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The National Security Dividend of Global Carbon Mitigation*

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Related Publication 07-18

June 2007

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Executive Summary

Energy and environmental security objectives are often conflated in political circles and in the popular press. Results from a well-established integrated assessment model suggest that policies designed to stabilize atmospheric carbon dioxide concentrations at levels above ~500 ppm generally do not align with policies to curb global oil dependence, because these atmospheric objectives can be achieved largely through reductions in global coal consumption. Policies designed to stabilize atmospheric carbon dioxide at levels below ~500 ppm, on the other hand, directly facilitate the alignment of environmental and security objectives because atmospheric targets in this range demand significant reductions in both coal and oil use. Greater recognition that investment in carbon mitigation can yield significant security dividends may alter the political cost-benefit calculus of energy-importing nations and could increase the willingness of some key global actors to seek binding cooperative targets under any post-Kyoto climate treaty regime.

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1. Introduction

Despite passage of major U.S. energy legislation within the last two years, ongoing concern over volatile fuel prices, escalating violence in the Middle East, and the looming threat of human-induced climate change has generated new legislative interest in reducing reliance on foreign oil and improving prospects for U.S. energy security.[1] While policies that expand or diversify domestic supply would arguably enhance U.S. energy security by increasing the availability and affordability of energy (*Yergin, 2005)*, limited domestic measures of this sort are unlikely to yield significant environmental or national security dividends unless the greater global threats posed by climate change and "petro-authoritarianism" are directly confronted.[2] Were a quorum of energy-importing nations to implicitly or explicitly embrace this larger mission, then existing institutions, like the 1992 Framework Convention on Climate Change (*UNFCCC, 1992*), could serve as a natural vehicle for progress. In fact, the "stabilization" objective of the FCCC is fully consistent with broader security objectives when atmospheric targets are chosen with imposed limits on global oil production in mind.

Article 2 of the FCCC defines the objective of the Convention as "stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system", while Article 3 states that "policies and measures... should be cost-effective so as to ensure global benefits at the lowest possible cost". The pursuit of additional objectives would thus seem to be consistent with Articles 2 and 3, provided that the benefit of the implied tightening could be shown to exceed the cost. The interpretive flexibility of the FCCC and its implications for policy have been noted previously (*Oppenheimer, 2005*).

In the remainder of this paper, we consider the energy system implications of a "business-as-usual" policy and compare the results to several scenarios in which the maximum concentration of atmospheric carbon dioxide is limited to values that have been suggested elsewhere as thresholds for "dangerous anthropogenic interference". We show that the resulting evolution of energy technology is sensitive to the particular atmospheric target and that only a subset of policies currently under consideration facilitate the alignment of environmental objectives with broader security goals. More precisely, our results show that policies designed to achieve atmospheric stabilization at levels above ~500 ppm will primarily encourage reductions in global coal consumption, while policies designed to achieve atmospheric stabilization at levels below ~500 ppm will target oil as well as coal and will therefore be more likely to yield significant security dividends. Full recognition of the security implications of carbon mitigation policy could alter the political cost-benefit calculus of energy-importing nations and ultimately increase the willingness of some key global actors to seek binding cooperative targets under any post-Kyoto climate treaty regime.

2. Modeling Protocol and Baseline Projections

Because growth in energy consumption is directly coupled to growth in economic output, global demand for energy is expected to rise steadily over the next century, as living standards in the developing world slowly converge to those in the developed world. In the absence of policy intervention, this increase in consumption will accompany an even greater reliance on fossil fuels, like coal and oil, as well as a potentially irreversible commitment to serious climate change (*Mignone et al., 2007*). Projections of primary energy supply and energy-related carbon emissions under "business-as-usual" (BaU) conditions are shown in panels (a) and (b) of Figure 1 (see also Table 1). These projections, like those that follow, are derived from MERGE (*Manne and Richels, 2004*), a well-established integrated assessment model that has been used extensively in previous assessments of carbon mitigation policy (e.g., *Clarke et al., 2007*). As in all such studies, the projections discussed here should be viewed as the unfolding of a given storyline – a probable response to one set of imperfect assumptions – not as a unique prediction of future energy use.

Base year (2000) values for energy production are supplied from the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA) (*IEA, 2002; EIA, 2003*). According to these sources, roughly 392 EJ (1 EJ = 10^{18} Joules) of primary energy was supplied to the global economy in 2000. By 2050, under BaU, global energy supply is projected to roughly double (to 850 EJ), and between 2050 and 2100, it is expected to double again (to 1664 EJ). Over the same period, the share of primary energy used to generate electricity is projected to increase from 38% in the base year to 52% in 2050 to 53% in 2100. The increased reliance on electric energy in later years reflects the fact that electricity is derived overwhelmingly from coal, which remains relatively inexpensive over the next century, while non-electric production (e.g. transport) relies more heavily on scarce oil and gas resources, which must be replaced by increasingly expensive unconventional resources or synthetic fuels.

The projected increase in coal consumption implies that the share of global emissions derived from coal will also increase. The numbers are illuminating. In 2000, emissions from coal accounted for 38% of global emissions; in 2050, this share is expected to climb to 67%, and in 2100, it is projected to reach 86%. The very large relative increase between now and 2100 reflects not only the substitution toward electric generation noted above, but also the significant growth of coal-based liquid fuels and other unconventional resources in the non-electric (transport) sector that fills the void left by waning conventional oil and gas resources later in the century (see panels (a) and (b) of Figure 1).[3]

The evolution of oil consumption over the same period is also worth examining. In 2000, oil accounted for about 35% of total energy supply and for 42% of global carbon emissions, and consumption of oil is projected to increase by more than 25% over the first three decades of the simulation. However, by 2100, oil supply falls 65% below the base year value and accounts for only 3% of total primary energy and carbon emissions. The well-defined peak in global oil production around 2030 reflects our particular assumptions about the size of the undiscovered resource stock as well as assumptions about the rates at which resources can be converted to proven reserves and at which proven reserves, in turn, can be converted into usable energy.[4] Our projections are consistent with a large body of literature that places the peak in oil production several decades into the future (e.g., *CERA, 2006*).

Our projections are also broadly consistent with the projections of BaU carbon emissions compiled by the Intergovernmental Panel on Climate Change (IPCC) (*Houghton et al., 2001*). Over the next century, BaU carbon emissions in our model grow from about 7 Pg C yr^{-1} in 2000 to ~15 Pg C yr^{-1} in 2050 to ~30 Pg C yr^{-1} in 2100. Even when uptake of CO_2 by the ocean is explicitly simulated, the resulting atmospheric concentration in 2100 is projected to reach 745 ppm, an outcome that is clearly inconsistent with the stabilization goal of the FCCC. [5] Most analyses suggest that the threshold for "dangerous interference" lies between 450 and 650 ppm (e.g., *O'Neill and Oppenheimer, 2002*), although the most recent of these favor targets at the lower end of this range (*Hansen et al., 2006*).

3. <u>Policy Scenarios</u>

3.1 Policies to Stabilize Atmospheric Carbon Dioxide

Carbon accumulation in the atmosphere is controlled by a balance between inputs (fossil fuel emissions) and outputs (uptake by the ocean and land sinks). When an atmospheric concentration target is imposed, the balance can be inverted for the "allowable" emissions, provided that the ocean sink is known and that terrestrial sources and sinks are assumed to balance (e.g., *Wigley et al., 1996*). For stabilization at 550 ppm, applying this procedure yields the allowable emissions trajectory seen in panel (d) of Figure 1. (The size of the total allowable emissions release in any period is shown by the height of the bar in that period).

In principle, the reductions in emissions needed to meet this objective can be achieved in a variety of ways (c.f., *Pacala and Socolow, 2004*). However, in this analysis, we allow the model to choose the unique path that minimizes global costs.[6] The resulting model-predicted *changes* in electric and non-electric energy (relative to BaU) are shown in panel (c) of Figure 1 (see also Table 1).

Several interesting observations follow. First, whenever (relatively cheap) carbon-intensive energy is replaced by (more expensive) carbon-neutral energy, the result is not necessarily zero-sum. Rather, total primary energy tends to decrease relative to the reference case, because higher energy prices tend to induce greater conservation. This demand effect is larger in the non-electric sector, where carbon-free alternatives are expensive, than in the power sector, where carbon-free alternatives are somewhat more affordable.

Electricity production is not disaggregated in the figure, although it is disaggregated in the model. Under BaU, most electricity is generated by coal-fired and nuclear plants, with a much smaller fraction generated by natural gas-fired and renewable sources (including hydroelectric). In the policy scenarios considered here, conventional coal generation is replaced by advanced coal plants equipped with technology to capture and store carbon (CCS), as well as by nuclear and renewable power. Different assumptions about the (real and perceived) costs of CCS, nuclear and renewables would alter the portfolio somewhat but not the general conclusion that the electric power sector can be decarbonized with less difficulty than the non-electric sector, by scaling up technologies that already exist (c.f., *Pacala and Socolow, 2004*). This explains how small reductions in total electric power *production* (seen in panel (c) of Figure 1) can accompany much larger reductions in electric power *emissions* (panel (d) of Figure 1).

An additional and noteworthy result of this scenario is that oil consumption remains largely untouched throughout the simulation. At the peak in 2030, oil consumption decreases by only 5% relative to the reference, and in 2100 it actually increases by ~3% (Table 1). These differences suggest that the near-term peak in oil consumption is merely being spread over a larger time horizon; indeed the total, integrated reduction over the simulation is negligible (< 1% relative to BaU).

The resilience of oil consumption in the face of rather significant emissions restrictions is worth exploring. A close inspection reveals that the allowable emissions release in 2030 under the 550 ppm target (~10 Pg C) requires only a slight deviation from BaU emissions (~11.5 Pg C). This implies that the atmospheric objective can be attained by deferring the bulk of the decarbonization burden to other forms of energy production, most notably to coal (which accounts for almost 7 of the 11.5 Pg C released in 2030). That this strategy should also minimize global costs follows from the fact, noted earlier, that substitutes for coal are far more plentiful and affordable than substitutes for oil and gas.

When the stabilization target is tightened to 450 ppm, some features of the energy system response are robust. The most conspicuous similarity is the fact that emissions from power generation – and from coal use more generally – are once again the first target of policy. The outcomes do differ in important ways, however (see panels (e) and (f) of Figure 1). While the reduction in emissions required under the weaker (550 ppm) constraint is relatively small (~1.5 Pg C in 2030 relative to BaU), the reduction required under the stronger (450 ppm) constraint is considerably larger (~6 Pg C in 2030).

Much, but not all of the additional mitigation burden can be achieved through further reductions in coal use. Even though coal consumption under BaU releases ~7 Pg C in 2030, the entire reduction cannot come from coal, because inertia in the capital stock prevents emissions from the conventional coal fleet from falling below about 2 Pg C in 2030. This implies that a reduction of about 5 Pg C can be achieved by mitigating coal emissions, but that an additional ~1 Pg C must be derived from other sources, making oil the obvious target. Because energy derived from oil releases ~3 Pg C in 2030, the relative reduction in oil consumption is found to be about 34%. And because the emissions constraint tightens further over time, oil consumption continues to be suppressed throughout the rest of the simulation. By 2100, the relative reduction is ~42%, and the integrated reduction over the simulation is ~30% (Table 1).

These results are provocative in suggesting that only a subset of the more stringent environmental targets currently under consideration are consistent with both traditional climate goals and the broader security objectives considered here. In fact, using identical modeling assumptions, we find that any target above about 500 ppm will yield only small (<10%) reductions in global oil consumption, while targets between 500 and 450 ppm will impel reductions in oil use between 10% and 34%. In other words, once the target falls below ~500 ppm, the size of the reduction in global oil consumption is proportional to the stringency of the policy.

Comparison with existing studies (*Clarke et al., 2007*) suggests that the basic qualitative result (that ambitious stabilization policies facilitate the alignment of climate and oil reduction objectives) is robust to the choice of model, although the exact threshold at which oil becomes a target of policy differs somewhat from one model to the next. In MiniCAM (*Brenkert et al., 2003*), for example, the oil-sector results are comparable to the MERGE results presented above. That is, oil consumption in the first half of the century decreases markedly when atmospheric carbon dioxide is limited to

450 ppm, but not when the target is relaxed to 550 ppm. On the other hand, in IGSM (*Sokolov et al., 2005*), oil consumption in the first half of the century decreases in all policy scenarios (in part because baseline demand for oil is higher), but the most significant reductions still occur when the target is tightened from 550 ppm to 450 ppm. The results are more difficult to compare in the latter half of the century because different models make different assumptions about the classification of unconventional resources. In MiniCAM and IGSM, baseline consumption of oil – and consequently, policy-driven reductions from the baseline – continue to increase over the 21st century. However, the long-term impacts on oil consumption are less likely to be relevant to the formulation of near-term policy.

3.2 Policies to Improve Energy Efficiency

In the simulations above, the overall energy intensity of the global economy (the ratio of energy consumed to economic output produced) is assumed to decline exogenously at an average rate of ~1% per year. This imposed trend explains how economic output can expand by a factor of 10 over the next century, while energy consumption expands by only a factor of four, and it reflects our assumption – supported by historical evidence – that, even in the absence of deliberate policy intervention, the world economy will continue to rely upon increasingly efficient technologies to drive global growth. Were such efficiency improvements to vanish overnight, baseline energy demand would grow at the same rate as economic output, and total energy consumption and carbon emissions would both increase by an order of magnitude over the next century (c.f., *Edmonds et al., 2007*). This outcome would seriously jeopardize attempts to stabilize atmospheric carbon dioxide by increasing the size of the "gap" (*Edmonds et al., 2004*) or "triangle" (*Pacala and Socolow, 2004*) between baseline and allowable emissions.

On the other hand, improvements in energy efficiency over and above what is assumed under BaU would facilitate the attainment of environmental objectives because these actions would reduce emissions relative to the baseline. While opportunities for greater efficiency improvements undoubtedly exist, the question of whether or not such improvements can be attained at low or even negative cost has long been the subject of controversy among environmental economists (e.g., *Porter and Van der Linde, 1995; Palmer et al., 1995*). A recent contribution to this debate is a report by the McKinsey Global Institute, which estimates that, at least over the next 15 years, growth in baseline energy demand could be cut in half by capturing the potential available from existing technologies whose large-scale deployment would yield an internal rate of return of 10 percent or more (*Bressand et al., 2007*). In principle, further improvements could be realized at lower rates of return.

Given the uncertain potential of efficiency, we decided to examine the sensitivity of our model results to assumptions about the rate at which global energy intensity is forced to decline. Such explorations are especially relevant in the context of this paper because policies that promote energy efficiency are often suggested as the most sensible and economical way to simultaneously advance climate and energy security goals. These arguments are often made at the national level, but they can be examined equally well at the global level.

In the baseline simulation, in which global energy intensity is forced to decrease at ~1% per year, the demand for energy grows at about 1.5% per year (yielding the four-fold increase in demand by 2100 observed in panel (a) of Figure 1). In order to explore scenarios in which the pursuit of efficiency is enabled through globally-coordinated policies, we consider two additional sets of simulations: one in which the global energy intensity is forced to decrease at 1.5% per year, which cuts the average growth rate of energy demand in half (from 1.5% per year to 0.8% per year) and one in which energy intensity is forced to decline at 2% per year, which cuts the growth rate in half once more (from 0.8% per year to 0.4% per year). For comparison, the McKinsey study assumes that baseline energy demand grows at 2.2% per year (through 2020) and concludes that the near-term growth rate could be cut by more than half – to less than 1% per year – at no net cost. The report is largely silent about whether such improvements could be sustained for more than one or two decades.

The evolution of primary energy demand and carbon emissions under baseline assumptions are shown again in panels (a) and (b) of Figure 2 (identical to panels (a) and (b) of Figure 1). The differences in energy demand under the scenario in which the decline rate of energy intensity is set to 1.5% per year (henceforth scenario "E1") and under the scenario in which the decline rate is set to 2% per year (scenario "E2") are shown in panels (c) and (e), respectively, while total carbon emissions under E1 and E2 are shown in panels (d) and (f). Under E1, carbon emissions are reduced by 22% relative to the baseline in 2050 and by 47% in 2100, while under E2, emissions are reduced by 35% in 2050 and by 67% in 2100 (Table 1). The latter reductions are almost sufficient to hold atmospheric concentrations below 550 ppm over the 21st century.

Despite the significant reductions in carbon emissions that accompany improvements in energy efficiency, the overall reduction in oil consumption is considerably smaller. At the peak in 2030, oil consumption decreases by only 4% relative to the baseline under E1 and by only 11% under E2 (Table 1), despite the fact that total energy demand decreases over the same period by 12% and 19%, respectively. The relatively weak response of oil consumption to more noticeable reductions in energy demand can be explained by the fact that unconventional fuels have started to penetrate the baseline non-electric market by 2030. These fuels, because they are more expensive than oil, tend to be displaced first. Indeed, the combined demand for biofuels and coal-based synfuels in 2030 decreases by almost 50% under E1 and by almost 60% under E2.

Although improvements in end-use efficiency of this magitude do not appear to drive significant reductions in global oil consumption, such improvements can nonetheless yield important economic benefits in a carbon-constrained world. The overall cost of policy depends largely on the implied demand for low-carbon technology, which depends, in turn, on the size of the "gap" between baseline and allowable emissions. By reducing baseline demand for energy, baseline carbon emissions and the size of the gap, improvements in energy efficiency can significantly lower the overall cost of mitigation.

Our simulations confirm this relationship. In our version of MERGE, the global GDP loss associated with a policy to stabilize atmospheric carbon dioxide at 550 ppm is 1.5% relative to BaU in 2050 and 2.3% relative to BaU in 2100, when baseline efficiency improvements are assumed. By contrast, under E1, the loss of GDP associated with stabilization at 550 ppm is 0% in 2050 and 0.6% in 2100; under E2, the loss is -0.6% in 2050 and -0.2% in 2100 (Table 1). Negative costs in the high-efficiency case suggest that the benefits associated with efficiency-driven productivity increases in these scenarios actually outweigh the costs associated with technology substitution. However, these results assume that improvements in efficiency can be realized at not net cost; less optimistic assumptions would reduce the net benefit of such efficiency measures.

When the stabilization constraint is tightened to 450 ppm, the results are qualitatively similar. Assuming baseline improvements in efficiency, the loss of GDP is 4.6% in 2050 and 2.7% in 2100 (costs are greater in the earlier years due to sluggish penetration of new technology in the non-electric sector). By contrast, under E1, the loss of GDP is 2.6% in 2050 and 1.0% in 2100, and under E2, the loss is 1.5% in 2050 and 0.2% in 2100 (Table 1). The difference in overall cost between the two stabilization scenarios is directly tied to the tolerance for oil under each policy. As noted earlier, stabilization at 550 ppm can be achieved largely through reductions in coal emissions, whereas stabilization at 450 ppm requires the emissions from other fossil fuels, chiefly oil, to be mitigated as well. Because substitutes for oil are more expensive than substitutes for coal, policies that demand greater reductions in oil will also demand greater economic sacrifices.

These cost projections are comparable to those found in other recent analyses of the costs and benefits of carbon mitigation (e.g., *Clarke et al., 2007*). Whether the additional benefits of stabilization at 450 ppm offset the greater costs is debatable, but any calculation that fails to acknowledge the broader set of benefits related to reductions in oil consumption that accrue under the tighter standard will be inherently incomplete.

4. Conclusions

In a time when budgetary priorities are shaped overwhelmingly by the pursuit of national security goals, the ancillary benefits of global carbon mitigation deserve greater attention. By simultaneously mitigating the severe risks posed by climate change and petro-authoritarianism, an ambitious global stabilization objective is more likely to enhance international and national security than any single piece of domestic legislation. Because ambitious atmospheric targets are fully consistent with both the stabilization and efficiency clauses of the FCCC, they can be naturally pursued within the existing institutional framework. Moreover, the promise of security dividends could widen stakeholder interest and enhance cooperation well beyond levels achieved during Kyoto.

Notes

1. The "Energy Policy Act of 2005" (Bill H.R. 6) became public law on August 8, 2005. A number of relevant bills have also been introduced in the 110th Congress, including the "America Fuels Act of 2007" (Bill H.R. 2354), the "Future Fuels Act of 2007" (Bill H.R. 2296) and the "SAFE Energy Act of 2007" (Bill S. 875), to name just a few.

2. "Petro-authoritarianism" refers to the tendency of petrolist states to use oil as a buffer against international pressure on a host of issues, ranging from civil liberties to nuclear armament (*Friedman, 2006*). For this reason, the worldwide increase in oil dependence has often been viewed as a direct threat to U.S. national security (e.g., *Deutch et al., 2006*).

3. As the text suggests, the term "coal" is used loosely in the non-electric sector. It includes not only coal-based synthetic fuels but also any fuels derived from unconventional fossil resources, like oil shale and tar sands.

4. Estimates of proven reserves are from the *2006 BP Statistical Review of World Energy* (*BP, 2006*); estimates of the undiscovered resource stock are the mean values that appear in *USGS World Petroleum Assessment 2000* (*USGS, 2000*). In 2000, world reserves and total undiscovered resources (including reserve growth) of oil exceeded 14,472 EJ, while total production in the same year was 139 EJ. This implies that current levels of consumption could be maintained for approximately another 100 years. Maximum production-reserve ratios are set to 0.01 and maximum resource depletion factors (shares of the resource stock that can be annually converted into reserves) are set to 0.05.

5. We employ a simple box model with parameters chosen so that carbon uptake under the imposed atmospheric forcing closely resembles uptake of the "PRINCE-2A" model (*Gnanadesikan et al., 2004*) under the same forcing. PRINCE-2A is one of several current generation ocean general circulation models that perform well against available observational metrics (*Matsumoto et al., 2004*).

6. More precisely, we allow the model to maximize the integrated stream of the discounted log of consumption. Because consumption in every period is equal to the difference between economic output (GDP) and the sum of capital investment and energy costs, the path that minimizes energy costs will render available the most revenue for direct consumption.

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Table 1

Policy Target	Rate of E.I.I. (% yr^{-1})	Economic Output		Energy Demand		Oil Demand		Carbon Emissions	
		2050	2100	2050	2100	2030	2100	2050	2100
No Carbon Policy	1.0	106.8 T$	391.4 T$	850.3 EJ	1664 EJ	174.0 EJ	48.6 EJ	14.8 PgC	30.1 PgC
	1.5	+0.6%	+0.5%	-22%	-46%	-4.0%	+2.2%	-22%	-47%
	2.0	+0.9%	+0.8%	-35%	-65%	-11%	+7.4%	-35%	-66%
550 ppm	1.0	-1.5%	-2.3%	-17%	-29%	-5.2%	+2.7%	-39%	-87%
	1.5	+0.0%	-0.6%	-30%	-60%	-9.0%	+6.6%	-41%	-86%
	2.0	+0.6%	+0.2%	-39%	-72%	-12%	+9.6%	-40%	-85%
450 ppm	1.0	-4.6%	-2.7%	-34%	-30%	-34%	-42%	-75%	-94%
	1.5	-2.6%	-1.0%	-46%	-61%	-37%	-45%	-75%	-94%
	2.0	-1.5%	-0.2%	-53%	-75%	-37%	-46%	-75%	-94%

Table 1. Results for the baseline simulation in which no carbon constraints are imposed and in which the average global rate of energy intensity improvement (E.I.I.) is set to 1% yr^{-1} are shown in the shaded cells near the top of the table. Here, output is measured in trillions of 2000 U.S. dollars, energy demand (production) and oil demand (production) are each measured in EJ and carbon emissions are measured in Pg C yr^{-1}. In all other simulations, results are reported as percent changes relative to the baseline. All values are reported for the year 2100 and for one intermediate year, generally 2050. Oil demand is reported at 2030 instead of 2050, since peak production occurs in 2030. For additional context, not that base year (2000) global economic output was 33.4 trillion U.S. dollars, energy demand was 392 EJ, oil demand was 139 EJ and the carbon release from all fossil sources was 6.6 Pg C yr^{-1}.

Figure 1

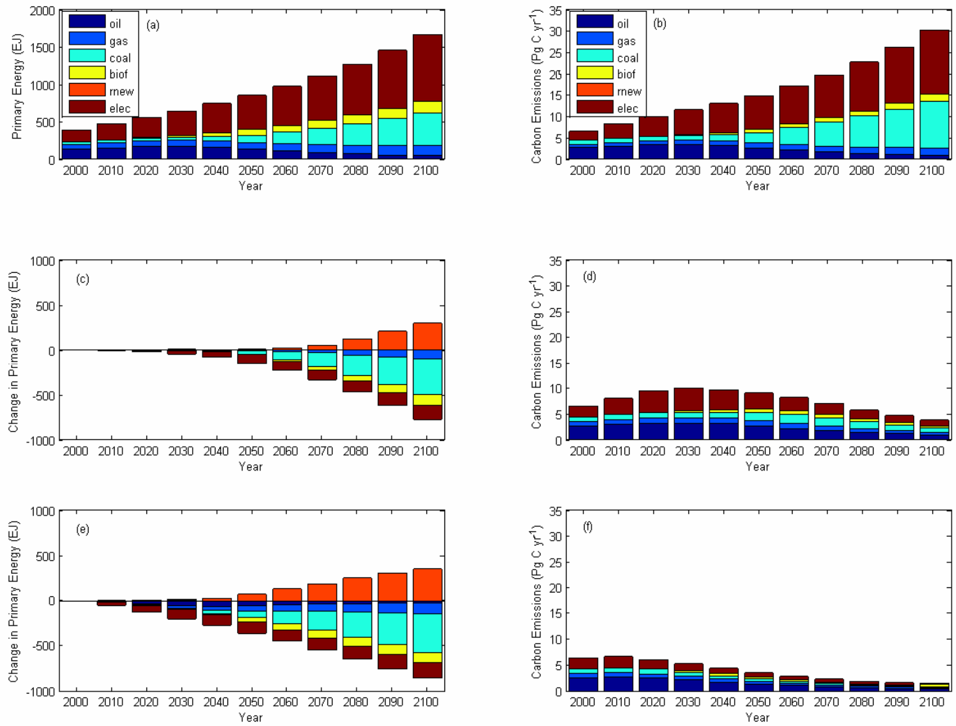

Figure 1. Energy supply and emissions from the baseline and stabilization scenarios discussed in the text. Panel (a) shows the baseline evolution of primary energy supply over the next century, while panel (b) shows the associated carbon emissions. Panels (c) and (e) show *changes* in primary energy (relative to the baseline scenario) when atmospheric CO_2 is constrained to 550 ppm and 450 ppm, respectively. Panels (d) and (f) show the implied emissions trajectories under 550 and 450 ppm, respectively. In all cases, the rate of global energy intensity improvement is set to the baseline value of 1% per year. Note also that all sources of electricity are aggregated into a single category (shown in brown), so that all other technology classes (oil, gas, coal, biofuels and renewables) include only the non-electric contribution.

Figure 2

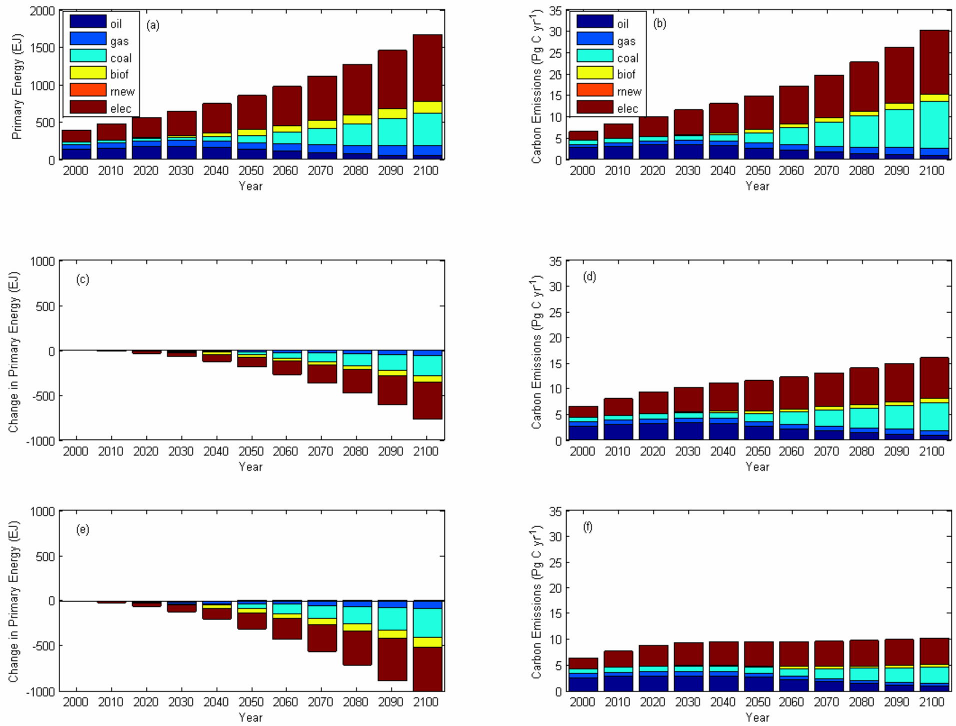

Figure 2. Energy supply and emissions from the baseline and increased efficiency scenarios discussed in the text. As in Figure 1, panel (a) shows the baseline evolution of primary energy supply over the next century, while panel (b) shows the associated carbon emissions. Panels (c) and (e) show *changes* in primary energy (relative to the baseline scenario) when energy intensity improves at 1.5% per year (scenario E1) and 2% per year (scenario E2), respectively. Panels (d) and (f) show the implied emissions trajectories under scenarios E1 and E2, respectively. No explicit carbon constraints are assumed in these scenarios, and technology is disaggregated as in Figure 1.