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Potentials of hydrogen and nuclear towards global warming mitigation—expansion of an integrated assessment model MARIA and simulations

Shunsuke Mori[a,*], Takahiro Saito[b]

[a]Department of Industrial Administration, Faculty of Science and Technology, Tokyo University of Science, Yamasaki 2641, Noda-shi, Chiba 278-8510 Japan
[b]Hitachi, Ltd. Kanagawa, Japan

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Abstract

This paper describes an extended version of an integrated assessment model called Multiregional Approach for Resource and Industry Allocation (MARIA) and how it was applied to assess the global and regional greenhouse gas (GHG) emission mitigation policies. The model has been developed to assess the potential contribution of fossil, biomass, nuclear and other energy technologies and land-use changes to future GHG emissions. In this paper, the MARIA model is extended to evaluate a new hydrogen production process through steam–methane reforming at a significantly lower temperature (300–500 °C) than that of conventional steam–methane reforming processes as a liquid fuel supplier under the long-term global warming strategies. Bern simple carbon cycle model is also included in the model to reflect the recent findings in climate science. The simulation results suggest that hydrogen with Fast Breeder Reactors could supply 5–8 GTOE of hydrogen in the second half of the 21st century when climate policy that stabilizes the atmospheric carbon concentration is introduced. Although biomass does not completely replace fossil energy sources, the simulations show that it effectively mitigates the marginal cost of carbon emission.

Keywords: Integrated assessment model; Climate change; Greenhouse gas (GHG) emissions; Hydrogen production

1. Introduction

It is now broadly recognized that the global warming issues may be a major barrier to world development, equity and sustainability. Intergovernmental Panel for Climate

* Corresponding author. Tel.: +81-4-7124-1501; fax: +81-4-7122-4566.
E-mail address: mori@ia.noda.tus.ac.jp (S. Mori).

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Change (IPCC) established in 1988 has summarized the scientific progresses in this field. In the IPCC Third Assessment Report (TAR), integrated assessment models (IAMs) contributed to evaluate the policy measures under the complex interrelationships among environment, energy, economy, technology, resource and societal issues. EMF-14 initiated organizing IAM developers and its successor EMF-19 activities have contributed to gather and investigate the "robust" model findings as well as IPCC conclusions. The recent activities of integrated assessment models are summarized in the special issue of *The Energy Journal* edited by Weyant (1999); Environment and Economics Policy Studies (2000) and the Chapter-2 of IPCC-TAR (2001a).

The MARIA, Multi-regional Approach for Resource and Industry Allocation, model utilized in this paper is developed to assess future greenhouse gas (GHG) reduction options and was used in the IPCC emission scenario activities (IPCC, 2000).

These research activities agree on the importance of low-carbon technologies and their development and implementation strategies. Among many energy technology options, hydrogen has been regarded as playing a "major role" in the future because of source flexibility as well as being carbon-free. Although many hydrogen production processes have been developed, hydrogen is used in only very limited area of energy systems due to the high cost. Recently, new technological options for hydrogen have been proposed in both demand side-fuel cells for automobiles and small residential buildings—and the supply side where hydrogen can be processed at lower temperature than the conventional process. Although they are not on the market yet, these lower temperature processes provide new opportunities to produce hydrogen based on nuclear heat, waste thermal heat, etc. The purpose of this paper is to assess these new hydrogen processes based on an integrated assessment model called MARIA. An extension of MARIA involving the Bern carbon circulation model Bern is also described.

2. Background of the MARIA model

The Multiregional Approach for Resource and Industry Allocation (MARIA), developed by the author aims at integrated assessment of global warming issues. MARIA aims at integrated assessment by generating international trade prices for fossil fuels as well as equilibrium prices for tradable carbon emission permits under certain constraints. The land-

Table 1
Regional Aggregation of MARIA-8

Region	Countries
NAM	USA, Canada
JPN	Japan
DC	Other OECD member countries in 1990
FSU	former USSR and eastern European countries
ANS	Indonesia, Malaysia, Philippines, Singapore, South Korea, Thailand, Taiwan
CHN	China
SAS	India, Bangladesh, Pakistan, Sri Lanka
ROW	Other countries

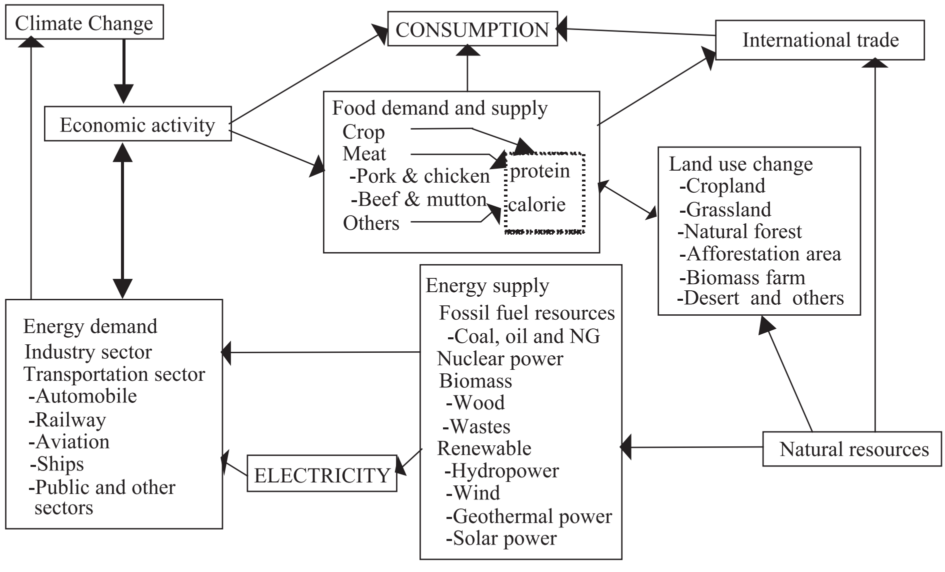

Fig. 1. Structure of the MARIA model (one region).

use subsystems and food demand–supply equations are also imposed to evaluate biomass energy resources under food supply constraints. The original MARIA incorporated the four world rgions (Mori and Takahashi, 1999) and currently has the eight world regions shown in Table 1. The basic structure of MARIA-8 follows MARIA-4, as is shown in Fig. 1.

MARIA includes carbon sequestration technologies as well as nuclear power technologies, e.g., once-through light water reactors (LWR), Plutonium thermal reactors (LWR-Pu), and fast breeding reactors (FBR). MARIA is formulated as an intertemporal nonlinear optimization model including around 18,000 variables and 15,000 constraints. The detailed parameters and formulations included in MARIA are documented in the other papers by the author (Mori, 2000a,b; Mori and Takahashi, 1999).

3. Expansion of MARIA—incorporating the Bern carbon circulation model

In the last decade, climate change researches have progressed through both theory development and model simulations. However, simulations of detailed climate models require the fastest super-computers. As the scale of the climate models and societal interest in global warming issue grow larger, on the other hand, the need for "simple" climate models as a policy evaluation tool has grown. MAGICC model (Wigley, 1993) which includes the radiative forcing of carbon and non-carbon GHGs is a famous pioneering work in this field. The Bern carbon circulation (Bern-CC) model (Joos et al., 1996) employed here is also developed for this purpose focusing on the carbon emission and concentration processes. The Bern model consists of an atmospheric carbon circulation block, carbon absorption by oceans and emissions and storage in the biosphere. The third feature enables

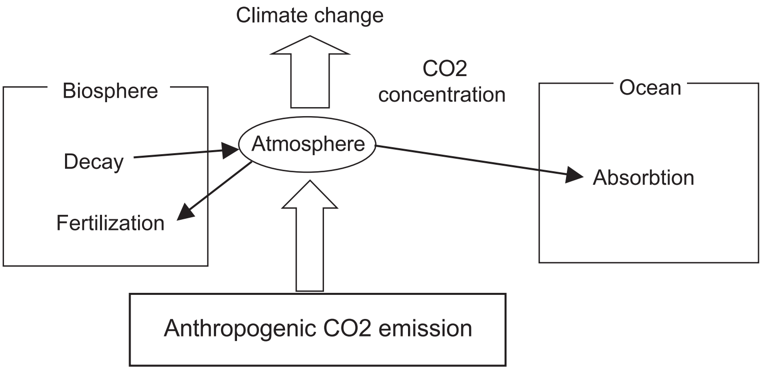

Fig. 2. Basic structure of Bern carbon cycle model.

us to evaluate the effects of CO_2 fertilization and land-use change. Although the formulation of the Bern model is simple, it follows the results of large GCMs well (IPCC, 2001b). Fig. 2 exhibits the basic structure of the Bern carbon circulation model. MARIA includes the Bern-CC model to reflect the new findings in climate science.

4. SER and palladium membrane process–low temperature hydrogen processes

Hydrogen is often expected to be a major fuel source in the future because of its low environmental impacts and flexibility of supply sources. Many industrial hydrogen production processes have been developed, which basically classified into three categories: electrolysis, steam reforming and hydrocarbon reforming. The first approach is simple but energy efficiency is low, while the second and the third ones require high temperatures.

Sorption-enhanced reaction (SER) is a new process being developed for the production of low-cost hydrogen through steam–methane reforming (Hufton et al., 1999, 2000). In this process, the reaction of methane with steam is carried out in the presence of a mixture of a catalyst and a selective adsorbent for CO_2. As a result, the reformation reaction occurs at a significantly lower temperature (300–500 °C) than that of conventional steam–methane reforming processes (around 800 °C) while achieving the same conversion of methane to hydrogen. According to Hufton, the hydrogen produced from the SER process is more than 99% pure while the conventional reactor provides only 70–75% purity. Fig. 3 exhibits the average gas composition of SER produced hydrogen (Hufton et al., 1999). According to them, the yield of hydrogen is high at 450 °C.

Shirasaki et al. (2001) also reports on a low temperature hydrocarbon reforming process using a palladium membrane for the selective separation of hydrogen. This system is, however, currently expensive and scale of economy does not likely appear due to the intrinsically high cost of palladium. Thin membrane synthesis technology would overcome this barrier.

The utilization of nuclear power for hydrogen production has recently been focused on, as can be seen in the proceedings of American Nuclear Society meeting in 2001 (ANS, 2001). It is not clear how and when their industrial marketability will appear although their

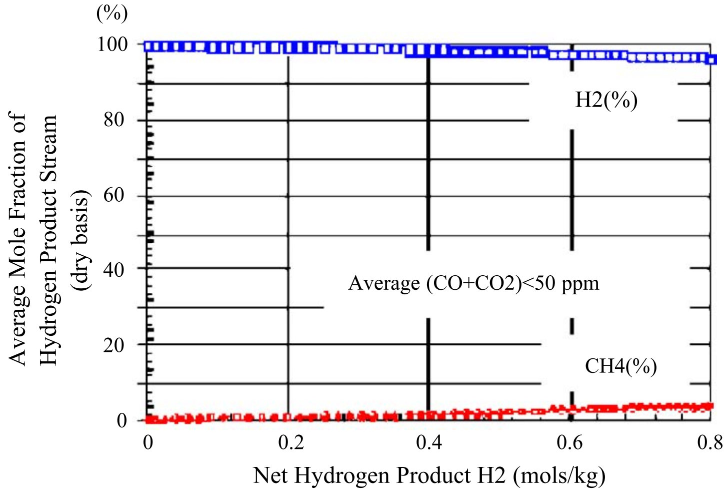

Fig. 3. Average product gas composition during a Sorption-Reaction Step with Initial H_2/Steam Pressurization as Measured on Lab-Scale SER#1 Unit; 6:1 steam/carbon feed, 1:1 adsorbent (HTC)/catalyst, 55 psig, 450 °C.

research feasibility has been demonstrated. However, when hydrogen production processes that operate under 500 °C are industrially realized, many opportunities for heat sources of them will be applicable, i.e., waste heat, gas turbine exhausts and FBR. In this paper, we focus on the possibility of FBR for electric power generation and SER hydrogen production process as well as the conventional electrolysis process using LWR, LWR-plutonium and FBR.

The fundamental chemical–thermal balances are the following:

Heat

$$CH_4 + H_2O = CO + 3H_2 - 206\ \mathrm{kJ/mol}$$

$$CO + H_2O = H_2 + CO_2 + 41\ \mathrm{kJ/mol}$$

$$CH_4 + 2H_2O = CO_2 + 4H_2 - 165\ \mathrm{kJ/mol}$$

$$\text{Combustion of } H_2\ (\text{net}):\ +242\ \mathrm{kJ/mol}\ (H_2)\ \text{or}\ 968\ \mathrm{kJ/mol}\ (4H_2)$$

$$\text{Combustion of } CH_4:\ +803\ \mathrm{kJ/mol}\ (CH_4)$$

Assuming 40% energy conversion efficiency in FBRs, the thermal heat of 1 GTOE-elec FBR and 12.167 GTOE methane generate 14.167 GTOE of hydrogen. Theoretically, this method can be applied to coal and other hydrocarbon-based processes.

It should be noted that these hydrocarbon-based processes are not carbon-free. However, carbon sequestration technologies are available if needed.

The cost assumptions are the keys to assess the potential contribution of FBR-based hydrogen production processes. However, the cost estimations have not been established yet since these processes are in the experimental stage. In this study, I set the parameters in the following manner:

(1) The production cost of hydrogen by electrolysis is assumed to be 4 Japanese yen per N m3 or, \$129 per TOE in 1990 price.
(2) The electric power generation cost of an FBR is 10% higher than that of an LWR. If an FBR is used for hydrogen production, a power generation steam turbine unit is replaced by SER or palladium membrane reactor. The maximum additional cost of FBR–SER process to FBR power generation is assumed to be equal to the cost of hydrogen production via electrolysis case. The lowest additional cost is set to be 0. In other words, in this the cost of the steam turbine of the FBR is equal to the cost oh the SER reactor. Needless to say, this lowest cost is no more than an assumption for the simulations.
(3) The energy end-use cost of hydrogen should be also imposed. In the industry, transportation and other end-use sectors, 10% higher energy cost coefficients than those of natural gas are assumed.

5. Scenarios and simulations

5.1. Potential contribution of hydrogen

In this paper, I assess the contribution of the FBR–SER process with the MARIA model based on SRES-B2 scenario and 550 ppmv atmospheric carbon concentration case. The effects of the carbon tax are also evaluated according to the EMF-19 scenarios. Other model parameters are identical with existing MARIA assumptions (Mori, 2000a).

Fig. 4 compares the hydrogen consumption paths in seven simulation cases changing hydrogen process costs from the reference value, where hydrogen end-use costs are 10% higher than that of natural gas.

Fig. 4 suggests that there is no incentive to introduce FBR–SER under no-carbon control policies when the hydrogen end-use cost is higher than that of natural gas. Even in the carbon concentration control case, additional hydrogen process cost to the FBR power generation needs to be lower than the 12.5% of electrolysis process for it to become competitive. These findings with respect to the B2-marker are understandable since direct use of natural gas and FBR power generation is more energy efficient than FBR–SER under the no-carbon control policy cases. In the carbon control cases, the cost of hydrogen production is essential. When the hydrogen process cost is low, demand for FBR–SER grows rapidly and comes to 3.5–4.3 GTOE in the end of this century which is more than 14–17% of total final energy consumption as shown below.

When the end-use cost of hydrogen declines to those of natural gas in the case of zero additional hydrogen process cost to the FBR electric power generation cost, the demands for FBR–SER hydrogen increase rapidly as shown in Fig. 5.

Fig. 5 shows that the potential demand for the hydrogen in carbon control policy cases will come to around 6 GTOE which is around 24% of total final energy demand. Even in the no-carbon control policy cases, the case with no additional cost to FBR-power generation and to natural gas end-use cost employs FBR–SER

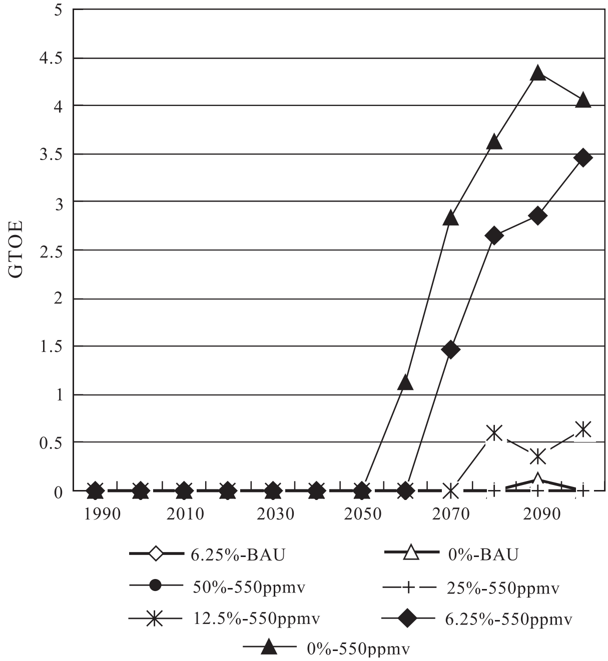

Fig. 4. Hydrogen consumption paths by changing hydrogen process costs in BAU and carbon control cases: 0%, 6.25%, 12.5%, 25% and 50% of the reference cost where hydrogen end-use cost is 10% higher than that of natural gas in all cases.

hydrogen in the second half of this century. However, its value diminishes in 2100. These findings suggest that potential of hydrogen production process is high but cost issues are critical.

Fig. 6(a and b) compares the world final energy flow profiles in B2-BAU scenario with reference hydrogen production and end-use cost and with zero additional production and end-use cost.

Fig. 7(a–c) shows the final demand profiles for hydrogen in the carbon concentration control cases. As the energy cost of hydrogen decreases, initial implementation of hydrogen becomes earlier and production increases.

Fig. 8 summarizes end-use hydrogen demand in the cases of (A) no additional hydrogen process cost to FBR-power generation and reference end-use cost and (B) no additional hydrogen process and end-use cost. Hydrogen input increases in all sectors uniformly. Unlike the B2-BAU cases, hydrogen is mainly input to industry and other sectors. Instead, biomass plays the main role in the transportation sector.

5.2. Effects of carbon tax options

Among various policy measures to mitigate carbon emissions, a carbon tax is still a major option since taxation institutions are already established well based on long tradition. Unlike carbon emission trading, carbon taxation does not guarantee meeting a

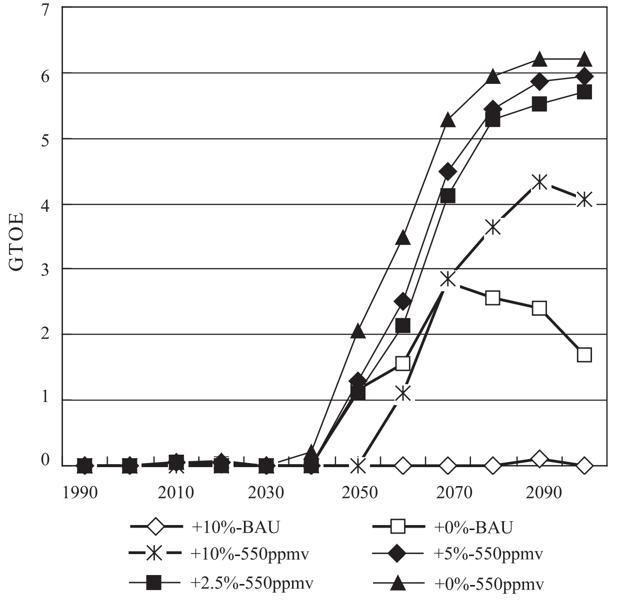

Fig. 5. Hydrogen consumption paths changing hydrogen end-use cost coefficients: 0%, 2.5%, 5% and 10% higher than those of natural gas where hydrogen additional process cost to the FBR power generation is set 0 in all cases.

carbon emission target. However, its revenue can be invested for the long-term R&D by public sector and tax reforming may be also expected. The short-term effects of such carbon taxes on the economy have been well investigated based on the CGE models as summarized in Chapters 8 and 9 of the IPCC-TAR-WG3 (IPCC, 2001a). The long-term

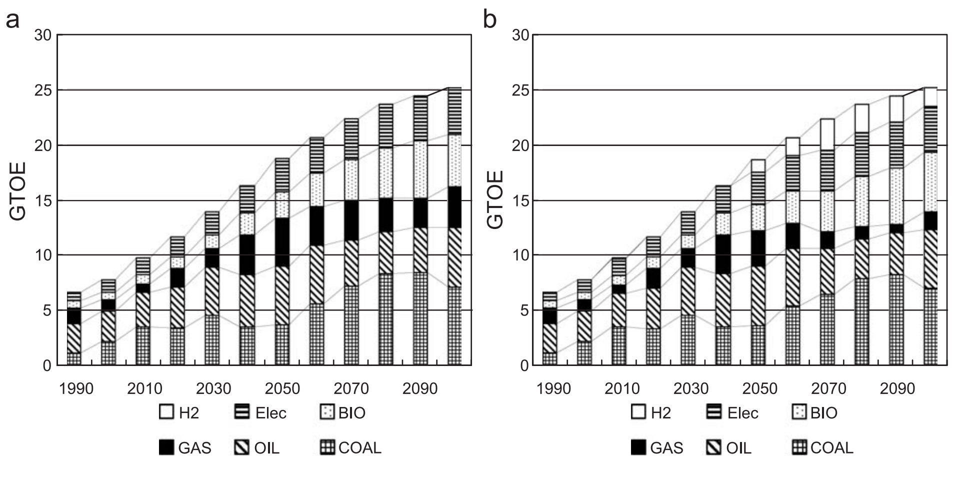

Fig. 6. (a) World final energy demand profiles in B2-Marker scenario with reference hydrogen production and end-use costs. (b) World final energy demand profiles in B2-Marker scenario with no additional hydrogen production and end-use costs.

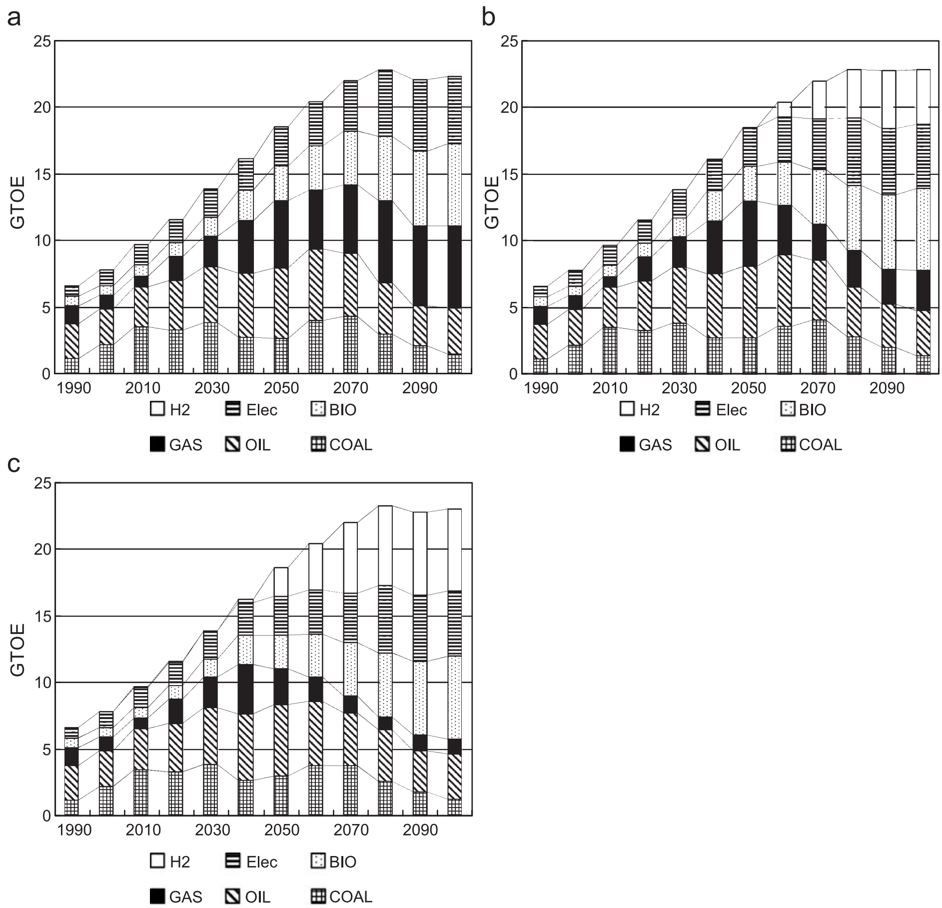

Fig. 7. (a) World final energy demand profiles in B2–550 ppmv control case with reference hydrogen production and end-use cost. (b) World final energy demand profiles in B2–550 ppmv control case with no additional hydrogen process cost to FBR-power generation and reference end-use cost. (c) World final energy demand profiles in B2–550 ppmv control case with no additional hydrogen process and no end-use cost.

impacts of carbon tax options have been discussed in the EMF-19 activities. In this paper, the following carbon tax scenarios provided by EMF-19 are evaluated.

(1) B2 Marker: business as usual (BAU) described in the previous section.
(2) WRE-550: carbon emission trajectory is set to stabilize the atmospheric carbon concentration at 550 ppmv following to the Wigley–Richels–Edmonds estimations.
(3) TAX-Low: increasing carbon tax \$10 per carbon ton per decade which begins at \$10 per carbon ton in 2010 and reaching \$100 in 2100.
(4) TAX-High: increasing carbon tax \$25 per carbon ton per decade which begins at \$25 per carbon ton in 2010, reaching \$100 in 2040 and staying at that level through 2100.
(5) TAX-100: constant carbon tax \$100 per carbon ton which is implemented in 2010 and maintained at that level through 2100.

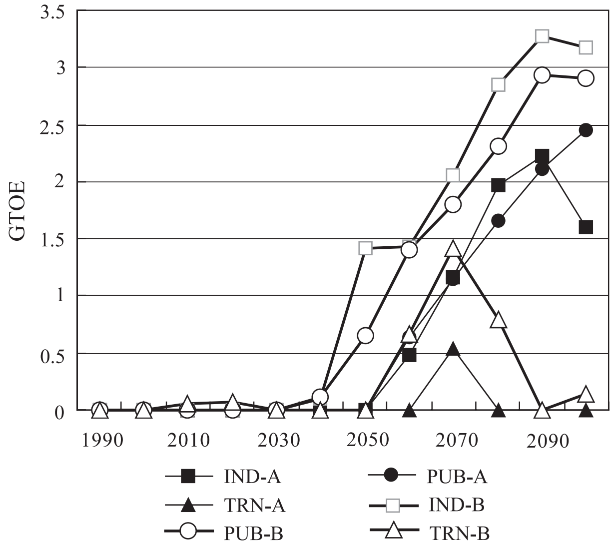

Fig. 8. Hydrogen end-use patterns for industry (IND), transportation (TRN) and public and other sectors (PUB) in B2–550 ppmv control cases under (A) no additional hydrogen process cost to FBR-power generation and reference end-use cost and (B) no additional hydrogen process and no additional end-use cost.

Fig. 9 shows the carbon emission trajectory of the above five scenarios. We can see that the WRE-550 trajectory is very similar to the TAX-High results. The constant carbon tax gives the largest carbon emission reduction in the first half of 21st century but emissions

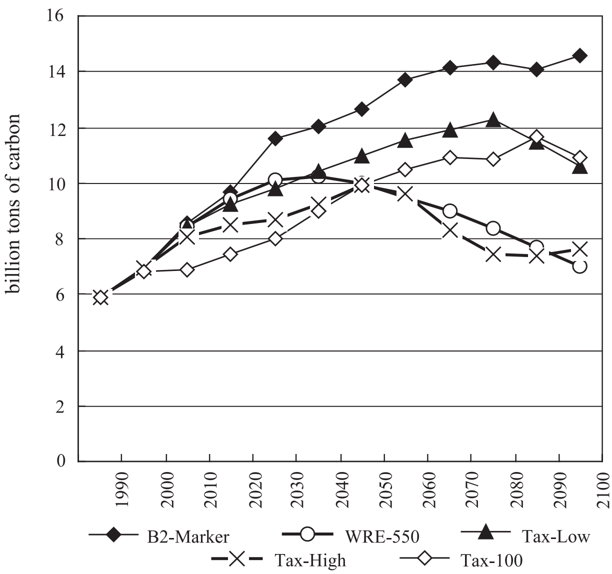

Fig. 9. Comparison of carbon emission trajectories of carbon tax options.

constantly increase. This suggests that the constant tax causes high net discounted emission reduction costs and fails to stabilize carbon concentrations.

Fig. 10 compares the nuclear power expansion results of the above scenarios. Although WRE-550 and TAX-High represent similar carbon emission trajectories, nuclear power in the latter is higher than that of the former. On the other hand, carbon sequestration is implemented in only WRE-550 case.

5.3. Interactions between nuclear and biomass

The previous sections suggest that the contribution of nuclear power is essential to stabilize the atmospheric concentration of carbon-dioxide. Although the nuclear power is the most cost-effective option, it is not indispensable as will be shown in this section. The B2−550 ppmv carbon control case with no expansion of nuclear power after 2010 leads to high biomass utilization. Carbon sequestration is also adopted at a 8.8-GtC in 2100 while it is at a 5.6-GtC rate in B2−550 ppmv case.

Fig. 11 shows that the loss of GDP where no nuclear expansion is assumed comes to more than 1.4% while that in B2−550 ppmv is no more than 0.6%. The potential expansion of biomass obviously mitigates the loss of GDP. Fig. 11 also shows that the lower carbon concentration target increases the maximum loss of GDP initially, but decreases it by the end of the century. This suggests that the social structure can adapt to the lower emission economy.

Fig. 12 provides similar results when one compares the trajectory of B2U450 with that of B2U550. These figures suggest that the impacts of the nuclear power saturation on the

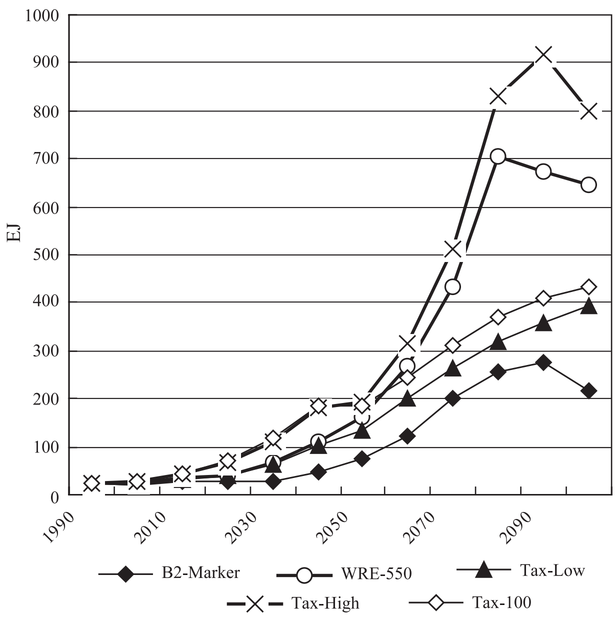

Fig. 10. Expansion of nuclear power of carbon tax options.

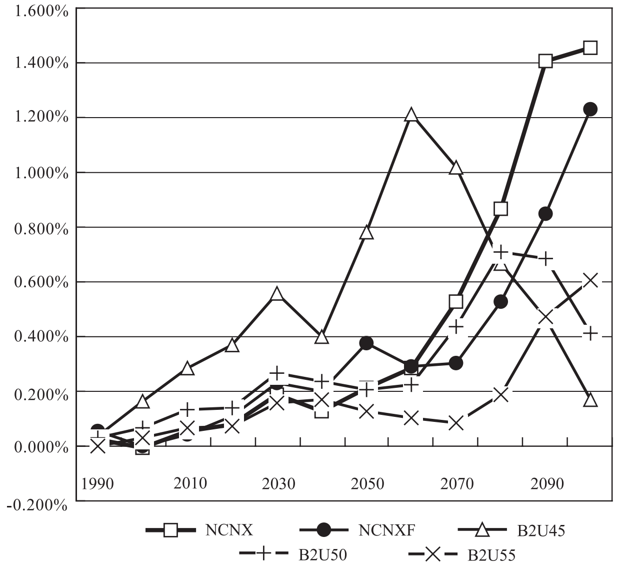

Fig. 11. Loss of World GDP when atmospheric carbon is stabilized. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

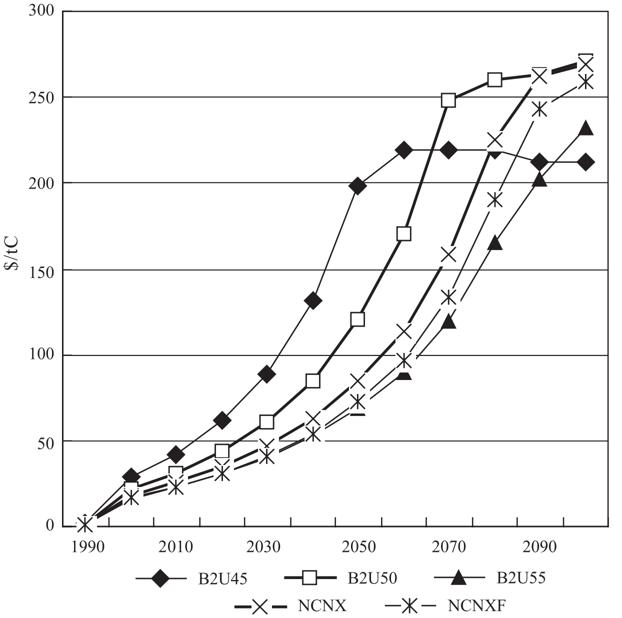

Fig. 12. Shadow prices of carbon emission. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

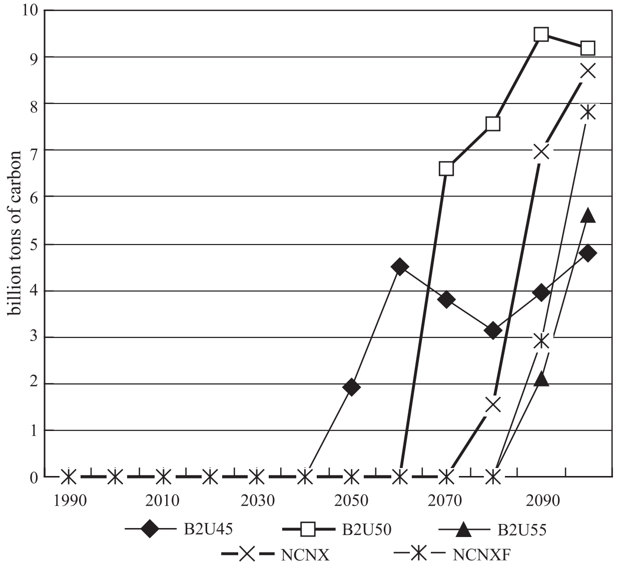

Fig. 13. Implementation of carbon sequestration. B2U45: 450 ppmv, B2U50: 500 ppmv, B2U55: 550 ppmv, NCNX: 550 ppmv no nuclear expansion, NCNXF/NCNX + increased potential biomass supply.

whole economy will be mitigated when the potential biomass supply increases. In the model, I assume that 10% of grassland and 5% of desert area can be converted to afforestation areas. Although the primary energy supply patterns do not change much, the loss of GDP and the shadow prices of carbon emission are apparently mitigated as are shown in Figs. 11 and 12.

Fig. 13 shows how carbon sequestration technologies are implemented. As the conditions become more stringent, earlier implementation of carbon sequestration is needed. The potential expansion of biomass supply mitigates the need for these options.

6. Conclusions

This study assesses the potential contribution of new hydrogen production processes utilizing FBRs using MARIA with the Bern-CC. Under a carbon concentration stabilization policy, FBR-based hydrogen can provide 6 GTOE in the second half of the century. However, the potential demand is sensitive to the supply cost. When additional process cost of hydrogen to FBR-electricity and additional energy cost to natural gas can be reduced, FBR-bases hydrogen can be implemented even in the no-carbon control case.

However, options with no nuclear power expansion policy are also possible under the carbon concentration control cases, where lower primary energy demand with around 1% additional GDP loss are observed. Higher carbon sequestration implementation is also required in this case.

The enhancement of biomass energy supply potential would mitigate the burden of carbon emission reduction as shown in the GDP losses and shadow prices of carbon emission figures, even if the primary energy supply profiles are not very different.

Low temperature hydrocarbon-based steam reforming processes are, however, applicable using heat sources other than nuclear heat. New heat cascading opportunities should also be evaluated as well as FBR-based processes. The assessments of these technologies should be the central in the future research.

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