

Stabilization of atmospheric carbon dioxide via zero emissions —An alternative way to a stable global environment. Part 2: A practical zero-emissions scenario

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Abstract: Following Part 1, a comparison of CO₂-emissions pathways between “zero-emissions stabilization (Z-stabilization)” and traditional stabilization is made under more realistic conditions that take into account the radiative forcings of other greenhouse gases and aerosols with the constraint that the temperature rise must not exceed 2 °C above the preindustrial level. It is shown that the findings in Part 1 on the merits of Z-stabilization hold under the more realistic conditions. The results clarify the scientific basis of the policy claim of 50% reduction of the world CO₂ emissions by 2050. Since the highest greenhouse gas (GHG) concentration and temperature occur only temporarily in Z-stabilization pathways, we may slightly relax the upper limit of the temperature rise. We can then search for a scenario with larger emissions in the 21st century; such a scenario may have potential for practical application. It is suggested that in this Z-stabilization pathway, larger emissions in the near future may be important from a socioeconomic viewpoint.

Keywords: greenhouse gas, radiative forcing, emissions scenario, climate policy, 2 °C target, representative concentration pathways

Introduction

In Part 1 of the present article, we proposed “zero-emission” stabilization (Z-stabilization) as an alternative to the traditional “emission-keeping” stabilization (E-stabilization) because of the former’s merits: larger emissions are permissible in the near future while the risk of sea level rise over a long-time scale could be diminished. To show this, we calculated the projections for the two types of emission pathways, which were confined to CO₂ emissions for illustrative purposes. Thus, in Part 2, we shall treat the more realistic situation where radiative forcings of non-CO₂ greenhouse gases (GHGs) and aerosols are included. Specifically, we will compare the two stabilization pathways

under the constraint that the temperature rise should not exceed 2 °C, in order to answer the question of whether the currently advocated political claim “GHG emissions must be reduced to 50% of the present level by 2050 to meet the 2 °C upper limit of the temperature rise” has a solid scientific basis.

Another aim of Part 2 is to examine the Z650 CO₂ emissions scenario, treated in Part 1, under realistic conditions including the effects of other greenhouse gases and aerosols, as a possible candidate for a practical emissions-reduction strategy. Recently, emission pathways have been discussed from the viewpoint of their feasibility and interplay between mitigation cost and long-term climate targets.^{1),2)} The present work has also been being conducted collaborating with energy technology experts, and the Z650 emissions pathway is presented as a test bed for their research on the future plan for global energy supply. In this work, we specifically examine emissions pathways including zero-emissions in the near future (next century), through which long-term climate change and associated risk of sea level rise can be taken into account in devising emissions pathways in the 21st century.

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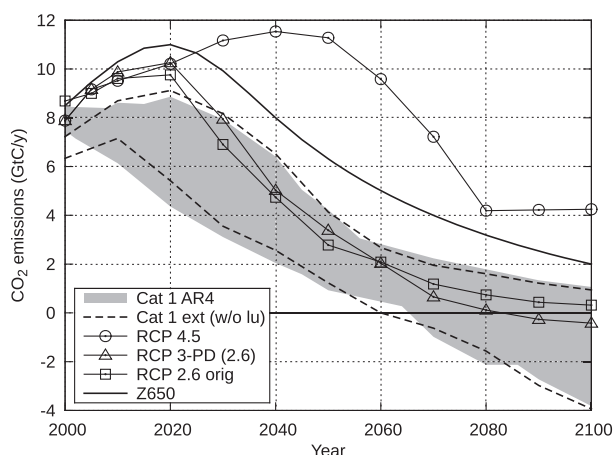


Fig. 1. CO₂ emissions of Z650 compared with the Category I ranges, RCP 3-PD (2.6) and RCP 4.5 for AR5, and an original form of RCP 2.6. The horizontal solid line indicates the zero-emissions level. The two Category I ranges are shown by shaded and dashed curves, which are reproduced from Figure SPM.7 of IPCC WG III AR4⁶⁾ and Fig. 1 of Ref. 7), respectively. The latter is based on new scenario studies since AR4 on CO₂ emissions from energy and industry sources. RCP data were obtained from <http://www.iiasa.ac.at/Research/ENE/IAMC/rep.html>.

Comparison of stabilization pathways including other GHGs and aerosols

RCP 2.6 emissions pathway. First, for comparison with the new types of pathway, we need a pathway to represent those of traditional stabilization. Fortunately, by the request of the IPCC, a new set of stabilization scenarios—representative concentration pathways (RCPs)—have been developed for the next-generation climate-change-projection experiments to be reported in the upcoming IPCC Fifth Assessment Report (AR5).^{3)–5)} The new emissions as well as concentration scenarios are available to the climate-change research community. Figure 1 shows low-emission pathways RCP 2.6 and RCP 3-PD, and a medium-emission pathway RCP 4.5. In the figure, the range of the most stringent mitigation scenarios, termed Category I, reproduced from Figure SPM.7 of IPCC WG III AR4⁶⁾ and Fig. 1 of Ref. 7), are plotted and will be referred to in the next section. The range of the latter has been created on the basis of fossil and industrial CO₂ emissions of post-AR4 scenario studies. In addition, a Z-stabilization pathway Z650, which was used in Part 1 to examine the basic characteristics of this new type of emissions pathway, is included for the sake of comparison. Note that the Z650 pathway is located between RCP 2.6 (RCP 3-PD) and RCP 4.5; in terms

of the total cumulative emissions in the 21st century, 650 GtC are between about 430 GtC for RCP 2.6 and about 930 GtC for RCP 4.5.

From the RCP stabilization scenarios shown in Fig. 1, we chose one with a target radiative forcing of 2.6 W m^{-2} at the stabilization stage, labeled RCP 2.6.^{8),9)} Apparently, this target corresponds to an equilibrium temperature rise of 2°C (to be precise, 2.1°C), if we adopt 3°C as the most likely value of climate sensitivity. Actually, RCP 2.6 was tentative and has been replaced by a similar but slightly different scenario labeled RCP 3-PD (2.6). In this finalized scenario, CO₂ emissions become negative after 2080; a rather exceptional situation that is not suited for comparison with our new pathway. Therefore, we decided to adopt the former scenario (hereafter, RCP 2.6) as a reference for comparison with Z-stabilization emissions pathways.

Radiative forcings of other GHGs and aerosols. In order to produce CO₂-emissions/concentration pathways of the Z-stabilization type, we have to account for the effects of other GHGs and aerosols. Since the major portion of radiative forcing is due to CO₂, we adopt a simplified method, as will be explained, to incorporate the other GHGs and aerosol effects, equally into the two pathways for comparison. In the year 2005, the total radiative forcing due to methane, nitrous oxide, halocarbons, and ozone amounted to about 1.3 W m^{-2} , while the negative radiative forcing due to aerosols (direct and indirect effects) of about -1.2 W m^{-2} almost offsets the positive effects.¹⁰⁾ In the future with a decrease in CO₂ emissions, the cooling effect due to aerosols, which come from fossil-fuel burning, will diminish to almost a zero level, so that other GHG effects will emerge. However, major halocarbon substances (0.3 W m^{-2} at 2005) are expected to become negligible by 2100, and the effect of tropospheric ozone (0.35 W m^{-2} at 2005) may also decrease owing to the reduction of its precursor NO_x derived from fossil-fuel combustion. Thus, we assume that in 2100, about 0.65 W m^{-2} will be the net radiative forcing (GHGs + aerosol effects). For the transition period, we assume a smooth increase in radiative forcing to take place in the period 2000–2075 in response to the reduction in SO₂ and NO_x emissions from fossil-fuel burning, which will be undertaken to reduce CO₂ emissions as well as to improve air quality. The net radiative forcing used in this experiment (idealized) is shown in Fig. 2 together with those of the RCPs. Note that the above-mentioned characteristics of the idealized form are found in the RCPs. After 2100, for

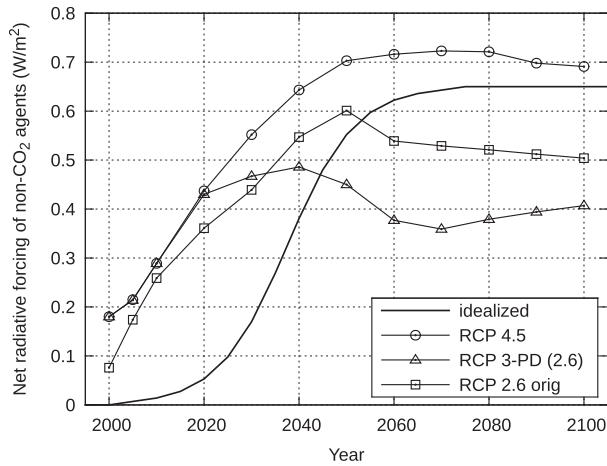


Fig. 2. Net radiative forcing of non-CO₂ agents in RCPs and its idealized form used in this study.

the sake of simplicity, we assume that 0.65 W m^{-2} radiative forcing continues as the contribution from other GHGs, which is effectively regarded as “essential use,” as discussed in Part 1, or termed the emissions floor.¹¹⁾ In the discussion of the final equilibrated state to be realized after a millennium-long period, it may be acceptable to discard this contribution because the reduction of other GHG concentrations to natural levels can be realized eventually. With this assumption, we incorporate the other GHGs and aerosol effects into both the RCP 2.6 and new Z-stabilization pathways.

CO₂ emissions pathways for comparison. As a CO₂-emissions pathway of the Z-stabilization type for comparison with the RCP 2.6, we have produced a new pathway by reducing the Z650 emissions to keep the temperature below the 2°C upper limit. This new pathway gives total cumulative emissions of 520 GtC in the 21st century, and we refer to this as Z520. As shown in Fig. 3, the Z520 pathway is similar to one of the pathways adopted by the United Kingdom Climate Change Committee (UKCCC) to be used for the planning of a climate-change mitigation strategy. In the study by UKCCC,¹²⁾ a number of emissions pathways were examined from very stringent reductions to moderate ones. In the comparison shown in Fig. 3, the one labeled 2016:3%low first follows a baseline scenario, but after 2016 the emissions decrease at a rate of $3\% \text{ y}^{-1}$ toward zero.

The CO₂ emissions of RCP 2.6 are specified until 2100 but not given beyond that; hence, we have to extend the emissions after 2100. Since RCP 2.6 is supposed to be a stabilization scenario with a target radiative forcing of 2.6 W m^{-2} or equivalently with

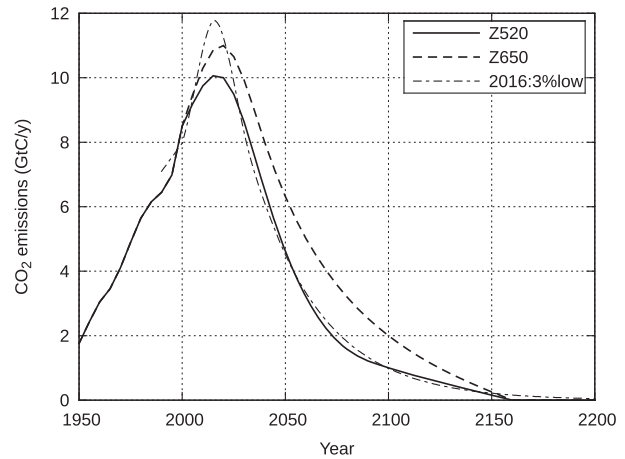


Fig. 3. CO₂ emissions of Z520, Z650 and a comparable emissions pathway (2016:3%low) from UKCCC.¹²⁾

a total GHG (plus aerosol effects) concentration of 450 ppm CO₂-eq, we assume that the radiative forcing of other GHGs and aerosols is kept constant at 0.65 W m^{-2} and the remainder is due to CO₂. By using an approximate formula¹³⁾ for the radiative forcing of CO₂

$$\Delta F = 5.35 \ln(C/C_0) \quad (\text{W m}^{-2}) \quad [1]$$

the stabilized CO₂ concentration is determined to be about 400 ppm. In the above equation, C is the CO₂ or equivalent GHG concentration, and C_0 is the preindustrial CO₂ concentration (~ 280 ppm). To avoid unnatural variations in the CO₂ emissions around 2100, the extension of RCP 2.6 was generated such that the CO₂ concentration stabilizes smoothly in the middle of the 22nd century, and the CO₂ emissions are inversely calculated from that stabilized concentration pathway. Note that our extended RCP 2.6 is different from RCP 3-PD (2.6) which is the finalized form of the lowest RCP scenario with a radiative forcing of 2.6 W m^{-2} prepared for the climate experiments to be included in AR5. In its extension beyond 2100 a constant negative emissions are assumed.¹⁴⁾

Figure 4 compares Z520 (solid line) with the extended RCP 2.6 (dashed line) together with its original form shown by asterisks (*). The extended RCP 2.6 during the historical period was made to be identical to that of Z520 for consistency. As shown in Fig. 4(a), the RCP 2.6 CO₂ emissions decrease to reach almost zero at one instance in the late 21st century, but begin to increase again after 2100 and then remain nearly at a constant emissions level, slightly below 1 GtC y^{-1} , over the period 2150–2300.

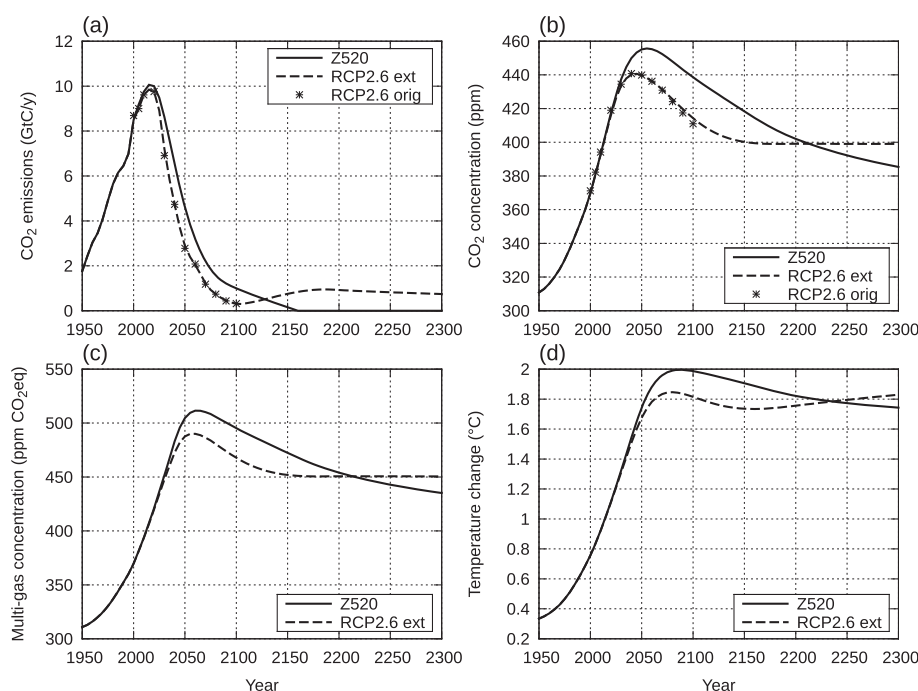


Fig. 4. Comparison of Z520 with the extended RCP 2.6 for CO₂ emissions (a), CO₂ concentration (b), CO₂-equivalent concentration of total GHGs and aerosols (c), and temperature rise (d). The original form of RCP 2.6 is shown by markers in panels (a) and (b).

As emphasized in Part 1, these emissions are to maintain the constant CO₂-concentration level (400 ppm) against natural uptake.

Comparison of stabilization types. Based on these CO₂ emissions pathways, the CO₂ concentrations are obtained as shown in Fig. 4(b). By adding the radiative forcing due to other radiative agents to the one due to CO₂, we obtain the CO₂-equivalent concentrations of total GHGs and aerosols, as shown in Fig. 4(c). In the early 21st century, the concentration of the extended RCP 2.6 makes a temporal overshoot to reach about 490 ppm CO₂-eq, but it decreases and stabilizes to the target level of 450 ppm CO₂-eq in the middle of the 22nd century. In contrast, the concentration of Z520 shows a similar overshoot, but over a longer period and decreases monotonically after the zero emissions point in 2160.

The temperature rises corresponding to these two concentration pathways are shown in Fig. 4(d). In the case of RCP 2.6, the temperature rise shows a small temporal maximum around 1.8 °C in 2080; this value corresponds to the CO₂ concentration overshoot. After the maximum, the temperature rise decreases slightly once, but after the concentration stabilization, it increases again toward the final equilibrium value 2.1 °C. However, the pace of warming is so slow that the temperature rise remains

at about 1.8 °C even by the year 2300, 150 years after stabilization. Thus, we can confirm that mitigation strategies to ensure the equilibrium temperature below a certain limiting value in the very far future could enforce unnecessarily stringent emission limitations in the near future. Especially in the case of RCP 2.6, its peculiar emissions pathway, as mentioned above, is a problem of the traditional E-stabilization. In contrast to this, in the case of the Z-stabilization pathway Z520, the temperature rise approaches the 2 °C upper limit once in 2085, corresponding to the GHG concentration maximum of about 510 ppm CO₂-eq, but it decreases gradually to about 1.8 °C after 130 years (~2200) and further decreases toward the final equilibrium value. Thus, we can confirm that the contrasting characteristics of the two types of stabilization pathways and temperature rises described in Part 1 are clearly seen in the present case, which also includes other radiative components.

Examination of the current emissions reduction strategy

One of the motivations of the present work is to examine the scientific basis of the policy claim “50% reduction of GHG emissions by 2050” anticipating that we may find a Z-stabilization pathway with more emissions at 2050. Looking for the source of this

Table 1. Characteristics of post-TAR stabilization scenarios.^{a)} (Reproduced from IPCC WG III AR4 Table SPM. 5, including the footnotes.)

Category	Radiative forcing (W/m ²)	CO ₂ concentration ^{c)} (ppm)	CO ₂ -eq concentration ^{c)} (ppm)	Global mean temperature increase above preindustrial at equilibrium, using “best estimate” climate sensitivity ^{b),c)} (°C)		Peaking year for CO ₂ emissions ^{d)}	Change in global CO ₂ emissions in 2050 (% of 2000 emissions) ^{d)}	No. of assessed scenarios
I	2.5–3.0	350–400	445–490	2.0–2.4		2000–2015	–85 to –50	6
II	3.0–3.5	400–440	490–535	2.4–2.8		2000–2020	–60 to –30	18
III	3.5–4.0	440–485	535–590	2.8–3.2		2010–2030	–30 to +5	21
IV	4.0–5.0	485–570	590–710	3.2–4.0		2020–2060	+10 to +60	118
V	5.0–6.0	570–660	710–855	4.0–4.9		2050–2080	+25 to +85	9
VI	6.0–7.5	660–790	855–1130	4.9–6.1		2060–2090	+90 to +140	5
Total								177

a) The understanding of the climate system response to radiative forcing as well as feedbacks is assessed in detail in the AR4 WGI Report. Feedbacks between the carbon cycle and climate change affect the required mitigation for a particular stabilization level of atmospheric carbon dioxide concentration. These feedbacks are expected to increase the fraction of anthropogenic emissions that remains in the atmosphere as the climate system warms. Therefore, the emission reductions to meet a particular stabilization level reported in the mitigation studies assessed here might be underestimated.

b) The best estimate of climate sensitivity is 3°C [WG 1 SPM].

c) Note that global mean temperature at equilibrium is different from expected global mean temperature at the time of stabilization of GHG concentrations due to the inertia of the climate system. For the majority of scenarios assessed, stabilisation of GHG concentrations occurs between 2100 and 2150.

d) Ranges correspond to the 15th to 85th percentile of the post-TAR scenario distribution. CO₂ emissions are shown so multi-gas scenarios can be compared with CO₂-only scenarios.

claim in the literature, we find the Table SPM.5 in the IPCC Working Group (WG) III AR4⁶⁾ and Table SPM.6 in the Synthesis Report,¹⁵⁾ which is reproduced here as Table 1. This table shows the compiled results of many emissions mitigation scenarios published after the publication of the IPCC WG III Third Assessment Report (TAR) in 2001.¹⁶⁾ A number of emissions scenarios are categorized following targeted stabilization concentrations of GHGs, or more precisely, following the values of total radiative forcing of GHGs and aerosols at the stabilized state (second column from the left in Table 1). Given a value of radiative forcing, the corresponding equilibrium temperature rise ΔT for the respective category is readily obtained by use of the simple mathematical formula¹⁷⁾

$$\Delta T = S \ln(C/C_0) / \ln(2) \quad [2]$$

based on the best estimate of climate sensitivity S (3°C). The estimated values are listed in the fifth column in Table 1. Some characteristic properties of the scenarios, such as peak-emissions year, are also shown as the range of the member scenarios involved in each category.

From Table 1, we see that for scenarios in Category I, the target stabilization concentrations of GHGs are in the range 445–490 ppm CO₂-eq with a corresponding equilibrium temperature rise of 2.0–2.4°C. Further, for member scenarios in this category, emissions of CO₂ are reduced by 50–80% of the 2000 emissions by 2050. Thus, the policy claim that GHG emissions in the world should be reduced by at least 50% by 2050 to maintain the global mean temperature rise below 2°C seems to rest on the results associated with Category I. In other words, the policy claim appears to have a scientific basis, as assessed by the IPCC. Although the base year for emissions reduction rates is not explicitly documented in the climate policy, hereafter we assume the year 2000 as a base year, in accordance with Table 1. Also, in the following discussion, we consider that emissions reduction of GHGs in the policy corresponds to that of CO₂.

In the previous section, we identified the RCP 2.6 scenario as being representative of a stabilization scenario with an equilibrium temperature of 2.1°C, *i.e.*, it is supposed to be a member of Category I. However, as seen in Fig. 1, the two post-AR4 RCP

scenarios, RCP 2.6 and RCP 3-PD, deviate from the range of Category I. The Category-I emissions range from IPCC AR4 does not show an increase during the earliest period of 2000–2030, but it remains nearly at a constant level. Note that this problem has been fixed in the revised range based on post-AR4 studies, but it does not include land-use related CO₂ emissions. Taking 1–2 GtC y⁻¹ emissions into account for land-use changes during the early period of the 21st century, the new Category I range appears consistent with the RCP scenarios. In this point (all) original Category I scenarios reviewed in IPCC AR4 definitely differ from RCP 2.6, which shows a clear increase from 2000 to 2020, as readily seen in Fig. 1: the annual emissions rate increases from about 8 GtC y⁻¹ in 2000 to nearly 10 GtC y⁻¹ in 2020. Apparently, this increasing trend is consistent with the emissions increase already observed (at least) up to 2009.^{18),19)} However, all original Category I emissions pathways fail to represent this actual observed increase. Because of these erroneously low emissions in the earliest period in the Category I scenarios, the emissions in the subsequent period, including 2050, might become larger. A crude estimate of the correction to be applied to them gives less emissions of 0.5–1 GtC y⁻¹ in the later period, which includes 2050. Thus, we recognize that the RCP 2.6 emissions pathway, which was developed after IPCC AR4 by correctly including the rapidly increasing trend in the most recent years, is more suited to represent E-stabilization pathways with the same target concentration (450 ppm CO₂-eq) as those in Category I.

Figure 5 shows enlarged versions of the two emissions pathways in Fig. 4(a) limited to the 21st century period. We see that the RCP 2.6 scenario (original and extension) undergoes more stringent reduction than the mitigation policy of 50% reduction by 2050; the emissions in 2050 are only 34% (66% reduction) of the level in 2000. This situation is the same for the other lowest scenario RCP 3-PD, as readily seen in Fig. 1. Thus, we see that in order to meet the 2°C limit, emissions by 2050 must be much less than 50% (around 35%) of the 2000 level, as long as we only consider E-stabilization as a mitigation strategy. In contrast, in the case of Z520, the CO₂ emissions in 2050 are 54% of the 2000 level, corresponding to a 46% reduction. Though this number does not differ greatly from 50%, we can say that a pathway that allows emissions larger than half of those of the year 2000 emissions, satisfying the condition that the temperature rise does not exceed

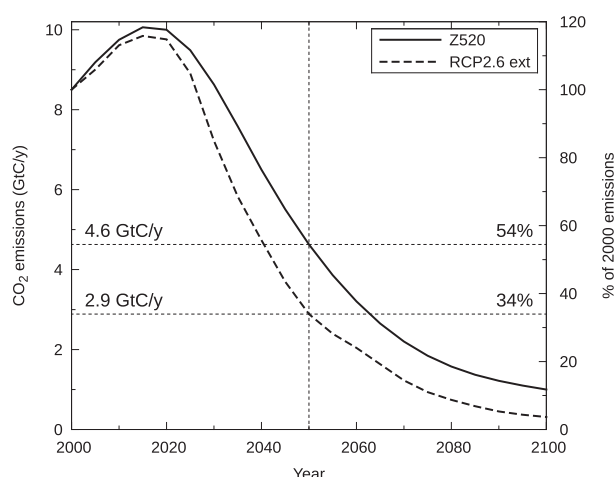


Fig. 5. Comparison of CO₂ emissions between Z520 and the extended RCP 2.6 in the 21st century. Annual emissions at 2050 and their relative values to the 2000 level (8.5 GtC y⁻¹) are indicated by dashed lines and attached numbers.

2°C above the preindustrial level, can be realized if we include a Z-stabilization pathway. Therefore, the result of our comparison of the two stabilization types supports the point that under a Z-stabilization pathway, more emissions are permissible in the near term than under E-stabilization with the same temperature-rise constraint. In the specific case we are discussing now, the total CO₂ emissions in the 21st century are 520 GtC for Z- and about 430 GtC for E-stabilizations. This is a significantly large difference in the context of an emissions reduction strategy.

With reference to the policy claim of 50% reduction by 2050, the claim does not appear to be based on sound or relevant scientific grounds if one examines the IPCC WG III AR4 critically. The claim cannot be supported by scientific arguments, as long as we consider only E-stabilization; more stringent reduction down to about 1/3 is required by 2050. However, by extending the emissions pathways to include Z-stabilization, this reduction target to avoid the 2°C temperature rise is now marginally correct. Thus, we arrive at a positive but somewhat ironic conclusion about our original anticipation.

A zero-emissions stabilization pathway with potential for practical application

In the previous section, we have shown that there is a pathway that satisfies the 2°C upper limit on temperature rise and still allows slightly more than 50% emissions by 2050 if we consider zero

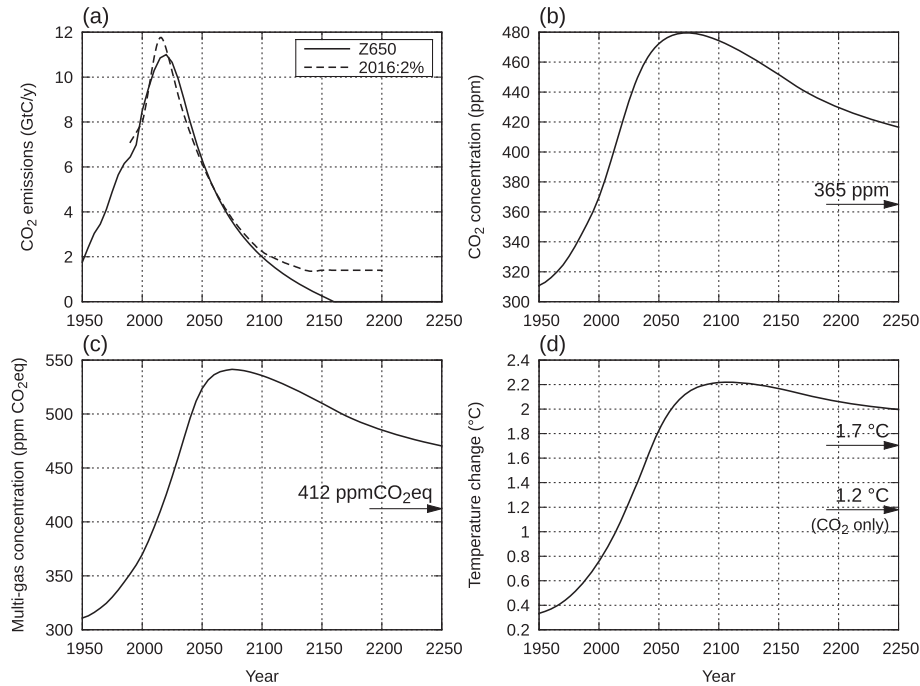


Fig. 6. Z650 pathway for CO₂ emissions (a), CO₂ concentration (b), CO₂-equivalent concentration of total GHGs and aerosols (c), and temperature rise (d). A comparable emissions pathway (2016:2%) by UKCCC⁽¹²⁾ is shown in panel (a). Arrows and attached labels show the final equilibrium state.

emissions or cessation of CO₂ emissions in the next century. We propose this as an alternative to replace the currently advocated mitigation strategy by attaining the CO₂ zero emissions.

However, our original motivation to abandon the traditional E-stabilization strategy for climate-change mitigation was to avoid long-term risks, such as sea level rise caused by long-lasting higher temperatures associated with stabilization. So far, it has been emphasized in the past IPCC reports, including WG I AR4,⁽¹⁰⁾ that even after the stabilization is realized, the sea level continues to rise. It has never been mentioned that there is the possibility of recovery or restoration of climate through a natural decrease in CO₂ concentrations by attaining sufficiently low CO₂ emissions. On these grounds, we understand that the 2°C upper limit for avoiding dangerous climate change was adopted by assuming that such high temperatures continue for a long time. Therefore, let us consider that the 2°C upper limit can be relaxed slightly, if the period of higher temperature is limited to a relatively short period from the viewpoint of long-term risks, *e.g.*, ice-sheet melting in Greenland.

On the basis of the above considerations, we shall now examine the Z650 emissions/concentration

pathways, including the effects of other GHGs and aerosols, by following the same methodology as in the previous section. Results of the calculated projections are shown in Fig. 6(a)–(d). As a reference, Fig. 6(a) includes one of the UKCCC pathways labeled as 2016:2%, which first follows a baseline scenario, but after 2016, the emissions decrease at a rate of 2% y⁻¹ until they reach 1.4 GtC y⁻¹ by about 2130. Beyond this, constant emissions of 1.4 GtC y⁻¹ continue and this is called the emission floor. Except for this last stage and the earliest two decades, the two emissions pathways are very similar.

Figure 6(a) shows the CO₂-emissions pathway (the same as the one shown by the solid line in Fig. 2(a) in Part 1). Figure 6(b) is the CO₂ concentration corresponding to the Z650 emissions (again the same as the solid line in Fig. 2(b) in Part 1). By adding the radiative forcing due to other GHGs and aerosols, as shown in Fig. 2, we obtain the equivalent CO₂ concentration of the total radiative forcing as shown in Fig. 6(c). The CO₂-equivalent concentration increases to a maximum of about 540 ppm but decreases to nearly 450 ppm, *i.e.*, the target level of a 2°C temperature rise, soon after 2250. According to Eq. [1] and the assumption of a constant non-CO₂ forcing of 0.65 W m⁻², the CO₂-equivalent concen-

tration of the total radiative forcing is given by the CO_2 concentration multiplied by a factor of 1.13 ($= e^{0.65/5.35}$). Comparing the increase in concentration due to the non- CO_2 forcing, *e.g.*, about 60 ppm in 2100, with the increase in the CO_2 concentration from the year 2000 to the maximum of about 100 ppm, we observe the large effect of other GHGs, implying that if we can reduce the emissions of other gases such as methane and nitrous oxide in the future, it would make a significant contribution to lowering the temperature or allowing greater CO_2 emissions, as discussed in Ref. 20).

The projected temperature rises in the Z650 case are shown in Fig. 6(d). The temperature exceeds 2°C from 2065 to 2245, a fairly long period of about 180 years. However, the excess temperature remains within 0.2°C , which may not be so serious. Moreover, we can infer that a reduction in other GHG concentrations by a half would enable maintaining the temperature rise below the 2°C upper limit from the case of the temperature rise in the CO_2 only case (the solid line in Fig. 2(c) in Part 1). In the final equilibrium state, the concentration is expected to decrease to 412 ppm $\text{CO}_2\text{-eq}$ (365 ppm in case of CO_2 only), which corresponds to an equilibrium temperature rise of 1.7°C , or 1.2°C in the CO_2 only case. The latter is the equilibrium temperature rise for the total CO_2 content in the climate system discussed in Part 1. On multiple century time scale, it is likely that the concentrations of other GHGs can be reduced to preindustrial levels, so that effective temperature rise for sea level rise will be 1.5°C or less. Then, we may consider that the 1.5°C limit noted in the Copenhagen Accord could be met by this scenario, if the limit comes from the concern about sea level rise.

As seen above, climate change would remain within what may be considered to be an acceptable range for this Z650 case. Total cumulative CO_2 emissions of 650 GtC in the 21st century are considerably larger than the lowest emissions scenarios, which keep the temperature rise below 2°C , where the total cumulative emissions are about 430 GtC (for RCP 2.6) or 520 GtC (for Z520). Now, we shall briefly examine the socioeconomic implication of these larger emissions. For this purpose, let us perform an exercise to understand how large this quantity is. Recently, at the 2009 G8 Summit, it was declared that G8 nations will reduce CO_2 emissions by 80% by 2050, and they proposed a reduction of the same magnitude to all developed countries.²¹⁾ We shall estimate the partition of the total worldwide

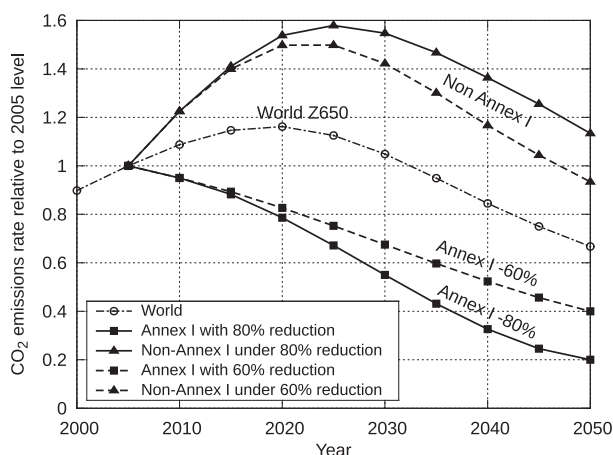


Fig. 7. Example of CO_2 -emissions rates relative to the 2005 level for Annex I (developed countries) and Non-Annex I (developing countries) based on the Z650 pathway. Changes from 2005 to 2010 are determined according to historical fossil-fuel CO_2 emissions,²²⁾ and it is assumed that the Annex I emissions rate declines smoothly from 2010 to achieve 60–80% reductions by 2050.

CO_2 emissions between developed (Annex I) and developing (Non-Annex I) countries in the case of Z650 by assuming that the reduction in developed countries proceeds smoothly from 2010 to reach the 60–80% reduction target by 2050. Figure 7 depicts the emissions of Annex I and Non-Annex I countries as ratios of the 2005 level, when CO_2 emissions of the two groups became almost equal. The total worldwide emissions are also shown. The emissions of developing countries increase for the first few decades, peaking at about 2020–2025 with the maximum around 1.5–1.6, *i.e.*, a 50–60% increase relative to the base year of 2005 (over 60% if we take 2000 as the base year). After peaking, the emissions decline but stay above the 2005 base-year level until about 2050. In 2050, the emissions of developing countries have come back to the present-day level. During the 2005–2050 period, the emissions of developed countries decrease monotonically to 20–40% of those of the base year. Note that the total worldwide emissions in 2050 are about 70% of the base year 2005 or about 75% relative to 2000. By considering the increase in population in developing countries, the partition as depicted in Fig. 7 may represent the minimal fulfillment of the demand on developing countries, which cannot be attained by lower total emissions. The relatively larger emissions are made possible by Z-stabilization at the expense of lower emissions in the later period to reach zero in 2160, the middle of the next century.

Summary and conclusions

The main purpose of Part 2 of this study is to examine whether or not the findings in Part 1, which pertain to the differences between the two types of stabilizations, hold under more realistic conditions including radiative forcings of other GHGs and aerosols. In particular, we were interested in determining how much more CO₂ emissions are permissible in the near future in the Z-stabilization pathway as compared with the emissions in the E-stabilization pathway, under the same temperature rise constraint of 2°C. The results show that though the Z-stabilization pathway Z520 allows significantly higher CO₂ emissions than the corresponding E-stabilization pathways RCP 2.6 (520 GtC vs. 430 GtC in the 21st century), the emissions in 2050 are estimated to be 54% of the 2000 level, slightly above 50%. Thus, we cannot have significantly larger emissions than the policy claim of 50% reduction by 2050, even though we anticipated that under Z-stabilization more emissions might be permissible. Tracing the origin of this unexpected result, we noticed that all CO₂-emissions pathways in Category I of the IPCC WG III AR4 (Table 1) have emissions that are much too low in the earliest period of 2000–2020, contradicting the actual observed amounts and increasing trend in the period, and as a consequence erroneously large emissions are permissible in the later period including 2050.

As a matter of fact, the RCP 2.6 pathway, designed as a stabilization scenario in the traditional sense, gives emissions in 2050 as low as about one third of the 2000 level, because this recently developed scenario assumes reasonably large emissions in the earliest period that reflect the actual observed increase. Thus, the strategy “50% emissions reduction by 2050 for preventing 2°C temperature rise” does not have a sound scientific basis within the past framework of traditional stabilization scenarios. When we introduced the Z-stabilization pathway Z520, the CO₂ emissions in 2050 could exceed 50% of the 2000 emissions. Note, however, that the reduction target at 2050 depends on the change (reduction) of non-CO₂ forcings, and that the total CO₂ emissions at the end of the 21st century and beyond in the Z-stabilization pathway compatible with the constraint is affected by the carbon cycle. Further, if the technology to remove CO₂ is assumed to become feasible in the latter half of the century, emissions by 2050 can be larger. Thus, the above result regarding the 2050 target should be limited to comparison of the two stabilization types.

As shown in Fig. 4(d), the temperature rise of the extended RCP 2.6 remains at 1.7–1.8°C, significantly lower than the upper limit of 2°C for more than 200 years after the minimum (almost zero) emissions. Then, the temperature rise continues a slow but steady upward tendency toward the upper limit to be reached after a very long time. In this way, we recognize the stringent emissions reduction in the 21st century is enforced by the requirement of E-stabilization. Such a large reduction as in RCP 2.6 is not needed if we explore the possibility of different types of emissions pathways like Z520 as mitigation strategies.

By noting problems arising from limiting emissions pathways to E-stabilization, we propose the adoption of emissions pathways with zero emissions. (Since the time for zero emissions is supposed to be in the middle of the next century, about 150 years from the present, there will be ample time for realizing a carbon-emissions-free society.) In this case, the temperature rise may exceed the often-quoted upper limit of 2°C for a limited period. We consider that the upper limit of 2°C for avoiding dangerous climate change comes from the assumption of stabilization, which implies continuation of this temperature for a very long time by definition. If the temperature excess above the limit is small and the period is limited, there might not be any critically serious problems. As far as the melting of ice sheets is concerned, such a short period of minimally higher temperatures would make very little difference. Rather, a state of much lower temperature rise to be realized centuries later as the final equilibrium must be much safer compared to the corresponding E-stabilization concerning the sea level rise. (Note that the final equilibrium state calculated in this study should be considered as an asymptotic level on centuries to millennium time scales because the carbon-cycle model does not contain geological processes that could start to be important on millennia time scales, by which a further reduction of the CO₂ concentration could take place as shown in Fig. 7.12 of Ref. 10).)

As one such pathway that is supposed to be relatively safe regarding long-term risks of sea level rise, we presented the emissions scenario Z650 and examined its merits, especially its relatively large emissions in the near future from a socioeconomic viewpoint. As discussed in the previous section, the mitigation strategy based on this emissions pathway might contribute to overcoming the difficulties we are now facing in selection of climate-change mitigation

strategies. Current climate-change issues are deeply rooted in science in their origin, but more scientific research that responds to current societal needs is desired.

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