World Energy Outlook 2007: CO2 Emissions Pathways Compared to Long-Term CO2 Stabilization Scenarios in the Literature and IPCC AR4

Nebojsa Nakicenovic, IIASA and TU Wien, November 2007

Stabilization of atmospheric concentrations of greenhouse gases (GHGs) is a declared objective of Article 2 of the United Nations Convention on Climate Change (UNFCCC, 1992). Carbon dioxide (CO2) is the most important of these gases followed by methane (CH4) and nitrous oxide (N2O). Current atmospheric concentrations of CO2 are about 380 ppmv (parts per million volume) CO2 only and are somewhere around 420 to perhaps 440 ppmv CO2 equivalent if other GHG concentrations are added, e.g. methane, nitrous oxide and cooling effects of aerosols subtracted. The pre-industrial concentrations of CO2 are estimated at about 280 ppmv for the end of the 17^{th} century. This means that we have increased the atmospheric concentrations of CO2 by some 100 ppmv (and CO2 equivalent concentrations close to 140 ppmv) since the beginning of the Industrial era primarily by burning of fossil fuels and also by massive deforestation and land use changes. The corresponding global CO2 emissions have increased from about 1.1 GtCO2 (billion tons of CO2 or 0.3 GtC, billion tons of elemental carbon) to about 24.6 GtCO2 (6.7 GtC) in 2000. This translates into an average annual growth rate of about 1.5 % per year[1]. IPCC (Intergovernmental Panel on Climate Change) in its Fourth Assessment Report (AR4 WGI and III, 2007) estimates that this increase in atmospheric concentrations of anthropogenic sources of GHGs have already resulted in an increase of global mean temperature by about 0.75 degrees Celsius, compared to the pre-industrial levels, or an increase of radiative forcing of about 1.6 W/m2 (Watts per meter square) and that just about equal additional increase will occur during the coming centuries even if concentrations are stabilized at current levels. This means that the humanity will have caused about a 1.5 degrees Celsius increase in mean global temperature through cumulative historical emissions since the beginning of industrialization.

There is a large volume of literature on future energy and emissions scenarios (Nakicenovic et al., 2005, IPCC, AR4, WGIII, 2007) and more than 500 global energy scenarios have been published. Some of them are of a more recent vintage, but most have been assessed by IPCC in the Special Report on Emissions Scenarios, (SRES, 2000) and Third Assessment Report (TAR, WGI and WGIII, 2001). Based on this literature, IPCC developed a set of 40 emissions scenarios that cover most underlying ranges in main driving forces and emissions (SRES, 2000).

Figure 1 shows future CO2 emissions in the more recent scenarios (no climate intervention) in the literature compared to the range of SRES scenarios and the older literature. The new scenarios range from almost no emissions in 2100 (these are those that stabilize concentrations at very low levels) to about 250 GtCO2 (over 65 GtC). SRES scenarios cover more than 50 percent of that range. They do not explore the high end tail above 135 GtCO2 of the distribution. Figure 2 shows the SRES ranges of CO2 emissions, atmospheric CO2 concentrations, radiative forcing and global mean temperature increases. SRES carbon emissions range from 10 to almost 235 GtCO2 (3 to 37 GtC) by 2100. The corresponding CO2 concentrations are about 500 to almost 1000 ppmv and global mean temperature increase (by 2100 compared to 1990) from 1.3 to 5.8 degrees Celsius.

[1] About 1.2 % per year from 1800 to 1900 and 1.8 % per year from 1990 to 2000.

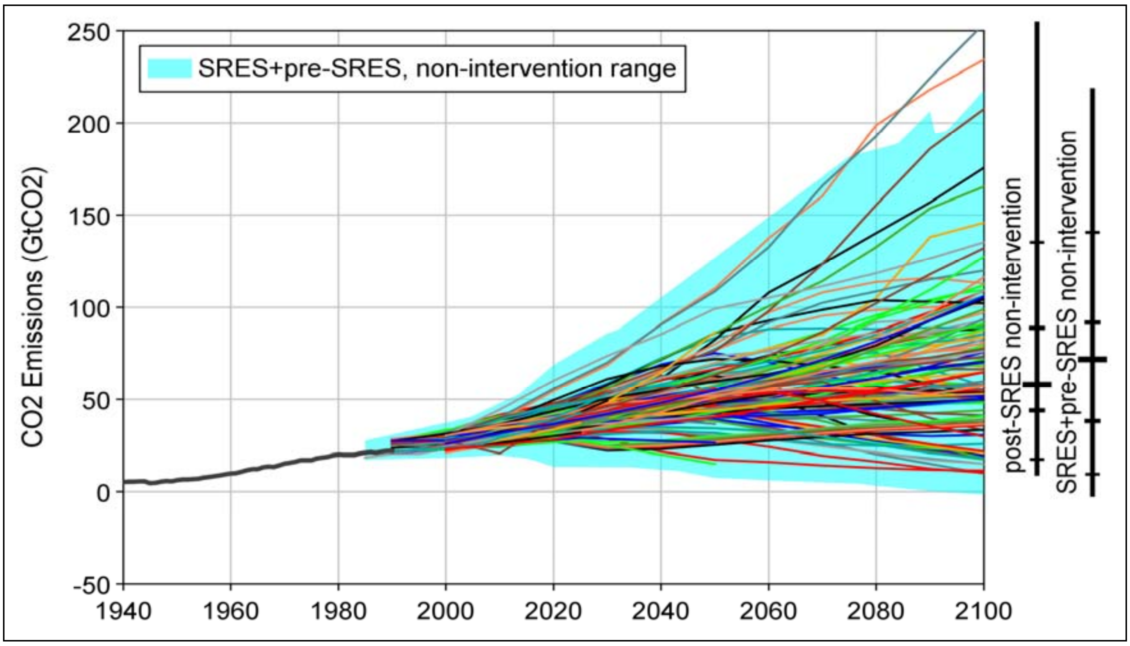

Figure 1. CO2 emissions in GtCO2 for the range of scenarios in the literature published before 2000 (shown in blue shaded area marked SRES and pre-SRES) compared to the new emissions scenarios published in 2000 or thereafter (IPCC SRES, 2000 and AR4, WGIII, 2007).

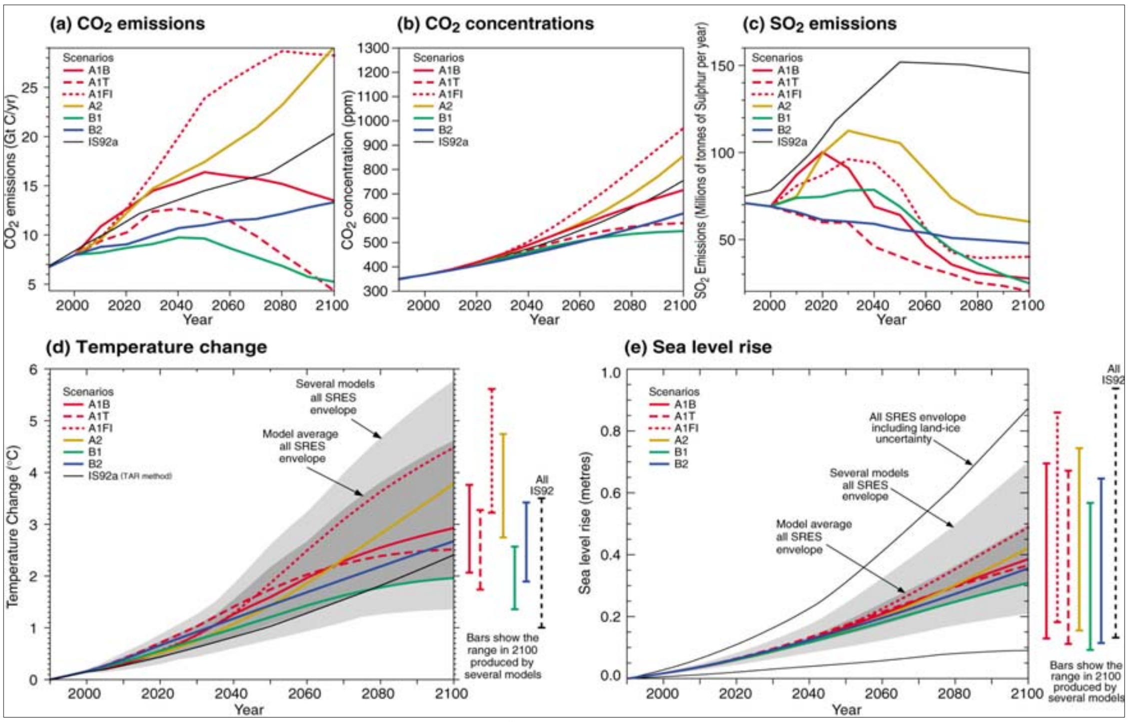

Figure 2. CO2 emissions, concentrations, sulfur aerosol emissions, global mean temperature and sea level increases for the range of SRES scenarios (IPCC SRES, 2000 and TAR, WGI, 2001).

Figure 3 illustrates the temperature increase associated with the two more extreme of the SRES scenarios, A2 and B1, based on the most recent climate model projections reported in the Fourth Assessment Report (AR4, WG1, 2007). Both scenarios lead to additional temperature increase of about one degree Celsius by 2030. Similar trends are seen in most of the scenarios in the literature by 2030 mostly because of the large inertia of the climate system. This means that the WEO scenarios can be expected to portray very similar climate implications by 2030. Thereafter, most scenarios start to diverge, leading to fundamentally different climate outcomes by 2100 and beyond. B1 is associated with slightly more than 2 degrees by 2100 while A2 is close to 4 degrees Celsius global mean temperature change by 2100.

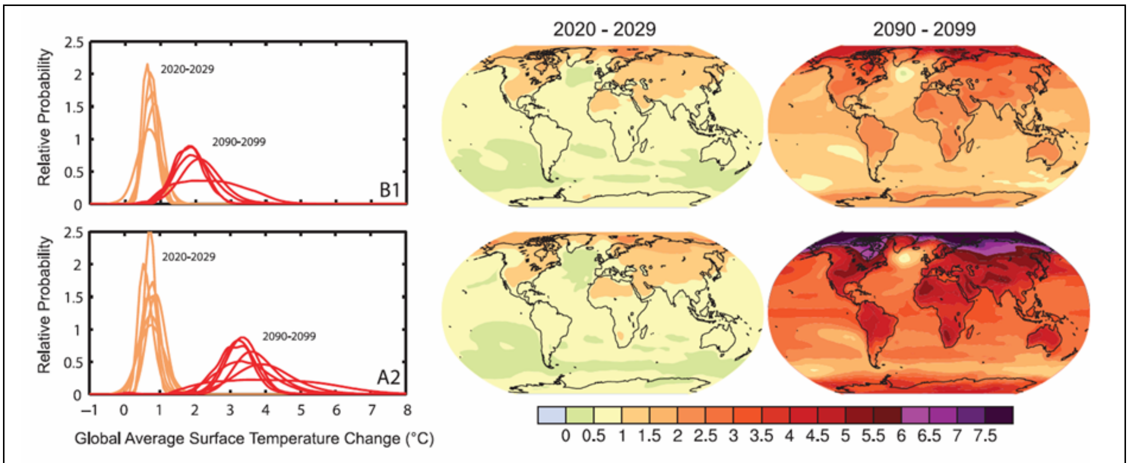

Figure 3. Global mean temperature change for two of the SRES emissions scenarios, B1 and A2 (IPCC AR4, WG1, 2007).

Table 1 Properties of emissions pathways for alternative ranges of CO2 and CO2-eq. stabilization targets compared to global emissions peak and relative emissions reductions. All stabilization scenarios assessed in IPCC AR4, WGIII (2007, see also sections 3.2 and 3.3; data source Nakicenovic et al., 2006 and Hanaoka et al., 2006).

Category	Anthropogenic addition to radiative forcing at stabilization (W/m^2)	Multi-gas concentration level (ppmv CO_2-eq)	Stabilization level for CO_2 only, consistent with multi-gas level (ppmv CO_2)	Number of scenario studies	Global mean temperature ºC increase above pre-industrial at equilibrium, using best estimate of climate sensitivity (3)	Likely range of global mean temperature ºC increase above pre-industrial at equilibrium (1)	Peaking year for CO_2 emissions (2)	Change in global emissions in 2050 (% of 2000 emissions) (2)
I	2.5 – 3.0	445 – 490	350 – 400	6	2.0 – 2.4	1.4 – 3.6	2000 – 2015	-85 to -50
II	3.0 – 3.5	490 – 535	400 – 440	18	2.4 – 2.8	1.6 – 4.2	2000 – 2020	-60 to -30
III	3.5 – 4.0	535 – 590	440 – 485	21	2.8 – 3.2	1.9 – 4.9	2010 – 2030	-30 to +5
IV	4.0 – 5.0	590 – 710	485 – 570	118	3.2 – 4.0	2.2 – 6.1	2020 – 2060	+10 to +60
V	5.0 – 6.0	710 – 855	570 – 660	9	4.0 – 4.9	2.7 – 7.3	2050 – 2080	+25 to +85
VI	6.0 – 7.5	855 – 1130	660 – 790	5	4.9 – 6.1	3.2 – 8.5	2060 – 2090	+90 to +140

Notes:

1. *Warming for each stabilization class is calculated based on the variation of climate sensitivity between 2ºC –4.5ºC, which corresponds to the likely range of climate sensitivity as defined by IPCC, AR4, WG I (Chapter 10, 2007).*
2. *Ranges correspond to the 70% percentile of the post-TAR scenario distribution.*
3. *'Best estimate' refers to the most likely value of climate sensitivity, i.e. the mode (see IPCC, AR4, WG I, Chapter 10, 2007).*

UNFCCC (1992) does not specify at what level CO2 and other GHGs concentrations should be stabilized so that the often practiced approach is to look at the implications of different stabilization levels on possible future emissions paths. Generally, stabilizing concentrations after the end of the 21st century means that annual emissions of CO2 need to fall well below current levels before the end of the century, e.g to about half or less of the year 2000 emissions by 2050 for the most stringent stabilization category shown in Table 1. In other words, the emissions need to peak during this century and proceed to decline thereafter. The lower the stabilization level chosen, the earlier the peak of emissions needs to be. All told, emissions need to peak within a decade or less to achieve very low stabilization levels such as the two degrees Celsius by 2100.

Table 1 gives an indication of this relationship from IPCC AR4 as it is important for determining the nature of future emissions paths that eventually lead to the stabilization of concentrations. For low levels of concentrations (category I, less than 400 ppmv of CO2 only or less than 490 CO2 equivalent), the peak of emissions needs to occur within less than 10 years, while for the high levels of concentrations (categories V and VI, from 570 up to 790 ppmv of CO2 only or from 710 up to 1130 ppmv CO2 equivalent) the peak is shifted to the second half of the century. However, it should be noted that the associated uncertainties are substantial so that there is quite a lot of variation possible in future emissions paths for any level of stabilization, radiative forcing and temperature change. This also explains the wide ranges of underlying scenarios in the following that are consistent with any given stabilization target.

Our objective is to indicate where in this range do the new WEO 2007 scenarios fall, how they compare with the stabilization literature and what measures and policies would be consistent with future emissions declines in the post-2030 period.

Table 1 groups the stabilization scenarios in six different categories to facilitate the comparison of different stabilization levels and their implications for the emissions pathways. The six categories range from category I for the lowest stabilization levels up to VI for the highest. The table also illustrates the approximate relationship between radiative forcing, temperature change and stabilization levels of CO2 only and CO2 equivalent concentrations. For example, scenario category IV is consistent with radiative forcing increase of between 4 and 5 W/m2 which translates into a wide range of future temperature increases, from 3.2 to 4.0 degrees Celsius above the pre-industrial levels using the best climate sensitivity estimate. The range is much larger (2.2 to 6.1 degrees Celsius) for different assumptions about possible climate sensitivities. In other words, the first range of 3.2 to 4.0 degrees Celsius shows the uncertainties of future temperature increase associated with range of different emissions pathways in category IV while the range of 2.2 to 6.1 degrees shows the additional uncertainties associated with how sensitive climate might be to those emissions. This illustrates how large are the uncertainties and indicates that the emissions paths need to be in the lower ranges if the objective is to keep future temperature changes below 2 degrees Celsius (e.g. according to the EU objective, or less than 2.4 degrees as reflected in the G8 Heiligendamm declaration).

Table 1 shows a corresponding range of CO2 concentrations for Category IV of 485 to 570 ppmv (an increase of 105 to 190 ppmv above current levels by 2100). Adding the equivalent effect of all other GHGs in the scenarios would correspond to additional CO2 concentrations of 105 to 140 ppmv (range of 590-710 ppmv).Table 1 thus shows the effective total concentration limits that are consistent with chosen temperature or radiative forcing ceilings.

An important question is whether and to what extent are the WEO 2007 scenarios consistent with the long-term emissions paths in the literature and how do they compare to alternative stabilization pathways. Clearly, the development of WEO scenarios beyond 2030 is indeterminate as this goes beyond the scenario time horizon. Nevertheless, the developments to 2030 include seeds of change for the later periods and thus the assessment of longer-term possibilities is relevant at least in this context. Furthermore, this question of relation of short to long-term developments is relevant given that the world community is committed to the very long-term stabilization of GHG concentrations through the ratification and coming into force of the UNFCCC.

Some of the OECD countries have adopted more specific emissions reductions commitments through the Kyoto Protocol. Its observation period for emissions reductions of 2008 to 2012 falls well within the WEO study time horizon. Some of these commitments are included in the Alternative Policy Scenario. In particular, the forth WEO 2007 scenario goes beyond the Alternative Policy Scenario to strive stabilization at 450 ppmv CO2 only. The WEO 450 Stabilization Case foresees an emissions peak around 2010, returns to the 2005 emissions levels around 2020 and comes in well below current emissions by 2030. Thus, the question is whether the Alternative Policy Scenario and the 450 Stabilization Case in particular are consistent with some of the lower stabilization levels and longer-term emissions paths. As shown in Figure 4 this is indeed the case.

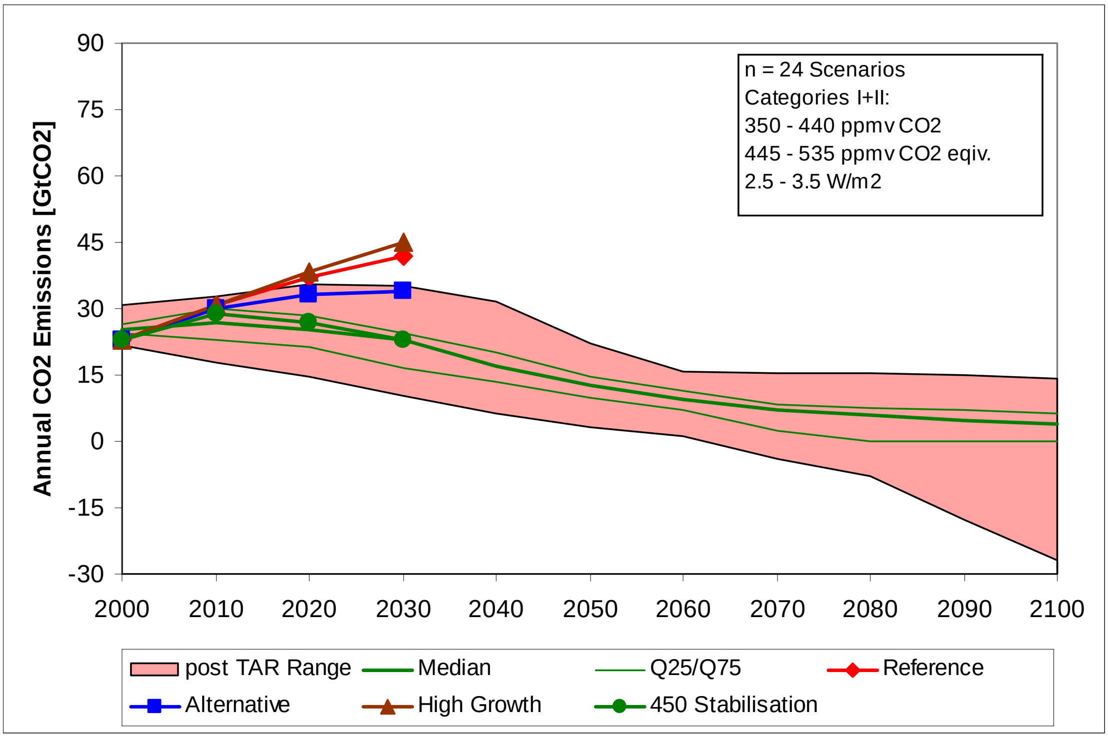

Figure 4. Stabilization of CO2 concentrations between 350 and 440 ppmv Shaded area gives the ranges of 24 stabilization scenarios (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007) in comparison to WEO 2007 through 2030.

Figure 4 compares the long-term stabilization scenarios that lead to CO2 concentrations stabilization of between 350 and 440 ppmv compared to current concentrations of 380 ppmv and pre-industrial ones of about 280 ppmv. See categories I and II in Table 1 above for the corresponding total GHGs concentrations in CO2 equivalent, the radiative forcing and temperature changes. The emissions ranges are quite broad with emissions peak varying from almost immediate up to the 2020s. The decline is vigorous during the second half of the century leading to emissions levels well below the current. Particularly noteworthy is that four of the more recent scenarios lead to negative emissions during the last three decades of the century because of policies and measure to increase CO2 sinks such as carbon capture and storage associated with biomass.

The four WEO 2007 scenarios cover a comparatively wide range of emissions by 2030. The WEO 450 Stabilization Case is consistent with the median emissions in Figure 4 and thus corresponds clearly to scenarios that stabilize CO_2 only concentrations at about 400 ppmv and CO_2 equivalent at about 500 ppmv.

Figures 5 and 6 compare the WEO 2007 scenarios with the ranges of stabilization emissions paths for the two categories, I and II, respectively. The separation of the two categories clearly shows that the WEO 450 Stabilization scenario is consistent with very low levels of stabilization shown in Figure 5. In contrast, the Alternative Policy Scenario is situated well above the range of the scenarios shown in Figure 5 and just within the range of the higher stabilization levels shown in Figure 6. The other two WEO 2007 reference scenarios are even higher compared with the range of the lowest stabilization scenarios in the literature, especially during the 2020s decade and portray emissions that push the possible stabilization envelope toward much higher levels in the range.

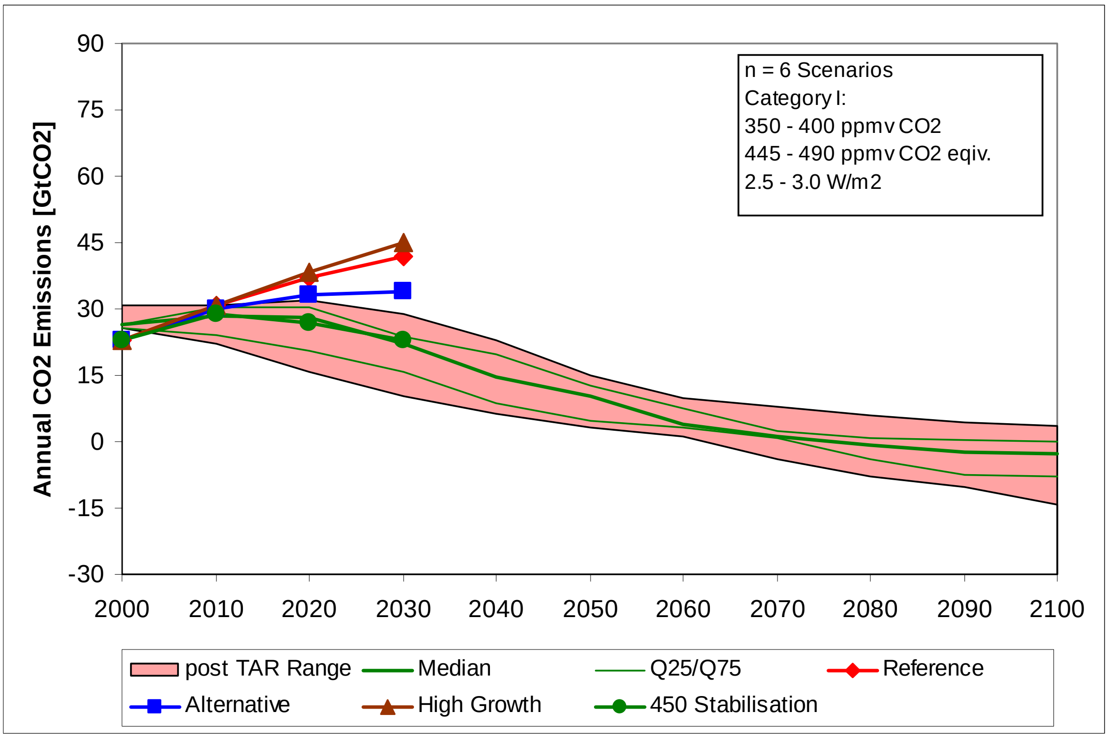

Figure 5. Stabilization of CO_2 only concentrations between 350 and 400 ppmv Shaded area gives the ranges of 6 stabilization scenarios (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007) in comparison to WEO 2007 through 2030.

Figure 5 shows that the WEO 450 Stabilization Case scenario is quite close to the median of stabilization pathways that lead to stabilization between 350 and 400 ppmv CO_2 only. This means that the emissions pathway of this scenario is consistent (through 2030) with lowest stabilization levels in the literature. Given multiple uncertainties, one can say with a high degree of confidence that the scenarios could in principle stay in the region up to 450 ppmv stabilization in the long run. In other words, the 450 Stabilization scenario leads to emissions levels through 2030 that appear to be consistent with long-term stabilization paths that result in mean global temperature increase of 2 to 2.4 degrees Celsius above pre-industrial levels by 2100 (assuming best estimate for the climate sensitivity). This range corresponds well to the EU and Heiligendamm targets of two or just above two degrees Celsius by 2100.

Figure 6 shows that the Alternative Policy scenario is quite close to the upper range of stabilization pathways that lead to stabilization between 400 and 440 ppmv CO_2 only. The 450 Stabilization Case is almost identical to the median emissions pathway. Thus, Alternative Policy scenario leads to emissions levels through 2030 that appear to be also consistent with somewhat higher long-term stabilization paths that result in mean global temperature increase of 2.4 to 2.8 degrees Celsius above pre-industrial levels by 2100 (assuming best estimate for the climate sensitivity). This range is considerably higher compared to the EU target of two degrees Celsius by 2100. However, one cannot in principle exclude the possibility of emissions "overshoot" in the case of the Alternative Policy scenario up to 2030 in combination with more vigorous mitigation profile in the following decades such as that of negative emissions profiles toward the end of the century as shown for the lowest scenarios in Figure 5. The main conclusion of this exercise is that the WEO 450 Stabilization scenario is consistent with both categories I and II up to 2030 depending what happens afterwards. However, a very robust conclusion is that it is with a high degree of certainty in the range of scenarios that stabilize below 450 ppmv CO2 only.

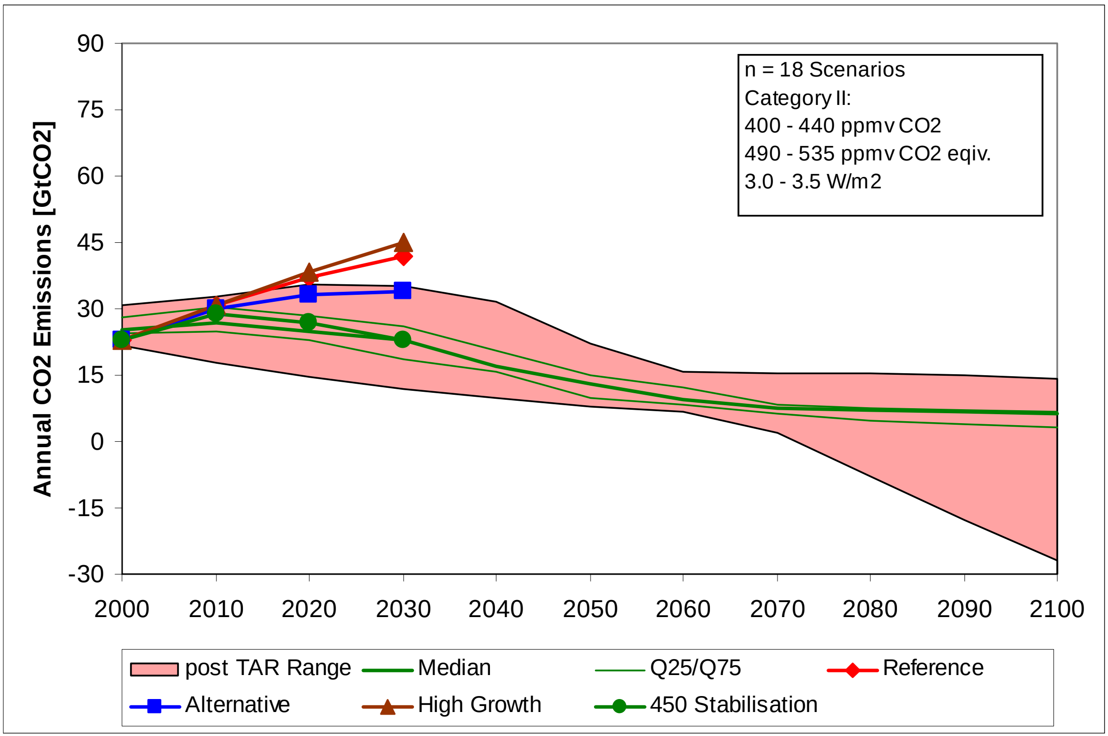

Figure 6 Stabilization of CO2concentrations of between 400 and 440 ppmv. Shaded area gives the ranges of 18 stabilization scenarios (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007) in comparison to WEO 2007 through 2030.

Figures 7 and 8 compare the four WEO 2007 scenarios with long-term stabilization emissions pathways from the literature of between 440 and 485 ppmv CO2 only in Figure 7 and 485 and 570 ppmv in Figure 8. These two figures clearly show that the Alternative Policy WEO scenario appears to be broadly consistent with long-term stabilization somewhere in between the two figures, corresponding to about 485 ppmv CO2 only or about 590 ppmv CO2 equivalent. Thus, the Alternative Policy scenario leads to emissions levels through 2030 that appear to be consistent with long-term stabilization paths that result in mean equilibrium global temperature increase of about 3.2 degrees Celsius above pre-industrial levels by 2100 (assuming best estimate for the climate sensitivity).

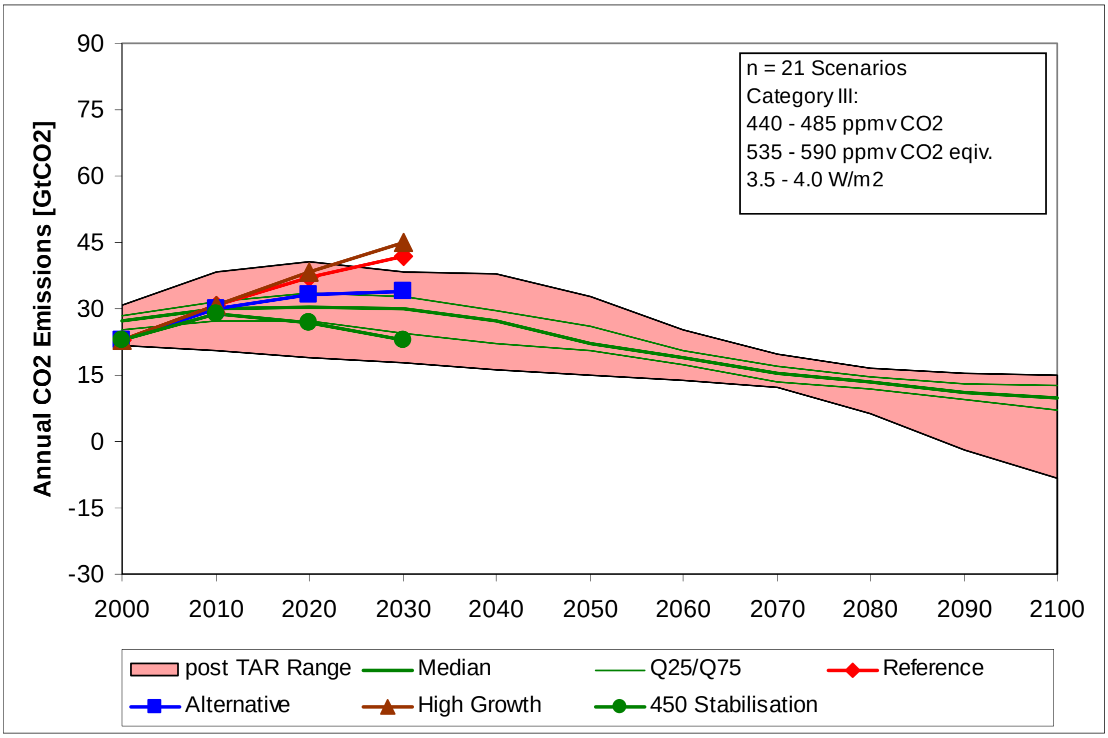

Figure 7. Stabilization of CO2 concentrations of between 440 and 485 ppmv. Shaded area gives the ranges of 21 stabilization scenarios (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007) in comparison to WEO 2007 through 2030.

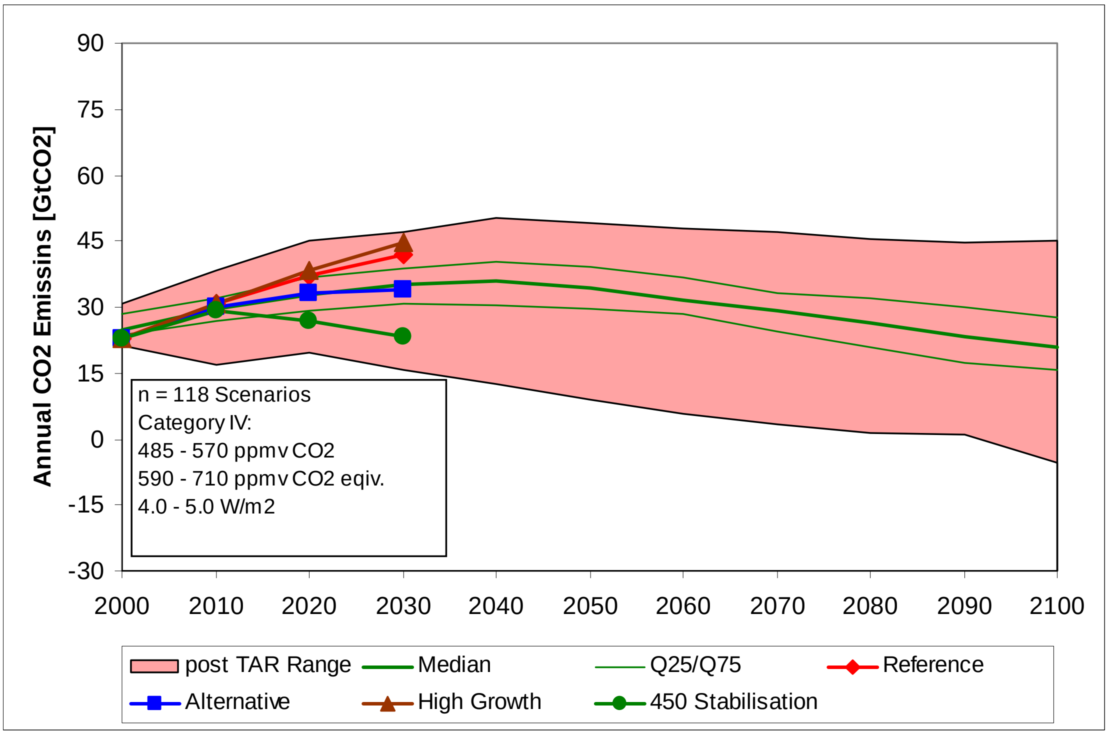

Figure 8 Stabilization of CO2 concentrations between 485 and 570 ppmv. Shaded area gives the ranges of 118 stabilization scenarios (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007) in comparison to WEO 2007 through 2030.

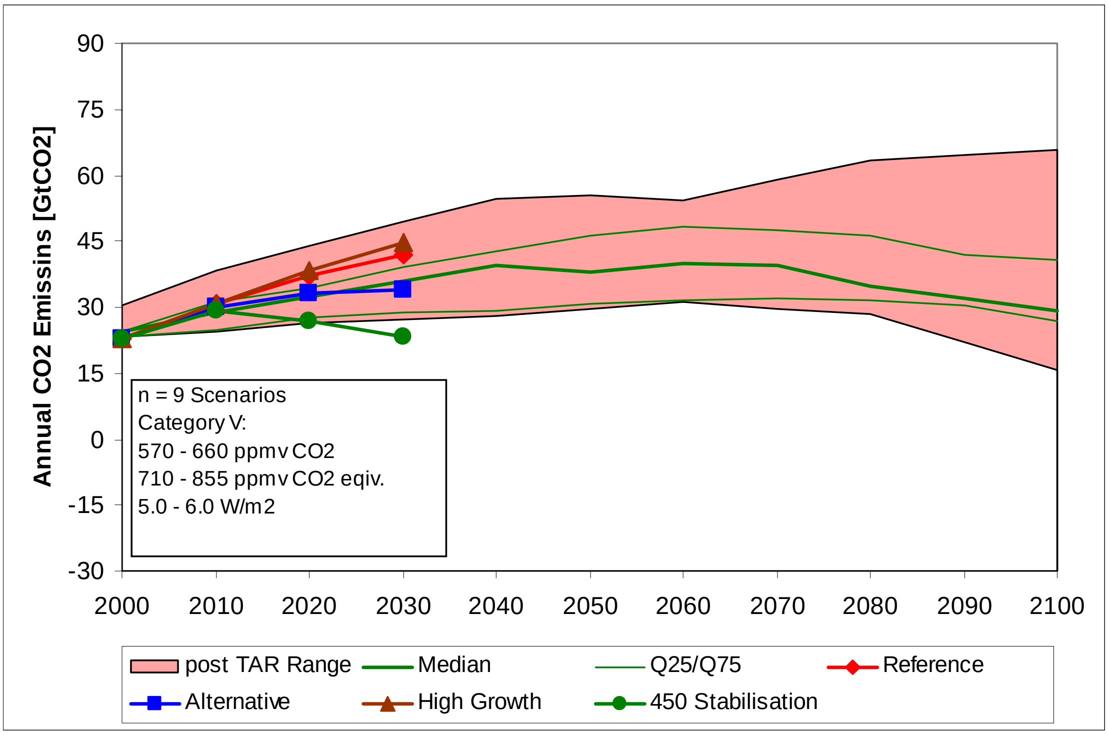

Figure 9. Stabilization of CO2 concentrations between 570 and 660 ppmv. Shaded area gives the ranges of 9 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

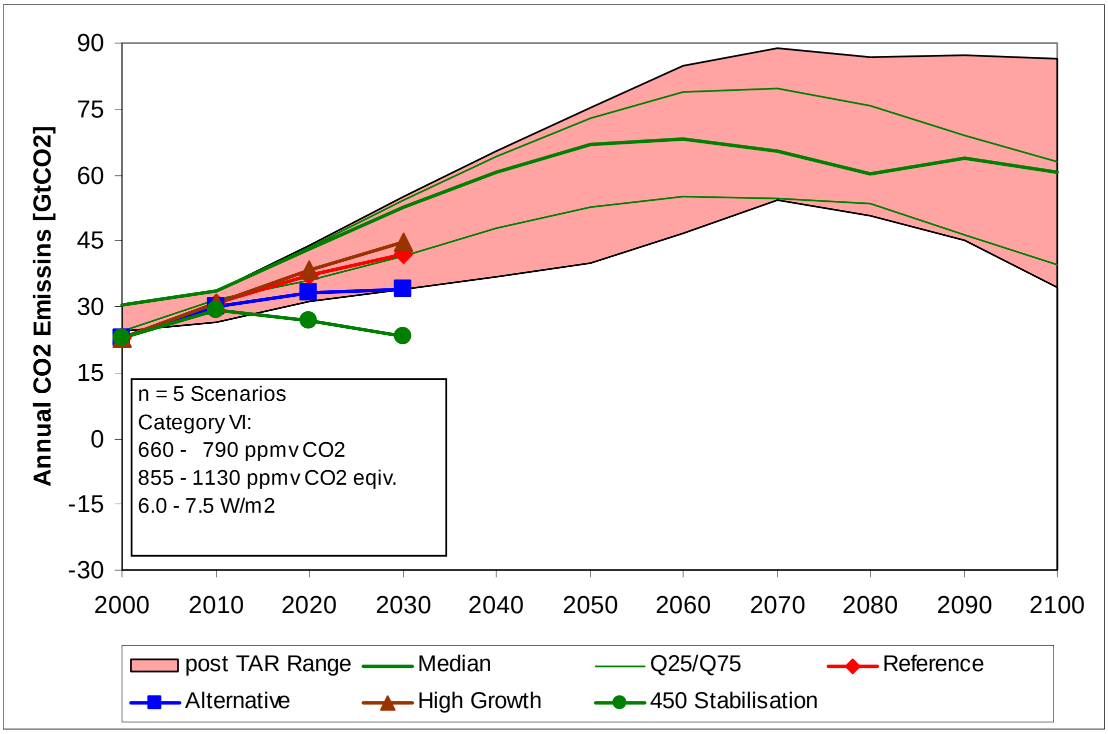

Figure 10. Stabilization of CO2 concentrations between 660 and 790 ppmv. Shaded area gives the ranges of 5 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

In contrast, the Reference and High Growth scenarios are well above the means of both Figures 7 and 8 extend above the highest pathways in Figure 7 while they are both below the highest pathways shown in Figure 8. Thus, a somewhat surprising outcome is that both could in principle evolve into stabilization cases in the long run, albeit at relatively high levels. Figure 9 shows that both the Reference and High Growth scenarios are still above the median but well below the highest scenarios in the range of category IV and Figure 10 indicates that the Reference corresponds almost exactly to the 25th percentile while the High is situated somewhat above the 25th percentile. The corresponding mean global temperature for category VI scenarios is 4.9 to 6.1 degrees Celsius (assuming the best estimate for climate sensitivity). Additional mitigation policies and measures including diffusion of low-emissions technologies would have to occur beyond 2030 in the scenarios and presumably would have to be initiated well before should they also lead to stabilization by 2100 and beyond.

As a first approximation, stabilization level is a function of cumulative CO2 emissions. In other words, the higher the cumulative emissions during the 21st century the higher is the corresponding stabilization level (assuming of course that the emissions are declining toward the end of the century). The next step in this comparison of WEO 2007 scenarios with those in the literature shows the relationship between cumulative baseline emissions and those in the stabilization scenarios.

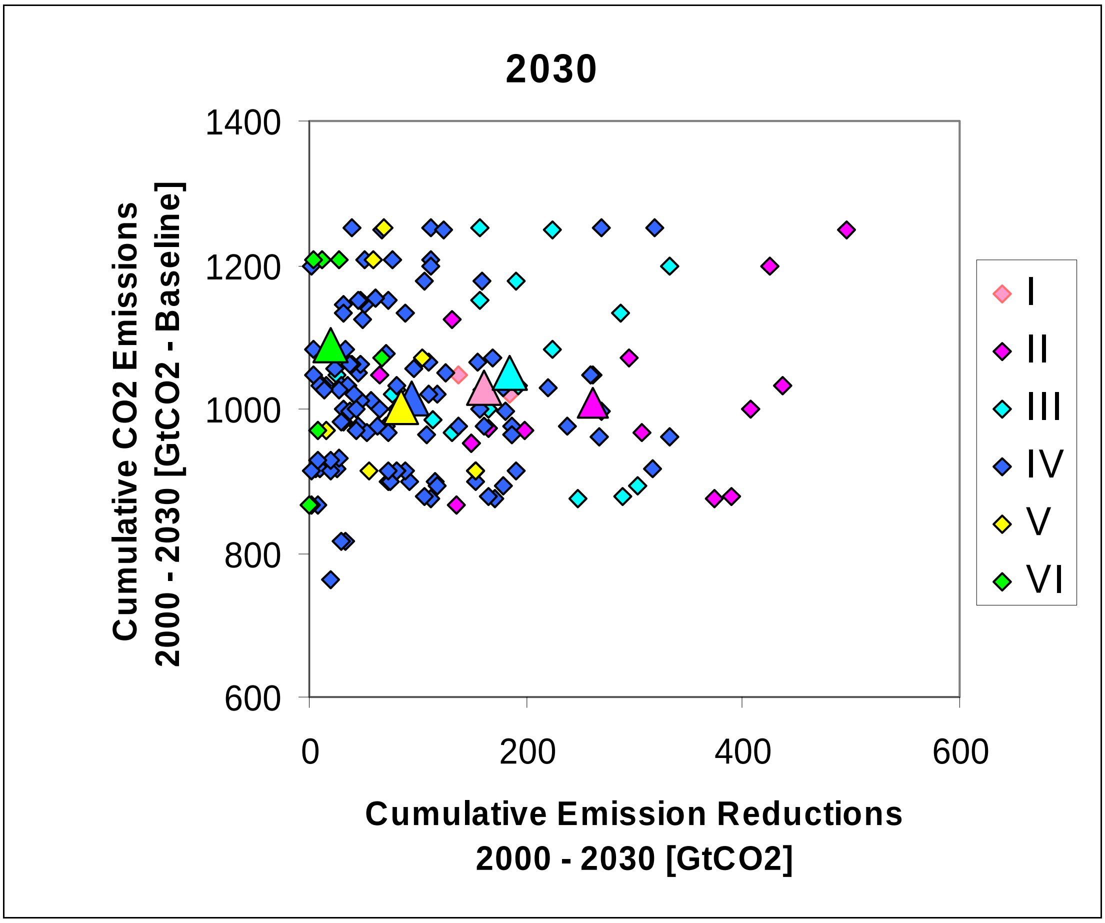

Figure 11 Relationship between cumulative CO2 emissions reductions and cumulative baseline CO2 emissions by 2030. Colored rectangles denote individual scenarios for alternative stabilization targets (categories I to VI from Table 1). The large triangles indicate the means for each category. Data source: Nakicenovic et al., 2006, and Kainuma et al., 2006.

Figures 11, 12 and 13 illustrate this relationship between baseline emissions and necessary emissions reductions to achieve long-term stabilization. Figure 11 shows this relationship for all six scenario categories from Table 1. Small squares show individual scenarios color coded for the five categories. The large triangles indicate that averages for each of the five categories. The figure shows on average that bigger (cumulative) mitigation efforts are needed for reference scenarios with larger (cumulative) emissions. This is also intuitively plausible result despite the large variation across different scenarios. In particular, the two more stringent stabilization categories I and II also imply on average larger (cumulative) mitigation efforts and thus larger cumulative emissions reductions. The lower the stabilization level, the higher the cumulative emissions reductions. What is interesting is that the range of cumulative baseline emissions is relatively independent of the stabilization level for all categories of scenarios through 2030.

Figure 12 focuses on the three more stringent stabilization categories. The large colored triangles give the averages for the three categories while the two gray rectangles show the mitigation of the WEO 2007 Alternative Policy Scenario and 450 Stabilization Case compared with the Reference Scenario. The first notable observation is that the cumulative emissions of the WEO 2007 Reference scenario are situated in the lower range of the literature with just under 1000 GtCO2 cumulative emissions by 2030 compared with the range from just above 800 to 1300 GtCO2 for the respective baselines associated with the three lower stabilization categories.

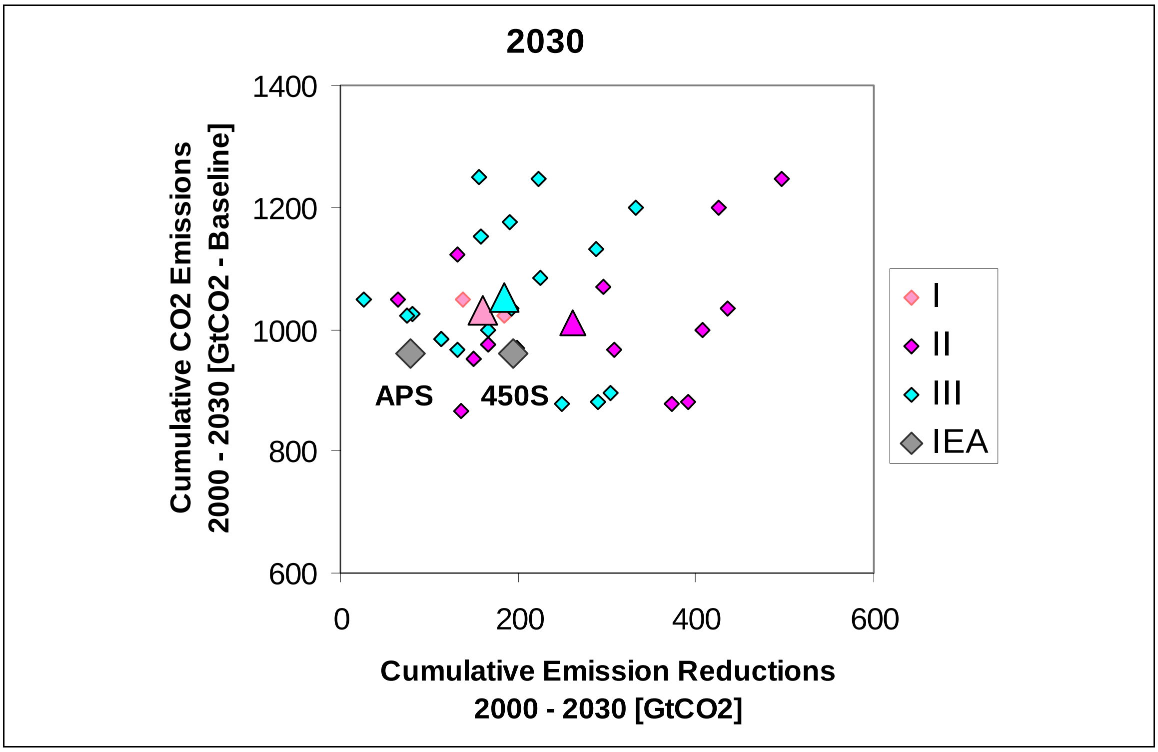

Figure 12. Relationship between cumulative CO2 emissions reductions and cumulative baseline CO2 emissions by 2030 for the three lower stabilization categories I, II and III from Table 1. Colored rectangles denote individual scenarios for alternative stabilization targets while the three colored triangles indicate the medians for the three categories. Large gray rectangles show the relationship between the cumulative emissions of WEO 2007 Reference and Alternative Policy ('APS') and 450 Stabilization ("450S") scenarios. Data source: Nakicenovic et al., 2006, and Kainuma et al., 2006.

At the same time, the cumulative mitigation effort is also in the lower range of the literature for the three stabilization categories. The cumulative mitigation of just under 80 GtC02 in the Alternative

Policy Scenario (APS) is larger than just two stabilization scenarios in the literature (i.e., it is very low). The WEO 450 Stabilization Case has considerably higher mitigation effort with about 200 GtCO2 cumulative reductions by 2030. This is higher compared to the medians of categories I and III and is just a bit lower than the median of category II. This is yet another strong indication that the 450 Stabilization Case is consistent with the lowest stabilization levels in the literature and in any case lies below the 450 ppmv stabilization path through 2030.

Figure 13 portrays a robust long-term (2100) relationship between cumulative baseline emissions and cumulative emissions reductions in the corresponding stabilization levels. The higher the baseline, the higher has to be the mitigation effort for any given stabilization level and apparently also across all the scenarios in the three lowest stabilization categories from Table 1. For the short-term, however, this relationship does not exist as shown in Figures 11 and 12. The reason for this is the flexibility of the emissions path. For any given stabilization level and by approximation any given cumulative emissions level, the emissions can be higher at the beginning followed by more stringent decline (this is referred to as an "overshoot" scenario in the literature) or the other way around; i.e. lower cumulative emissions by 2030 allowing for higher emissions later.

There is however one important conclusion that one can draw from the Figures 12 and 13. WEO 2007 Reference has relatively low cumulative emissions while the 450 Stabilization Case has relatively high cumulative mitigation effort by 2030. This means that there is considerable inherent flexibility in this scenario to be consistent with the lowest stabilization levels in the long run, assuming of course that the emissions continue to decline post-2030.

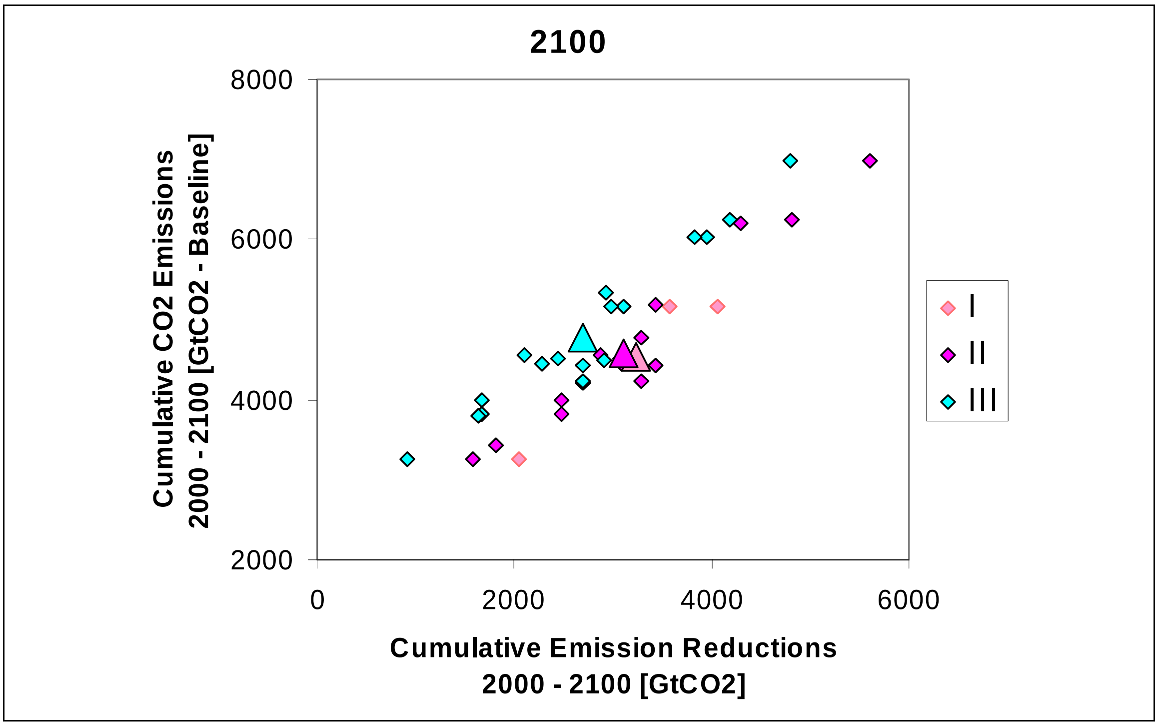

Figure 13. Relationship between cumulative CO2 emissions reductions and cumulative baseline CO2 emissions by 2100. Colored rectangles denote individual scenarios for alternative stabilization targets (categories I, II and III from Table 12). The three large colored triangles indicate the medians for three categories. Data source: Nakicenovic et al., 2006, and Kainuma et al., 2006.

The final assessment of the WEO 2007 with the scenarios in the literature considers emissions of other GHGs. WEO 2007 scenarios include detailed accounts of energy-related CO2 emissions. Most of the scenarios included in Table 1 and the preceding comparisons include other sources of CO2 emissions, primarily associated with land use changes. This means that the WEO CO2 emissions underestimate total CO2 emissions. However, this is not likely to be a big issue, because the energy-related CO2 emissions in the WEO 450 Stabilization Case are lower compared to most of the stabilization scenarios in the literature. In other words, adding land-use related CO2 emissions is not likely to shift the scenario much higher than those that stabilize at up to 450 ppmv CO2. However, other GHGs such as CH4 and N2O also play an important role in determining the radiative forcing and thus also temperature increase associated with any scenarios. Below, we estimate with a very simple method the possible GHG emissions that appear to be consistent with WEO scenarios.

Figure 14 shows emissions of energy-related CO2 and estimates for other GHG emissions for land-use CO2, CH4 and N2O from all sources for all four WEO 2007 scenarios. The emission estimates are based on most recent IIASA integrated assessment scenarios that are available on IIASA website in form of a databank (http://www.iiasa.ac.at/Research/GGI/DB/index.html) and were published in a Special Issue of Technological Forecasting and Social Change (Riahi and Nakicenovic, eds., 2007).

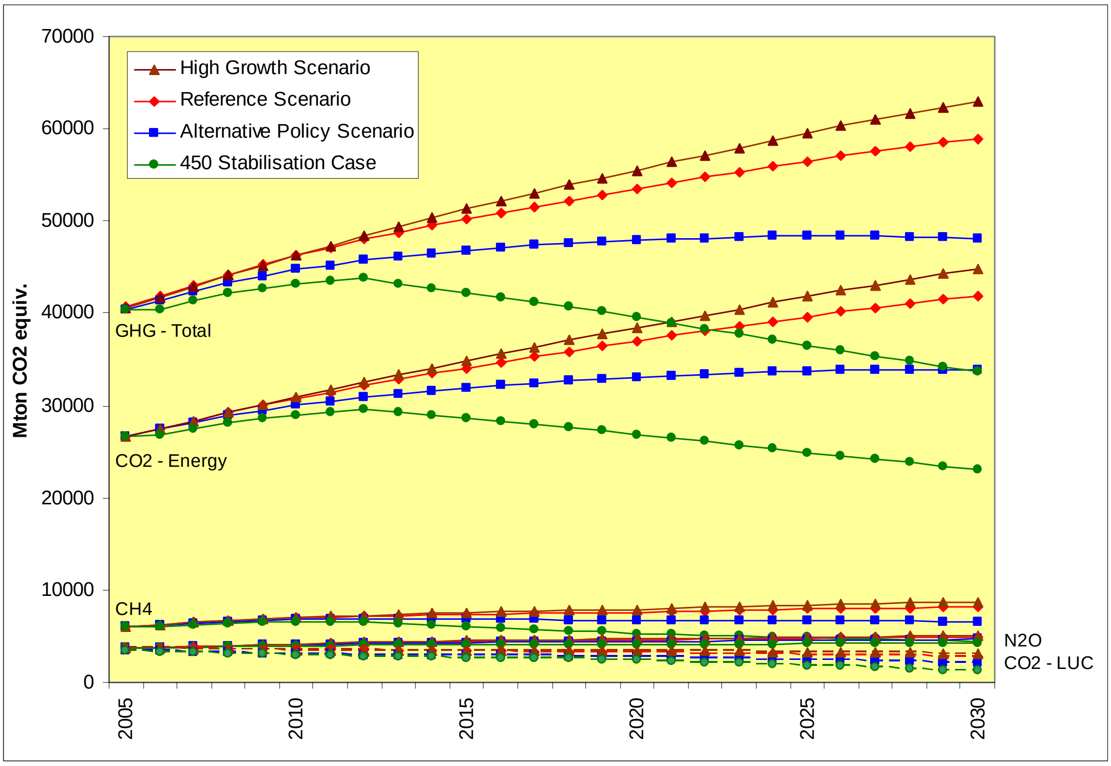

Figure 14. Total GHG emissions of the four WEO 2007 scenarios consisting of original energy-related CO2 and estimated land-use CO2, total CH4 and N2O emissions in GtCO2 equivalent.

The IIASA scenario set is based on three new baselines that are updates of the original SRES scenarios (Nakicenovic et al., 2000). The names of the three baselines are similar to those in SRES: B1, B2 and A2R (A1 was not considered). Each of these three baselines is associated with a number of stabilization scenarios. With regard to energy CO2 emissions: WEO Reference is very close to B2 baseline; WEO High Growth to A2R baseline and A2R 970 ppmv stabilization scenarios; WEO Alternative Policy is between B1 baseline and B1 520 ppmv stabilization scenario; and WEO 450 stabilization Case is somewhat below B1 480 ppmv stabilization scenario (which is also the lowest stabilization case in the whole set and consistent with stabilization at about 3W/m2 or about 2 degrees Celsius at equilibrium).

Two different methods were used to obtain the equivalent emissions of other GHGs. They have been applied to estimate the other GHGs for the WEO 2007 scenarios. CH4 and N2O emissions correlate well with energy CO2 emissions, and this relationship was used to scale CH4 and N2O emissions based on IIASA scenarios that are close to one of the WEO 2007 scenarios. On the other hand, land-use CO2 emissions are quite independent of other scenarios characteristics and those were simply taken directly from the closest (in terms of emissions) IIASA scenario. All emissions shown in Figure 14 are given in CO2 equivalents so they can be added together to get the total GHG emissions associated with the four WEO 2007 scenarios.

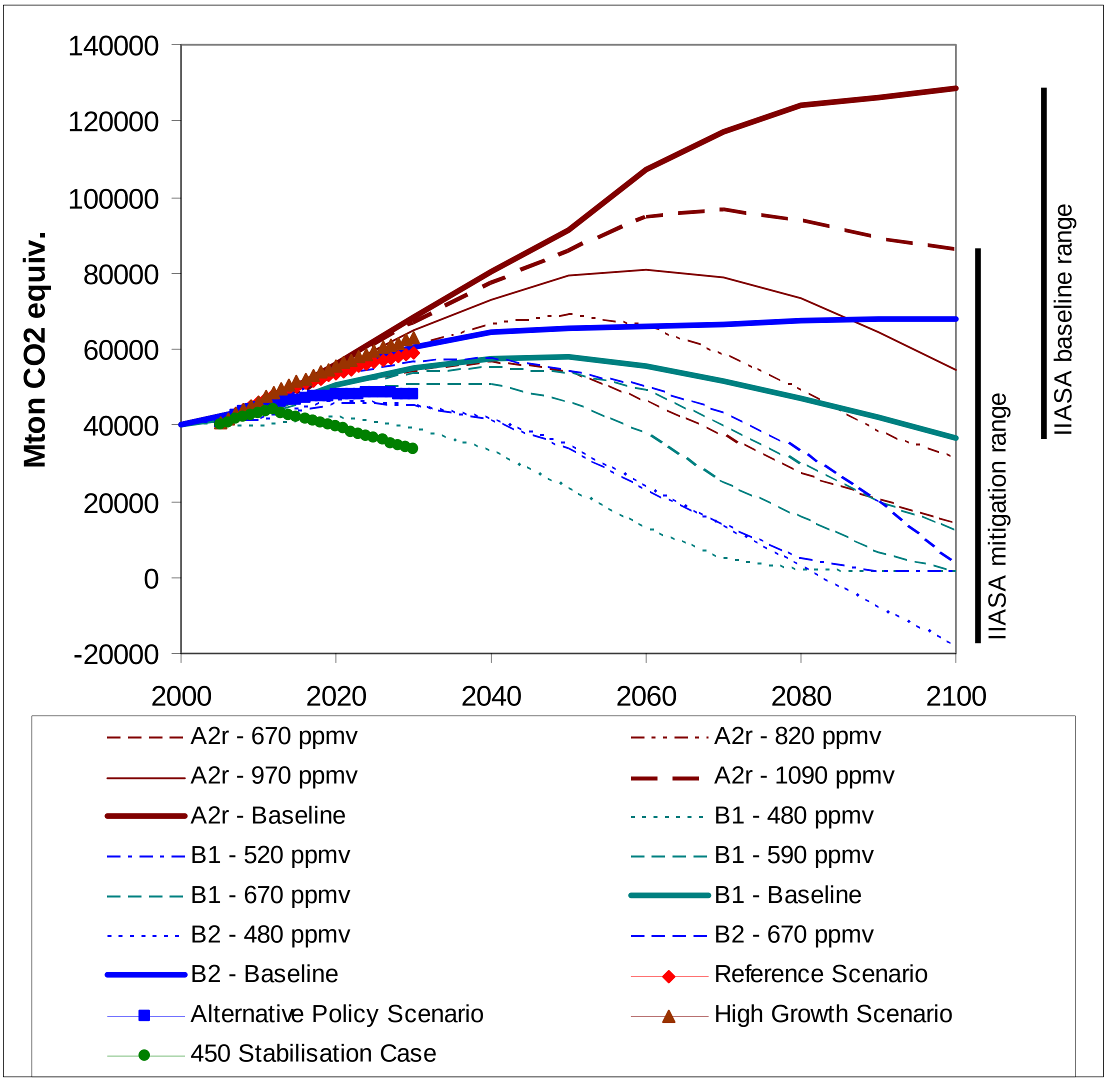

Figure 15. Total GHG emissions of the four WEO 2007 scenarios compared to the IIASA set of integrated assessment scenarios. WEO Scenarios are shown through 2030.
Data source: (http://www.iiasa.ac.at/Research/GGI/DB/).

Figure 15 compares the total (estimated) GHG emissions of WEO 2007 with the IIASA integrated assessment scenarios. The WEO 450 Stabilization Case is below the IIASA B1 480 ppmv CO2-

eqivalent (about 370 ppmv CO2-only) scenario so that one can again conclude with a high degree of certainty based on this analysis that it is consistent with stabilization at 450 ppmv CO2 equivalent stabilization and lower. The Alternative Policy scenario is situated below B1 590 ppmv CO2 equivivalent and above the B1 520 ppmv CO2 equiv., so that is very likely to be consistent with about 550 ppmv CO2-equivalent stabilization. This corresponds broadly with the category III shown in Figure 7 and Table 1.

A salient question is how other drivers and developments portrayed by the WEO 2007 scenarios compare to those across long-term stabilization cases in the literature. Particularly important in this context is the energy development as this is the most important source of GHG emissions and by extension also where mitigation measures and policies would have to be applied. In the following we first compare total primary energy developments and thereafter the contribution of different energy sources across the range of scenarios.

Figures 16, 17 and 18 show primary energy across the first three categories of long-term stabilization scenarios from Table 1 above compared to WEO 2007 scenarios, respectively. The overall tendencies are consistent with the previous comparison of emissions paths shown above. All WEO scenarios push the upper envelope of primary energy requirements across the long term scenarios that lead to CO2 stabilization of up to 400 ppmv shown in Figure 16. It is noteworthy that the Alternative Policy Scenario is situated well above the median while the 450 Stabilization Case is closer to the median but still higher. Basically the same picture emerges in Figure 17 for somewhat higher stabilization levels. Again, the WEO 2007 scenarios are situated in the upper range.

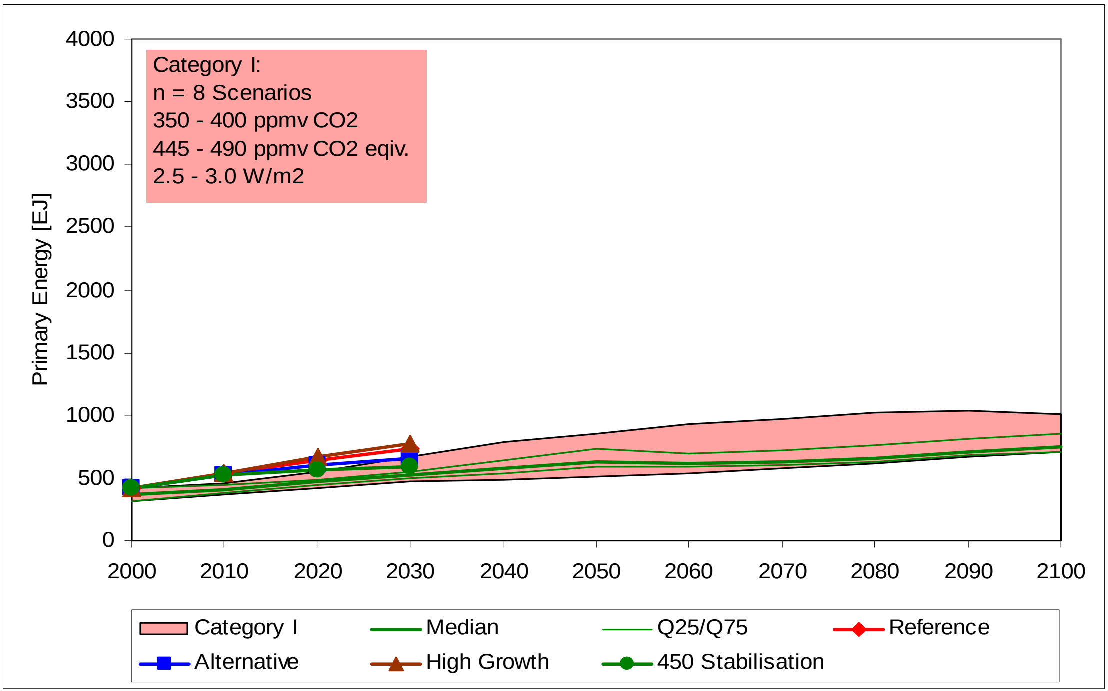

Figure 16. Global primary energy in stabilization scenarios with CO2 concentrations of between 350 and 400 ppmv. Shaded area gives the ranges of 8 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

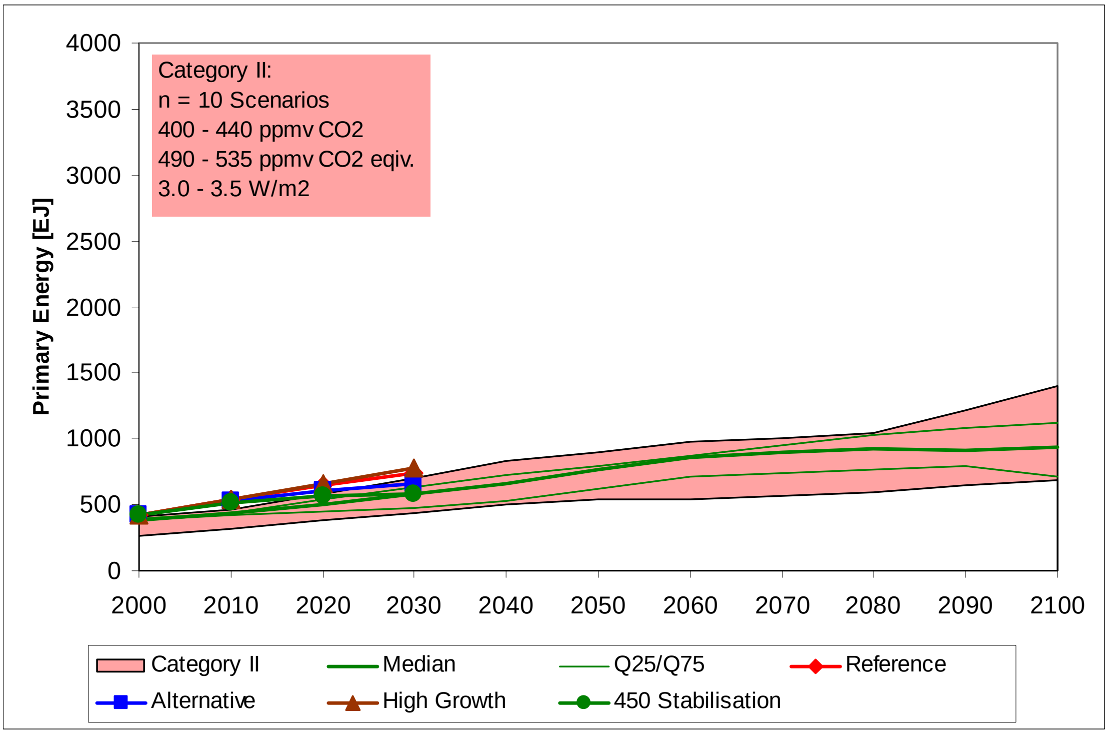

Figure 17. Global primary energy in stabilization scenarios with CO2 concentrations of between 400 and 440 ppmv. Shaded area gives the ranges of 10 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

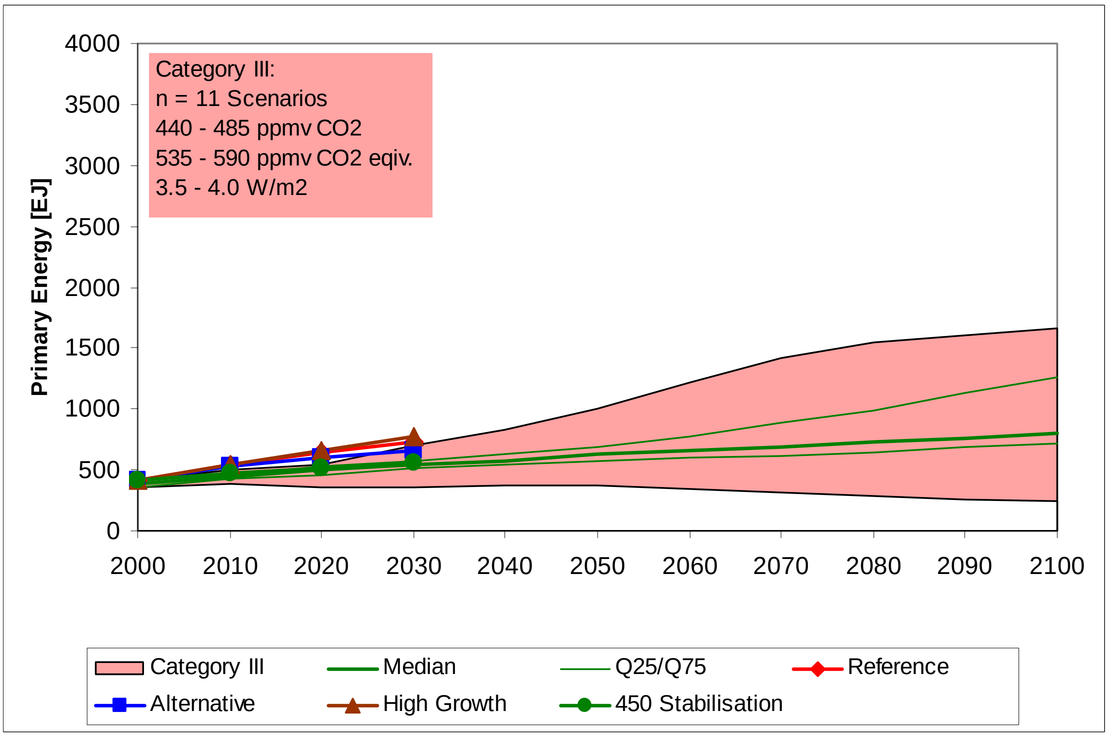

Figure 18. Global primary energy in stabilization scenarios with CO2 concentrations of between 440 and 485 ppmv. Shaded area gives the ranges of 10 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

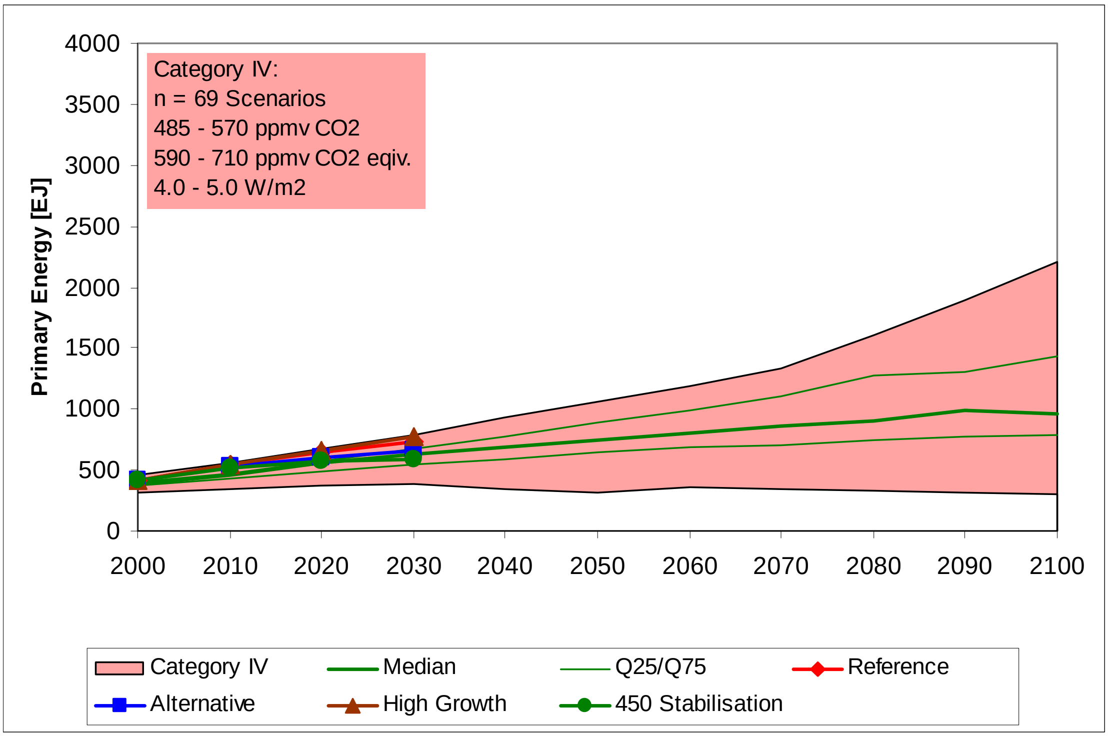

Figure 19. Global primary energy in stabilization scenarios with CO2 concentrations of between 485 and 570 ppmv. Shaded area gives the ranges of 69 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

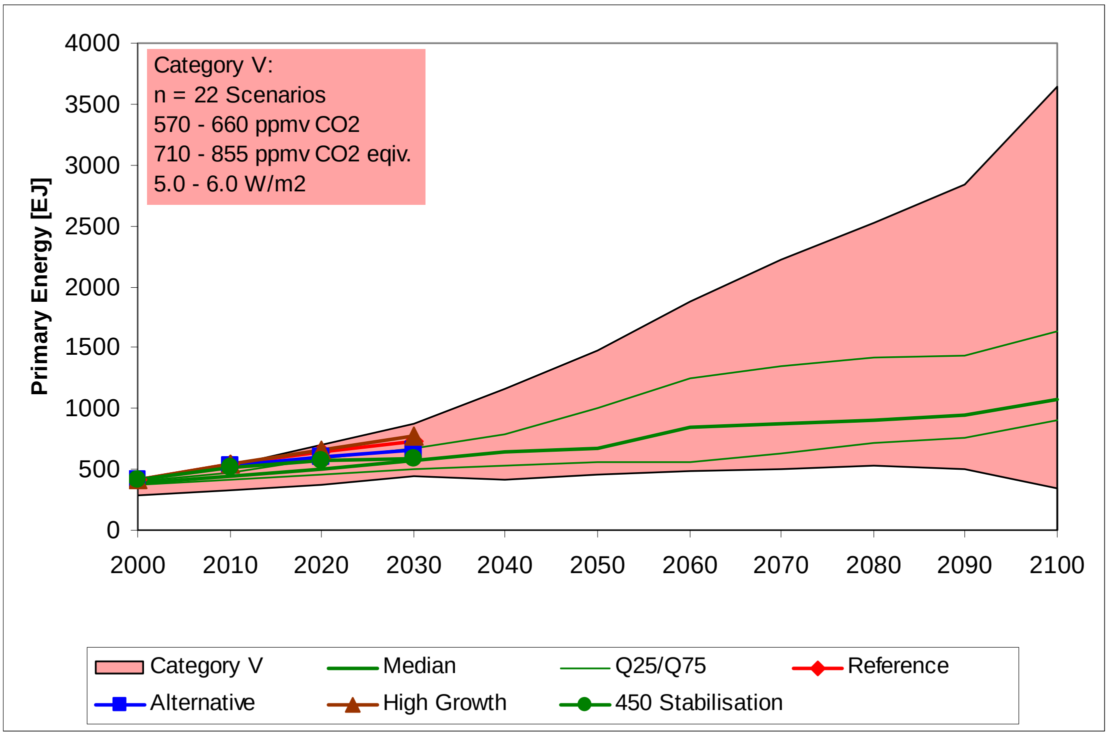

Figure 20. Global primary energy in stabilization scenarios with CO2 concentrations of between 570 and 660 ppmv. Shaded area gives the ranges of 22 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

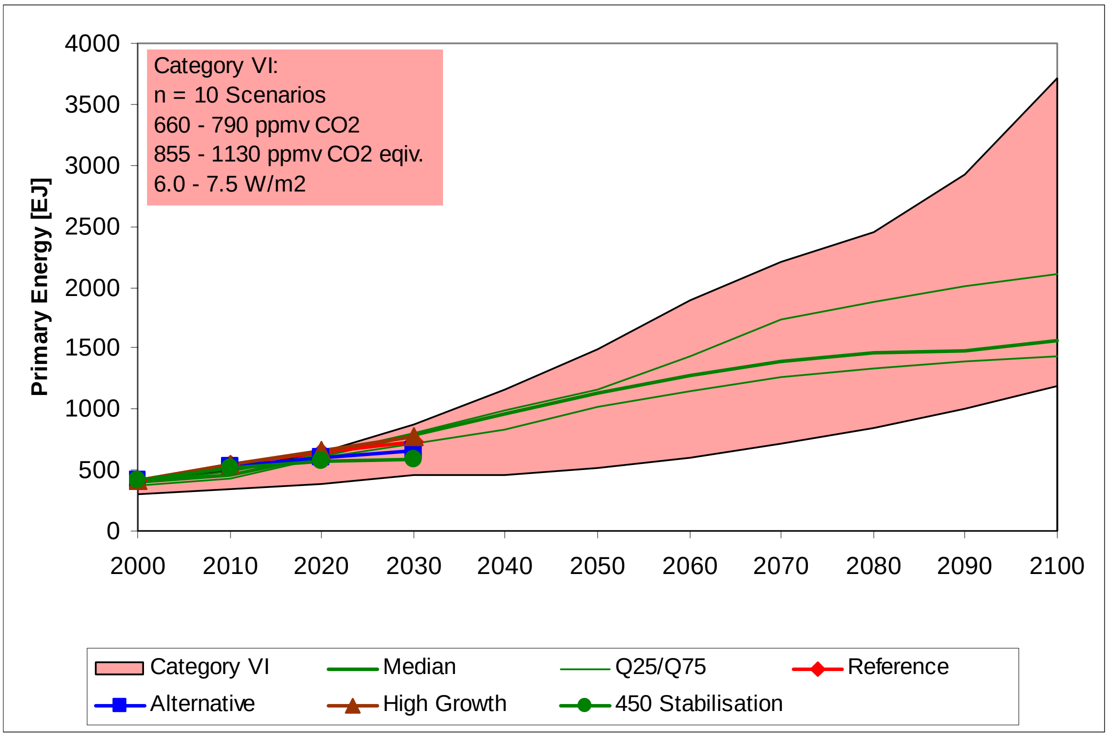

Figure 21. Global primary energy in stabilization scenarios with CO2 concentrations of between 660 and 790 ppmv. Shaded area gives the ranges of 108 more recent scenarios published since 2001 (Nakicenovic et al., 2006 and IPCC AR4, WGIII, 2007). WEO Scenarios are shown through 2030.

Figures 19, 20 and 21 show that the global primary energy of the WEO 2007 scenarios are clearly consistent with the higher stabilization categories. For example, WEO 450 Stabilization Case is consistent with CO2 stabilization of up to 440 ppmv while its primary energy is close to the medians of categories IV and V corresponding to the stabilization levels from 485 to 660 ppmv. Even the WEO High Growth Scenario has primary energy in line with the mean of category VI with stabilization between 660 and 790 ppmv CO2.

In contrast with the CO2 comparison of WEO 2007 scenarios with those in the literature that has shown that the WEO 450 Stabilization Case is among the lowest through 2030, in case of energy WEO 2007 scenarios fall in the mid range of stabilization levels. Energy-related mitigation measures would have to be intensified beyond 2030 in order to enforce the downward trend of emissions all the way to the end of the century. This means that more vigorous mitigation measures and policies would have to be included in the WEO 2007 scenarios to achieve lower stabilization and thus lower temperature increases. Clearly, many of these could be brought to bear in the post-2030 period, but they would need to initiate during the next decades because of the long lead times associated with fundamental changes in the energy systems.

Figure 22 compares the primary energy sources of WEO 2007 scenarios with the literature of long-term scenarios. Shown are contributions of coal, gas, oil, nuclear and biomass toward total primary energy requirements in 2030. Ranges on the left, labeled B, show baseline scenarios including WEO Reference and High Growth, while ones on the right, labeled S, show stabilization scenarios including WEO Alternative Policy and 450 Stabilization cases. WEO Reference indicates coal contribution toward the upper bound of the literature. WEO Reference gas contribution falls squarely in the median region while oil, nuclear and biomass are all relatively high.

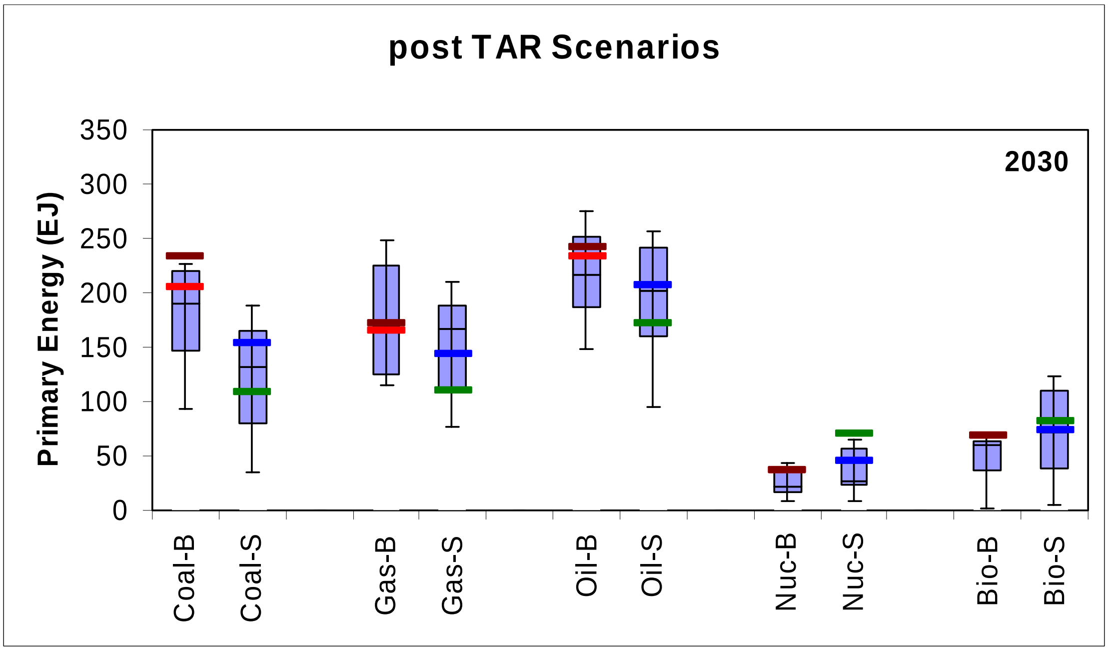

Figure 22. Deployment of primary energy technologies across post-2001 scenarios by 2030: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark).The red bar shows the WEO 2007 Reference and brown the High Growth scenarios while the blue one shows the Alternative Policy and green the 450 Stabilization cases. Based on IPCC AR4, WGIII, 2007.

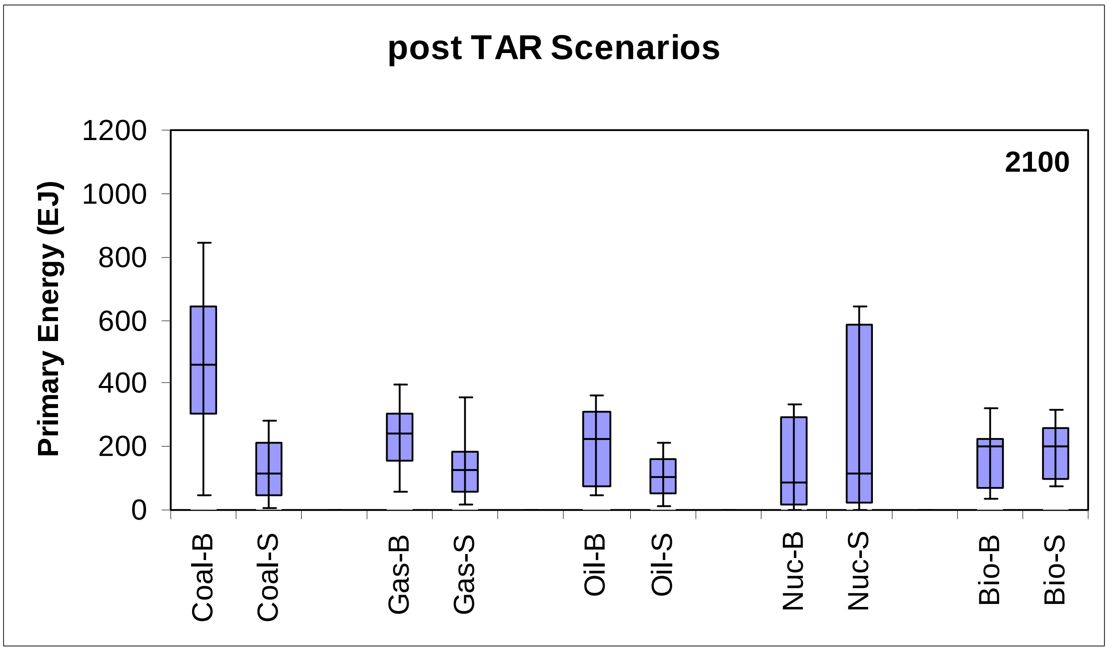

Figure 23 Deployment of primary energy technologies across pre-2001 scenarios by 2100: Left "error" bars show baseline (non-intervention) scenarios and right ones intervention and stabilization scenarios. Shown the full ranges of the distributions (full vertical line with two extreme tic marks), the 25th and 75th percentiles (gray area) and the median (middle tic mark.). Source IPCC AR4, WGIII, 2007.

In comparison, the Alternative Policy Scenario corresponds more closer to median development across the stabilization scenarios in the literature while the 450 Stabilization Case is more extreme with significantly lower shares of fossils and higher shares of non-carbon sources. Biomass in Alternative Policy Scenario corresponds almost exactly to the median of the literature, coal is higher and gas lower while oil and nuclear are higher compared to the median developments. Figure 23 shows that these tendencies in the literature are further amplified in the stabilization scenarios toward the end of the century. In the stabilization scenarios, fossil contributions remain in the same region as in 2030, say between 150 and 250 EJ per year, while nuclear and biomass increase considerably from between about 50 and 100 EJ per year to up to 600 EJ per year (in case of nuclear and up to 300 EJ per year in case of biomass).

This result indicates that there is a significant difference between stabilization and reference (baseline) scenarios. As we think of how WEO 2007 scenarios and their underlying technology portfolio can be extended into the future, we need to consider that there is a wide range of possible development that appear plausible today. However, by 2030 the range of possibilities would be much narrower because of the intervening decisions during the next three decades.

The main objective of this assessment and possible post-2030 developments was to consider a range of alternative developments of future energy technologies rather than to attempt to project any one particular direction of change. As shown, there is a range of long-term scenarios that are in principle consistent with development paths to 2030 portrayed in the WEO 2007. This is important because the future is inherently unpredictable and any one single long-term projection is therefore inappropriate as the assessment tool. Technological change is a complex process that is associated with many uncertainties particularly in the very long term. Degrees of freedom in technology portfolios increase beyond 2030 as most decisions that will affect the nature of the capital stock have not been made yet. Consequently, our approach was to capture a wide spectrum of developments in order to assess the implications and possibilities of the materialization of different alternatives. Scenarios in the literature offer, in general, a large set of alternative future developments that could be used to assess the ranges and distributions of costs and other characteristics of future energy technologies. These should of course not be confused with actual future developments that are unpredictable. Instead, collectively the scenarios in the literature outline a range of possible developments that presumably also includes the relevant future development path.

The five main findings of the assessment are that:

- This paper presents non-CO2 and land-use related CO2 emissions consistent with the four WEO 2007 scenarios. On aggregate these emissions categories add about 41 to 46 percent to non-energy GHGs to the WEO energy-related CO2 emissions by 2030.

- The WEO 450 Stabilization Case (450S) is consistent with the lowest stabilization scenarios found in the literature. Depending on the stringency of the mitigation efforts beyond 2030 the 450S could be consistent with stabilization levels as low as 350-440 ppmv CO2 only or 450-540 ppmv CO2 equivalent. This would correspond to an average temperature change at equilibrium of about 2.0-2.8 degrees C compared to pre-industrial levels (or about 1.3 to 2.1 degrees C compared to the current temperatures).

- The Alternative Policy Scenario (APS) is broadly consistent with stabilization at intermediate levels of about 400 to 570 ppmv CO2 or 490 to 710 ppmv CO2 equivalent corresponding to the temperature change at equilibrium of about 2.4 to 4.0 degrees C compared to pre-industrial levels (or about 1.7 to 3.3 degrees C compared to the current temperatures). Taking into account possible non-energy GHG emissions based on the

IIASA scenarios, it could correspond to a narrower range of concentrations of between 440 to 485 CO2 or 535 to 590 CO2 equivalent corresponding to the temperature change at equilibrium of about 2.8 to 3.2 degrees C compared to pre-industrial levels (or about 2.1 to 2.5 degrees C compared to the current temperatures).

- Achieving the long-term goal of stabilization requires in both policy scenarios, APS and 450S, a further and significant tightening of climate change policies beyond 2030.

- Cumulative CO2 emissions of the Reference scenario are in the lower range of the scenarios in the literature compared with other scenarios that do not include specific climate mitigation policies. However, the Reference scenario is in principle consistent with stabilization at relatively high concentrations levels provided the emissions peak between 2060 and 2090. The High emissions scenario is situated somewhat higher but is in principle still consistent with stabilization at these extremely high levels. The range of concentrations is between 660 and 790 CO2 and 855 and 1130 CO2 equivalent corresponding to the temperature change at equilibrium of about 4.9 to 6.1 degrees C compared to pre-industrial levels (or about 4.2 to 5.4 degrees C compared to the current temperatures).

References

Fisher, B., Nakicenovic, N., Alfsen, K., Corfee-Morlot, J., de la Chesnaye, F. *et al*., 2007: *Issues Related to Mitigation in the Long-term Context*, Chapter 3 *in* Climate Change 2007 - Mitigation, Fourth Assessment Report, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Hanaoka, T., Kainuma, M., Kawase, R., Matsuoka, Y., 2006: Emissions Scenarios Database and Regional Mitigation Analysis: A Review of Post-TAR Mitigation Scenarios, *Environmental Economics and Policy Studies*, **7**(3), 367-389.

Houghton, J.T., Ding, Y., Griggs, D.J, Noguer, M., P. J. van der Linden, P.J., Xiaosu, D. (eds): 2001, *Climate Change 2001: The Scientific Basis*, Third Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Metz, B., Davidson, O., Bosch, P., Dave, R., Meyer, L. (eds): 2007, *Climate Change 2007 - Mitigation*, Fourth Assessment Report, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Morita, T., Robinson, J., Alcamo, J., Nakicenovic, N., Zhou, D. *et al*.: 2001, *Greenhouse Gas Emission Mitigation Scenarios and Implications*, Chapter 2 *in* Climate Change 2001: Mitigation, Third Assessment Report, Working Group III of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Nakicenovic, N., and Riahi, K. (eds): 2007, Greenhouse Gases – Integrated Assessment, *Technological Forecasting and Social Change*, Special Issue, **74**(7).

Nakicenovic, N., Kolp, P., Riahi, K., Kainuma, M., Hanaoka, T., 2006: Assessment of Emissions Scenarios Revisited, *Environmental Economics and Policy Studies*, **7**(3), 137-173.

Nakicenovic, N., Alcamo, J., Davis, G., de Vries, B., Fenhann, J. *et al.*: 2000, *Special Report on Emissions Scenarios*, Special Report of WGIII of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

Solomon, S., Qin, D., Manning, M., Marquis, M., Averyt, K. *et al.* (eds): 2007, *Climate Change 2007 - The Physical Science Basis*, Fourth Assessment Report, Working Group I of the Intergovernmental Panel on Climate Change (IPCC), Cambridge University Press, Cambridge.

UNFCCC (United Nations Framework Convention on Climate Change), 1992: *United Nations Framework Convention on Climate Change.* Convention text, UNEP/WMO Information Unit of Climate Change (IUCC) on behalf of the Interim Secretariat of the Convention. IUCC, Geneva.