Wedge decomposition analysis: Application to SRES and Post-SRES Scenarios

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Abstract
We introduce a general methodology for displaying the gross assumptions behind any carbon emissions trajectory, relative to a reference trajectory, and we apply this methodology to a limited number of IPCC SRES scenarios [1]. These scenarios have been used widely for climate change analysis. We examine four scenarios (A1B, A2, B1, B2) together with three paired "post-SRES" scenarios [2, 3] that achieve CO_2 stabilization at 550 ppm by 2100. Our analysis is guided by the concept of the "stabilization wedge" introduced in a recent paper by Pacala and Socolow [4], which measures the quantitative contributions of specific technologies and strategies over the next 50 years in units of 1 GtC/yr reductions in 2050. We find that autonomous carbon-emissions reduction activity in the SRES scenarios account for a large number of "virtual" wedges, ranging from 8 to 35 in 2050. Roughly half of the virtual wedges in each scenario is due to energy efficiency improvements and structural change in the economy; most of the remaining half is due to high penetrations of non-fossil energy technologies. Post-SRES scenarios require only 2 to 4 "real" wedges in 2050, accounted for largely by greater non-fossil energy, greater energy efficiency, and CO_2 sequestration. Our results reveal that the SRES and post-SRES scenarios share a number of common assumptions. In particular we find that the baseline development path, i.e., the number of virtual wedges and "autonomous" trends in absence of any climate policies, play a central role in determining the mitigation effort needed for achieving climate stabilization.

Keywords: carbon dioxide (CO_2), climate change, stabilization wedge, SRES, non-fossil energy

Introduction

We introduce an expression for the difference in emissions between any two CO_2 emissions trajectories as a sum of four terms, each associated with a broad explanatory category: the total size of the economy or GDP, the energy intensity of the economy, the fossil fraction of total primary energy, and the carbon intensity of the fossil fuel mix. When two trajectories over any 50-year period are considered, we use the "wedge" unit, introduced in 2004 [4], where 1 wedge is a reduction of 1 GtC/yr of CO_2 emissions in 2050. We illustrate the method by reporting comparisons of well-known IPCC SRES scenarios [1] with two kinds of trajectories: 1) "reference trajectories" that rise in proportion to economic output, and 2) modified versions of the SRES scenarios that achieve stabilization at a target concentration [2, 3].

The SRES scenarios were developed to explore a future without policies directed toward the mitigation of climate change—so-called "business as usual" or "baseline" scenarios. The 40 SRES scenarios are understood, as a set, to bracket such a future. Each embodies a different package of plausible quantitative assumptions about key variables, such as population, global economic growth rate, and regional disparities in development. Our analysis highlights the key modeling assumptions that determine each scenario for the period 2000-2050, including the rate of achievement of energy efficiency in the economy and the market penetration rates of nuclear and renewable energy. We limit our attention to four specific SRES scenarios, the versions of A1B, A2, B1, and B2 developed at IIASA using the MESSAGE model [2, 3]. In these scenarios, the CO_2 emission rates grow from approximately 7.3 GtC/yr in 2000[1] to between 9.4 (B1) and 16.1 (A2) GtC/yr in 2050, while the global economy grows from $27 trillion in 2000 to between $82 (A2) and $187 (A1B) trillion in 2050 (all 1990 U.S. dollars). Thus, the carbon intensity of the global economy falls significantly in all scenarios over the fifty-year period, by a factor of 1.4 (A2) to 7.0 (B1), in the absence of any climate change policy. The most salient driving force of this trend is the anticipated reduction in energy intensity (energy use per unit of GDP). Energy intensity reduction rates in the scenarios range between 0.5%/yr (A2) to 1.7%/yr (B1) or nearly a factor of four. For comparison, the historical rate of reduction is about 1%/yr.

The post-SRES scenarios were also developed at IIASA using MESSAGE [2, 3], and are almost identical in assumptions to the baseline SRES scenarios with which they are paired, except that a least-cost path to stabilization of atmospheric CO_2 in 2100 at 550 ppm is imposed. In the post-SRES scenarios, the CO_2 emission rates grow to between 10.4 (B2) and 13.4 (A1B) GtC/yr in 2050, but decline thereafter and reach between 5.3 (A1B) and 6.7 (A2) GtC/yr in 2100. We examine three post-SRES scenarios, which we label A1B-550, A2-550, and B2-550; there is no post-SRES scenario for B1, because B1 remains below 550 ppm without a climate policy (emissions are 9.4 GtC/yr in 2050 and 4.8 GtC/yr in 2100). Economic output in 2050 is almost identical across the three pairs, suggesting negligible costs to achieve stabilization. Our analysis provides a simple quantitative representation of the optimal mix of carbon-emissions reduction strategies chosen in 2050 for each post-SRES scenario.

Methodology

We identify the carbon emissions from any scenario as the product of four terms:

$$C_i(t) = [C_i(t)/F_i(t)]\cdot[F_i(t)/P_i(t)]\cdot[P_i(t)/E_i(t)]\cdot E_i(t), \quad (1)$$

where C is gross carbon emissions per year (10^{15} gC/yr, 10^9 tC/yr or GtC/yr), F is fossil primary energy consumed per year (10^{18} J/yr or EJ/yr), P is total primary energy consumed per year (EJ/yr), and E is gross annual economic output or GDP (10^{12} US$/yr). The subscript *i* labels the scenario, and *t* indicates the time step. We then express the difference in carbon emissions between any two scenarios as a sum of four terms:

$$\Delta C(t) = C_1(t) - C_2(t) = W_{C/F}(t) + W_{F/P}(t) + W_{P/E}(t) + W_E(t), \quad (2)$$

where, e.g., for $W_{F/P}$:

$$W_{F/P} = [(C_1 - C_2)/\ln (C_1/C_2)]\cdot[\ln (F_1/F_2) - \ln (P_1/P_2)]. \quad (3)$$

Note that the W terms all have units of carbon emissions (GtC/yr). We identify the terms as changes in the carbon intensity of the fossil fuel mix ($W_{C/F}$), the fossil fraction of total primary energy ($W_{F/P}$), the primary energy intensity of the economy ($W_{P/E}$), and gross economic output (W_E).

As an example, consider the calculation of $W_{F/P}$ for the A1B and A1B-550 scenario pair in 2050. Carbon emissions are 17.00 and 15.25 GtC/yr, respectively, while fossil primary energy consumption is 874.6 and 802.4 EJ/yr, and total primary energy consumption is 1892.1 and 1870.1 EJ/yr. Combining these terms together in equation (3), we obtain

$$W_{C/F} = [(1.75 \text{ GtC/yr})/(0.1086)]\cdot(0.0862 - 0.0117) = 1.20 \text{ GtC/yr}. \quad (4)$$

[1] Range of fossil fuel and industrial CO_2 emissions (including also gas flaring, cement production, and non-energy feedstocks) is 7.01 (B1) to 7.67 (B2) GtC/yr. Actual emissions in 2000 range between 7.2 and 7.4 GtC/yr [5, 6].

Non-fossil energy $W_{N/P} = -W_{F/P}$ is further decomposed according to individual primary energy contributions N^k (where k = nuclear, biomass, etc.):

$$W_{N^k/P} = -[(N^k_1 - N^k_2)/(P_1 - P_2)]/[(F_1 - F_2)/(P_1 - P_2)]\cdot W_{F/P} \quad (5)$$

such that $W_{N/P} = \Sigma_k W_{N^k/P}$. CO_2 sequestration is treated by writing the difference in gross carbon emissions ΔC as the sum of the difference in net emissions (ΔC_{net}) and the difference in sequestered CO_2 (ΔC_{seq}):

$$\Delta C(t) = \Delta C_{net}(t) + \Delta C_{seq}(t). \quad (6)$$

When differences between two trajectories after the passage of 50 years are considered, we use the term "wedges." Note that at least two definitions of the wedge unit are possible [4]: 1 GtC/yr reduction in CO_2 emissions in 2050, and 25 GtC CO_2 emissions reductions *integrated* between 2000 and 2050. We adopt the first definition exclusively in this report. Measured using the second definition, differences between 2000-2050 trajectories will be a smaller number of wedges, whenever trajectories rise faster than linearly with time, as all cases examined here do.

We distinguish "real wedges" and "virtual wedges." Real wedges are carbon-emission reductions that result when deliberate carbon policy is imposed on a baseline scenario. "Virtual wedges" are carbon-emission reductions that occur in any baseline scenario over time, in the absence of carbon policy, relative to an emissions trajectory that climbs in lock step with gross economic output [7]. In the latter trajectory (a "virtual reference scenario") the carbon intensity of fossil fuels, the fossil fraction of primary energy, and the primary energy intensity of the economy are all fixed over time.

Results: Virtual wedges

Figure 1 shows the B2 scenario for illustrative purposes. We see that virtual emissions are greater than actual emissions by 2050, reflecting the tremendous growth in economic output over the period. Figure 2 decomposes the B2 virtual emissions into virtual wedges, indicating that virtual wedges of energy intensity contributes the lion's share, followed by virtual wedges of solar energy (electric and thermal uses) and then virtual wedges of nuclear energy. Figure 3 shows that the relative contributions of these components is robust in 2050 across the four scenarios, though the total number of virtual wedges varies by more than a factor of four, reflecting large differences in economic growth.

Results: Real wedges

Figure 4 shows the B2 and B2-550 trajectories; the difference between them (green) is the "stabilization triangle" [3]. Figure 5 shows the calculated real wedges for the B2 scenario pair, and Figure 6 shows the actual emissions and real wedges for 2050 across scenario pairs. (Recall that B1 has no real wedges because atmospheric CO_2 concentrations remain below 550 ppm through 2100). Stabilization requires reductions of CO_2 emissions in 2050 by 3.6, 3.0, and 2.0 GtC/yr for the A1B, A2, and B2 pairs, respectively. For the A1B pair, half of the wedges (1.8 GtC/yr) are attributable to carbon sequestration, but for the A2 and B2 pairs the CO_2 sequestration role in 2050 is much smaller (0.3-0.5 GtC/yr). For the A1B pair nuclear contributes 0.8 GtC/yr; for the A2 and B2 pairs biomass contributes 0.6 GtC/yr; for all three pairs, fossil fuel carbon intensity contributes between 0.4 and 0.7 GtC/yr; no other wedge contributes more than 0.3 GtC/yr.

The number of wedges required by mid-century in the simplified framework of Pacala and Socolow [4], 7 GtC/yr, is more than twice as large as the number projected for the three scenarios analyzed above. Pacala and Socolow assumed a lower stabilization level (500 ppm), a weaker land sink (constant at 0.5 GtC/yr), and flat emissions through mid-century, rather than emissions which rise substantially before they fall. Their principal qualitative argument—that a combination of strategies is required to achieve stabilization—is found also to be a feature of the post-SRES scenarios.

Although Pacala and Socolow noted the importance of assumptions about the rate of growth of carbon-reducing technology in the baseline (later called "virtual wedges" [7]), the analysis here of the SRES scenarios drives home the centrality of these assumptions. As illustrated for the B2 scenario pair in Figure 4, over the course of the next five decades the number of virtual wedges in the SRES scenarios far exceeds the number of real wedges. We thus find that the characteristic of the baseline scenarios is decisive for the absolute levels of future emissions and thus the required strength of additional mitigation measures for achieving stabilization of CO_2 concentrations. As illustrated in Figure 3, the dominant virtual wedge across all scenarios is to a large extent due to energy intensity improvements that primarily arise from structural changes of the economy toward less energy-intensive sectors. In addition, carbon-saving technologies can also achieve great prominence in a scenario without climate policy, as a result of its assumptions of falling capital costs for carbon-saving technologies and rising prices for fossil fuels [2, 3]. The wedge decomposition analysis demonstrates how these assumptions determine both the level of deployment of carbon-saving technology in the absence of carbon policy, and the specific mitigation effort required to achieve stabilization.

Results: Regional disaggregation

The SRES scenarios are disaggregated into four world regions, but for simplicity we disaggregate into only two regions: the OECD countries (comprising the U.S., Canada, Western Europe, Japan, Australia, and New Zealand) and the rest of the world ("ROW"). In Table 1, we display consumption of selected primary energy sources in 2000 and 2050. Relative to average 2000 consumption, we see large expansions of all technologies, but we highlight nuclear, wind, solar, hydro and natural gas here. While expansions do not exceed the technical potentials in any scenario, much smaller expansions, or even (in the case of nuclear) contractions are plausible as well.[2]

Table 1. Primary energy consumption (quadrillion kJ or EJ) of selected energy sources.

Year	Scenario	Region	Nuclear	Solar	Wind	Hydro	Natural gas
2000	Average	OECD	20	–[a]	–[a]	–[a]	42
		ROW	5.1	–	–	–	44
		Global	25	7.0	0.6	28	87
2050	A1B	OECD	81	–	–	–	97
		ROW	170	–	–	–	281
		Global	251	426	51	85	381
2050	A2	OECD	58	–	–	–	58
		ROW	82	–	–	–	187
		Global	140	134	39	63	246
2050	B1	OECD	63	–	–	–	84
		ROW	45	–	–	–	213
		Global	104	271	34	60	298
2050	B2	OECD	63	–	–	–	111
		ROW	98	–	–	–	167
		Global	161	174	41	63	279

[a]The disaggregation between OECD and ROW was not reported for solar, wind or hydro.

[2] We note that the calculated wind capacities in 2050 across scenarios (~1200-1800 GW) are all lower than the projection by the European Wind Energy Association of 3000 GW by 2039 [8], and are consistent with 7-8%/yr growth from the 2005 level of 60 GW (global growth has been near 30%/yr for the last decade) [9].

Figure 7 shows actual emissions and virtual wedges by scenario and region for 2050. Note that regional virtual wedges do not sum to the global total, because the relative changes in the components of equation (1) are much larger in the ROW than for the globe as a whole. Virtual wedges of ROW energy intensity dwarf other regional wedges. As noted above the energy intensity improvements are to a large extent an "autonomous" trend, explained by structural changes of the economy rather than technological measures to enhance energy efficiency. There is also a large variation in total virtual wedges among the scenarios, for both OECD and ROW regions.

Figure 8 shows real wedges by scenario and region for 2050. It is noteworthy that the difference in scale between this Figure and Figure 7 is 25-fold, indicating far less carbon-reduction activity in real wedges. ROW wedges again dominate, but the ratios of ROW wedges to OECD wedges are much smaller than the corresponding ratios in Figure 7. Most CO_2 sequestration occurs in ROW (especially in A1B-550); most nuclear and biomass wedges occur in ROW as well. One exception to this pattern is in A1B-550, where most non-biomass renewables occur in the OECD region.

Conclusions

Wedge decomposition analysis provides a quantitative understanding of the multiple factor differences between pairs of scenarios that contribute to overall differences in CO_2 emissions. Moreover, virtual wedges provide a means of identifying the autonomous changes in factors responsible for CO_2 emissions over time. The application of the method to some SRES and post-SRES scenarios reveals a number of common assumptions. In particular we find that the uncertainty of the baseline development path, i.e., the number of virtual wedges and "autonomous" trends in absence of any climate policies, play a central role in determining the additional mitigation effort needed for achieving climate stabilization.

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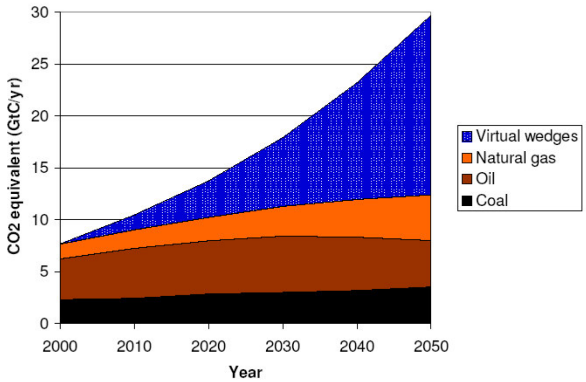

Figure 1. B2 actual emissions and virtual wedges.

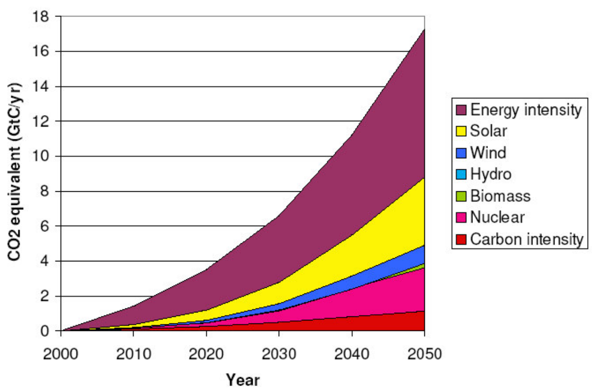

Figure 2. B2 virtual wedges.

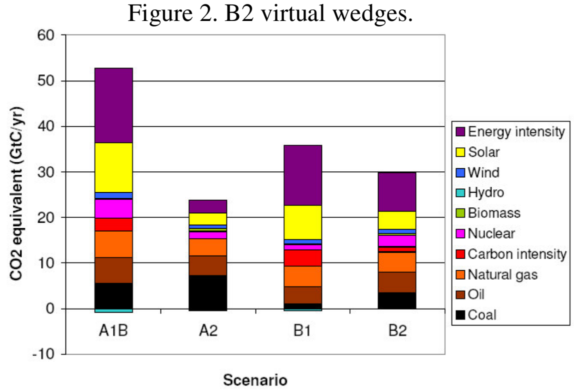

Figure 3. Actual emissions and virtual wedges across scenarios in 2050.

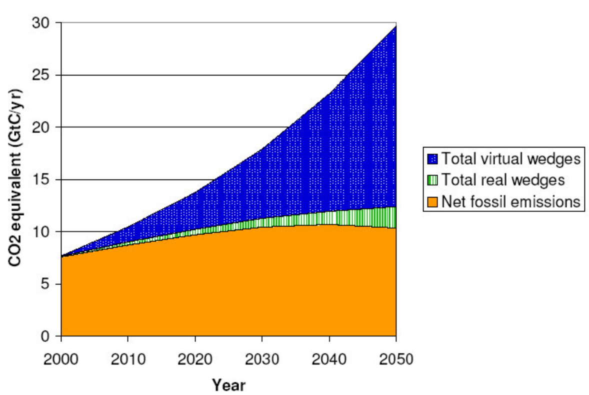

Figure 4. B2/B2-550 emissions, real & virtual wedges.

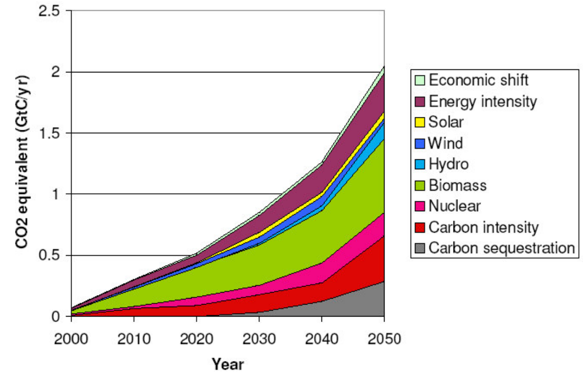

Figure 5. B2 scenario pair real wedges.

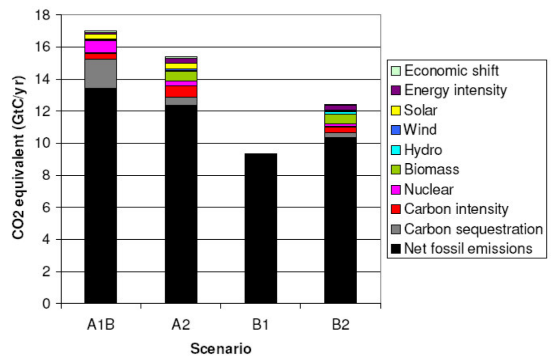

Figure 6. Actual emissions and real wedges across scenarios in 2050.

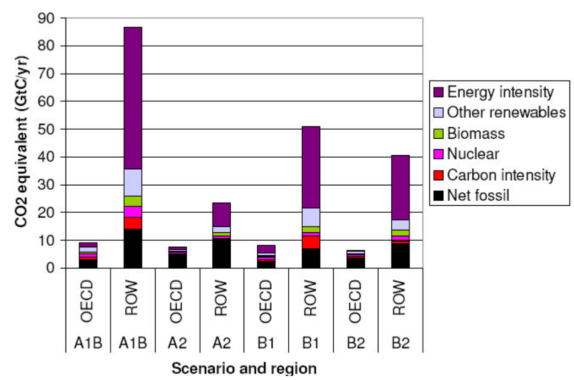

Figure 7. Actual emissions and virtual wedges across scenarios and regions in 2050.

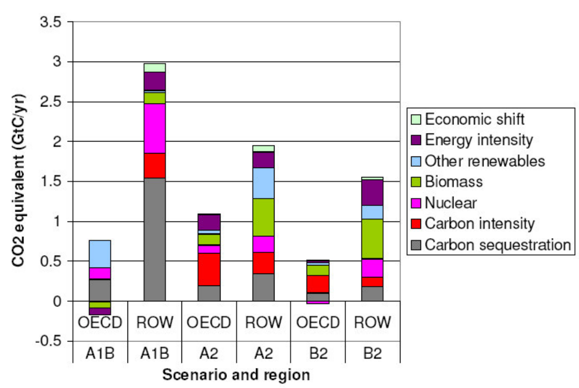

Figure 8. Real wedges across scenarios and regions in 2050.