Originally published as:

Fuminori Sano, Kenichi Wada, Keigo Akimoto, Junichiro Oda (2013). Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro and sectoral decomposition analyses, *Technological Forecasting and Social Change*, in press.

DOI:10.1016/j.techfore.2013.11.002

Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro and sectoral decomposition analyses

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Abstract

Macro- and sectoral-decomposition analyses were conducted using emission reduction scenarios from a global energy-system model. Emission reduction scenarios with targets of 550 ppmCO_2eq and 450 ppmCO_2eq, which consider variations in short-term emission fixes, up until 2030, based on extensions of the Copenhagen pledges, were selected from the AMPERE scenarios. All of the assessed emission reduction scenarios are technologically feasible through radical transformations in energy systems. Within the power sector, improvement of CO_2 intensity requires wide deployment of carbon-dioxide capture and storage, nuclear power, and renewable energies. In end-use sectors, not only energy intensity improvements but also CO_2 intensity improvements must be achieved by switching from fossil fuels to decarbonized energy by means of CO_2 intensity improvements on the energy supply side. The feasibility of improvements in CO_2 and energy intensities differs between sectors according to the types of mitigation options employed. The required carbon prices are \$183/tCO_2 for the 550 ppmCO_2eq target and \$645/tCO_2 for the 450 ppmCO_2eq target. When the short-term emission reduction is fixed at the level set by extensions of the Copenhagen pledges, long-term emission reductions by 2050 are more difficult to achieve because rapid and radical transformation of energy systems is required between 2030 and 2050.

1. Introduction

The development and deployment of climate change mitigation technologies are key measures for achieving ambitious greenhouse gas (GHG) emission reductions. It is, however, equally important to consider how these ambitious emission reductions can be achieved under real world constraints such as international politics and the availability of technology.

Decomposition analyses of GHG emissions proposed by Kaya [11] are frequently used by researchers across the world, including in the Intergovernmental Panel on Climate Change (IPCC) assessment reports [9, 10], as they provide insight into the efficacy of emission reduction strategies. The Kaya approach incorporates emissions per primary energy (carbon intensity of energy), primary energy per GDP (energy intensity), GDP per capita, and population. At the sectoral level, the decomposition can be represented by emission per primary energy, primary energy per production (e.g., crude steel production), production per capita, and population, for example. Decreases in the GDP per capita or production per capita, and population cause emission reductions and could also be considered for ambitious emission reductions; however, this paper particularly focuses on two factors, namely, the carbon intensity of energy and energy intensity.

Improving the carbon intensity of energy includes fuel switching from coal to natural gas, deployment of nuclear power and renewables such as hydro power, wind power and solar, and carbon dioxide capture and storage (CCS). These options are mainly considered as climate mitigation measures in the energy supply sector. However, improving the carbon intensity of energy not only in the energy supply sector but also in the energy end-use sector will also contribute to emission reductions, such as switching vehicle fuel from gasoline or diesel to electricity or CCS introduction in the iron and steel sector. Improving the energy intensity includes deployment of highly energy-efficient power plants in the energy supply sector, such as ultra-supercritical coal power, integrated coal gasification combined cycle (IGCC), and advanced natural gas combined cycle with high inlet temperature. In the energy end-use sector, various kinds of technologies exist for improving energy intensity. For example, coke dry quenching (CDQ) and top-pressure recovery turbines (TRT) are typical energy efficient technologies that can be used in the iron and steel sector. For road transportation, highly efficient internal combustion engine vehicles (ICEV) and hybrid electric vehicles (HEV) are more energy efficient technologies than conventional ICEVs. Furthermore, electric vehicles (EV) and fuel-cell vehicles (FCV) are expected to improve energy efficiency and also allow fuel switching to decarbonized energies combined with emission intensity improvements in the energy supply sector.

To achieve ambitious emission reductions, such technologies should be evaluated not only for use in the energy supply sector but also for the energy end-use sectors. However, there is a complex relationship between the energy supply and end-use sectors for certain technologies, and these must be assessed consistently across all sectors in the emission reduction scenarios. We have developed a technology-rich global energy-system model, which we call DNE21+, and have conducted various analyses of climate change mitigation [2, 3]. Studies by the IEA [6, 8] and Akashi and Hanaoka [1] were also analyzed for global emission reduction scenarios using technology-rich global energy system models, which explicitly considered several kinds of technologies both in the energy supply and end-use sectors. However, few studies have accounted for the costs and achievability of technologies in the assessment of ambitious emission reduction targets.

In this study, a subset of the AMPERE CO_2 emission reduction scenarios [14] were analyzed using the DNE21+ model and decomposition analyses of the scenarios were conducted not only on a macroeconomic level but also on a sectoral level so as to better understand the implications of the results. The AMPERE is a project which aims for a broad exploration of mitigation pathways and associated mitigation costs under real-world limitations while offering insights into the differences across models and the relation to historical trends. 18 models including the DNE21+ model participate in the AMPERE study. The scenarios include emission reductions to achieve 550 ppmCO_2eq and 450 ppmCO_2eq atmospheric concentration levels by 2100, which correspond to category III and category I stabilization targets in IPCC AR4 [10], respectively. In addition, variations of the short-term emission outlook to 2030 are examined in these scenarios in order to assess current real world conditions for climate change mitigation.

Section 2 provides a description of the assessment model DNE21+ and the scenarios considered in this study. Section 3.1 gives an overview of the results of the analysis for the scenarios with a macro decomposition analysis. Section 3.2 outlines the sectoral decomposition analyses and discusses the results, focusing on the power, iron and steel, and road transport including technology mix. Section 4 provides the conclusions of this study.

2. Assessment model

The DNE21+ model [2, 3] is used for the analysis in this paper. The model is an inter-temporal linear programming model for assessing global energy systems and global warming mitigation. The overview of the DNE21+ model is available in the electronic supplementary material.

2.1 Models for main sectors

CO_2 emissions from the power, iron and steel, and road transport sectors represent major contributions to global emissions. Their CO_2 emissions in 2010 are 9.7 $GtCO_2$/y, 1.7 $GtCO_2$/y, and 5.0 $GtCO_2$/y, respectively, and the share of three sectors in the total CO2 emission is 53% [5]. Therefore, CO_2 emission reduction measures in these three sectors will have large impacts on global warming mitigation. In this section, the modeling of the power, iron and steel, and road transport sectors is described.

In the power sector, both widely used technologies and novel technologies including CCS are considered [15, 16]. Technologies are explicitly modeled not only by energy source but also by generation efficiency level. For example, a coal power plant is divided into three options: low efficiency (e.g., sub-critical), middle efficiency (e.g., critical in the present, super-critical (SC) in the future), and high efficiency (e.g., ultra SC in the present, IGCC and IGFC in the future). Current regional variations in generation efficiency [13] are considered as exogenous assumptions by estimating the installed capacity through technology options in the model.

In the iron and steel sector, crude steel production by blast furnace–basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) are modeled [12]. For EAF, scrap-based EAF and direct-reduced iron (DRI)-based EAF are considered. Several kinds of technology options for energy efficiency improvements such as CDQ and TRT are also considered. Furthermore, CCS technologies for BF-BOF are also considered. Crude steel production is included as an exogenous scenario by region, and the scenario is fixed for all the scenarios analyzed in this study. The world total crude steel production in 2050 is assumed to be 2,200 million ton per year, which is almost double that in 2005.

Road transport is modeled with explicit consideration of specific technologies. The transportation service is divided into five categories: small passenger car, large passenger car, bus, small truck, and large truck. The transportation service is included as an exogenous scenario by region and by the five categories, and the scenario is fixed for all the scenarios analyzed in this study. For example, the transportation service for small and large passenger cars in 2050 is assumed to be 31 trillion km/y, which is almost 2.7 times larger than that in 2005. The technology options considered for passenger cars are ICEV, HEV, plug-in HEV, EV, and FCV. In addition, alternative fuels such as bio-fuel and natural gas are also considered.

Further detail information of the iron and steel sector and road transport sector in the DNE21+ model is given in the electronic supplementary materials.

2.2 Emission reduction scenarios

This study analyzes a subset of AMPERE scenarios [14] (see Table 1). The Base-FullTech-OPT scenario does not include any climate change mitigation policies, and it assumes that all of the technologies in the model are available. The long-term emission target is defined by cumulative CO_2 emissions between 2000 and 2050. The assumed cumulative CO_2 emissions are 1,500 $GtCO_2$ for achieving 450 ppmCO_2eq by 2100 and 1,800 $GtCO_2$ for achieving 550 ppm CO_2eq by 2100.

In order to include current international discussions on climate change mitigation, the short-term emission outlook is also assumed as a different GHG emission pathway to 2030, based on an extension of the Copenhagen pledges for 2020 [14]. In this paper, emission pathways until 2030 are assumed as global emission cap scenarios by time-point. The assumed global GHG emissions are 55 $GtCO_2$eq/y and 61 $GtCO_2$eq/y for 2020 and 2030, respectively, in the high estimate case. In the low estimate case, the global emissions are 51 $GtCO_2$eq/y and 53 $GtCO_2$eq/y for 2020 and 2030, respectively. After 2030, global emission cap scenarios are generated that achieve the assumed cumulative emissions between 2000 and 2050 for both the 550 and 450 ppm CO_2eq scenarios. Therefore, the least-cost measures for global and uniform carbon prices across all countries are estimated by time-point.

Table 1 Subset of AMPERE scenarios focused on in this paper.

Scenario name	Long-term target	Short-term target
Base-FullTech-OPT	Base	OPT (Optimal)
450-FullTech-OPT	450 ppm CO_2eq	OPT (Optimal)
450-FullTech-HST	450 ppm CO_2eq	HST (High estimate case of extension of the Copenhagen pledges)
450-FullTech-LST	450 ppm CO_2eq	LST (Low estimate case of extension of the Copenhagen pledges)
550-FullTech-OPT	550 ppm CO_2eq	OPT (Optimal)
550-FullTech-HST	550 ppm CO_2eq	HST (High estimate case of extension of the Copenhagen pledges)
550-FullTech-LST	550 ppmCO_2eq	LST (Low estimate case of extension of the Copenhagen pledges)

3. Results and discussion

3.1 Macro decomposition analysis

Figure 1 shows global CO_2 emissions, CO_2 intensity (CO_2 per total primary energy), and energy intensity (total primary energy per GDP) in the reference scenario (Base-FullTech-OPT) and in the emission reduction scenarios. In this paper, GDP is expressed in market exchange rates (MER). In the Base-FullTech-OPT scenario, CO_2 emissions increase toward 2050. The CO_2 emissions in 2050 are 71 $GtCO_2$/y, which are almost double those in 2005. CO_2 intensity remains almost constant until 2050, whereas energy intensity improves toward 2050. The annual average improvement in energy intensity from 2005 to 2050 is 1.2%/y, which is fairly consistent with historical changes, e.g., the improvement rate from 1980 to 2000 was 1.2%/y [7] globally.

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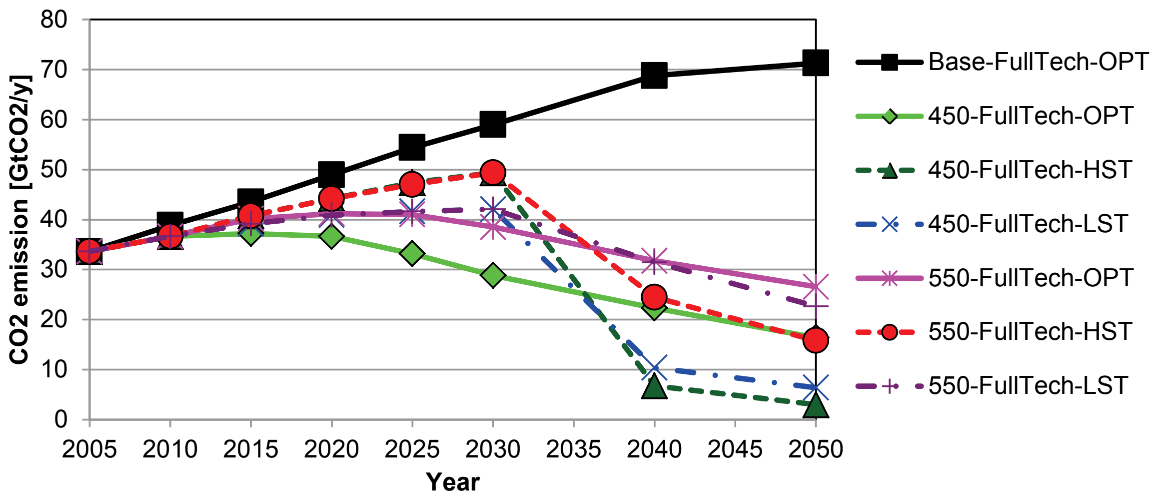

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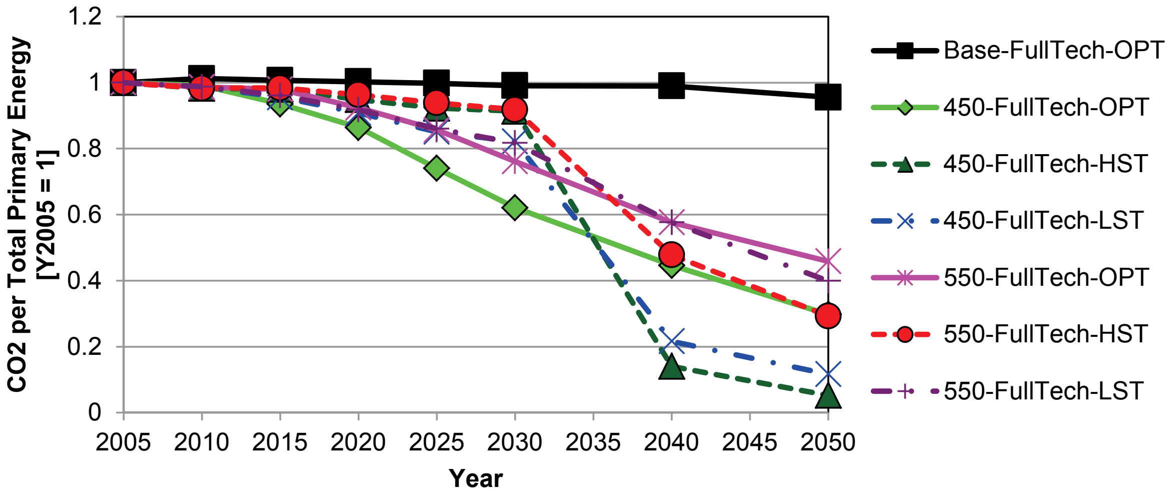

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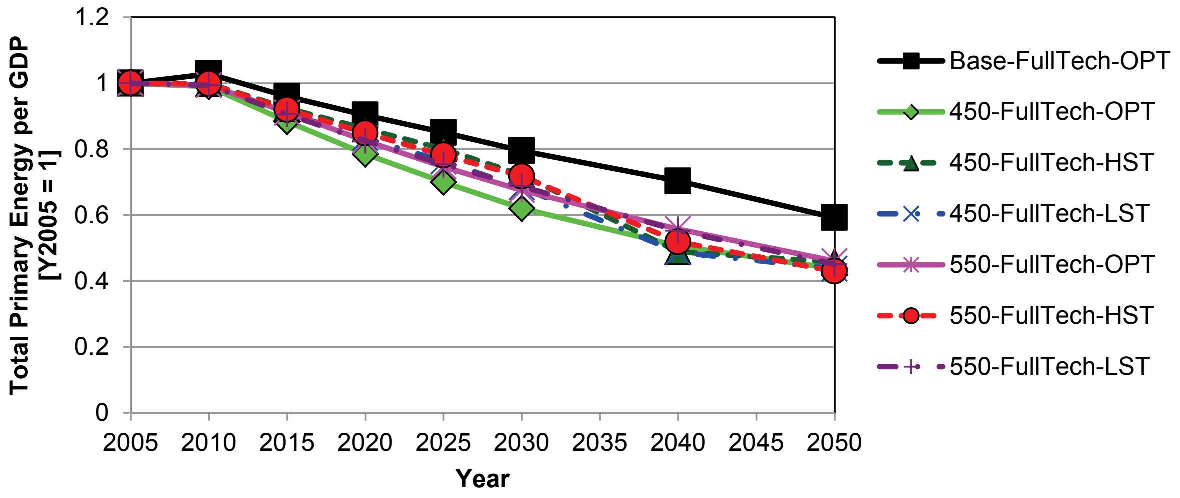

Figure 1 Global CO_2 emissions, CO_2 intensity (CO_2 per total primary energy), and energy intensity (total primary energy per GDP) in Base-FullTech-OPT scenario and emission reduction scenarios. (a) CO_2 emission. (b) CO_2 intensity (CO_2 per total primary energy). (c) Energy intensity (total primary energy per GDP).

In the emission reduction scenarios, large reductions in CO_2 emissions are required from the Base-FullTech-OPT scenario in order to meet the assumed targets. In 2050, the required CO_2 emission reductions from the Base-FullTech-OPT scenario are varied from 45 $GtCO_2$/y to 68 $GtCO_2$/y. CO_2 emissions in 2050 relative to 2000 vary from -12% to -48% for the 550 ppm CO_2eq scenarios and from -46% to -90% for the 450 ppm CO_2eq scenarios, respectively. These emissions are almost consistent with the emission range in the study by van Vuuren and Riahi [17]. They classified characteristics of the CO_2 emission pathways of new scenario literature published after IPCC AR4 in line with the categories of IPCC AR4. However, our upper limits (-48% for the 550-FullTech-HST scenario and -90% for the 450-FullTech-HST scenario) are lower than the emission range of the IPCC categories III and I reported in van Vuuren and Riahi [17]. Both CO_2 intensity and energy intensity must be improved significantly to achieve the CO_2 emission reductions. The CO_2 intensities in both the 550-FullTech-OPT scenario and the 450-FullTech-OPT scenario improve continuously toward 2050, and the intensities in 2050 are 0.46 and 0.30 of the 2005 value, respectively. The annual average improvement rates of the CO_2 intensity from 2005 to 2050 are 1.7%/y and 2.7%/y. Until 2030, the scenarios with assumed short-term emission fixes show slower improvements in CO_2 intensity than the scenarios without short-term CO_2 fixes. After 2030, rapid improvements in CO_2 intensity are required to meet the long-term targets by 2050. For the 550 ppmCO_2eq scenarios, the annual average improvement in CO_2 intensity from 2030 to 2050 is 5.7%/y with the short-term emission fix by the high estimate, and 3.6%/y with the low estimate. For the 450 ppmCO_2eq scenarios, the corresponding values are 14.3%/y and 9.8%/y. These annual average improvement rates are significantly higher than those in historical data or in the Base-FullTech-OPT scenario.

The energy intensities in both 550-FullTech-OPT and 450-FullTech-OPT scenarios also improve with time. The energy intensities in 2050 in the 550-FullTech-OPT and the 450-FullTech-OPT scenarios are 0.46 and 0.44 times the 2005 value, respectively. The annual average improvement rates of the energy intensity from 2005 to 2050 for the two scenarios are 1.7%/y and 1.8%/y, respectively. The difference in the energy intensities in 2050 between the six emission reduction scenarios is smaller than that in the CO_2 intensities. There are opportunities for energy intensity improvements in the reference scenario and the 550 ppm-CO_2eq scenario. However, additional cost-effective measures to improve the energy intensities of the 550 ppm-CO_2eq and 450 ppm-CO_2eq scenarios are limited. In comparison to historical trends of global CO_2 intensity improvement, e.g. 0.5%/y between 1980 and 2000 [5, 7], a huge contribution from CO_2 intensity improvements to reduce CO_2 emissions is required between 2030 and 2050, which is the period during which large CO_2 emission reductions will be required.

3.2 Sectoral decomposition analysis

Huge improvements in the CO_2 intensity and the energy intensity are required to achieve the emission reduction targets assumed in the scenarios, as shown in the previous section. Decomposition analyses at the macroeconomic level provide the general direction of the assumed targets. However, a more detailed understanding on how they can be achieved in each sector is also important. In this section, the sectoral emission reduction measures and the sectoral decomposition analyses are described.

Figure 2 shows the sectoral CO_2 emissions in 2030 and 2050 in the reference and emission reduction scenarios. In the Base-FullTech-OPT scenario, CO_2 emissions from the power sector are largest, accounting for 23 GtCO2/y and 28 GtCO_2/y in 2030 and 2050, respectively, which is almost 40% of the total in the both years. The CO_2 emissions from the energy end-use sectors (industrial, transportation, and residential and commercial sectors) are 28 GtCO_2/y in 2030 and 34 GtCO_2/y in 2050. Within the energy end-use sectors, the CO_2 emissions from the industrial sector are the largest.

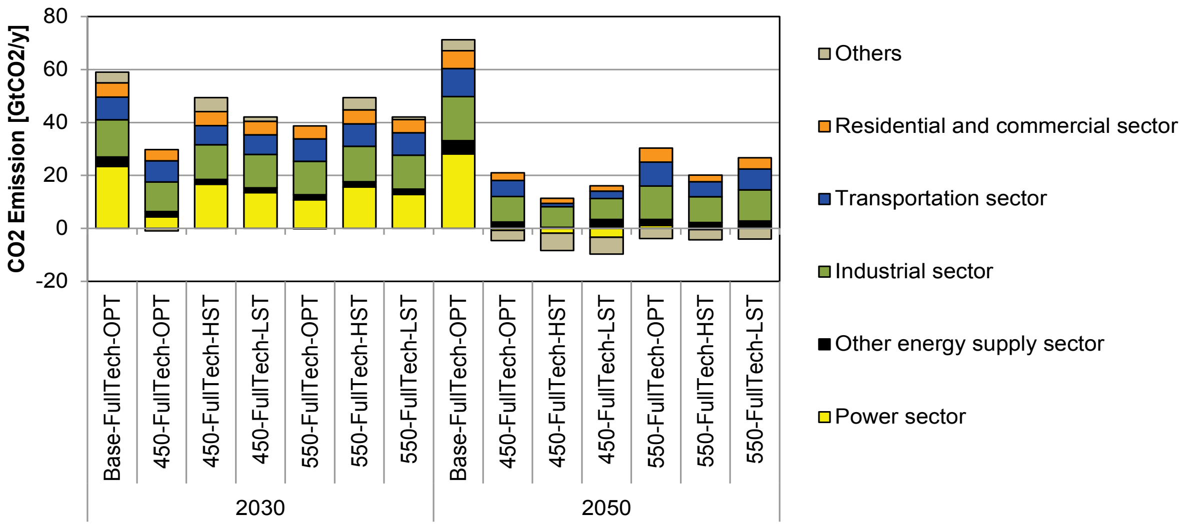

Figure 2 Sectoral CO_2 emissions in 2030 and 2050 in the Base-FullTech-OPT scenario and the emission reduction scenarios (World total).

In the emission reduction scenarios, CO_2 emissions from the power sector are significantly reduced relative to the Base-FullTech-OPT scenario. They are almost zero for the 550 ppmCO_2eq scenarios in 2050 and negative for the 450 ppmCO_2eq scenarios. To improve the CO_2 intensity, technology mixes in the power sector are significantly different to the Base-FullTech-OPT scenario. Large CO_2 emission reductions in energy end-use sectors are also observed to achieve the assumed emission reduction targets. CO_2 emissions from the energy end-use sectors for the 450 ppmCO_2eq scenarios are 11–19 GtCO_2/y in 2050, and their emission reduction rates relative to the Base-FullTech-OPT scenario are 45%–68%. Significant changes to energy systems are required to achieve such ambitious emission reductions, not only in the energy supply sector but also in the end-use sector. Furthermore, a large amount of CO_2 emission reduction through CO_2 fixation in 2050 will be required as negative CO_2 emissions from others seen in Figure 2.

In the following part of this section, quantitative analyses of the CO_2 and energy intensities and technological measures for the power and iron and steel sectors, and the passenger cars road transport are described.

3.2.1 Power sector

Figure 3 shows global CO_2 emissions, CO_2 intensity (CO_2 per electricity generation), and energy intensity (electricity generation energy per GDP) for the power sector in the reference scenario (Base-FullTech-OPT) and the emission reduction scenarios. As shown in Figure 2, CO_2 emissions from the power sector in the emission reduction scenarios are drastically reduced by 2050. Radical emission reductions after 2030 are required especially for the scenarios in which the short-term emissions are constrained. The improvements in CO_2 intensity are considerably larger than the improvements in energy intensity, while both intensities must be improved to achieve the targeted emission reductions. On the other hand, the energy intensities in the 450-FullTech-HST and the 450-FullTech-LST scenarios are worse after 2040. This is because (1) the expansion of CCS requires a lot of power to capture CO_2, (2) electrolytic hydrogen production is developed to partly meet the demand for liquid energies in the transportation sector and natural gas demand in the industrial, residential, and commercial sectors, and (3) electrical technologies in various sectors, including EVs in the road transport sector, are widely deployed. The latter two reasons have a large effect on large CO_2 emission reductions, which rely on the low CO_2 intensity of electricity.

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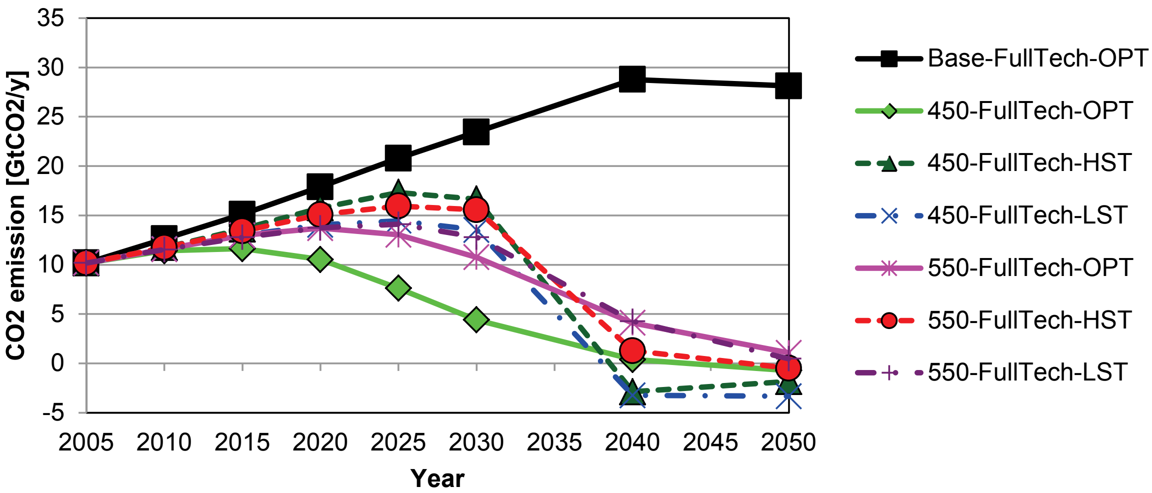

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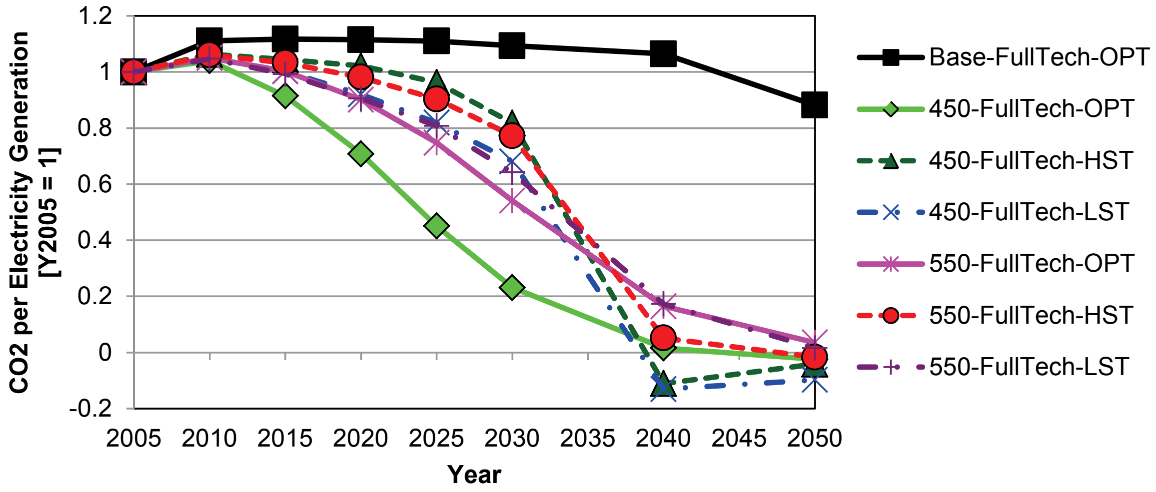

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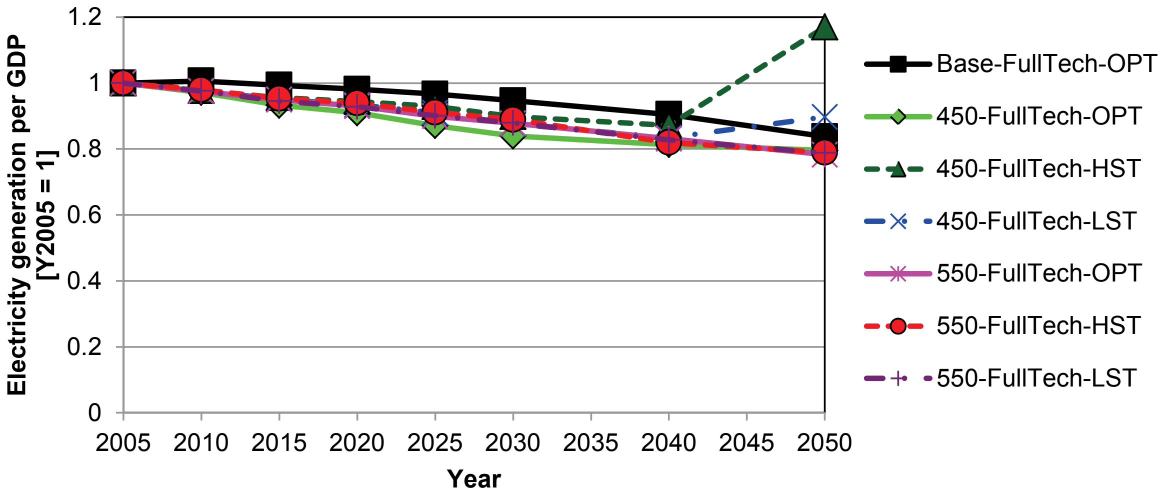

Figure 3 Global CO_2 emissions, CO_2 intensity (CO_2 per electricity generation), and energy intensity (electricity generation per GDP) for power sector in Base-FullTech-OPT scenario and emission reduction scenarios. (a) CO_2 emission. (b) CO_2 intensity (CO_2 per electricity generation). (c) Energy intensity (Electricity generation per GDP).

The electricity generation mixes in 2030 and 2050 are shown in Figure 4, and differences are seen between the emission reduction scenarios and the Base-FullTech-OPT scenario to achieve improvements in the CO_2 intensities, as shown in Figure 3. In 2030, the measures used to improve the CO_2 intensities are fuel switching from coal to gas, deployment of CCS, and expansion of zero-emission technologies such nuclear power, wind power, and solar. Efficiency improvements of fossil-fuel power plants through the widespread deployment of high-efficiency fossil-fuel power plants are also undertaken as cost effective measures. In 2050, improvements to the CO_2 intensities from CCS and the zero-emission power supply technologies become larger than in 2030. Many fossil-fueled power plants, particularly coal power plants with low efficiency, cease operating before the end of their assumed lifetime (40 years) to realize rapid CO_2 intensity improvements by the deployment of zero-emission technologies.

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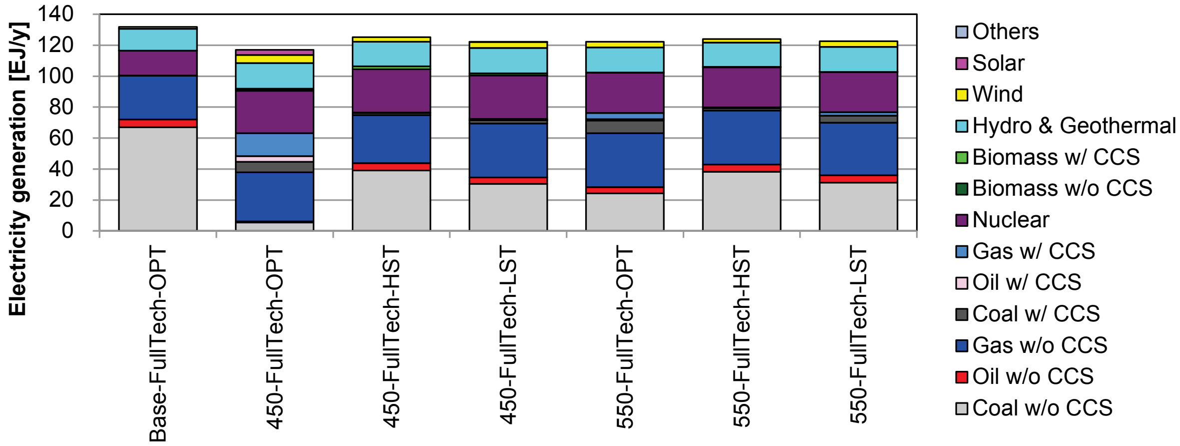

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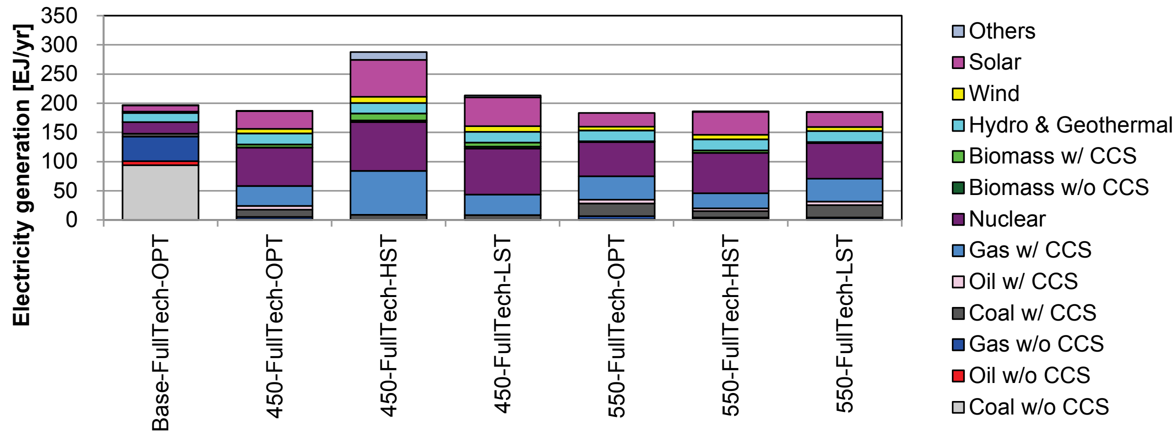

Figure 4 Electricity generation mix in Base-FullTech-OPT scenario and emission reduction scenarios in 2030 and 2050 (World total). (a) 2030. (b) 2050.

Note: Others include hydrogen power generation and PV generation for electrolysis without grid connection.

3.2.2 Iron and steel sector

Figure 5 shows the global CO_2 emissions, CO_2 intensity (CO_2 per final energy consumption), and energy intensity (final energy consumption per crude steel production) from the iron and steel sector in the Base-FullTech-OPT scenario and the emission reduction scenarios. CO_2 emissions include indirect CO_2 emissions from electricity consumption. As mentioned in Section 2.1, the assumed global crude steel production grows with time and by 2050 is almost double that in 2005. CO_2 emissions increase toward 2050. CO_2 emissions from the iron and steel sector in the Base-FullTech-OPT scenario are 3.4 $GtCO_2$/y in 2050, which is 1.5 times larger than the corresponding value in 2005. Although the CO_2 intensity remains almost constant until 2050, the energy intensity is improved by the deployment of highly energy efficient plants.

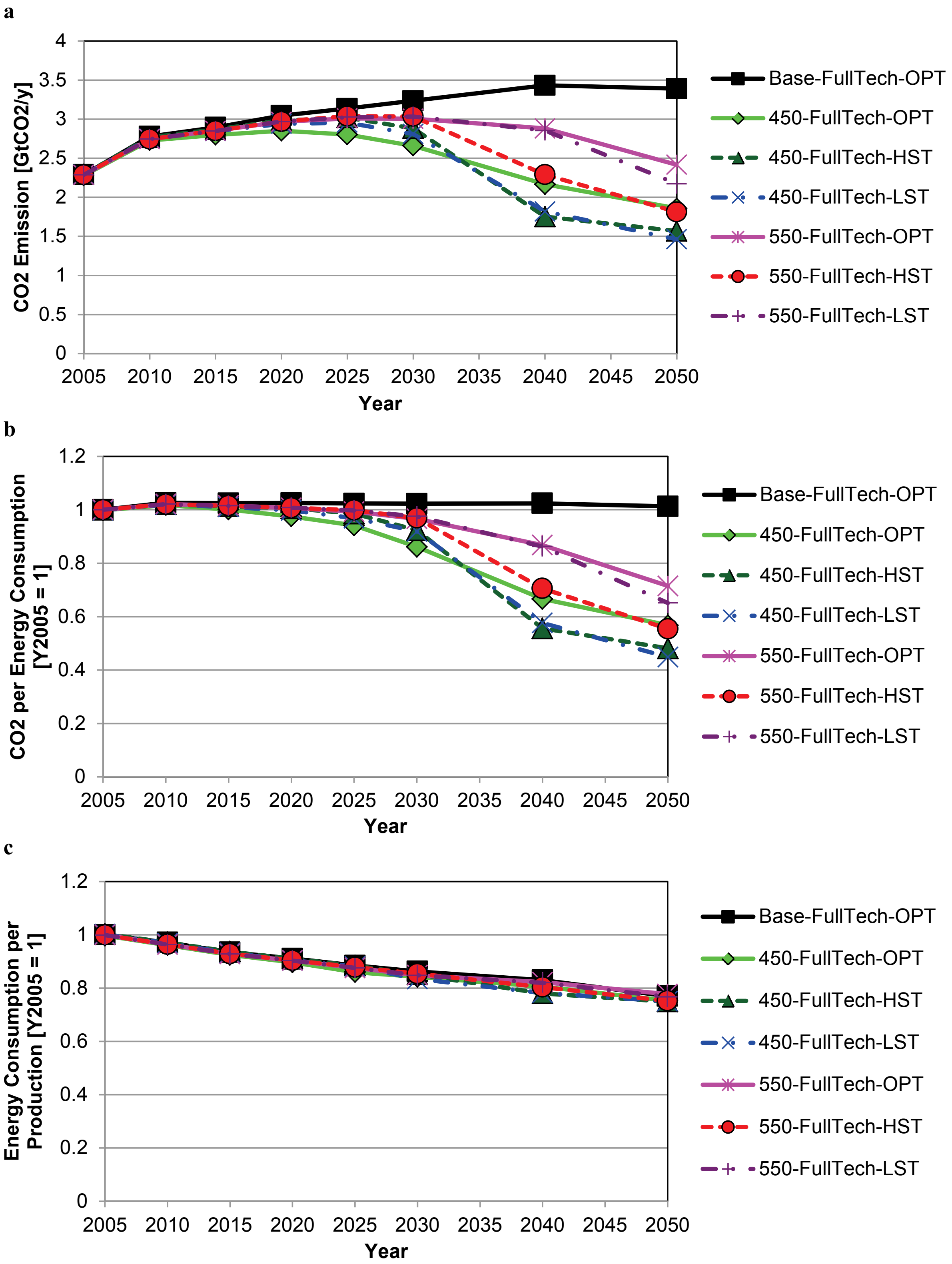

Figure 5 Global CO_2 intensity (CO_2 per energy consumption) and energy intensity (energy consumption per crude steel production) for crude steel production in Base-FullTech-OPT scenario and emission reduction scenarios. (a) CO_2 emission. (b) CO_2 intensity (CO_2 per energy consumption). (c) Energy intensity (Energy consumption per crude steel production).

Note: Indirect CO_2 emission from electricity consumption is included.

The CO_2 intensities in the emission reduction scenarios are drastically improved compared to those in the Base-FullTech-OPT scenario, while the energy intensities improve steadily, and the differences between scenarios are not very large. Technological measures to facilitate drastic CO_2 intensity improvements include widespread deployment of CCS for BF-BOF and expansion of highly efficient EAF combined with decarbonization in the power sector, as mentioned above. In 2050, CCS is deployed for almost all BF-BOF, as shown in Figure 6, not only in the 450 ppmCO_2eq scenarios but also in the 550 ppmCO_2eq scenarios. In the 450-FullTech-HST and 450-FullTech-LST scenarios, after 2030, the CO_2 intensity improvements are quite rapid to meet the total CO_2 emission reductions, as shown in Figure 3. Steel production plants are usually operated for a long time, and the lifetime is assumed as 40 years in the DNE21+ model. Such rapid emission reductions require the operation of many low efficiency steel production plants to be ceased earlier than this, and that higher efficiency plants be introduced to improve the CO_2 intensity in the short term.

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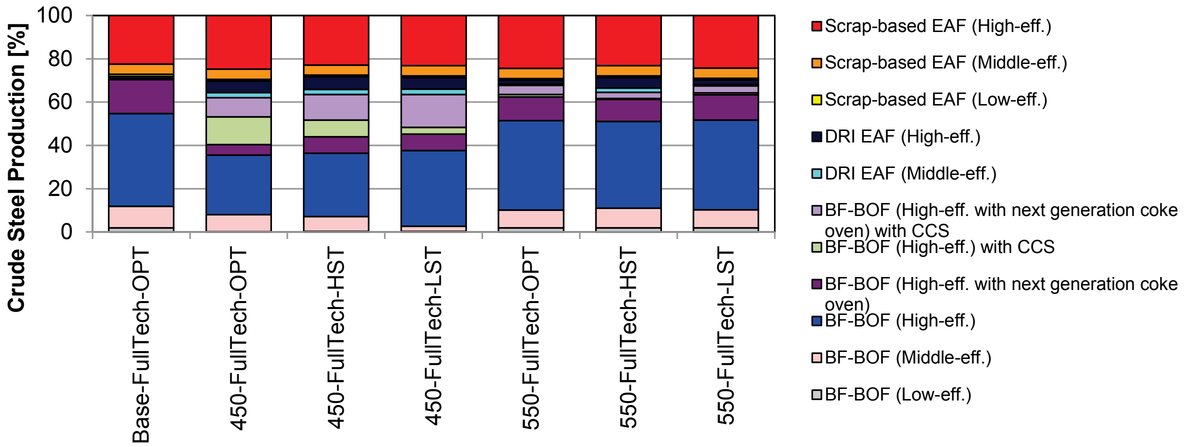

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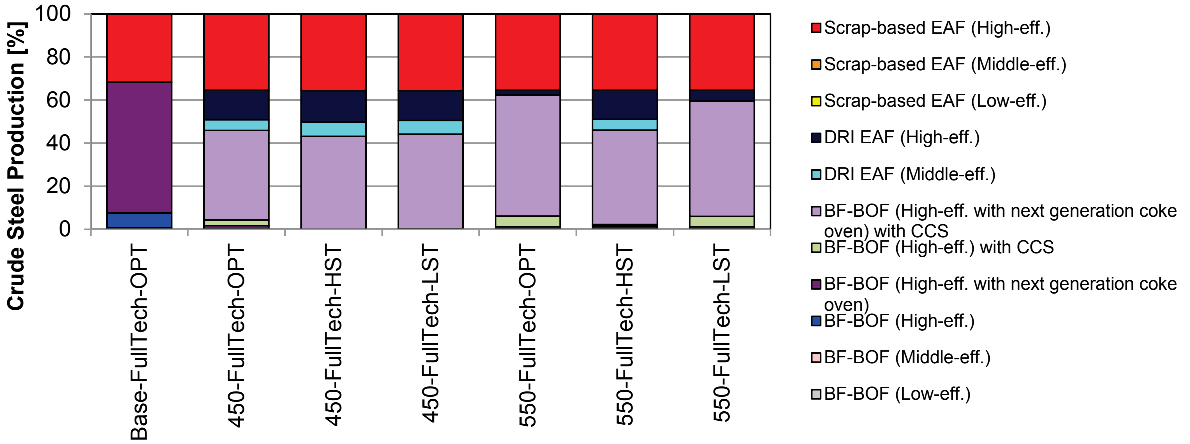

Figure 6 Technology mix for crude steel production in Base-FullTech-OPT scenario and emission reduction scenarios in 2030 and 2050 (World total). (a) 2030. (b) 2050.

3.2.3 Passenger cars road transport

Figure 7 shows global CO_2 emissions, CO_2 intensity (CO_2 per final energy consumption), and energy intensity (final energy consumption per transportation service) of passenger cars in the Base-FullTech-OPT scenario and the emission reduction scenarios. The assumed level of transportation by passenger car grows toward 2050 and is 2.7 times greater than that in 2005, as mentioned in Section 2.1. CO_2 emissions in the Base-FullTech-OPT scenario increase according to this growth. However, CO_2 emissions in 2050 are only twice those in 2005 as a result of predicted improvements in energy intensity. Improved energy intensity in the Base-FullTech-OPT scenario arises from presumed technological advances in the road transport sector which, even in that scenario, are driven by factors such as strengthened fuel economy policies and higher oil prices. On the contrary, the CO_2 intensity remains almost constant.

In the emission reduction scenarios, both of the intensities improve. Significant improvement in the CO_2 intensity is achieved through switching from conventional fossil fuels to bio-fuel, electricity, and hydrogen. The CO_2 intensity of electricity is substantially improved by decarbonization in the power sector, as previously mentioned. Hydrogen is produced by electrolysis with decarbonized electricity or natural gas reforming with CCS, and therefore, the CO_2 intensity of hydrogen production is also low. An application of CCS for bio-fuel production is not considered in this study and the future assessments are important. The very low CO_2 intensities in the 450-FullTech-HST and 450-FullTech-LST scenarios after 2030 are achieved by a huge expansion of those three energy carriers. The energy intensity is improved through the deployment of highly efficient vehicles. In 2030, ICEVs have the largest share in the passenger car market, followed by HEVs, as shown in Figure 8. In 2050, further deployment of HEVs contributes to the energy intensity improvement. Furthermore, plug-in HEVs, EVs, and FCVs also contribute to that improvement. In the 450-FullTech-HST and 450-FullTech-LST scenarios, which require more significant emission reductions in 2050, EVs represent the largest share in the passenger car market, and substantial improvements in the energy intensity are realized. Compared with fossil-fuel power plants and steel production plants, the lifetime of a passenger car is shorter (the lifetime is assumed to be 10–20 years, depending on the region). However, changes in the production systems of automobile manufacturers for various kinds of vehicle and infrastructure transition from conventional liquid fuel to electricity and hydrogen are required to realize such a technology-mix transition in passenger cars, and this will depend on consumer demand and preference. Therefore, rapid transition of the technology mix of passenger cars also faces real world difficulties, as in the other sectors.

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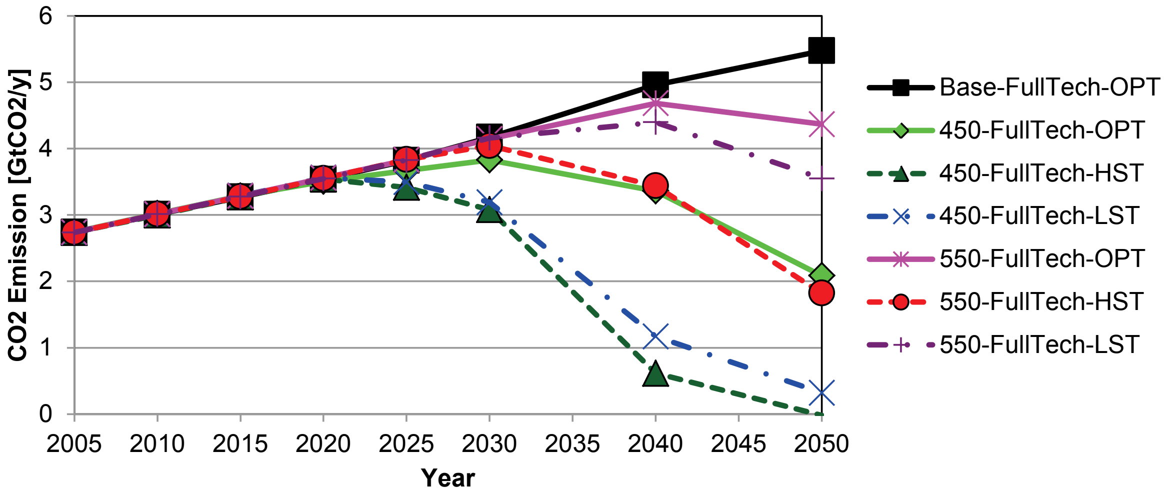

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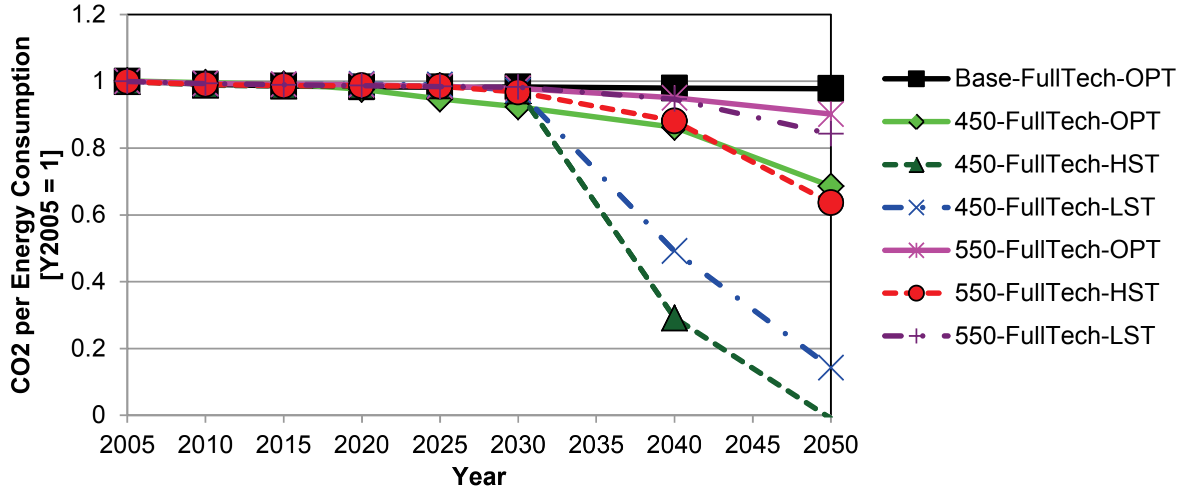

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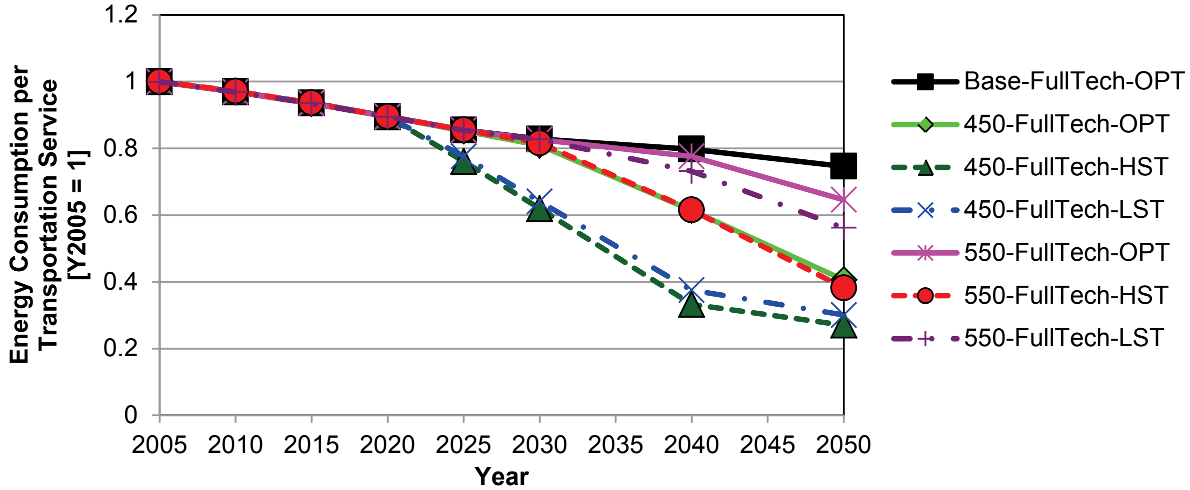

Figure 7 Global CO_2 intensity (CO_2 per energy consumption) and energy intensity (energy consumption per transportation service) for passenger cars in Base-FullTech-OPT scenario and emission reduction scenarios. (a) CO_2 emission. (b) CO_2 intensity (CO_2 per energy consumption). (c) Energy intensity (Energy consumption per transportation service).

Note: Indirect CO_2 emission from electricity consumption is included.

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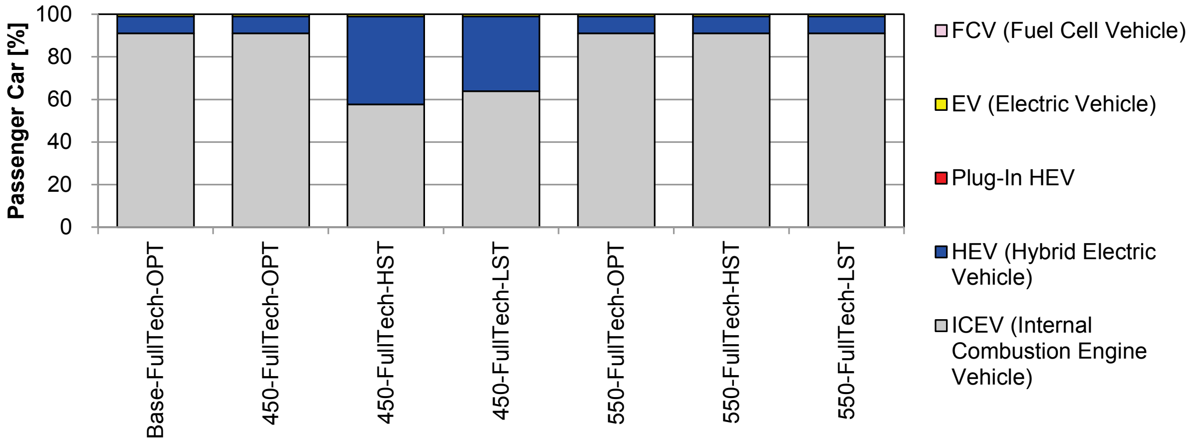

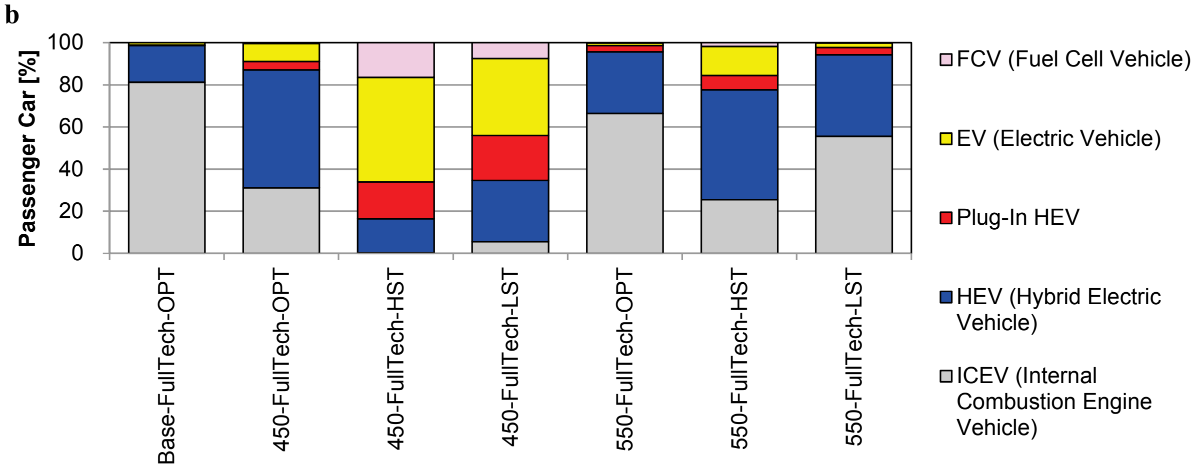

Figure 8 Technology mix for passenger cars in Base-FullTech-OPT scenario and emission reduction scenarios in 2030 and 2050 (World total). (a) 2030. (b) 2050.

3.2.4 Cross-sectoral analysis

Figure 9 shows the correlation between the reduction in energy intensity and the reduction in carbon intensity in the Base-FullTech-OPT scenario, the 550-FullTech-OPT scenario, and the 450-FullTech-OPT scenario for all sectors, and for the power sector, iron and steel sector, and passenger cars road transport separately. The CO_2 intensity improvements in the power sector for achieving the assumed long-term emission reduction targets are substantially larger than those in the other sectors because various kinds of technology options such as CCS, nuclear power, and renewable energies are available. In the iron and steel sector, the energy intensity improvement in the emission reduction scenarios is not so large compared with that in the Base-FullTech-OPT scenario, and the emission reductions tend to rely on CO_2 intensity improvements. The trend is the same as that in the power sector, but the level of CO_2 intensity improvements is smaller due to the limitations of the technological options. On the other hand, the energy intensity improvement for the passenger car contributes more to the CO_2 emission reduction than the CO_2 intensity improvement through the deployment of more efficient vehicles such as HEVs, as shown in Figure 8. CO_2 intensity improvement is more difficult than energy intensity improvement according to historical data. Measures to accelerate the deployment of highly efficient vehicles (e.g., regulation of energy efficiency) may be practical in the real world.

The assumption of future technological advances is a key factor that affects sectoral energy and CO_2 intensity improvements. Further consideration and analysis (e.g., sensitivity analysis) of future technological advances will be needed, although the model considers several kinds of innovative technologies. Analyses of inter-sectoral impacts of efficiency improvement measures are also important; for example, the substitution of steel in vehicles by other materials will influence emissions from both the road transport and the iron and steel sectors.

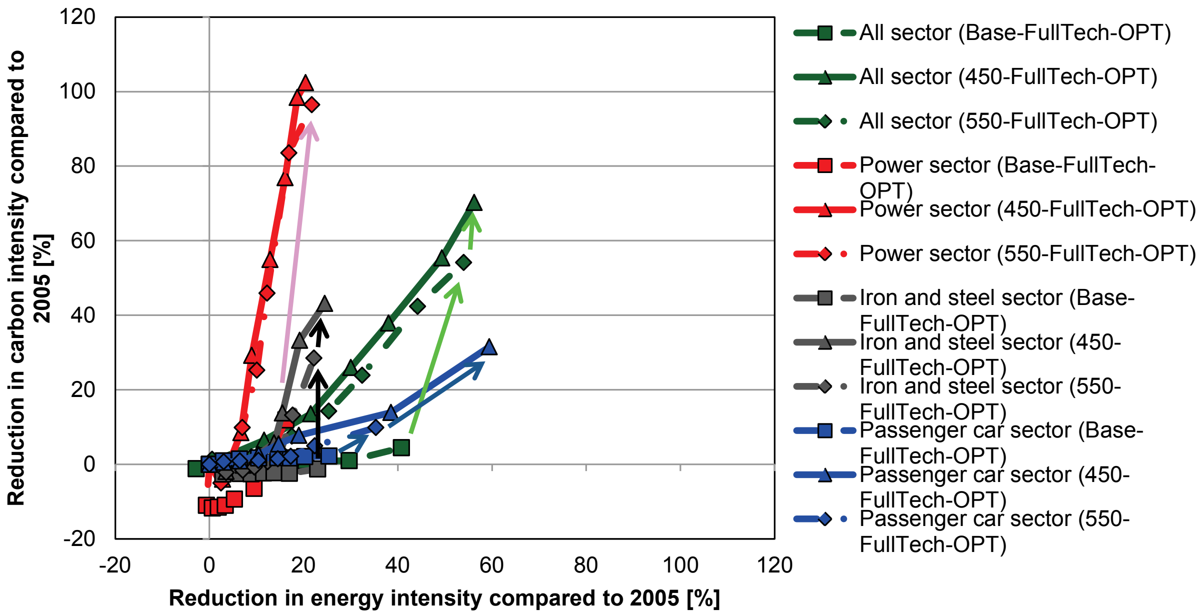

Figure 9 Correlation between reduction in energy intensity and reduction in carbon intensity in Base-FullTech-OPT scenario, 550-FullTech-OPT scenario, and 450-FullTech-OPT scenario.

3.2.5 Carbon price and effects of short-term emission fixes

Figure 10 shows the carbon price for the emission reduction scenarios. The carbon prices in 2020, 2030, and 2050 are \$23/tCO_2, \$52/tCO_2, and \$183/tCO_2, respectively, in the 550-FullTech-OPT scenario. The carbon price in the 450-FullTech-OPT scenario is much higher than that in the 550-FullTech-OPT scenario. The carbon prices in 2020, 2030, and 2050 are \$46/tCO_2, \$156/tCO_2, and \$645/tCO_2, respectively. IEA [6, 8] and Akashi and Hanaoka [1] evaluated the carbon price for achieving huge emission reductions, corresponding to 450 ppmCO_2eq targets, using a technology-rich model. The carbon price in 2050 as a result of halving global emissions relative to 2005 is \$175/tCO_2 in IEA ETP 2010 [8]. The previous analysis for the same emission reduction target by IEA ETP 2008 [6] showed that the price in the most optimistic and pessimistic cases is \$200/tCO_2 and \$500/tCO_2, respectively. The study by Akashi and Hanaoka [1] estimates that the carbon price in 2050 for halving global emissions relative to 1990 is \$600/tCO_2. The estimated carbon price for achieving such large emission reduction targets is very high based on these studies and also on this study. In addition, uniform carbon pricing across all countries is assumed in these analyses, so that emission reduction is conducted by the lowest cost measures. However, this assumption is unrealistic in the real world, and the economic impact will be larger than that estimated in this analysis.

The impact of the assumed short-term emission fixes based on the extensions of the Copenhagen pledges for 2020 on carbon price is very large. Rapid transformation of energy systems after 2030 is required to meet the assumed CO_2 emission budget, which is an indicator of the GHG concentration targets. Thus, carbon prices in the emission reduction scenarios with the assumed short-term emission fixes increase greatly after 2030. For the 550 ppmCO_2eq scenarios, carbon prices in 2050 are \$333/tCO_2 for the 550-FullTech-LST scenario and \$1095/tCO_2 for the 550-FullTech-HST scenario, which are about 2 and 6 times larger than that in the 550-FullTech-OPT scenario. The impact of the assumed short-term emission fixes in the 450 ppmCO_2eq scenarios is more serious than in the 550 ppmCO_2eq scenarios, because larger emission reductions are needed after 2030. Carbon prices in 2050 for the 450-FullTech-HST scenario and the 450-FullTech-LST scenario are \$7235/tCO_2 and \$3866/tCO_2, respectively. Such high carbon prices are required for the radical transformation of energy systems needed to achieve rapid CO_2 emission reductions.

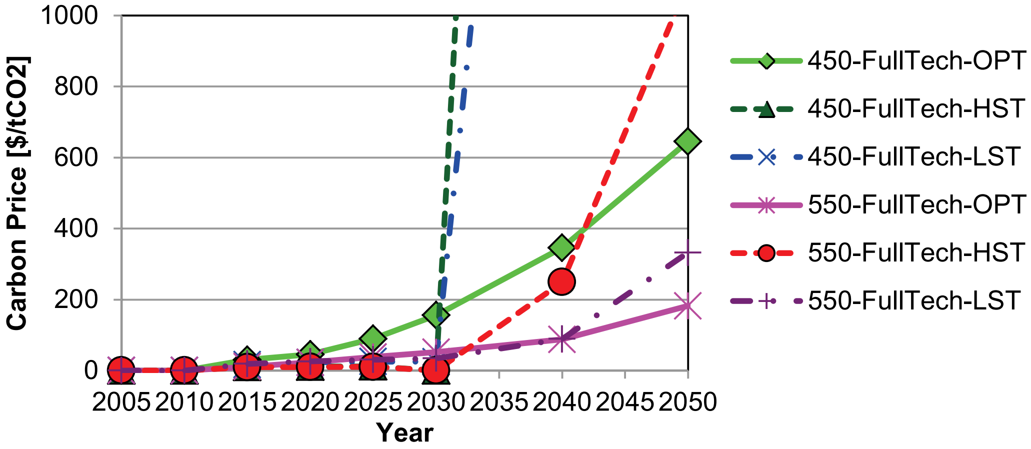

Figure 10 Carbon prices in emission reduction scenarios.
Note: Carbon prices in 2050 of the 450-FullTech-HST scenario, the 450-FullTech-LST scenario, and the 550-FullTech-HST scenario are \$7235/tCO_2, \$3866/tCO_2, and \$1095/tCO_2.

3.2.6 Discussion

In this paper, a decomposition analysis of various emission reduction scenarios was conducted using the DNE21+ model, which is a technology-rich energy system model that treats all sectors consistently. All of the evaluated emission reduction scenarios are technologically feasible. However, a radical transformation of energy systems is required to achieve the ambitious emission reductions, especially for the scenarios according to the emission outlooks based on the extensions of the Copenhagen pledges. The required carbon prices for such radical energy system transformation are very high, especially for the 450 ppmCO_2eq target, as shown in Figure 10. The acceptance of such carbon prices in the real world is uncertain. Furthermore, an ideal allocation of emission reductions by region and sector is assumed in this paper. In the short term at least, uniform carbon pricing across all countries will be very difficult, and large differences in carbon prices by country for the Copenhagen pledges are projected [18]. CO_2 and energy intensities in various sectors differ by region at this time [13], and it is difficult to see how the most efficient intensities will be achieved under such fragmented regional circumstances, including carbon price; thus, achieving the required radical transformation in the energy system across the world will be difficult.

The assumed short-term emission fixes based on the extensions of the Copenhagen pledges have a large impact on the long-term targets for 2050. For the 450 ppmCO_2eq target, carbon prices will jump up to several thousand dollars per ton CO_2 after 2030, which not seems to be practical solutions. On the other hand, large emission reductions will be difficult in the near term under the conditions of current international discussions on climate policies including the Copenhagen pledges, although large emission reductions by 2030 are required in the 450-FullTech-OPT scenario.

A stringent stabilization level, such as the 450 ppmCO_2eq target, requires radical transformation of energy systems both in the energy supply and end-use sectors and could have a huge negative impact on the economy, which will have trade-offs with other sustainable goals, such as indicators of income, poverty, food access, etc. [4]. More flexible targets or approaches will be important to explore more practical and feasible solutions at a global level.

4. Conclusions

A decomposition analysis of emission reduction scenarios was conducted at the macroeconomic level and also at the sectoral levels using a technology-rich model, DNE21+.

All of the assessed emission reduction scenarios considered in this study for the 550 ppmCO_2eq and 450 ppmCO_2eq targets with and without short-term emission fixes are technologically feasible by implementing

radical transformations of global energy systems both in the energy supply sector and end-use sectors, including the early shutdown of inefficient plants and the widespread deployment of CCS, nuclear power, and renewable energies such as solar. In energy end-use sectors, energy intensity improvements are accelerated, and CO_2 intensity improvements play a significant role for greater emission reductions. CO_2 intensity improvements can be achieved within each sectors but require the widespread adoption of decarbonized energies in the energy supply sector through CO_2 intensity improvements. Feasibilities of improvements in CO_2 and energy intensities are different by sector because of differences in types of mitigation options across sectors. Power sector has various kinds of technological options to improve the CO_2 intensity, and the potentials of the CO_2 intensity improvement are larger than those in the iron and steel sector and passenger cars. For the energy intensity improvements, passenger cars have larger potentials through deployment highly efficient vehicle than those in the iron and steel sector.
The carbon prices resulting from the assumed emission reductions, particularly for the 450 ppmCO_2eq target, are very high (\$645/tCO_2 in 2050 for the 450 ppmCO_2eq) and could negatively affect the economy, even if the lowest cost measures are assumed.

When the short-term emission pathways are fixed at the levels of the extensions of the Copenhagen pledges, the predicted carbon prices after 2030 for the 450 ppmCO_2eq target are several thousand dollars per ton CO_2. According to our model, there are technologically feasible solutions, but they would be really difficult to carry out in the real world. Although greater short-term emission reductions than those in the extensions of the Copenhagen pledges could reduce the impact of this, the 450 ppmCO_2eq pathways will still lead to high carbon prices in the real world.

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Electronic Supplementary Materials

Assessments of GHG emission reduction scenarios of different levels and different short-term pledges through macro and sectoral decomposition analyses

S1 Overview of DNE21+ model

The DNE21+ model (Akimoto et al. 2008, Akimoto et al. 2010) is an inter-temporal linear programming model used for assessing global energy systems and global warming mitigation strategies. In this model, the sum of the discounted total world energy systems costs is minimized. The model covers the first half of the 21st century, with the years 2000, 2005, 2010, 2015, 2020, 2025, 2030, 2040, and 2050 as representative points. The model represents energy systems (e.g., capacities of energy-related facilities, and performances and costs of various technologies) consistently via a minimum-cost combination of technologies in order to meet assumed production activities (e.g., amount of crude steel production), service activities (e.g., amount of traffic in the transportation sector), and final energy demands in other sectors where technologies are not explicitly modeled (e.g., non-energy-intensive industries). If any emission restrictions (e.g., carbon taxes) are applied, the model determines the energy systems with the minimum costs while satisfying the assumed requirements. The salient features of the DNE21+ model are described in the following.

(1) The world is divided into 54 regions. Large countries such as the United States, Canada, Australia, China, India, and Russia are further disaggregated into several regions, which allows for the consideration of regional differences, such as in the distribution of fossil fuels and renewable energies, and the transportation of energy and CO_2 across regions.

(2) About 300 specific technologies in both the energy supply and end-use sectors are explicitly modeled. The sectors are fully integrated and can be assessed consistently in terms of the included technologies. The lifetimes of facilities are also explicitly taken into account, and the transition of technology deployment can be evaluated explicitly. The model includes technologies such as carbon capture and storage (CCS) that are in their incipient stages as well as already available technologies. In addition, CO_2 fixation through afforestation and the use of bioenergy technologies are also explicitly modeled by estimating the potential productivity of land areas via a food supply and demand and land-use model (Hayashi et al. in press, Kii et al. in press).

A non-CO_2 GHG (greenhouse gas) assessment model has been also developed based on Hyman et al. (2003), and with some modifications considering new insights for non-CO_2 GHGs. The non-CO_2 GHG assessment model is calibrated using recent historical emissions of non-CO_2 GHGs.

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S2 Iron and steel sector in DNE21+ model

The iron and steel sector in the DNE21+ model is expressed in a bottom-up fashion with exogenous assumptions of technology options and crude steel production scenarios.

Blast furnace-basic oxygen furnace (BF-BOF) and electric arc furnace (EAF) are explicitly modeled for crude steel production. Scrap-based and direct-reduced iron (DRI)-based EAF types are considered. Several technological options for improved energy efficiency are considered, such as coke dry quenching (CDQ) and top-pressure recovery turbines (TRT). Several steelmaking routes with differing energy efficiencies are modeled, including four types of BF-BOF steelmaking. Assumed capital costs and energy efficiencies are available in Oda et al. (2007).

Furthermore, the DNE21+ model also models CCS technologies for BF-BOF. CCS is applicable to high-efficiency BF-BOF options (Types III and IV in Oda et al. 2007), and CO_2 captured by CCS is assumed to be 0.6 tCO_2/t-Crude steel, which corresponds to about 30% of the direct CO_2 emissions from BF-BOF steelmaking. Table S1 shows the assumed capital cost and energy consumption of CCS for BF-BOF. These assumptions are based on several studies, e.g., Daniels (2002), IEA (2006), and Tonomura (2013).

Table S1 Assumed capital cost and energy consumption of CCS for BF-BOF

Facility cost [Million $/(ktC/day)]	66.9–57.6
Electricity consumption [kWh/t-Crude steel]	111–90
Utility consumption [GJ/t-Crude steel]	0.98–0.43

Note: The ranges in the table depend on the time period (2010 to 2050).

Crude steel production is assumed as an exogenous scenario by region. For the top sixteen steel-producing countries, we assumed a future scenario of apparent total consumption of crude steel per capita, taking into consideration historical trends, the relationship with GDP per capita, and the theoretical scope that steel consumption would increase steeply during the primary stage of economic growth then later stabilize or decline during a fully developed economic stage. The crude steel production scenario for the minor steel-producing countries was assumed simply based on the relationship between the historical GDP and future GDP scenario. Future population and GDP scenario is assumed to be harmonized within the AMPERE project (Riahi et al. this issue).

Assumed crude steel production is fixed for all the scenarios analyzed in this study. Therefore, the impacts of climate change mitigation on the amount of crude steel production cannot be evaluated endogenously in this analysis.

The technology mix to meet the assumed crude steel production is evaluated by the DNE21+ model. The availability of scrap for EAF is a key factor in this evaluation. In this study, the lower and upper bounds of scrap-based EAF steel production scenarios are assumed by region, taking steel stock into consideration.

Future steel stock is estimated based on crude steel production (historical data is derived from World Steel Association, etc.), assumed market share, and the lifetime of finished products. The market is classified into civil engineering, buildings, machinery and appliances, transport, shipbuilding, and others. Future end-of-life recycling rate (old scrap per old scrap + waste + obsolete stock) is assumed as 53%, which is estimated based on historical data (Oda et al. Unpublished results).

Figure S1 shows the assumed scenarios of world total crude steel and scrap-based EAF steel production. The world total crude steel production in 2050 is assumed to be 2,200 million tons per year, which is almost double that in 2005. Scrap-based EAF steel production also increases over time and the assumed lower and upper bounds in 2050 are 680 and 770 million tons per year, which correspond to 31% and 36% of total crude steel production, respectively. The assumed regional total crude steel production is shown in Figure S2 for selected countries. In the assumed scenario, China remains the top steel-producing country until 2050; however, growth in China's steel production slows after 2010 and India assumes a greater share. In 2050, total steel production in China and India is assumed to be 680 million and 500 million tons per year respectively, representing 31% and 23% of the global total.

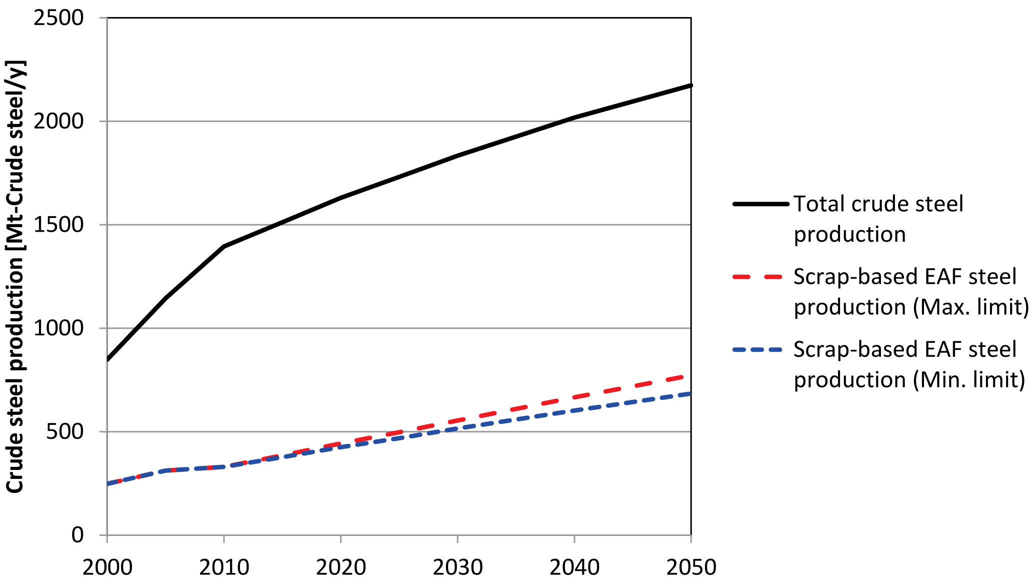

Figure S1 Assumed scenarios of world total crude steel and scrap-based EAF steel production

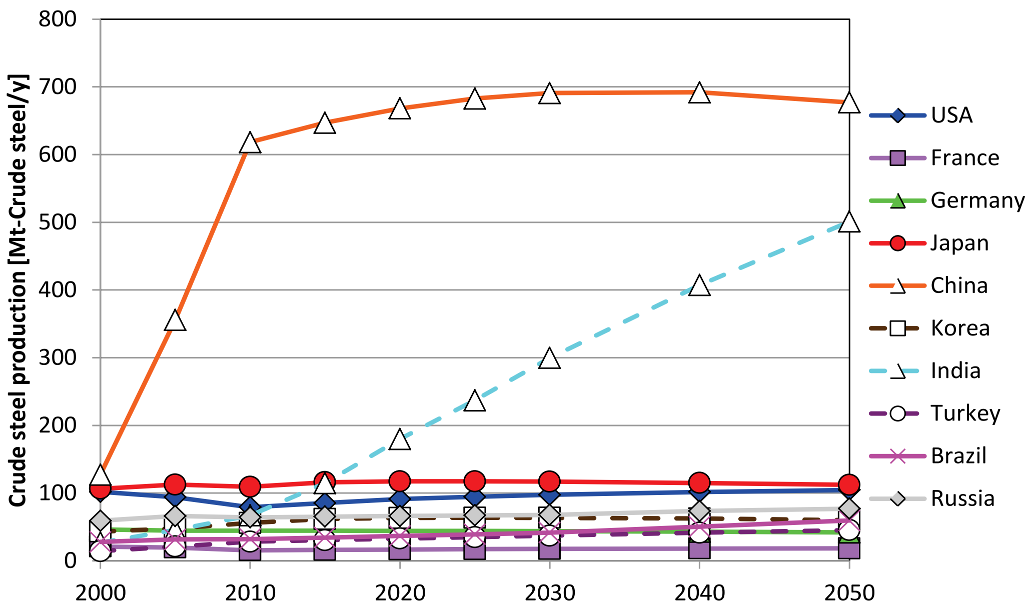

Figure S2 Assumed scenarios of total crude steel production for selected countries

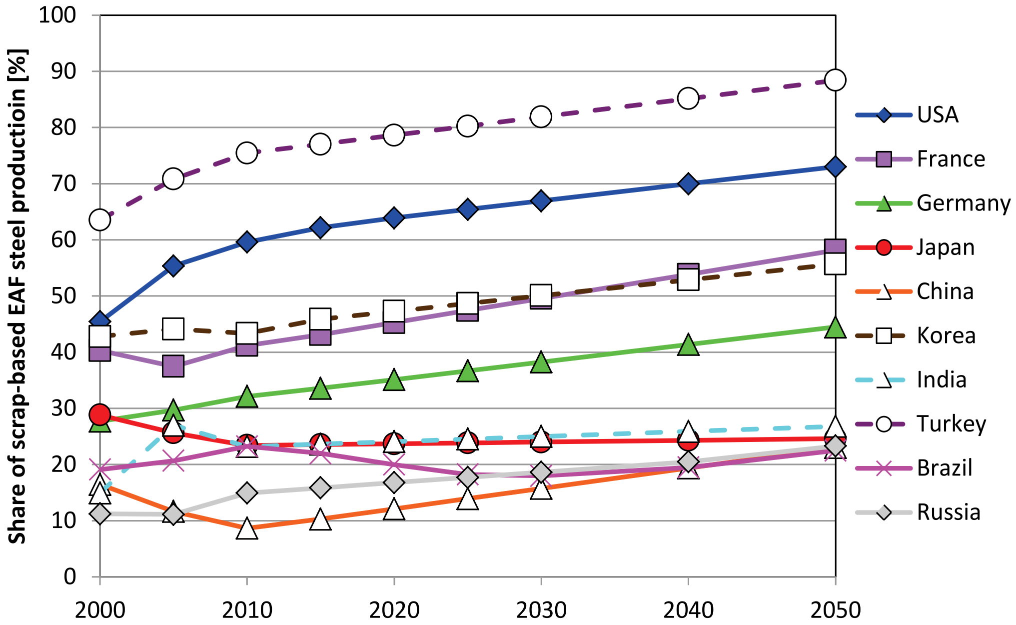

Figure S3 Assumed production of scrap-based EAF steel as a proportion of total crude steel production for selected countries.
Note: The share is calculated based on median in lower and upper bounds of scrap-based EAF steel production scenario.

Figure S3 shows the assumed regional scenario for scrap-based EAF steel as a share of total crude steel production for selected countries. Currently, the proportions of scrap-based EAF steel production vary by country. In the assumed future scenario, this variation is taken into account because steel production plants usually have a long operational lifespan.

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S3 Road transport sector in DNE21+ model

The road transport sector in the DNE21+ model is expressed in a bottom-up fashion with exogenous assumptions of technology options and traffic service demand scenarios.

Modeling of energy use of the road transport sector is shown in Figure S4. The transportation service is divided into five categories: small passenger car, large passenger car, bus, small truck, and large truck. The transportation service is assumed to be exogenous according to region and the five categories, and the scenario is fixed for all the scenarios analyzed in this study. Therefore, the impacts of climate change mitigation on the level of road transport service cannot be evaluated endogenously in this analysis.

We assumed the transportation service scenario based on: (1) relationship between vehicle stock per capita and GDP per capita; and (2) relationship between transportation service and vehicle stock. Historical data for vehicle stock and transportation service are derived from several references such as JAMA and OECD statistics. However, the available data are insufficient to develop the transportation service scenario by region and by the five categories. Therefore, data in the IEA/SMP model (Fulton and Eads 2004) is used for interpolation. Future population and GDP scenarios are assumed to be harmonized within the AMPERE project (Riahi et al. this issue).

Figure S5 shows the assumed scenario of world total transportation service for passenger cars, and Figure S6 shows the assumed regional scenarios for selected countries. In the assumed scenario, global use of passenger cars increases continuously to 31 trillion km/y in 2050. Passenger car usage in China is assumed to exceed that of the USA after 2030, reaching 9 trillion km/y in 2050, which is about 30% of the global total.

For technology options, not only internal combustion engine vehicles but also hybrid electric vehicles, electric vehicles, and fuel-cell vehicles are considered. The assumed vehicle price and vehicle efficiency for passenger cars are shown in Tables S2 and S3. The assumption incorporates several references, e.g., IEA 2008, JHFC/JARI 2011, and the 2006 study group on next-generation vehicle battery technology. Cost reduction of vehicles and improved vehicle efficiency through technological development are exogenously assumed.

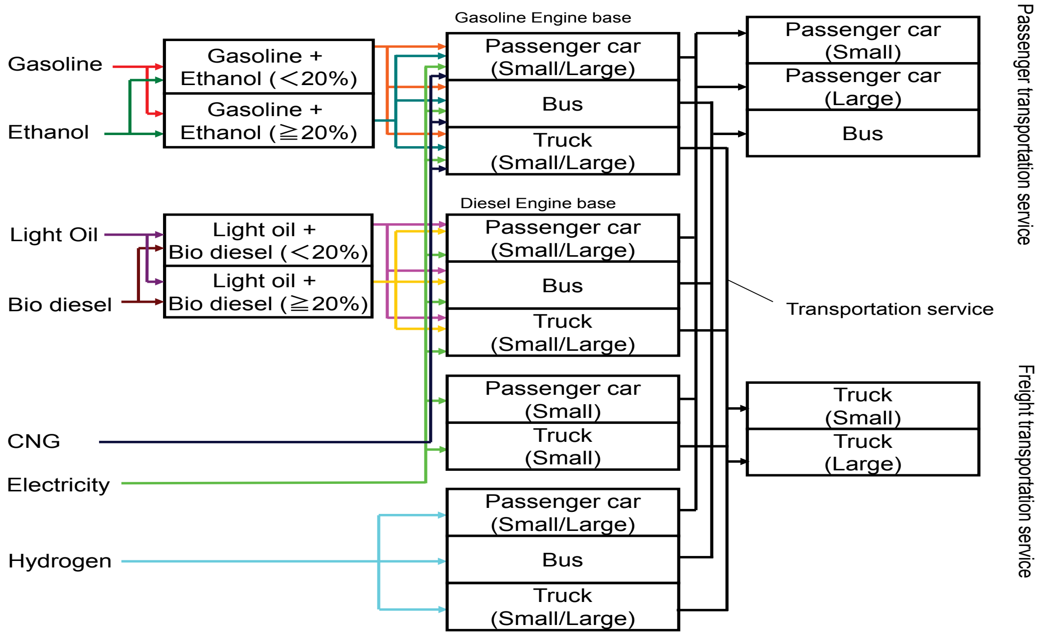

Figure S4 Modeling of energy use of the road transport sector in DNE21+

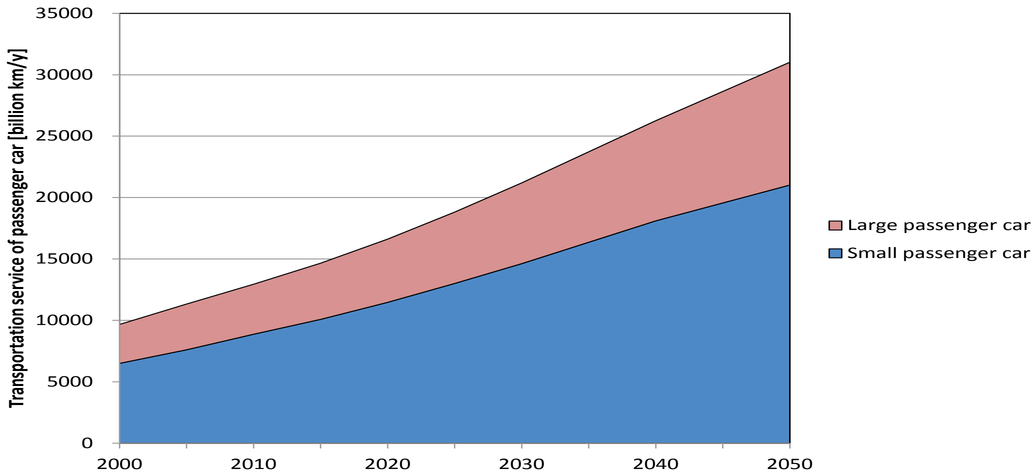

Figure S5 Assumed scenario of world total transportation service for passenger cars

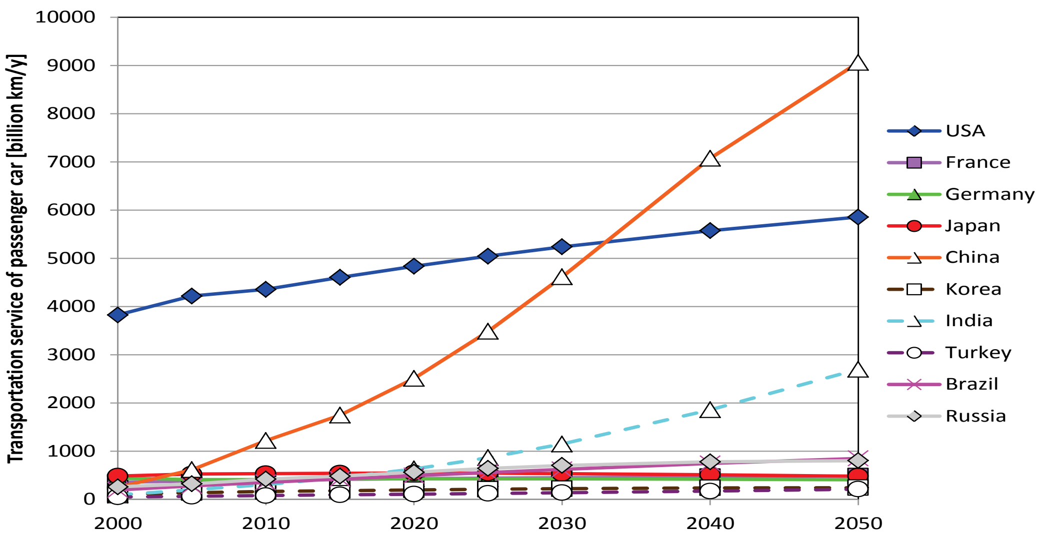

Figure S6 Assumed scenario for transportation service of passenger cars for selected countries

Table S2 Assumed vehicle price and vehicle efficiency for small passenger cars

	Vehicle price [Thousand $/vehicle]	Vehicle efficiency [L-gasoline eq./100 km]
ICEV Gasoline (Low Eff.)	17.6	8.0 – 7.1
ICEV Gasoline (High Eff.)	20.7	4.4 – 3.9
ICEV Bio ethanol (Low Eff.)	19.0 – 17.8	8.4 – 7.5
ICEV Bio ethanol (High Eff.)	22.4 – 20.9	4.6 – 4.1
ICEV CNG (Low Eff.)	24.2 – 18.7	8.4 – 7.5
ICEV CNG (High Eff.)	28.5 – 22.0	4.6 – 4.1
HEV Gasoline	24.0 – 21.0	3.4 – 1.9
HEV Bio ethanol	26.0 – 21.2	3.5 – 2.0
HEV CNG	33.1 – 22.3	3.5 – 2.0
Plug in HEV Gasoline	36.9 – 21.6	2.6 – 1.5
Plug in HEV Bio ethanol	40.0 – 21.8	2.7 – 1.5
ICEV Diesel (Low Eff.)	18.5	7.0 – 6.2
ICEV Diesel (High Eff.)	21.7	3.8 – 3.4
ICEV Bio diesel (Low Eff.)	20.0 – 18.6	7.3 – 6.5
ICEV Bio diesel (High Eff.)	23.5 – 21.9	4.0 – 3.5
HEV Diesel	25.2 – 22.0	2.9 – 1.7
HEV Bio diesel	27.3 – 22.3	3.1 – 1.7
Plug in HEV Diesel	38.8 – 22.7	2.3 – 1.3
Plug in HEV Bio diesel	42.0 – 22.9	2.4 – 1.4
EV	84.7 – 22.7	1.5 – 0.9
FCV	133.6 – 24.1	5.1 – 2.1

Note 1: The ranges in the table depend on the time period (2010 to 2050).
Note 2: ICEV: Internal Combustion Engine Vehicles, HEV: Hybrid Electric Vehicles, EV: Electric Vehicles, FCV: Fuel Cell Vehicles.
Note 3: Flexible-fuel vehicles are noted as 'Bio ethanol' and 'Bio diesel'. Flexible-fuel vehicles are allowed to use bio fuel with high blend rate (more than 20%).

Table S3 Assumed vehicle price and vehicle efficiency for large passenger cars (more than 2,000 cc class)

	Vehicle price [Thousand $/vehicle]	Vehicle efficiency [L-gasoline eq./100km]
ICEV Gasoline	38.3	12.1 – 10.7
ICEV Bio ethanol	41.4 – 38.6	12.7 – 11.2
ICEV CNG	52.7 – 40.6	12.7 – 11.2
HEV Gasoline	48.0 – 42.0	6.6 – 3.7
HEV Bio ethanol	52.0 – 42.4	6.9 – 3.9
HEV CNG	66.1 – 44.6	6.9 – 3.9
Plug in HEV Gasoline	73.8 – 43.2	5.0 – 2.9
Plug in HEV Bio ethanol	80.0 – 43.6	5.2 – 3.0
ICEV Diesel	40.2	10.5 – 9.3
ICEV Bio diesel	43.5 – 40.6	11.0 – 9.8
HEV Diesel	50.4 – 44.1	5.7 – 3.2
HEV Bio diesel	54.6 – 44.5	6.0 – 3.4
Plug in HEV Diesel	77.5 – 45.3	4.4 – 2.5
Plug in HEV Bio diesel	84.0 – 45.8	4.6 – 2.7
FCV	267.1 – 48.2	9.9 – 4.1

Note 1: The ranges in the table depend on the time period (2010 to 2050).
Note 2: ICEV: Internal Combustion Engine Vehicles, HEV: Hybrid Electric Vehicles, EV: Electric Vehicles, FCV: Fuel Cell Vehicles.
Note 3: Flexible-fuel vehicles are noted as 'Bio ethanol' and 'Bio diesel'. Flexible-fuel vehicles are allowed to use bio fuel with high blend rate (more than 20%).

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