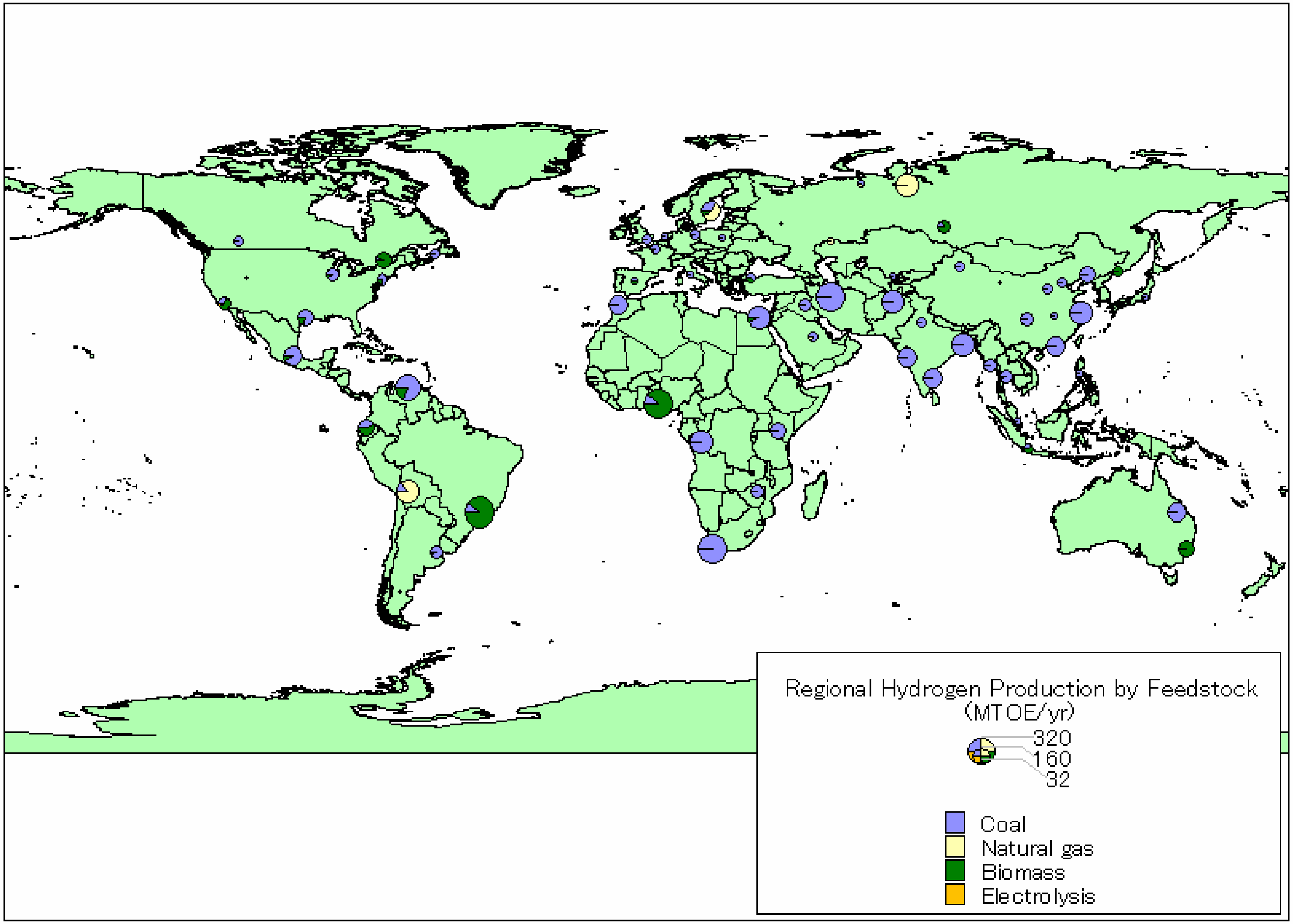
- Despite of its carbon intensive feature, coal remains important under the CO_2 constraint on condition that the CO_2 resulting from coal conversion processes is properly captured.



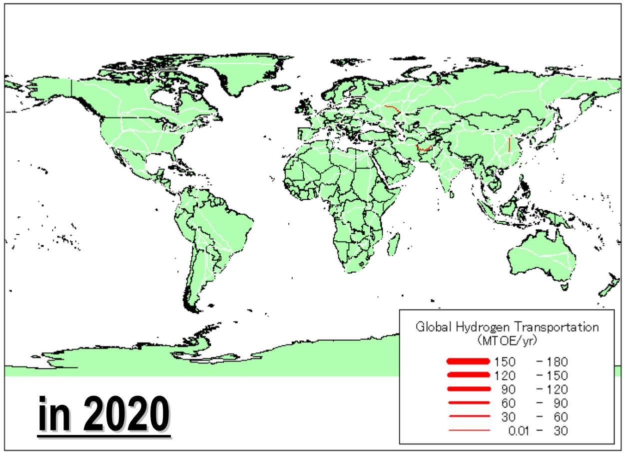
Rate of recovering CO_2 from coal conversion processes in the CO_2 550 ppm case

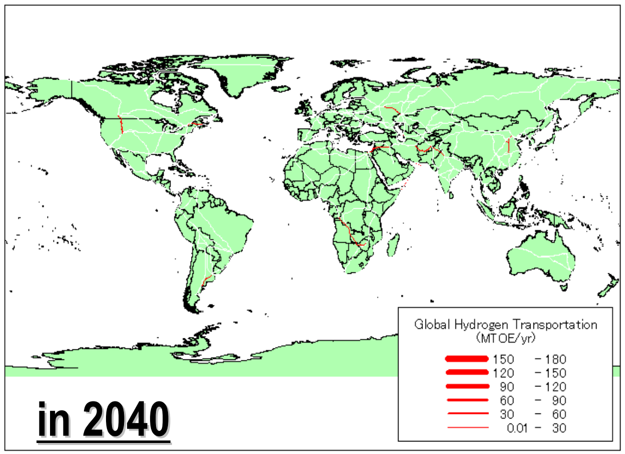
Hydrogen Production by Region

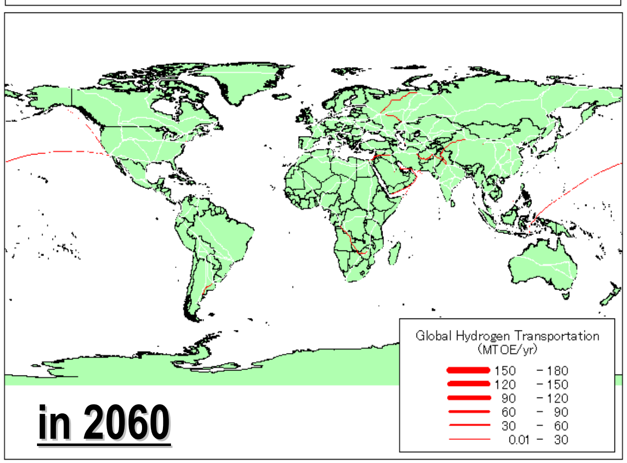
- Each region produces hydrogen from the feedstock that is attractive and plentiful there (Coal in China, India; Biomass in South America and Central Africa; and Natural gas in Russia)

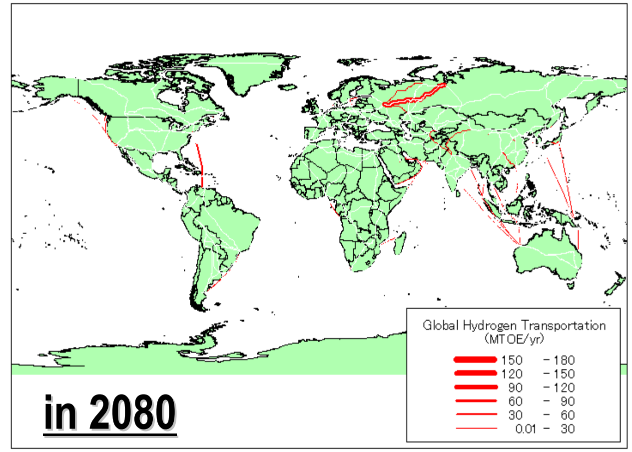


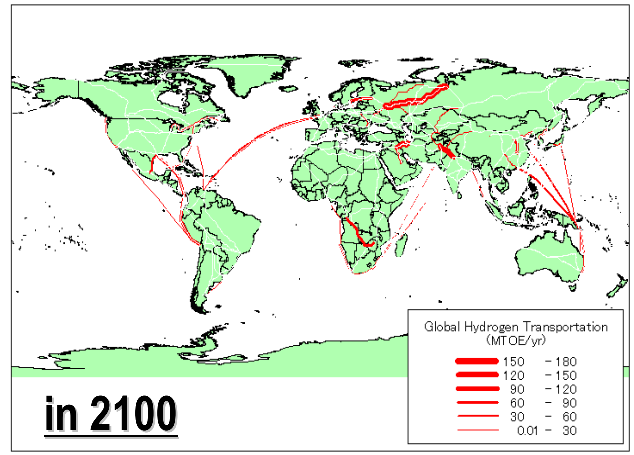
Optimal composition of feedstocks for H_2 production by region in 2100 in the CO_2 550 ppm case







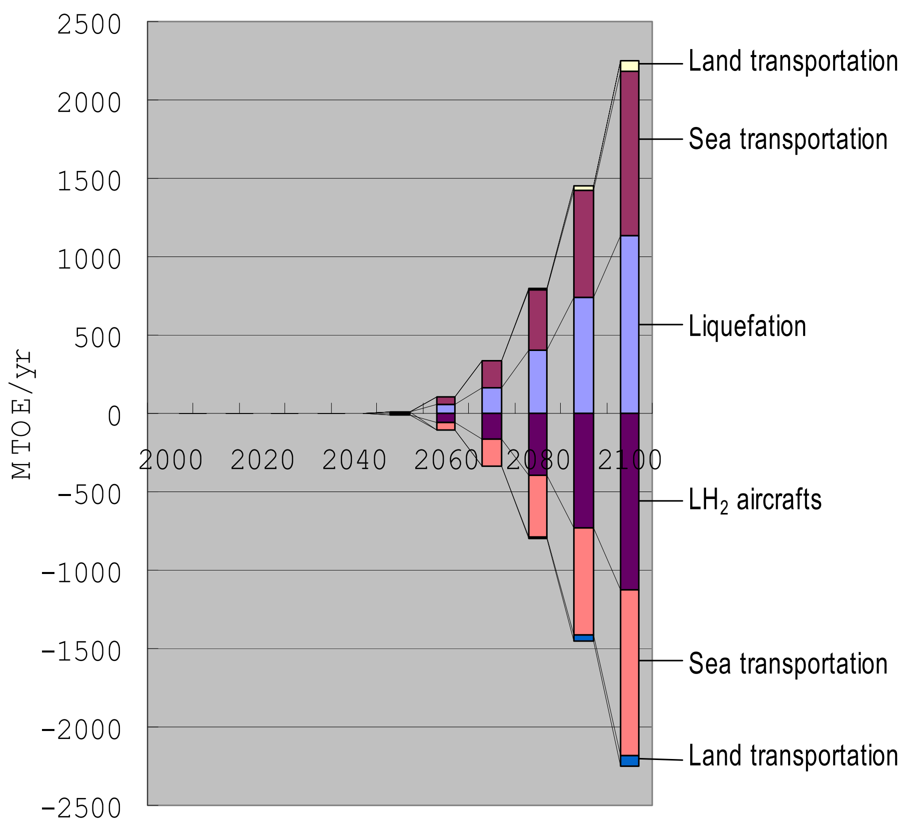




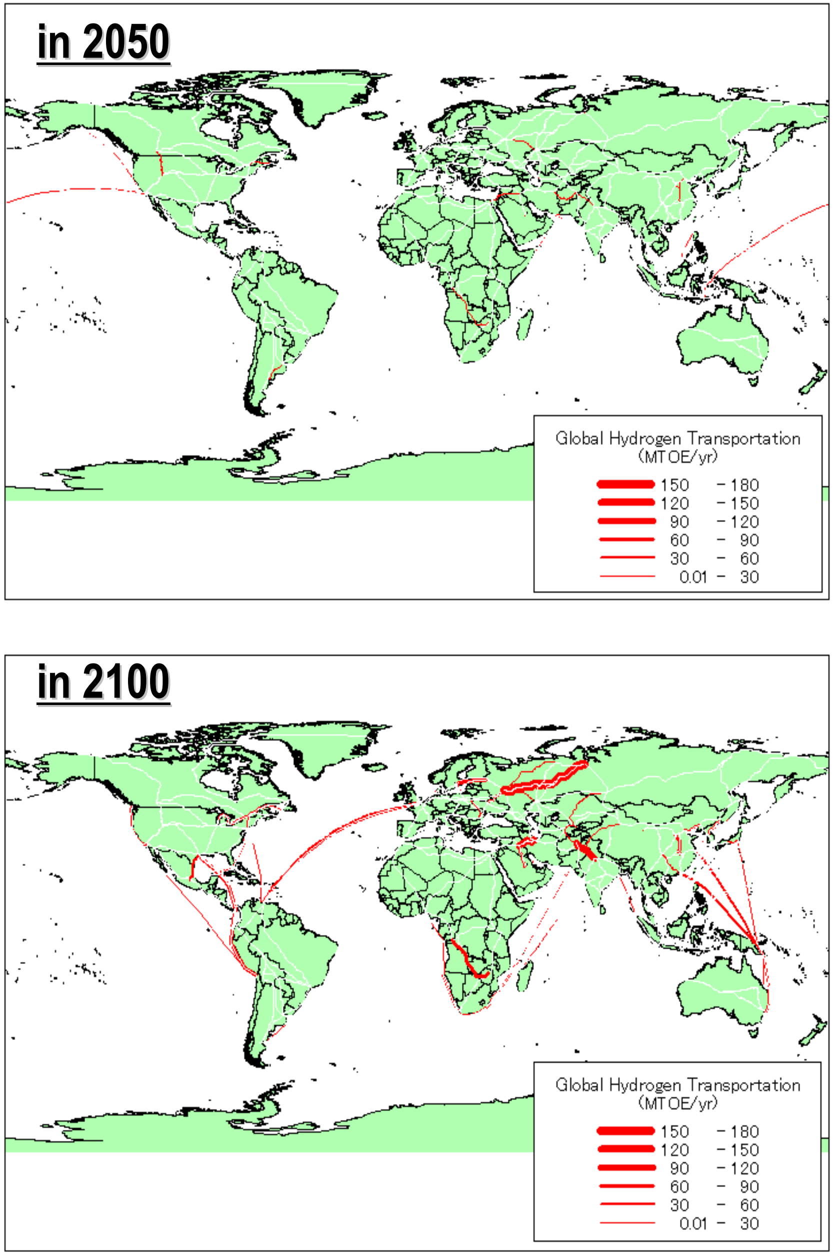
Optimal pattern of global hydrogen transportation over time in the CO_2 550 ppm case

Transport of Hydrogen or Its Feedstock (4)

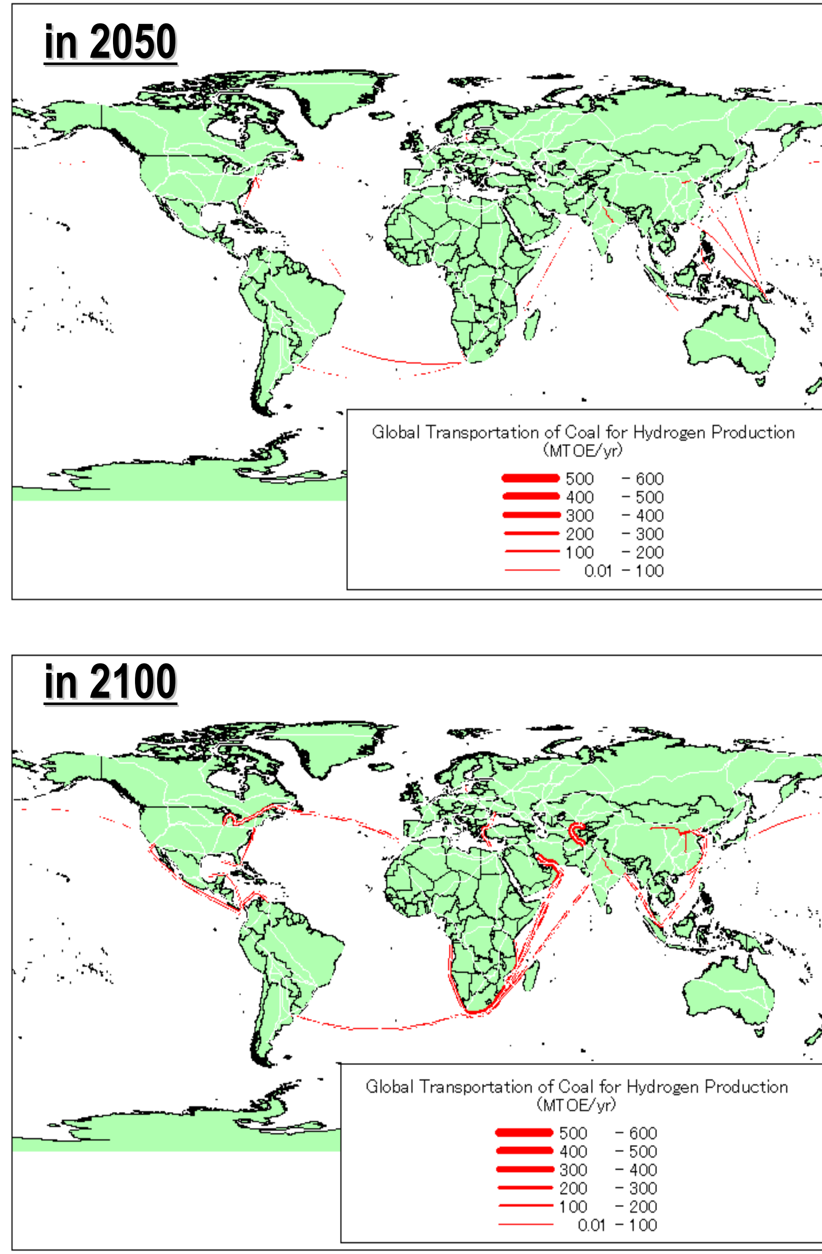
- Amount of LH_2 transportation is always less than the LH_2 demand by the aviation sector.
- With the optimal transportation patterns of hydrogen and coal for hydrogen production in 2050 also taken into consideration, this implies that LH_2 transportation becomes attractive due to the increasing LH_2 demand by the aviation sector.



Optimal global liquid hydrogen supply-demand balance in the CO_2 550 ppm case



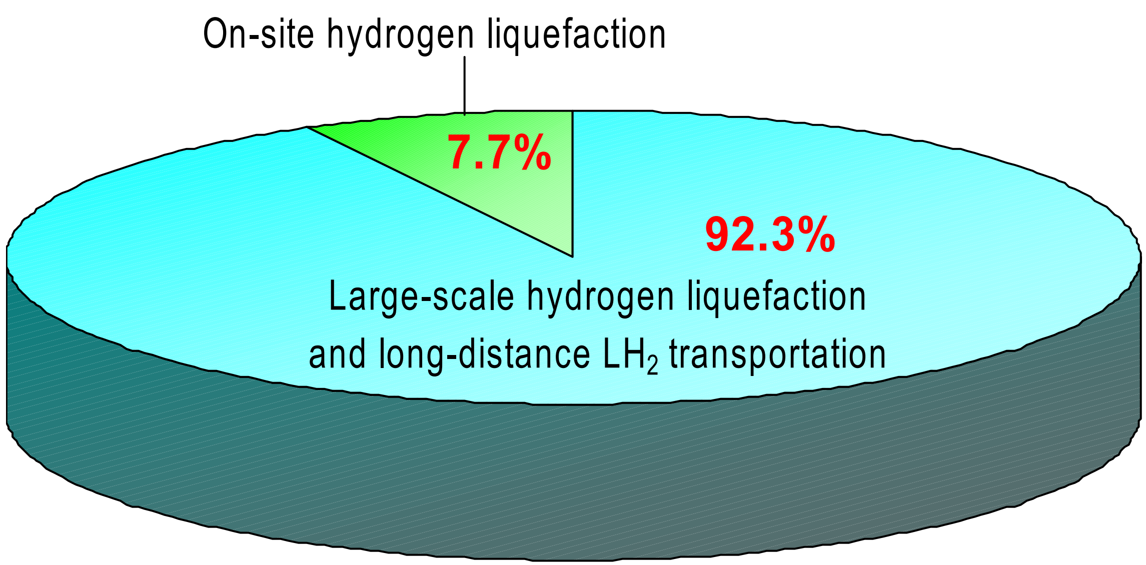
Optimal pattern of hydrogen transportation in the CO_2 550 ppm case



Optimal pattern of coal transportation for H_2 production in the CO_2 550 ppm case

On-Site Liquefaction or LH_2 Transportation

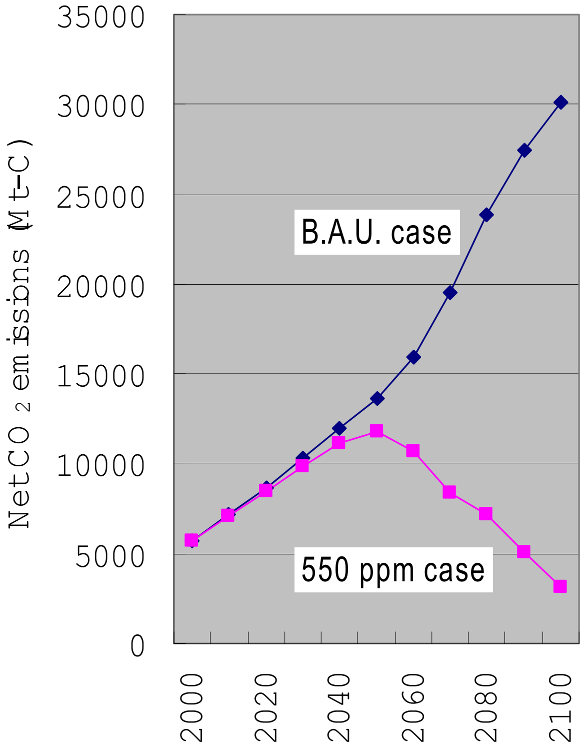
- Question of "*large-scale hydrogen liquefaction and long-distance LH_2 transportation*" v.s."*on-site hydrogen liquefaction*"
- A long-distance LH_2 transportation option is superior to the on-site H_2 liquefaction, where hydrogen is liquefied for both the purposes of long-distance sea transportation and LH_2 consumption by the aviation sector.
  (this supports the finding that LH_2 transportation becomes attractive due to LH_2 demand)



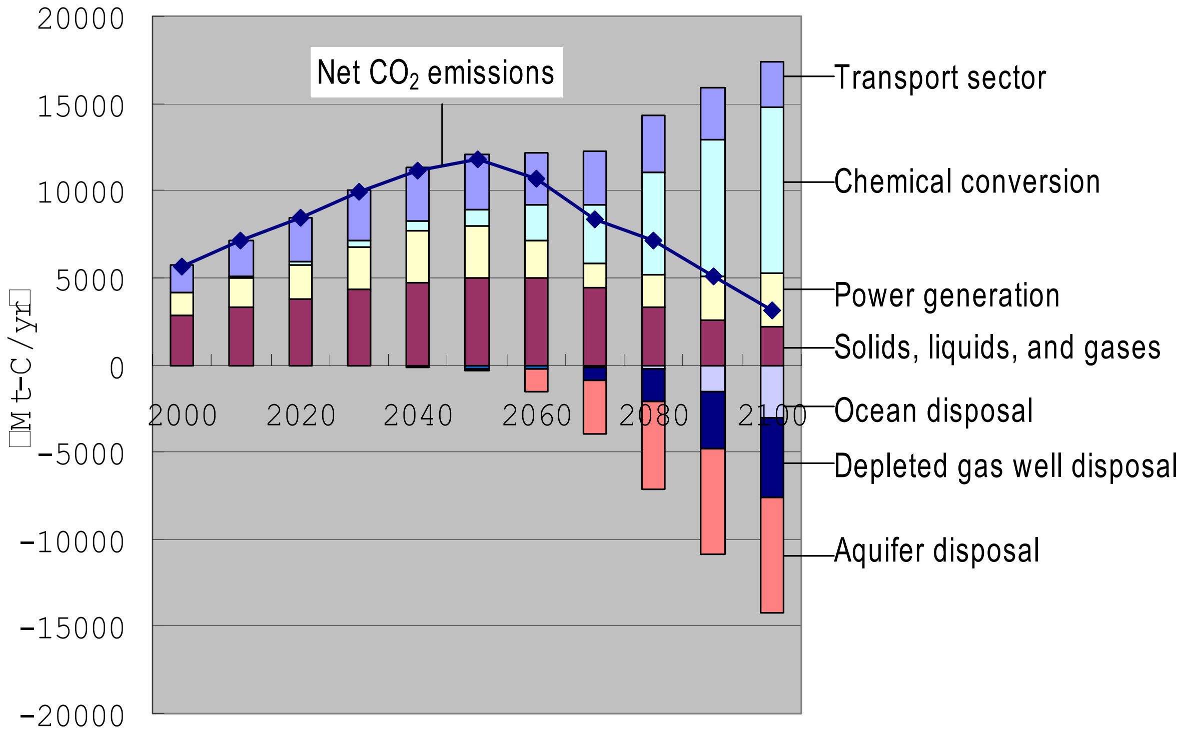
Global share of liquefied hydrogen consumed in the liquefaction sites
and liquefied hydrogen transported elsewhere
in 2100 in the CO_2 550 ppm case

Optimal CO_2 Management

- In the optimal global energy strategy, CO_2 abatement actions are actively taken in later periods due to technological improvements and discounting effects.
- Fuel switch is a major option for stabilizing the global atmospheric CO_2 concentration from 2050 to 2070 (see the gloss emissions), and CO_2 sequestration is substituted as a major option for reducing the net global CO_2 emissions thereafter.



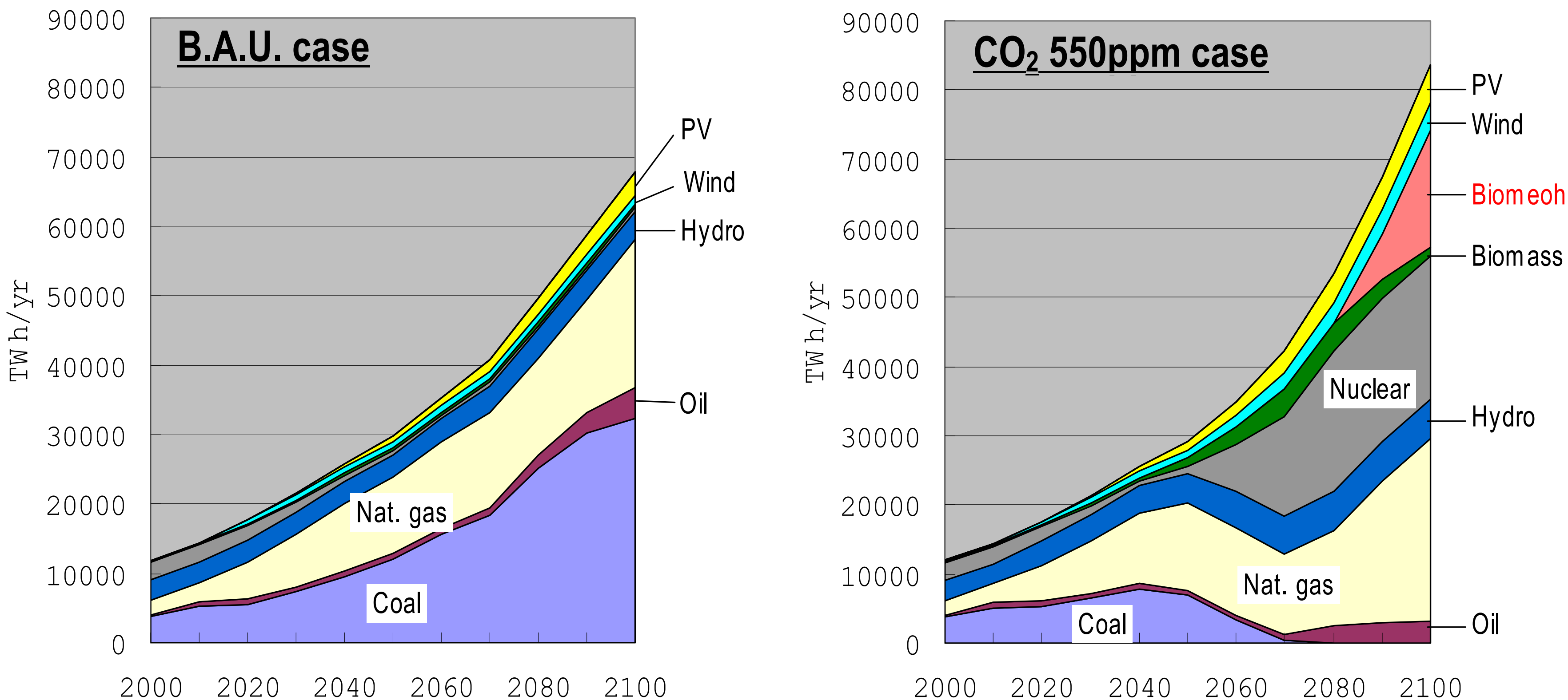
Net CO_2 emissions in the B.A.U. and CO_2 550 ppm cases



Optimal global CO_2 management in the CO_2 550 ppm case

Optimal Mix of Power Generation

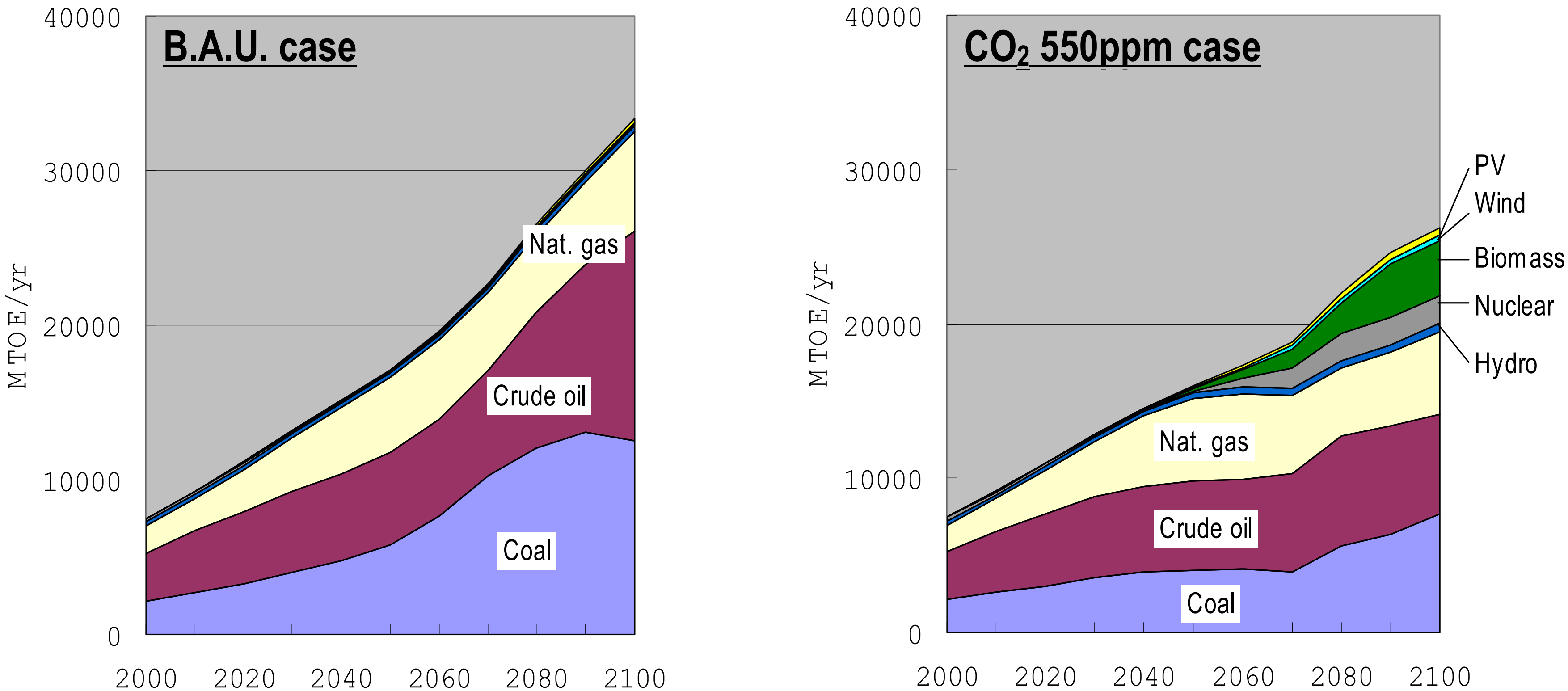
- Optimal composition of global power generation dramatically changes under the CO_2 constraint, where natural gas, nuclear, and biomass are particularly important options.
- Biomethanol is not used as a transportation fuel but for power generation with CO_2 sequestration in power plants because this leads to a net CO_2 emissions reduction. Biomethanol becomes more competitive than biomass because transportation of biomass-derived liquid fuel is easy and facilitates its widespread utilization.



Optimal composition of global power generation in the B.A.U. and CO_2 550 ppm cases

Optimal Mix of Primary Energy

- Optimal composition of global primary energy production becomes diversified to stabilize the atmospheric CO_2 concentration, in which primary energy sources of little or no carbon content such as nuclear and renewable energies are introduced on a large scale.
- Despite of its carbon intensive feature, coal remains important under the CO_2 constraint on condition that the CO_2 resulting from coal conversion processes is properly captured.



Optimal composition of global primary energy production in the B.A.U. and 550 ppm cases

FAQs

Q. How do you take into consideration the difficulties associated with hydrogen storage?

- I considered the difficulties associated with hydrogen storage in the following way:
  - If LH_2 is transported by sea to supply gaseous hydrogen, LH_2 tank (with the storage capacity of one week) and vaporizer are assumed to be required.
  - For hydrogen-fueled vehicles, it is assumed in this study that hydrogen is stored on-board in the form of compressed gas. The capital cost of hydrogen-fueled vehicles includes the tank of compressed gaseous hydrogen.
  - I also took into consideration the alternatives such as gasoline/methanol-fueled fuel cell vehicles. These alternatives do not require the expensive carbon tank, but require chemical reformer whose cost is estimated to be somewhat higher than that of storage tank.

Q. Can the CO_2 sequestration measures be regarded as completely reliable?

- It is too optimistic to assume that 100% of the CO_2 injected into oil fields, gas fields, aquifers, and the deep ocean can be properly sequestered. For example, approximately 40% leak is reported for the CO_2 injection into oil fields, even though it is a well-established technology. In such a context, the sensitivity analysis has been carried out with respect to how much of the injected CO_2 leaks into the atmosphere.
- The injection of CO_2 into the ocean has many potential risks; e.g., acidification of ocean water and its impact on ocean ecosystem.

Q. What if CO_2 sequestration measures remain unreliable even in the future?

- The sensitivity analysis with respect to how much of the injected CO_2 leaks into the atmosphere shows that the technological reliability of CO_2 sequestration has a large impact on the optimal global energy strategy. If 10% of the injected CO_2 leaks into the atmosphere, coal is hardly introduced to the optimal global energy system in which the global atmospheric CO_2 concentration is constrained below 550 ppm in 2100. In such a case, biomass and electrolysis (using the electricity from nuclear and renewable energy sources) are the important hydrogen production options.

Q. Why is the share of fuel costs larger for trucks than for LDVs?

- This is because it is estimated in the model that lifetime and annual distance traveled are longer for trucks than for LDVs. The total fuel consumption throughout the life is thus larger for trucks than for LDVs. Hence, hydrogen-fueled fuel cell vehicles with superior fuel economy but high capital cost are more advantageous to trucks.

Q. Why is the contribution of WGS larger than that of coal gasification?

- First, carbon monoxide inputted into water-gas shift reaction is produced not only from coal gasification but also from steam methane reforming of natural gas and biomass gasification. Secondly, the conversion efficiency of shift reaction is very high, near 90%. Therefore, I think that the simulation results are attainable.

Q. How do you take into consideration the inconveniences associated with FCVs?

- There are some inconveniences associated with the utilization of FCVs compared with that of conventional ICE vehicles such as longer refueling time and longer starting time. It is true that not only capital, operating and maintenance, and fuel costs but also local distribution and refueling costs are taken into consideration, but the inconveniences (or utility loss) mentioned above are not fully taken into consideration. However, until the time when FCVs become widespread, technological improvements might solve some of these inconveniences. I think that we should pay attention to this point in interpreting simulation results, but that this does not deny the soundness of this model study.

Q. Is the technology available to safely transport and store hydrogen?

- It is true that there are some difficulties associated with hydrogen storage and distribution. In Iceland which has promoted the utilization of hydrogen produced from renewable energy as a national project to reduce the imports of fossil fuels, commercial hydrogen refueling stations have already been in service. For hydrogen transportation, several demonstration projects have reported its technical feasibility. Therefore, it can be argued that the technologies for hydrogen transportation and storage have already been established fundamentally, but that further R&D efforts are required to improve them in order to develop a large-scale hydrogen-based energy system.

Q. What should the public sector do to reach such a sustainable transportation sector?

- First, it is necessary for the public sector to take further measures to generate a demand for alternative vehicles with superior environmental features; for example, in the form of tax incentives and subsidies, because mass production effects are important to reduce the cost of alternative vehicles to a competitive level.
- Secondly, (in closer cooperation with the private sector) it is necessary for the public sector to play an active role in developing the infrastructures for hydrogen transportation, distribution, and refueling to develop a large-scale hydrogen-based energy system. Because it takes long time to develop such infrastructures on a large scale, we should prepare for the infrastructure development from now on. Especially, it will be important to establish multinational cooperative frameworks and funding schemes. Taking into consideration that short-term profits cannot be expected, the role of the public sector is particularly important.
- The transportation sector is closely related with people's lifestyle, so this sector is inelastic to public policy. The important point is thus to mitigate the negative effects of transport without damaging the economy, constraining the freedom of individuals, or reducing the social welfare derived from transportation.

Q. What kind of fuel cells do you consider?

- Polymer electrolyte membrane (PEM) cell.

Q. What are the difficulties associated with MeOH utilization as a transportation fuel?

- First, MeOH is a corrosive material and the infrastructures for MeOH are required to be equipped with alcohol-resistant materials, so incremental cost arises. Secondly, the energy density is lower for MeOH compared with petroleum products. Thirdly, MeOH is poisonous and it is difficult to separate MeOH from water once it leaks out.

Q. What are the next steps?

- First, I will try to improve the reliability of data set for hydrogen-related technologies again. I will then carry out extensive sensitivity analyses with respect to the cost and efficiency of hydrogen-related technologies and the future mobility of developing countries. This will lead to interesting policy implications.