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GHG emission pathways until 2300 for the 1.5 °C temperature rise target and the mitigation costs achieving the pathways

Keigo Akimoto[1] · Fuminori Sano[1] · Toshimasa Tomoda[1]

Abstract The Paris Agreement of the 21st Conference of the Parties of the United Nations Framework Convention on Climate Change refers to the 1.5 °C target as well as the 2 °C target, and it is important to estimate the emission pathways and mitigation measures for the 1.5 °C target for the discussions on the target. The possible emission pathways vary widely because of the uncertainties involved. We assumed three kinds of temperature trajectories for meeting below 1.5 °C compared with the pre-industrial level, and three numbers for the climate sensitivity. The first trajectory remains below 1.5 °C all the time until 2300, the second overshoots but returns to below 1.5 °C by 2100, and the third overshoots but returns to below 1.5 °C by 2300. There are large differences in terms of 2030 emissions between the estimate from the submitted Nationally Determined Contributions (NDCs) and any of assessed emission pathways involving climate sensitivity of 3.0 °C or higher, and high emission reduction costs were estimated, even for 2030. With climate sensitivity of 2.5 °C, only the third trajectory exhibits consistent emissions in 2030 with the NDCs. However, this case also appears very difficult to achieve, requiring enormous amounts of negative emissions after the middle of this century toward 2300. A climate mitigation strategy aiming for the 1.5 °C target will be debatable, because we face serious difficulties in near- or/and long-term for all the possible emission pathways, and therefore, we should rather focus on actual emission reduction activities than on the 1.5 °C target with poor feasibility.

Keywords Climate change mitigation · Emission pathway · Below 1.5 °C · Mitigation cost

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1 Introduction

The Paris Agreement was adopted at the 21th Conference of Parties (COP21) of the United Nations Framework Convention on Climate Change (UNFCCC) in December 2015 in Paris, France (UNFCCC 2015). Under this framework, almost all countries tackle greenhouse gas (GHG) emission reductions for the post-2020 terms with internationally legal force. The Paris Agreement was adopted as a so-called "pledge and review" type of framework. All of the member nations are required to submit their emission targets, which are to be internationally and comparatively reviewed and evaluated from the viewpoint of meeting long-term targets constituting a form of "global stocktaking."

Regarding the long-term targets, the Paris Agreement contains the following words: "To hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels" (Article 2, Paragraph 1), while the UNFCCC mentions atmospheric GHG concentration stabilization as the ultimate objective. In addition, it states: "In order to achieve the long-term temperature goal set out in Article 2, Parties aim to reach global peaking of greenhouse gas emissions as soon as possible [...] and to undertake rapid reductions thereafter in accordance with best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century" (Article 4, Paragraph 1). Such a long-term climate change goals or targets cannot be identified only by scientific analysis (e.g., Hellegatte et al. 2016; Knutti et al. 2016; Tol and Yohe 2006). Hellegatte et al. (2016) states "One major reason is that individuals and groups have distinct values and priorities. Because climate and climate policy have a wide range of impacts that differ across countries, communities and individuals, a temperature target also depends on preferences regarding equity and fairness. The need to aggregate the wide variety of impacts also involves value judgments […]" The long-term targets remarked in the Paris Agreement are not scientifically identified but are decided politically.

The Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) summarized a number of the emission scenarios for different levels of atmospheric GHG concentration. However, the emission scenarios for below 430 ppm CO_2eq, which correspond to the pathways likely necessary for results below 1.5 °C, were so small in number that the AR5 hardly succeeded at achieving a full evaluation of the 1.5 °C target to provide the policy implications. Ranger et al. (2012) assessed the emission pathways for the 1.5 °C target including the scenarios with temporary over-shooting within a duration of 50 years. The estimated emission pathways require rapid declining of global emissions after 2020, very low emissions by 2100 and zero (or less) in the twenty-second century. However, Ranger et al. (2012) did not assess the emission reduction costs or measures. Even after the AR5 publication, only a few studies, e.g., Luderer et al. (2013); Sanderson et al. (2016); Rogelj et al. (2015a, b); Su et al. (2017) evaluated the 1.5 °C target in terms of emission pathways and emission reduction costs and measures. Sanderson et al. (2016) estimated plural pathways until 2125 for the temperature targets of 1.5, 2.0, 3.0 °C, and the above, and compared with the faster and later emission reduction pathways. Rogelj et al. (2015a) conclude that "energy-system transformations [for the 1.5 °C target] are in many aspects similar to 2 °C-consistent scenarios, but show a faster scale-up of mitigation action in most sectors, leading to observable differences in emission reductions in 2030 and 2050." Rogelj et al.

provide important analyses and implications, but their time horizon is limited to 2100, which is not sufficient to gain deep understanding of possible emission pathways whose flexibility will be increased when longer time spans are considered, or regarding mitigation measures and costs for possible emission pathways for the 1.5 °C target. Su et al. 2017 also estimated the emission pathways for the 2 and 1.5 °C targets, and the economic costs for achieving the targets by (DICE) Dynamic Integrated Climate-Economy model and (AIM/CGE) Asia-Pacific Integrated Model/Computable General Equilibrium models. However, the time horizon is also limited to 2100.

This article focuses on the 1.5 °C target, and it estimates GHG emission pathways for a greater length of time (up to 2300), and the mitigation measures and costs. (Mitigation measures and costs have been analyzed only up to 2050 due to large uncertainties about technology improvements, particularly in the distant future.) Considering to the long-term pathways up to 2300, larger possibilities including the flexibilities to meet the 1.5 °C target under the Paris Agreement can be investigated in this paper. On the other hand, the emission reduction targets should be discussed not only in climate change mitigation but also in climate change damages, and synergies and trade-offs among sustainable development goals including water stress and biodiversity (see e.g., Schleussner et al. 2016 for this topic). However these broad topics are outside the scope of this study.

2 Interpretations of the temperature rise target

2.1 Policy uncertainties regarding the temperature target

The Paris Agreement describes a target "well below 2 °C above pre-industrial levels," but some unclear points that cannot be ignored exist, particularly in emission reduction assessments. Firstly, when should the temperature goal be achieved for "well below 2 °C?" Secondly, how high probability should be assigned to achieve the 2 °C target or any other target as the expected temperature increase when the "well below" is interpreted scientifically? Thirdly, the climate sensitivity and its probability density function is still uncertain. Fourthly, to what timeframe does the expression "pre-industrial levels" refer? The IPCC reports usually employed the year of 1750 for "pre-industrial levels," but actual temperatures are difficult to determine for years before 1850 (Knutti et al. 2016). The different definitions of "pre-industrial" time generate differences in temperature of around 0.1−0.2 °C. Such temperature difference may appear negligibly small, but this is not by any means small when considering the allowable scale of emissions. As described for the 2 °C target, the 1.5 °C target also presents a similar uncertainty in terms of timing and the probability of achievement under the Paris Agreement, while the Agreement does not contain the phrase "well below" for the 1.5 °C target. These uncertainties generate large uncertainties regarding the possible emission pathways, as discussed below in this paper.

2.2 Uncertainties regarding climate sensitivity

IPCC published the AR5 between 2013 and 2014. There are still extensive scientific uncertainties regarding climate change, although scientific understanding of climate change has

improved a great deal. One of the typical uncertainties is climate sensitivity. The equilibrium climate sensitivity (the equilibrium temperature rise levels when the atmospheric CO_2 concentration is stabilized double) had been evaluated as likely to be 1.5−4.5 °C and 2.5 °C as the best estimate in the Third Assessment Report (TAR) of IPCC (2001). The climate sensitivity was evaluated as likely to be 2.0−4.5 °C and 3.0 °C as the best estimate in the Fourth Assessment Report (AR4) published in 2007 (IPCC 2007). However, according to the latest report of AR5 (IPCC 2013), the climate sensitivity was evaluated as likely to be 1.5−4.5 °C with no consensus reached on the best estimate, indicating the lower bound was lower than that of the AR4 and the same as that before the AR4. Rogelj et al. (2014) estimated the temperature increase impacts of the shift to a lower value in climate sensitivity and concluded that the expected impact would involve only about one decade of retardation in exceeding the 2 °C rise above pre-industrial levels, and that this small shift in the climate sensitivity would not extensively affect the time window for the baseline emission scenarios. (In the paper, the likely ranges of climate sensitivity are consistent with the AR5, but the median is almost unchanged from the AR4-based value of 3.0 °C.) This is true as long as the baseline emissions increase rapidly. On the other hand, as Kaya et al. (2015) discussed more generally, the impact on allowable global emissions for a certain temperature target (e.g., the 2 °C target) is substantially large, even with the small change of only 0.5 °C.

2.3 Assumed trajectory of temperature

As described above, the 1.5 °C target of the Paris Agreement contains uncertainties concerning the achievement timing and probability. Therefore, we employed typically three kinds of temperature trajectories as shown in Table 1: (I) stabilization below a 1.5 °C increase in which the increase does not at any time exceed 1.5 °C above pre-industrial levels; (II) the temperature overshoots 1.5 °C before 2100 but declines to below 1.5 °C by 2100 (and continues to decline gradually thereafter); and (III) the temperature increase overshoots 1.5 °C before 2300 but declines to below 1.5 °C by 2300. (We chose 1850−1900 as the reference years for the pre-industrial era.) The IPCC WG3 AR5 (IPCC 2014a) summarized several emission pathways until 2100 that were obtained via integrated assessment models, and these pathways include not only 2.0 °C stabilization (as with the temperature trajectory I) but also an overshoot scenario that returns to below 2.0 °C by 2100 (as with the temperature trajectory II). The latter types of scenarios are much larger in number in the AR5. This paper assessed the emission pathways for the 1.5 °C target until 2300, assuring more flexibility in temperature trajectory. The temperature trajectory III has the largest extent of flexibility among the assumed temperature trajectories

Table 1 Nine assumed cases for generating emission pathways from different temperature trajectories for the 1.5 °C target, using different values of equilibrium climate sensitivity

Temperature trajectories	Equilibrium climate sensitivity		
	(a) 3.4 °C	(b) 3.0 °C	(c) 2.5 °C
(I) 1.5 °C stabilization (below 1.5 °C over time)	I-a	I-b	I-c
(II) Below 1.5 °C by 2100 (temperature overshoot; peak temperature: around 1.75 °C)	II-a	II-b	II-c
(III) Below 1.5 °C by 2300 (temperature overshoot; peak temperature: around 2.0 °C)	III-a	III-b	III-c

in this study. In addition to the emission pathways until 2300, this paper assesses the mitigation measures and costs until 2050, because significant uncertainties in technology perspectives increase when moving toward the distant future.

In obtaining emissions pathways from the temperature trajectory, we employed three kinds of climate sensitivity, i.e., (a) 3.4, (b) 3.0, and (c) 2.5 °C, in accordance with the probability of achieving the temperature target and scientific uncertainties in climate sensitivity. The IPCC WG3 AR5 provided categorized emission scenarios with corresponding temperatures that were estimated using the simple climate change model (MAGICC) Model for the Assessment of Greenhouse Gas Induced Climate Change (Meinshausen et al. 2011a) employing the probability density function (PDF) of equilibrium climate sensitivity provided by Rogelj et al. (2012) and Schaeffer et al. (2015). The PDF was developed based on the information that equilibrium climate sensitivity is likely to be 2.0−4.5 °C and 3.0 °C as the most likely value. According to the PDF provided by Rogelj et al. (2012), the over 66% probability for climate sensitivity is about 3.4 °C. We assumed a climate sensitivity of 3.4 °C with an achievement probability of over 66% which corresponds to the climate sensitivity of 2.0−4.5 °C as being likely, and with the most likely value being 3.0 °C (which is nearly consistent with IPCC AR4 and the estimates of the Coupled Model Intercomparison Project Phase 5 (CMIP5) by Atmosphere-Ocean Global Circulation Models (AOGCMs)). In case that the 1.5 °C target is achieved at 66% probability, that is, under the climate sensitivity of 3.4 °C, the temperature increase which is achieved at 50% probability (the expected temperature increase) is 1.2 °C. We also employed the climate sensitivity of 3.0 °C with an achievement probability of over 50% using the same probability distribution function for the climate sensitivity. Furthermore, we employed a climate sensitivity of 2.5 °C, because the IPCC WG1 AR5 changed from 2.0−4.5 °C in the AR4 to 1.5−4.5 °C in the AR4 according to the studies estimating the climate sensitivity as well as the CMIP5 studies, and the best estimate (or most likely value; over 50% achievement probability) before the AR4 was 2.5 °C corresponding to the likely range of 1.5−4.5 °C. On the other hand, the climate sensitivity of 2.5 °C corresponds to that for an achievement probability of over about 33% under the PDF assumed by Rogelj et al. (2012).

Table 1 shows the assumed cases generated from the combinations of the temperature trajectories and the climate sensitivity.

Figure 1 shows the different assumed trajectories of global mean temperature for the nine cases of Table 1. It may be better to adjust other parameters as well as equilibrium climate sensitivity in the MAGICC in order to achieve a higher degree of consistency with the historical temperature. However, this study changed only the climate sensitivity parameters within the range of 0.5 °C from the normal setting of climate sensitivity (3.0 °C) according to the assumed cases. Small differences in historical temperatures across different levels of climate sensitivity can be observed in Fig. 1 due to the above treatment of adjusting the climate sensitivity but not in other parameters. However, this treatment does not cause large differences in the estimated future temperature.

Here, we compare the temperature trajectories of this study for the 1.5 °C target with one of the existing typical scenarios for below 2 °C, the Representative Concentration Pathway for 2.6 W/m^2 (RCP2.6) (Meinshausen et al. 2011b). The estimated global mean temperature of RCP2.6 in 2100 is below about 1.6 °C under the median climate sensitivity (3.0 °C; 50% probability) and below about 1.9 °C under a climate sensitivity of about 3.4 °C (66% probability), and that in 2300 is below about 1.1 °C under a climate sensitivity of about 3.0 °C (50% probability) and below about 1.5 °C under a climate sensitivity of about 3.4 °C (66% probability) (Meinshausen et al. 2011b). Thus, the assumed temperature trajectories II
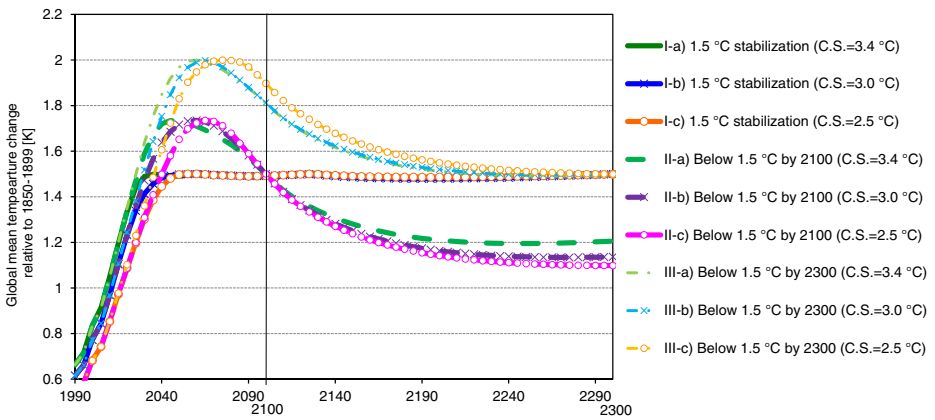
Fig. 1 Assumed trajectories of global mean temperature changes

and III are similar to the upper limit of temperature trajectories of RCP2.6 under the climate sensitivity of about 3.0 °C (50% probability) and about 3.4 °C (66% probability), respectively, as seen in Fig. 1.

3 Emission pathways for the 1.5 °C target

This section describes the emission pathways for the 1.5 °C target corresponding to the temperature trajectories as shown in Fig. 1. The CO_2 emission pathways between 2010 and 2300 and GHG emission pathways between 1990 and 2100 are shown in Figs. 2 and 3, respectively. The emission scenarios for each GHG gas were developed until 2050 by keeping uniform equal marginal abatement costs across GHG gas species, using a global energy and climate change mitigation model, (DNE21+) Dynamic New Earth 21 Plus (Akimoto et al. 2010, 2014; RITE 2015; see Section 4.1 for more details) and a non-CO_2 GHG assessment model of our own (Akimoto et al. 2010; RITE 2015), and by extending toward 2300 the emission reductions of GHGs,
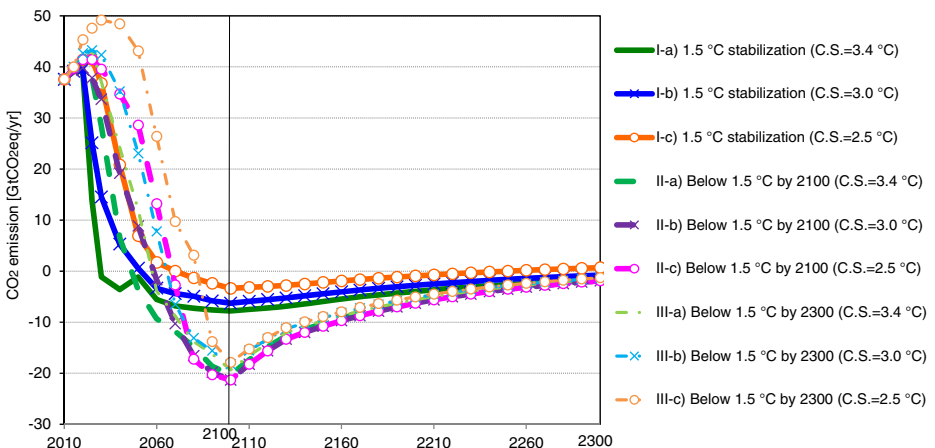

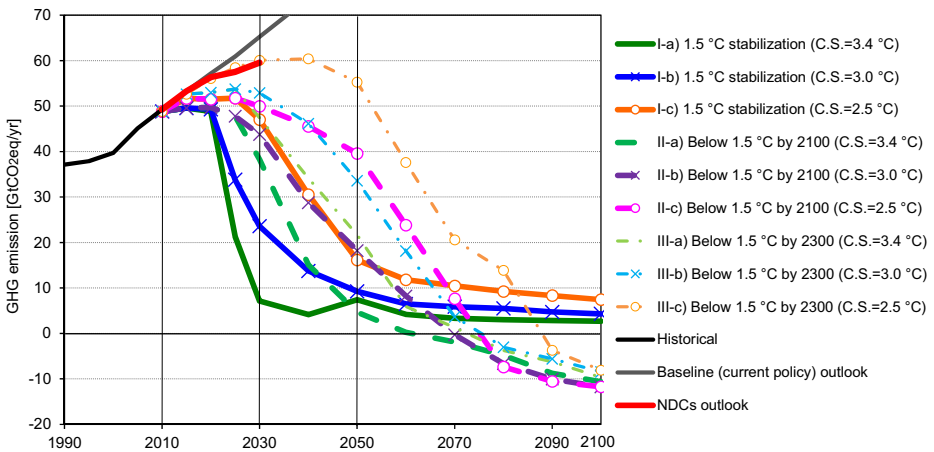**Fig. 2** Global CO_2 emissions from energy and industry

Fig. 3 Global GHG emissions (until 2100). The NDC outlook evaluated 119 NDCs submitted as of October 1, 2015, which cover about 88% of global emissions in 2010

keeping the reduction ratios constant across gas species thereafter. The atmospheric GHG concentrations for achieving at 1.5 °C by 2300 are about 395, 410, and 445 ppm CO_2eq. under the climate sensitivity of 3.4 °C (cases I-a and III-a), 3.0 °C (cases I-b and III-b), and 2.5 °C (cases I-c and III-c), respectively.

The CO_2 emission pathways for the temperature trajectory II (overshoot and decline to below + 1.5 °C by 2100) and III (overshoot and decline to below + 1.5 °C by 2300) can allow short-term larger emissions than those for the temperature trajectory I (no overshoot overtime), but large amounts of net negative emissions (around 20 $GtCO_2$/year in 2100) are required for several decades before 2100. The amounts of maximum net negative CO_2 emissions in 2100 and the emission pathways after 2100 for the temperature trajectory III are similar to those for the temperature trajectory II, while the allowable emissions before 2100 for the temperature trajectory III are larger than those for the temperature trajectory II.

All the emission pathways will converge at zero CO_2 emissions in accordance with temperature stabilization. This is consistent with the nearly linear relationship between cumulative CO_2 emissions and global mean temperature change shown in the IPCC WG1 AR5 and pointed out by e.g. Rogelj et al. (2015b).

In contrast, the GHG emission pathways (cases I-a and I-b) for stabilizing below 1.5 °C with over 50 and over 66% achievement probabilities under the PDF of the climate sensitivity developed by Rogelj et al. (2012), which is consistent with the IPCC AR4, require over 50% reduction compared with 2010 by 2030. There are significantly large gaps between the expected emissions in 2030 from the submitted Nationally Determined Contributions (NDCs) (Kaya et al. 2015) and the required allowable emissions window for the 1.5 °C targets (see Table 2). The emissions in 2030 under climate sensitivity of 3.0 and 3.4 °C for the 1.5 °C stabilization (cases I-a and I-b) entail 52 to 85% reductions compared with 2010. The 2030 gap for GHG emission for stabilization below 1.5 °C with over 50% achievement probabilities under the PDF of the climate sensitivity with a median value of 2.5 °C (cases I-c) is relatively small, but still difficult to fill.

The total of annual CO_2 emissions that have negative values between 2016 and 2100 for cases I-a and I-b are 230 and 469 $GtCO_2$, respectively (see Table 2). IPCC AR5 (IPCC 2014b) summarized that the cumulative CO_2 emissions between 2011 and 2100 are about 400 and

Table 2 Required emission reductions and cumulative emissions for the 1.5 °C targets

	Global mean temperature relative to 1850–1900			Required GHG emission reductions in 2030 (GtCO$_2$eq./year)		Required GHG emissions compared with 2010 (%)		Cumulative net CO$_2$ emissions (GtCO$_2$)		Cumulative net negative CO$_2$emissions (GtCO$_2$)[a]
	2100	2300	Peak temp.	From baseline	From NDCs	2030 (%)	2050 (%)	2016–2100	2016–2300	2016–2300
I-a	1.5 °C	1.5 °C	1.5 °C	58.1	52.4	− 85	− 85	230	− 210	− 615
I-b				41.6	35.9	− 52	− 81	469	154	− 414
I-c				18.2	12.5	− 4	− 67	873	756	− 148
II-a		1.1−1.2 °C	1.75 °C	27.0	21.3	− 22	− 90	394	− 360	− 1069
II-b				21.5	15.8	− 10	− 63	577	− 221	− 1065
II-c				15.3	9.6	+ 2	− 19	919	121	− 1024
III-a	1.8−1.9 °C	1.5 °C	2.0 °C	17.8	12.1	− 3	− 56	711	− 3	− 950
III-b				12.3	6.6	+ 8	− 31	926	261	− 862
III-c				5.2	− 0.5	+ 23	+ 13	1427	777	− 738

[a] Only annual net negative CO$_2$ emissions are summed up for the period between 2016 and 2300

550 GtCO$_2$ for below 1.5 °C with over 66 and 50% probability, respectively, which are nearly consistent with the estimates of this study. The cumulative net CO$_2$ emissions between 2016 and 2300 are negative for all the pathways under climate sensitivity of 3.4 °C. For the 1.5 °C stabilization (temperature trajectories I), the cumulative net CO$_2$ emissions reductions between 2016 and 2300 are between − 210 and 756 GtCO$_2$; the required GHG emissions from the NDCs aggregation in 2030 are between 52.4 and 12.5 GtCO$_2$eq./year; and the cumulative net negative CO$_2$ emissions are between 615 and 148 GtCO$_2$.

Houghton et al. (2015) estimates about 3−5 GtC/year (about 11−18 GtCO$_2$/year) of global negative emission opportunities with tropical forest management (reforestation/afforestation) for 50 years (for a total of 550−900 GtCO$_2$), for example. When the possible total negative emissions achievable through reforestation/afforestation are considered conservatively to be 550 GtCO$_2$, only the I-b and I-c cases will be achievable even if global CO$_2$ emissions from energy and industrial processes are assumed to be zero. (This assumption is very unrealistic, and it is discussed again in Section 4.2.) On the other hand, Smith et al. (2015) took a pessimistic view of a large amount of negative emissions for the 2 °C target pathway based on several constraints, including examples involving land use and fresh water.

4 Emission reduction costs and measures for the 1.5 °C target

In accordance with the emission pathways discussed above, this chapter estimates the emission reduction measures and costs until 2050 using a global energy and climate change mitigation model, DNE21+ (Dynamic New Earth 21 Plus).

4.1 Assessment models

DNE21+ is an energy and global warming mitigation assessment model developed by RITE (Akimoto et al. 2010, 2014; RITE 2015). The model is an intertemporal linear

programming model for assessment of global energy systems and global warming mitigation in which the worldwide costs are to be minimized. The model represents regional differences and assesses detailed energy-related CO_2 emission reduction technologies up to 2050. When any emission restrictions (e.g., an upper limit for emissions, emission reduction targets, targets for energy or emission intensity improvements, or carbon taxes) are applied, the model specifies the energy systems whose costs are minimized, meeting all the assumed requirements, including assumed production for industries such as iron and steel, cement, and paper and pulp, transportation by automobile, bus, and truck, and other energy demands. The energy supply sectors are hard-linked with the energy end-use sectors, including energy exporting/importing, and the lifetimes of facilities are taken into account so that assessments are made while maintaining complete consistency over the energy systems. The reforestation/afforestation and bioenergy potentials are estimated by using a global grid-base land use and land cover model (Hayashi et al. 2015), and the cost-effective measures of reforestation/afforestation and bioenergy are estimated within DNE21+ model. Salient features of the model include (1) analysis of regional differences between 54 world regions while maintaining common assumptions and interrelationships, (2) a detailed evaluation of global warming response measures that involves modeling of about 300 specific technologies that help suppress global warming and can assess the limits of energy efficiency improvements by industry sector and technology, and (3) explicit facility replacement considerations over the entire time period. The model assumes energy efficiency improvements from several kinds of technologies and cost reductions from renewable energy, carbon dioxide capture and storage (CCS) not only for fossil fuel power but also for steel production processes and the like for the future within plausible ranges based on many examples of literature. The assumptions for population and GDP assumed for this study are shown in Table 3.

Technology innovations are very uncertain, particularly in the distant future, and therefore, we estimated the emission reduction costs and measures only until 2050. Global least-cost measures that entail equal marginal abatement costs among all countries are assumed for the estimations. It should be noted that this assumption is too idealistic.

Table 3 Population and GDP assumed in the DNE21+ model

	Population (million)			GDP-MER (%/year)	
	2010	2030	2050	2010–2030	2030–2050
USA	312	364	397	2.3	1.6
EU28	507	515	503	1.2	1.1
Japan	127	118	102	1.6	0.1
Australia	22	27	30	2.2	1.5
Russia	144	132	119	5.3	3.2
China	1367	1477	1432	6.6	3.1
Korea	48	49	44	2.4	1.2
Mexico	118	135	137	3.1	2.5
India	1206	1474	1602	6.2	4.3
Turkey	72	86	93	3.4	2.5
South Africa	51	56	58	3.0	3.1
World	6916	8308	9139	3.0	2.2

Only a few selected countries are shown

4.2 Emission reduction costs

Figure 4 shows CO_2 marginal abatement cost (MAC) for the assumed emission pathways for below 1.5 °C targets. There were no feasible solutions of DNE21+ in cases I-a and II-a. The MACs vary widely and are between 0 and 660 $/tCO$_2$ in 2030 and between 27 and 5880 $/tCO$_2$ in 2050 under climate sensitivity of 3.0 and 2.5 °C. While the cumulative net negative emissions in cases I-b and I-c are relatively low (414 and 148 GtCO$_2$, respectively) compared with other cases as seen in Table 2, the MACs in 2050 are 5880 and 1290 $/tCO$_2$, respectively, even under the assumption of global least-cost measures. The MAC in 2030 is 11−36 $/tCO$_2$ for cases III-b, II-c, I-c, and II-b, and it is zero for case III-c. The MAC for expected global emissions in 2030 from the NDCs aggregation with the global least-cost measures is about 6 $/tCO$_2$, while in an actual case, the MACs vary widely across countries as largely different NDCs are submitted.

The total emission reduction costs compared with the baseline costs are about 22.1, 4.7, and 1.1 trillion US2000$ per year in 2050 for cases I-b, II-b, III-b (under climate sensitivity of 3.0 °C), respectively. The reduction costs per GDP are about 18.8, 4.0, and 0.9%, respectively. For cases I-c, II-c, III-c, the reduction costs per GDP in 2050 are about 5.0, 0.6, and 0.2%, respectively. It is difficult to compare with the costs under the same emission pathway levels in other studies; however, Rogelj et al. (2015a) provide a consumption loss of around 5% (discounted costs from 2010 to 2100) for the 1.5 °C target with over 50% achievement probability under the intermediate baseline energy demand assumption.

One major caveat is the future socioeconomic outlook including technology innovations. The cost estimations in this study were conducted under a socioeconomic scenario. In addition, models cannot consider technologies that we cannot assume quantitative performances of technologies because of too innovative technologies. Depending on socioeconomic scenarios, the emission reduction costs might be largely different particularly in the distant future.
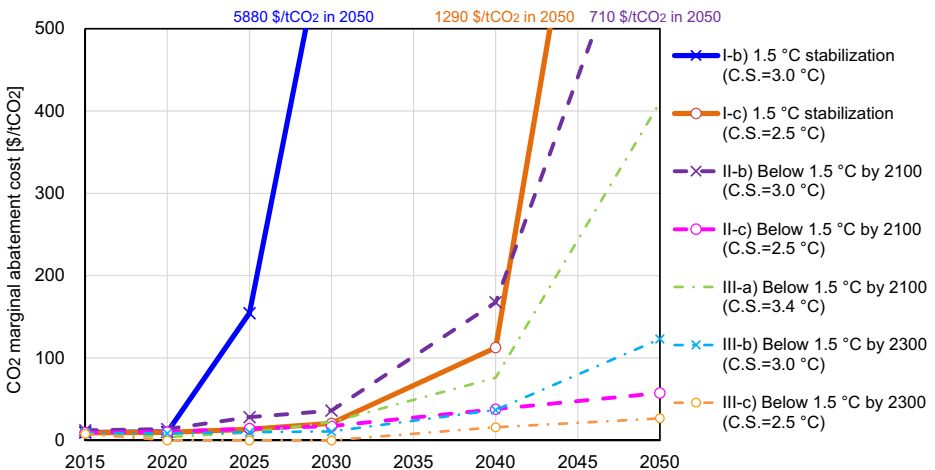

Fig. 4 CO_2 marginal abatement costs. There are no feasible solutions of DNE21+ in cases I-a and II-a

4.3 Emission reduction measures

Figures 5, 6, and 7 show primary energy supply, electricity generation, and final energy consumption on a global basis for the 1.5 °C targets, respectively (only cases I-b, I-c, III-b, and III-c are shown in the figures).

As seen in Figs. 5 and 6, amounts of electricity generation are observed to be larger for deeper emission reduction pathways corresponding to higher climate sensitivities and reaching earlier to below 1.5 °C while the total amounts of primary energy decrease. More de-carbonization is also observed in deeper emission reduction pathways, and larger amounts of renewable energy and nuclear power generation are cost-effective in the pathways. Batteries and hydrogen uses for stable power grids are also observed in the case of large deployments of renewables. However, reduced use of CO_2 CCS is observed because from around several to 10% of CO_2 are unavoidably released into the air even in the CO_2 capture process, and this is one of the greatest bottlenecks for such a deep reduction for the 1.5 °C target. However, total stored CO_2 by CCS including bioenergy with CCS (BECCS) is about 10−16 $GtCO_2$/year in 2050 except in case III-c (in which it is about 4 $GtCO_2$/year). In addition, CO_2 fixation from land-use change is also about 9 −10 $GtCO_2$/year in 2050 for all of the analyzed cases in which mitigation measures are employed (climate sensitivity of (b) 3.0 and (c) 2.5 °C). The global net CO_2 emissions as shown in Fig. 2 become negative after 2050 in most cases. However, extensive negative emission measures employed through BECCS and reforestation/afforestation are required even in 2050 for most of the cases due to the difficulty in achieving zero CO_2 emissions in many sectors, including the iron and steel and cement sectors. Therefore, extensive negative emission measures are required even in 2050 in order to cancel the inevitable positive emissions.

The final energy consumption in 2050 in cases I-b and I-c is much smaller than that in cases III-b and III-c. In case I-b, more than half of all gaseous fuels are supplied by
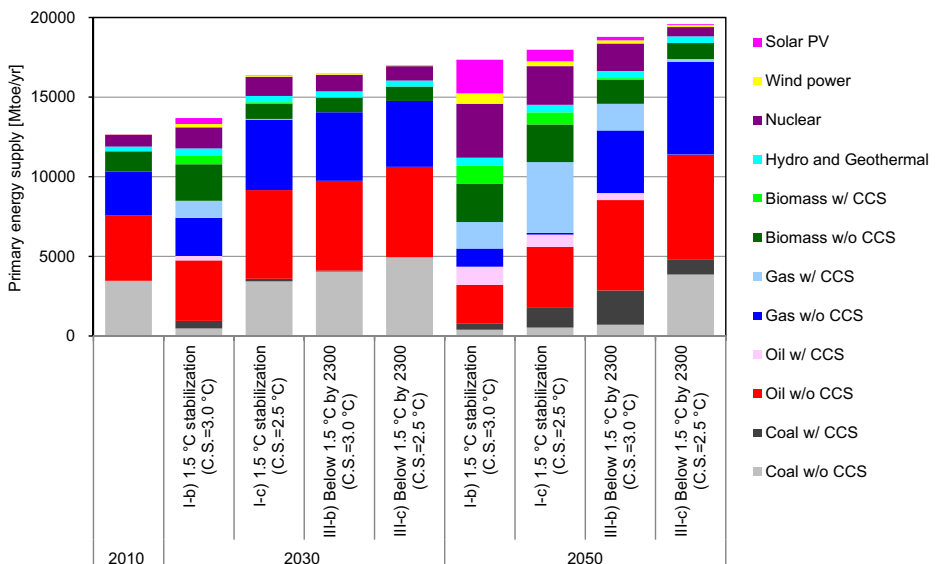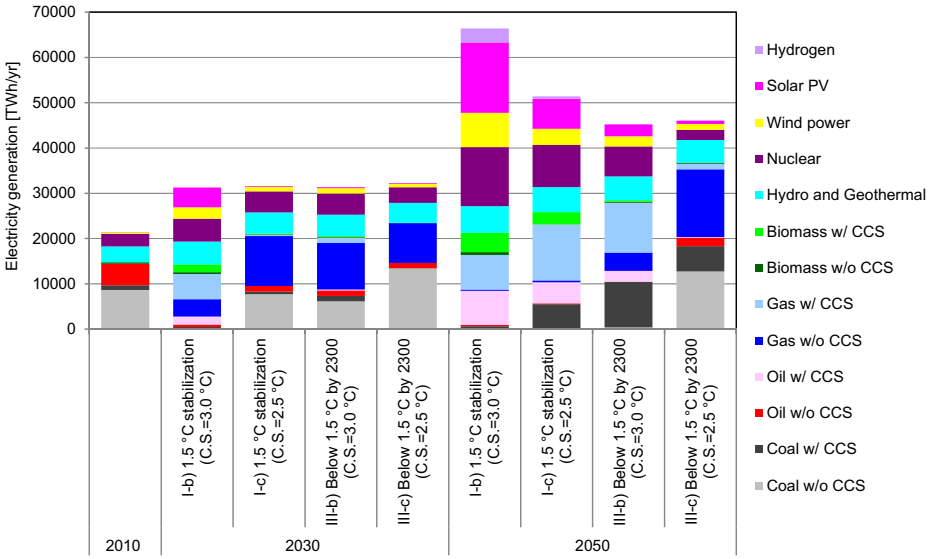

Fig. 5 Global primary energy supply

Fig. 6 Global electricity generation

hydrogen, and more than half of all liquid fuels are supplied by bioenergy. The electricity share out of total final energy consumption in case I-b is about 40% accompanying with more de-carbonized electricity supplies while the share is about 26% in cases III-b and III-c. A certain level of coal uses remain due to the requirements for some industry sectors such as iron and steel and cement even achieving the highest energy efficiencies in all of the world countries.
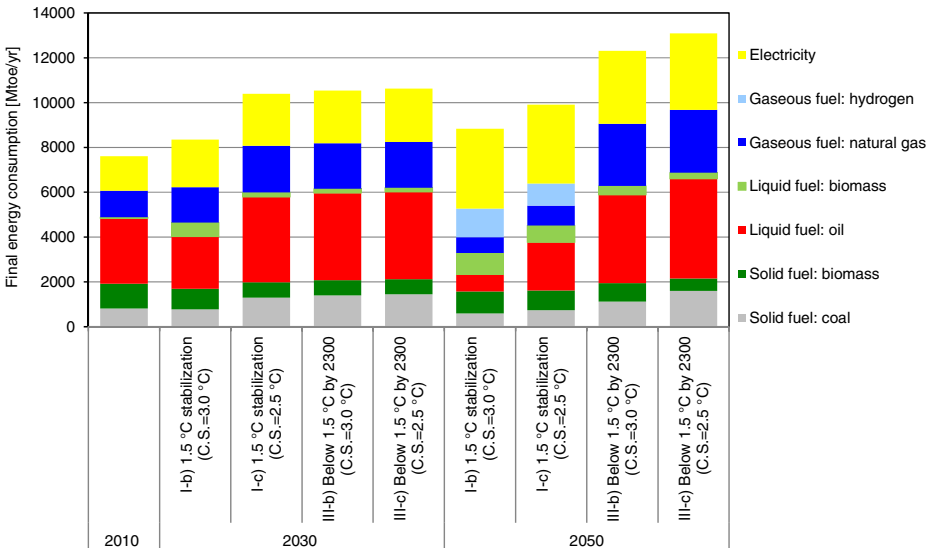

Fig. 7 Global final energy consumption

5 Conclusion and policy implications

The Paris Agreement was adopted on December 2015, and it mentions ambitious temperature targets of 1.5 °C as well as the 2 °C target. However, the emission pathways and mitigation measures and costs for the 1.5 °C target have not been sufficient to gain deep understanding regarding the flexibilities of emission pathways and the induced uncertainties in costs and measures. The IPCC AR5 was not able to also summarize the long-term emission reductions scenarios for the 1.5 °C target. This study evaluated the emission pathways and mitigation costs and measures for the 1.5 °C target considering political and scientific uncertainties in order to contribute to decision-making support for international negotiations on climate change.

In fact, there are several political and scientific uncertainties regarding the temperature target, and therefore, the emission pathways vary widely when political and scientific uncertainties regarding the 1.5 °C target are considered. However, there are large differences between the emissions in 2030 estimated based on the submitted NDCs and most of the emissions that are consistent with the 1.5 °C target in most of the cases, considering the uncertainties. In addition, the emission reduction costs in 2050 are high for cases above the equilibrium climate sensitivity of 3.0 °C even under the global least-cost measures. The GHG emissions in 2030 are nearly consistent with the NDCs only in cases in which the temperature exceeds 1.5 °C and reaches 1.7−1.8 °C by around 2050 and declines to below 1.5 °C by 2300, with a climate sensitivity of 2.5 °C. In addition, the marginal abatement costs keep under 30 \$/tCO_2 by 2050 for the emission pathway. However, in this case, enormous amounts of global net negative emissions are required after the middle of this century; about 740 $GtCO_2$ of cumulative net CO_2 fixation is required until 2300 even if energy-related and industrial process CO_2 emissions are assumed to be zero. In addition, it should be noted that the temperature in such case exceeds 1.5 °C for a period of about 270 years.

In summary, all pathways that have certain levels of potential (e.g., over 50% achievability) to realize increases lower than 1.5 °C are difficult in reality, while the Paris Agreement mentioned pursuing efforts to limit the temperature increase to 1.5 °C above pre-industrial levels. The only small chance of realizing the 1.5 °C target can exist when the climate sensitivity is well below 2.5 °C, or geoengineering measures including large-scale of BECCS, direct air capture (DAC), and solar radiation management (SRM) are implemented; however, the former is regarded as not having much potential probabilities under current scientific knowledge, and the latter has large uncertainty regarding side effects in earth systems and no capability to cope with ocean acidification for SRM. We should consider such risk-risk trade-offs in the strategy for achieving the 1.5 °C target. Therefore, so far, it will be a reasonable strategy that seek the achievement for the 2 °C target which is more realistic than the 1.5 °C target, and change to seek the opportunity to meet the 1.5 °C target when the actual climate sensitivity is lower than the expected one or/and innovative technologies that can mitigate climate change effectively can be prepared. In the climate change mitigation strategy, we should rather focus on actual emission reduction activities than on the 1.5 °C target with poor feasibility.

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