SUPPORTING ON-LINE MATERIAL

SECTION 1. EMISSIONS TRAJECTORIES FOR BUSINESS AS USUAL AND STABILIZATION BELOW DOUBLING

The Stabilization Triangle is bounded on two sides by a “ramp” scenario and a “flat” scenario, each departing from the present world. The ramp scenario is intended to be an abstraction of carbon emissions for Business As Usual (BAU), and the flat scenario is intended to be an abstraction of stabilization below doubling. In this section, we discuss each in turn.

Carbon Emissions for Business As Usual and the “Ramp” Scenario

Our Business As Usual (BAU) carbon emissions (or, equivalently, CO_2 emissions) simply continue to grow for the next fifty years with the 1.5%/y average growth rate of the past three decades. The corresponding emissions path, shown in Fig. S1(A), starts at 7.0 GtC/y in 2004 and rises at 1.53%/y to 15.0 GtC/y in 2054. A carbon emissions trajectory that increases linearly with the same cumulative emissions (525 GtC) rises to 14.0 GtC/y in 2054. This linear-increase scenario, or “ramp” scenario, conceptually easier to work with, is our BAU emissions scenario in all subsequent sections of the Supporting On-Line Material.

Looking backward, according to the International Energy Agency (IEA), carbon emissions rose 51% from 1973 to 2001 or 1.5%/y (S1). According to the Energy Information Agency of the U.S. Department of Energy (EIA), emissions growth averaged 1.6%/y from 1970-2001, 1.3%/y from 1980-2001, and 1.0%/y from 1990-2001 (1.5%/y if the former Soviet Union is omitted) (S2). The IPCC (S3) reports that emissions averaged 5.4 GtC/y in the 1980s and 6.3 GtC/y in the 1990s, which works out to an average increase of 1.5%/y. Finally, the BP statistical review (S4) reports 1.0%/y growth during the 1990s, but 1.6%/y if China and the former Soviet Union are omitted.

A growth in carbon emissions of 1.5%/y is bracketed by the emissions forecasts of the International Energy Agency and U.S. Department of Energy, and it is similar to the mean and median of the 40 IPCC SRES future emissions scenarios over the next fifty years (S1-S5). The IEA predicts 1.3%/y growth in carbon emissions through 2030 (S1). The EIA predicts 1.9%/y growth through 2025 (S2). The IPCC (S5) has compiled a set of 40 future emissions scenarios called the SRES scenarios. The mean and median 2054 emissions for the SRES scenarios are both approximately 15 GtC/y, with half the scenarios between 12 and 18 GtC/y. With 2004 emissions in these scenarios at approximately 7 GtC/y, the average 50-year growth rate for carbon emissions works out to 1.5%/y for the mean and median of the scenarios, and 1.1%/y - 1.9%/y for the range covered by the central 20 scenarios.

Assuming a carbon emissions growth of 1.5%/y over the period 2004-2054, cumulative emissions are 525 GtC/y for the 50 years. For growth rates of 1.2%/y and 1.8%/y, 2004-2054 cumulative emissions are smaller and larger by about 50 GtC, or approximately 2 wedges.

Primary Energy Consumption and Gross World Product

The approach taken in this paper’s analysis is to specify as little as possible of BAU and to concentrate on the activities (“wedges”) required to alter emissions dramatically, whatever the details of a full-blown BAU. Specifically, we do not need to specify the BAU growth rates of primary energy or gross world product. The many self-consistent, highly disaggregated analyses of BAU primary energy and BAU gross world product are nonetheless useful, because they provide insight into the level of conservation and energy decarbonization likely to be undertaken over the next 50 years, even in the absence of a specific concern for carbon emissions.

The EIA, IEA and BP report the following historical annual growth rates of primary energy consumption:

> EIA (S2): 1.9% for 1970-2001, with 3.2% during the 70’s, 2.0% during the 80’s and 1.4% during the 90’s.
>
> IEA (S1): 1.9% for 1973-2001.
>
> BP (S4): 1.5% for 1977-2002, with 2.0% during the 80’s and 1.2% during the 90’s.

The EIA predicts 1.9%/y growth in primary energy through 2020 (S2). This is the same as the predicted growth rate in carbon emissions. Thus, the EIA is predicting a departure from the historic decarbonization of the energy system that, in recent years, has resulted from larger market shares for natural gas and nuclear power. For the past 100 years, each decade has seen a fall in the carbon intensity of the energy system, with annual emissions growth, on average, 0.3-0.5% slower than annual energy growth (S5).

The IEA predicts 1.8%/y growth in primary energy through 2020. This prediction is from their 2002 assessment; the most recent IEA handbook predicts 1.6%/y growth in the primary energy through 2030 (S1). The median annual growth rate of primary energy from the 40 SRES scenarios is 1.8% from 2004 to 2054, while the 25% and 75% bounds are 1.2% and 2.0% (S5).

Gross World Product grew at 3.1%/y from 1970 to 2001. The EIA predicts 3.1%/y growth through 2025 (S2), and the IPCC predicts approximately 3% /y growth for the next half century (S5). The SRES are divided into four “families” labeled A1, A2, B1 and B2. From 1990 to 2050, the ranges of predicted annual percent growth rates for the scenarios in each family are, respectively: 2.9-3.7, 1.7-2.3, 2.9-3.5, and 2.1-2.9.

Carbon Emissions for Stabilization Below Doubling and the “Flat” Scenario.

The “flat” emissions scenario, constant emissions at 7 GtC/y for 50 years, is presented for simplification of discussion in the body of the paper as a representative emissions scenario for stabilization below doubling of the pre-industrial concentration of 280 ppm. Here, we relate the “flat” trajectory to traditional analysis of the connection of emissions and concentrations. This analysis requires, first of all, models of the future net land sink and future ocean sink and an understanding of current uncertainty about these sinks.

The Net Land Sink

Terrestrial ecosystems were a net sink of 0.2±0.7 GtC/y during the 1980's and 1.3±0.8 GtC/y during the 1990's (S6, as modified by S7), or 0.7±1.1 GtC/y over the combined period[1]. Our BAU scenario for land use is simply that the net terrestrial sink will continue at 0.5 GtC/y for the next fifty years, or at approximately the level of the last 20 years. The terrestrial biosphere thus supplies one wedge of reduced net emissions to the atmosphere in the BAU scenario.

Estimates of the net terrestrial flux are best constrained by the more certain estimates of fossil emissions, atmospheric inventory and oceanic uptake (fossil emissions minus atmospheric increase minus oceanic uptake). The sink is partially the result of land use change in the temperate zone that causes a sink of ~1.5 GtC/y, roughly half of which is due to forest regrowth and management (S8, S9, S10). This sink is offset by a tropical source, due to deforestation.

The size of the deforestation sink is controversial. Houghton (S10 and references therein) uses FAO data and a model of the effect of land use on terrestrial carbon fluxes to estimate a tropical source of 2.0±0.8 GtC/y in the 1980's and 2.2±0.8 GtC/y in the 1990's, or 2.1±1.1 GtC/y over the combined period. However, Houghton's model does not reproduce the relatively well-constrained values for U.S. forests from the U.S. Forest Service Inventory (S8, S10). Two recent satellite surveys put the tropical source at 0.9±0.5 GtC/y and 1.3 GtC/y in the 1990's (S11, S12, as modified by Houghton in S10).

If Houghton's estimate of a tropical source of 2.1 GtC/y were correct, then there would be a "missing" carbon sink of approximately 1.3 GtC/y. (The tropical source of 2.1 GtC/y minus the temperate sink of 1.5 GtC/y gives a net *source* of 0.6 GtC/y, whereas the average net terrestrial flux in the 1980s and 1990s was actually a *sink* of 0.7 GtC/y.) A missing sink this large is usually explained, as in the models of the IPCC Third Assessment, by CO_2 fertilization of the terrestrial biosphere (S6). In contrast, if the S11 satellite survey is correct and also applies to the 1980s, then temperate land use minus tropical deforestation yields a net sink of 0.4 GtC/y, which is within 0.3 GtC/y of the actual net terrestrial flux over the last 20 years. Thus, if the S12 estimate is correct, then both the missing sink and the effect of CO_2 fertilization must be small. The difference between the tropical deforestation estimates in (S10) and (S12) is important for our purposes here, because it implies two different futures for the terrestrial sink. A sink caused by CO_2 fertilization will increase in the future as CO_2 builds up in the atmosphere, whereas a sink caused solely by recovery from past land use will diminish as the affected ecosystems approach full recovery (S13).

How big is this difference? The six global vegetation models included in the carbon cycle chapter of the IPCC Third Assessment (S6) provide a guide. These models were run with an emissions scenario very similar to our BAU scenario of 1.5% fossil emissions growth, and they included climate-induced carbon cycle feedbacks. Their mean prediction was for a sink of 1.7 GtC/y in 2000 that rose to 4.5 GtC/y in 2050. Using the same proportional change over fifty years , the CO_2 fertilization sink of 1.3 GtC/y implied by Houghton's deforestation estimate would grow to 3.4 GtC/y by 2054 and produce a total of ~5 wedges' worth of carbon sink. In contrast, we can expect the temperate land-use sink to decay over time with a time constant of roughly 100 years (S13). Thus, the ~1.5 GtC/y temperate land use sink should diminish to ~0.9 in fifty years, producing a cumulative sink of 58 GtC over the period, or roughly 2 wedges.

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[1] Ranges preceded by ± are plus or minus one standard deviation.

Putting all this together, Houghton's large tropical deforestation estimate implies a total terrestrial sink of ~7 wedges over the next 50 years, whereas the smaller estimate in (S12) implies a sink of ~2 wedges. Evidence continues to accumulate that the models of CO_2 fertilization in (S6) drastically overstate the likely benefits of CO_2 fertilization (see for example S14, S15 and the discussion in S10). For this reason, we adopt the conservative course of accepting the estimate of ~1 GtC/y for the current tropical deforestation source, and that the terrestrial sink will provide only 2 wedges' worth of benefits over the next half century.

To complete the BAU scenario for terrestrial ecosystems, we must specify a 50-year future for tropical deforestation. The 40 SRES scenarios (S5) are of some use here, because most predict diminished deforestation. The land use fluxes in the SRES scenarios are normalized at a source of 1 GtC/y in 2000 (tropical deforestation plus temperate sink), and they thus imply a "missing" sink of ~1.7 GtC/y (because the average net terrestrial flux in the period 1980-1999 was a sink of 0.7 GtC/y). The 1 GtC/y net source from land use in the scenarios diminishes to a mean of 0.5 GtC/y in 2054 with a range for the central 50% of scenarios of 0.0-0.9 GtC/y, and a full range for all 40 scenarios of –0.7 GtC/y to +1.2 GtC/y. Thus, nearly all predict a decrease in tropical deforestation.

Together, the decreased tropical deforestation predicted by the SRES scenarios and our prediction of a decreasing temperate land-use sink and no CO_2 fertilization, provide a simple rationale for our BAU scenario. Again, we propose a BAU land sink that for 50 years is constant at 0.5 GtC/y, approximately the average net terrestrial flux in the 1980's and 1990's of 0.7 GtC/y. Our BAU land sink thus provides one wedge. Note that this is consistent with the philosophy of simple extrapolation of current trends that was used for fossil emissions, energy and GDP. It is also consistent with a tropical source and a temperate sink that both diminish by ~0.5 GtC/y over 50 years, or with an infinite number of other combinations of trajectories for tropical deforestation, temperate land use and the missing sink that add up to a net sink of one wedge.

At the same time, it is important to keep in mind how uncertain our BAU land use sink is. If the mean of the SRES land use scenarios and the mean of the IPCC Third Assessment terrestrial ecosystem models were correct, then the terrestrial biosphere would supply a net sink totaling almost five wedges. In contrast, if Houghton's estimate were correct for tropical deforestation and were to persist, if the missing sink were suddenly to disappear, and if the temperate land use sink were to decay away as in our BAU scenario, then the terrestrial biosphere would be a net source of two wedges.

The Ocean Sink

Carbon uptake by the oceans is much better constrained by observations than uptake by the land. From 1980-2000, the oceans were a net sink of 1.9 ± 0.7 GtC/y (S16). Predictions of ocean models also exhibit relatively high consistency. For example, (S6) used seven ocean models to predict carbon uptake under fossil fuel emissions very similar to those in our BAU scenario of 1.5% growth, and observed a range of ± 0.5 GtC/y in 2000 and ± 0.8 GtC/y in 2050.

Here, we use the HILDA ocean model to calculate the ocean sink. HILDA, a multi-box ocean model (S17), calibrated with measurements of natural and bomb-produced $^{14}CO_2$, has been shown to predict carbon uptake over time scales of a century or less with the accuracy of a general circulation model (S18). The mean ocean uptake from 1980-1999 calculated using HILDA is 2.4 GtC/y, within the uncertainty of the observations. Following the WRE500 atmospheric concentration scenario (see below), HILDA predicts an ocean uptake of 2.82 GtC/y in 2004, rising to 3.92 GtC/y in 2054, with a cumulative uptake of 180 GtC. Accepting the stated uncertainty in the observations (approximately ±40%) as our estimate for future uncertainty in ocean uptake, we obtain ±72 GtC in 50 years, or ±3 wedges. An additional wedge is at stake in the difference between the 1980-1999 observed uptake of 1.9 GtC/y and HILDA's 2.4 GtC/y calculation (0.5 GtC/y x 50 years), giving an overall uncertainty of approximately 1±3 wedges.

Future changes in ocean CO_2 uptake due to climate change feedbacks are also uncertain. In the first half of the century, they are dominated by reduced CO_2 solubility and increased stratification that result from warming of the surface ocean. Ocean models predict a reduction in cumulative ocean uptake between 1990 and 2050 of 6 to 25% (S3). The HILDA model does not include any climate-driven feedback effects; therefore, based on the estimated range stated above, it could overestimate ocean uptake by between 10 and 45 GtC, or approximately 1±1 wedges.

Assuming these two sources of uncertainty are independent, the ocean sink may be weaker than we have estimated by 2±3 wedges.

Construction of Stabilization Emissions Scenarios

To locate the "flat" emissions scenario of the Stabilization Triangle among traditional emissions scenarios for stabilization below doubling, we consider six stabilization emissions scenarios and their corresponding stabilization concentration trajectories (S19). The six emissions scenarios are shown in Fig. S1(A), and the corresponding concentration trajectories are shown in Fig. S1(B).

We consider three stabilization targets: 450, 500 and 550 ppm. For each target, we construct a pair of concentration trajectories, one leading to a "delayed reduction" scenario and one leading to an "early reduction" scenario. The delayed reduction scenarios have higher emissions in the first decades and lower emissions later, relative to the early reduction scenarios with which they are paired. The increase in effort required by early action in the first fifty years translates into a more permissive emissions schedule later. Such trade-offs must, of course, be analyzed in a full economic framework to assess costs and benefits properly.

Each fossil fuel emissions scenario in Fig. S1(A) is the sum of 1) the rate of increase in atmospheric carbon, 2) the net land sink, and 3) the ocean sink. The rate of increase in atmospheric carbon is the derivative of the corresponding concentration trajectory. The net land sink is assumed to be constant at 0.5 GtC/y. The ocean sink is found from the HILDA model.

The delayed reduction scenarios are similar to the "WRE" scenarios (S20, S21) used in the IPCC Third Assessment (S3), which depart from Business As Usual emissions between 2005 and 2010. But our concentration trajectories have been updated to reflect recent atmospheric CO_2 growth. In addition, the specified atmospheric concentration in 2050 has been lowered by 5 ppm (for the 450 ppm scenario) or 10 ppm (for the 500 and 550 ppm scenarios) in order that future emissions do not exceed those of the Business As Usual scenario.

The early reduction scenarios are similar to the "S" series scenarios used in the IPCC Second Assessment (S22), which departed from historical emissions in 1990. These have been updated to follow historical and Business As Usual emissions through 2004. The 2004-2054 average emissions from these scenarios differ from those which depart from BAU in 1990 by less than 2%.

The "flat" emissions scenario, measured by 2004-2054 cumulative emissions, is bracketed by the 450 ppm and 500 ppm delayed reduction scenarios and also by the 500 ppm and 550 ppm early reduction scenarios.

How different are the six emissions scenarios from one another? We measure these differences by the difference in the size of the corresponding 50-year stabilization triangle. These triangles are bounded by our BAU emissions scenario and the particular stabilization emissions scenario, for 2004-2054. Since a "wedge" is 25 GtC, the size of such a triangle can be expressed alternatively as a number of 25 GtC "wedges." The sizes of the six emissions scenario triangles, in GtC and "wedges," are given in Table S1.

From Table S1, we see that the 500 ppm delayed reduction scenario requires two more wedges than the 550 ppm delayed reduction scenario, but the 500 ppm early reduction scenario requires only one more wedge than the 550 ppm early reduction scenario. This is a reflection of the greater divergence of the delayed emissions scenarios than the early reduction emissions scenarios seen in Fig. S1(A). Furthermore, the early reduction scenarios require 1-3 more wedges, relative to the delayed reduction scenarios, for the same stabilization level.

In the period 2054-2104, the average rate of decline in CO_2 emissions is steeper in all six scenarios, relative to 2004-2054. As Fig. S1(A) shows, the maximum rate of decline in 2054-2104 in the early reduction scenarios is significantly smaller, and occurs later, than in the delayed reduction scenarios.

Eventually, to achieve stabilization of the atmospheric concentration, the rate of emissions falls to a rate equal to the total net uptake rate of CO_2 by the ocean and land, so that there is no further atmospheric build-up. In Table S2, the time when this happens is called the "Stabilization Year." For stabilization below doubling, we see that atmospheric build-up ends in the first half of the 22nd century.

SECTION 2. CONSERVATION AND EFFICIENCY

The Carbon Intensity of the Economy

Economy-wide (societal, macroeconomic) energy efficiency is measured by the energy intensity of the economy – the ratio of global primary energy production to gross global economic product. Today's roughly 350 EJ/y throughput of fossil energy and 35 trillion dollar per year global economy result in a global *fossil energy intensity* of approximately 10 MJ (fossil)/$. The full "energy intensity" includes non-fossil energy, approximately 15 to 25% of the total; the amount of non-fossil energy cited varies from reference to reference, depending on whether non-commercial energy (firewood, charcoal, dung) is included and depending on conventions about hydropower (S23, S24).

From a carbon perspective, the carbon intensity of the economy – the ratio of atmospheric carbon emissions to gross global economic product – is the crucial ratio. The global value today, roughly 7 GtC/y divided by $35T/y, is about 200 gC/$. The economy is decarbonizing at the same time as it is becoming more energy efficient, as discussed in Section 1 of the Supporting On-Line Material.

The Bush administration has chosen to frame the U.S. contribution to mitigating climate change in terms of national carbon efficiency (carbon emissions per unit GNP). Specifically, the goal is to reduce national carbon intensity by 18% over the next decade, or 1.96%/y. Continuing this pace for 50 years would reduce the U.S. carbon intensity by 62.9%. Following a faster pace of decline for 50 years, namely declining 2.11% per year, would reduce U.S. carbon intensity by 19.2% in ten years and 65.6% in 50 years. The U.S. carbon emissions would be reduced an additional one part in 14 from this toughening of the goal by 0.15%/y and staying the course for 50 years. It turns out that toughening *any* such goal by the same increment, 0.15%/y, and staying the course for 50 years, will result in reduction of carbon emissions by one part in 14. Thus, if every country were to toughen whatever target it started with by 0.15% per year, the result would be carbon emissions down by 1/14, which is a wedge (1 GtC/y) relative to a BAU of 14 GtC/y.[2]

An economy-wide focus on carbon intensity helps to remind us that reduced carbon intensity is achieved not only by more efficient devices. An economy decarbonizes when less carbon-intensive sectors grow more rapidly than more carbon-intensive sectors. The faster growth of services than primary materials in advanced industrial societies is an example.

In our BAU emissions scenario, carbon emissions grow 1.5%/y and double in 50 years. If, as well, the economy were to grow at 3%/y, then, in 50 years, the economy would quadruple, and its carbon intensity would fall to half its original value. Some complex combination of structural

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[2] If the Bush targets are continued for 50 years, U.S. carbon emissions after 50 years are 37.1% of what they would have been had there been *no* change in carbon intensity. With the tougher target, 0.15%/y more stringent, they are 34.4% of what they would have been had there been no change in carbon intensity, which is almost exactly 13/14 of what they would have been with the more lenient target. (Compare 0.344/0.371 = 0.927, with 13/14 = 0.929.) So, U.S. 2054 carbon emissions with the tougher target would be reduced by one part in 14. The absolute toughening of *any* carbon intensity goal by 0.15%/y will always produce a level of carbon consumption that is down by one part in 14, as long as the original goal is not more than a few percent per year. This is because the fraction which, raised to the 50th power, gives 13/14 is 0.9985; multiplying a number close to 1.00 by 0.9985 will give the same number minus 0.0015.

changes and improved efficiency in specific devices would have brought this about. No one can foresee exactly how and where in the economy improvements in carbon intensity will be achieved, and, therefore, where further improvements are and are not available. The best we can do is to admit for consideration *all* the major opportunities for improved energy efficiency, and to acknowledge that an unknowable subset of these opportunities are wedges.

Wedges from Specific Carbon-Emitting Activities

A complementary perspective on reducing carbon emissions is provided by examining where fossil-fuel carbon enters the atmosphere, as opposed to where it comes out of the ground. Analyses of global emissions from this perspective are very difficult to do, because national data are usually not organized in these categories. One comprehensive review from this perspective is available, performed by Working Group III (Mitigation) of the Intergovernmental Panel on Climate Change (S25). Of a total of 5.5 GtC/y emissions in 1995, this report associates 1.73 GtC/y with buildings (31.5%); 1.21 GtC/y with transport (22.1%); 2.34 GtC/y with industrial uses (42.5%); and 0.22 GtC/y with agricultural uses (3.9%) (S25, Table S3)[3].

Here, instead, we choose five categories, combining industry and agriculture and splitting out two categories to describe carbon emissions associated with energy production, distribution, and conversion.

1. Sites involved in bringing fossil fuels to users, including sites of extraction, distribution, and refining.
2. Electric power plants.
3. Vehicles.
4. Buildings.
5. Direct use of fuel at the factory and farm.

Upstream carbon overheads The first category of sites are the sites where upstream "carbon overheads" are incurred, for *all* energy sources. The carbon overheads of fossil fuels are incurred at sites such as wells and mines; tankers, pipelines, and railroads; refineries; trucks delivering fuel oil and gasoline; and compressors of propane and LPG. The carbon overheads of other energy sources are incurred at sites such as uranium isotope enrichment plants and factories making fertilizer for the fields where biofuel is grown. A portion of this overhead is called "transformation, own use, and losses" in IEA accounts. (S24, p. 410. See also Table S4 in Section 3, Energy Supply, of the Supporting On-Line Material). For the sake of argument, we imagine that in 2054, carbon emissions associated with production, upgrading, refining, and distributing energy are 2 GtC/y under BAU (an overhead rate of 2/12, or 17%). In 2054, oil will be extracted from what we today call non-conventional sources (tarsands, shales), a much larger fraction of gas will be transported by LNG, some coal will be converted to liquid fuels, and as a reflection of greater world trade the average distance between extraction and use of fuel will grow. All of these developments of the energy system will increase carbon overheads. Because our BAU is a world oblivious to carbon concerns, we assume that it does not deploy substantial amounts of carbon capture and storage, which would raise overheads even more.

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[3] A different but similar disaggregation among final users, for 2000, from the International Energy Agency's *World Energy Assessment 2002* (S24) is presented in the Supporting On-Line Material, Section 3.

Thus, in our BAU, of the 14 GtC/y in 2054, 2 GtC/y is emitted during production and delivery, and 12 GtC/y is emitted at the points of use (specifically including power plants). Halving this overhead to 1 GtC/y achieves a wedge. Targets of recent attention in this category include flaring and venting at oil fields, the CO_2 present in natural gas as an impurity, and methane emissions from coal fields. The management of carbon emissions in this category is usually presumed to be the responsibility of the fossil fuel industries themselves.

Electric power plants Emissions from power plants can be reduced both by changing the fuel and by converting the fuel to electricity more efficiently at the power plant. We treat more efficient conversion here, and changing the fuel in Section 3 of the Supporting On-Line Material. More efficient conversion results at the plant level, for example, from better turbines, from high-temperature fuel cells, and from combining fuel cells and turbines. At the system level, more efficient conversion results from load leveling, from cogeneration (the co-production of electricity and useful heat), and from polygeneration (the co-production of chemicals and electricity).

Restricting the discussion here to 2054 coal power plants, we choose a reference baseload coal plant that operates at 50% lower-heating value efficiency, and hence emits 25.80 kgC for each one-half GJ of output electricity. 1 kWh is 3.6 MJ, so the carbon intensity of electricity from such plants is 186 gC/kWh.

To develop a wedge from the efficiency of coal power, we note that 40% and 60% efficient coal plants have carbon intensities of 232 gC/kWh and 155 gC/kWh, respectively, and thus a difference in carbon emissions of 77 gC/kWh. Hence, a wedge is achieved when 13,000 TWh (13 trillion kWh) are produced per year in 2054 at 60% instead of 40% efficiency. By comparison, global electricity output from coal in 2000 was 6000 TWh, according to the World Energy Outlook (S24, p. 411). Thus, a wedge is achieved if, in 2054, roughly twice today's output of coal power is produced at 60% instead of 40% efficiency.

All the carbon intensities considered here for coal plants in 2054 exceed the current average carbon efficiency. Year 2000 carbon in and electricity out for coal-based power plants were, respectively, 1712 MtC/y and 5989 TWh/y, resulting in a carbon intensity of 290 gC/kWh (S24, p. 411 and p. 413).

Electricity production is already more decarbonized than non-electric end uses of energy. Only about 20% of all primary energy comes from sources other than fossil fuels, but for electricity production the share from other than fossil fuels is 40%[4]. The difference in share is the result of non-carbon primary energy (dominated by hydropower and nuclear energy) being used almost exclusively in the electricity sector. This trend is likely to continue. Wind and other renewables will also have their primary impact, for the foreseeable future, as sources of electricity. To decarbonize the fuel supply system, in contrast to the electricity supply system, there are fewer options available, as discussed in Section 3 of the Supporting On-Line Material. This is why wedges available from improved efficiency of fuel use are especially important.

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[4] The share of primary energy from non-fossil sources varies across data sources, depending on whether traditional energy sources are included and on how hydropower is treated. According to the IPCC Mitigation Report, the share of electricity from non-fossil sources in 1995 was 38%, 5000 TWh out of 13,200 TWh (S25, Table 3.29, p. 238).

Vehicles A light-duty vehicle ("car") consumes 330 gallons of gasoline per year if it goes 10,000 miles with a fuel economy of 30 mpg. The carbon content of a gallon of gasoline is about 2.4 kg (specific gravity = 0.74; 85% carbon by weight), leading to 3 kg of carbon emissions per gallon of gasoline when one adds about 25% carbon "overheads" incurred at production, at the refinery and further downstream (S26). Thus, a typical car emits a ton of carbon into the air each year. Then, accepting 30 mpg and 10,000 miles per year as the baseline, a world with two billion cars on the road offers two wedges if the fuel can be totally decarbonized and one wedge if the fuel is unchanged but the fuel efficiency is doubled.

Note that the improved fuel efficiency required to achieve a wedge is strongly dependent on the average fuel economy assumed in the BAU. Assuming 24 mpg, a wedge is available from fuel efficiency by achieving 40 mpg instead. Assuming a 36 mpg baseline, a wedge is available from fuel efficiency by achieving 90 mpg instead.

Note also that the assumption of 10,000 miles of driving per year for the average car is only slightly larger than the 14,000 km/y (8700 miles/y) value used by the U.S. Energy Information Agency as a world average today (S23). The assumption of two billion light-duty vehicles in 2054 is consistent with the 530 million cars in 1999 (S23), if the growth rate in number of cars is 2.4% per year.

The decarbonization of freight transport presents challenges similar to those for personal transport. It is widely agreed, however, that the decarbonization of aviation will be more difficult. And aviation is the fastest growing component of transportation.

Buildings When energy is examined comprehensively from the end-use perspective, the buildings sector stands out as particularly promising. The buildings sector is traditionally subdivided into residential and commercial buildings. The largest savings are in space heating and cooling, water heating, lighting, and electric appliances.

The 2001 "Mitigation" report of the Intergovernmental Panel on Climate Change (IPCC) contains historical data and projections across all economic sectors and levels of industrial development. The report cites a 1996 paper commissioned by the IPCC that judges the buildings sector as a whole to have the "technological and economic potential" to cut emissions in half, relative to a particular base case, from 3.9 GtC/y to 2.0 GtC/y. Thus, two wedges are achieved. One wedge is achieved in residential and another in commercial buildings. In the base case, two-thirds of the carbon emissions are from residential buildings, but the carbon savings achievable from commercial buildings are judged to be larger than from residential buildings (65% vs. 45%). In both the residential and commercial buildings, almost half of the savings are achieved in the buildings of developing countries (S25, Table 3.5, p. 189). The paper cautions, however, that only "between 35% and 60% of the efficiency measures that are technically and economically feasible… could be adopted in the market through known and established approaches (S25, p. 188, fn. 13)."

We can read this observation in either of two ways, depending on how we view Business As Usual. 1) We can judge the savings available using "known and established" approaches as sufficiently difficult to achieve that they would not occur as part of Business As Usual. Then, one wedge would be available through implementing these approaches, and a second wedge would be available if unknown and not yet established approaches could be implemented to bring about the second half of the identified technical potential for carbon savings. 2) We can view the savings through “known and established” approaches to be part of Business As Usual, and thus very likely to occur without a focus on carbon. In that case, only the second wedge above would be available.

Carbon savings from space water heating will come from synergisms between end-use efficiency strategies, like wall and roof insulation, and renewable energy strategies, like solar water heating and passive solar design. These synergisms are further discussed in Section 3 of the Supporting On-line Material.

There are often critical interactions between two strategies that diminish the combined effect, relative to the sum of the two activities acting independently. Consider household lighting and the decarbonization of electricity. A wedges calculation could distinguish two 2054 worlds, one with half and one with full displacement of incandescent bulbs (IBs) with compact fluorescent bulbs (CFBs). About 10 kgC/y is at stake for each fixture, if we assume: 1) the bulbs are on 4 hrs/day; 2) a 15W CFB replaces a 60W IB, providing the same light output; and 3) the carbon intensity of electricity is 160 gC/kWh, the same as in recent years[5]. If we imagine 50 billion light fixtures in 2054 (there are about 10 billion today), half versus full penetration would be one-fourth of a wedge (25 billion fixtures where 10 kgC/y is saved). But, less than one-fourth of a wedge will be available, to the extent that the carbon intensity of electricity falls by 2054 from its current value. The carbon intensity of electricity fell 28% over the 29 years between 1971 and 2000, from 204 gC/kWh to 159 gC/kWh, or 0.9%/y (S24, p. 411 and 413). One would expect substantial further reductions in the carbon intensity of electricity in a world where global carbon is taken very seriously.

Direct use of fuel at the factory and farm The abundant literature on energy efficiency (S27-S32) provides grist for numerous estimates of opportunities for carbon emissions saving in all sectors of the economy. In the area of energy use in industry and agriculture, the identification of wedges is work for the future. The best we can do is to provide a template for such calculations, using vehicle fuel efficiency as an example. There are two steps to the identification of a wedge:

> 1) Invent a plausible baseline level of activity and carbon intensity in 2054, consistent with little attention being paid at that time to the global carbon problem. Take into account that many carbon intensities (like the analogous *energy* intensities) have been falling steadily and that many measures of level of activity have been growing with the economy. For vehicle fuel, the level of activity is the total vehicles miles traveled, or VMT, 20 trillion miles per year; and the carbon intensity is 0.10 gC/mile.
>
> 2) Invent either a lower level of activity, or a lower carbon intensity, or some combination of the two, that is a plausible representation of a world in 2054 that takes the global carbon problem very seriously.

Note that some (level of activity)-(carbon intensity) pairs will introduce the time dimension via the level of activity; an example is (tons of steel produced *per year*)-(carbon emissions per ton of

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[5] In 1995, according to IPCC Working Group III, 13,200 TWh of global electricity were produced with the emission of 2.09 GtC, or 158 gC/kWh (S25). In 2000, according to the IEA World Energy Outlook tables for its Reference Scenario, 15,400 TWh were produced with the emission of 2.44 GtC, or 159 gC/kWh.

steel). Other pairs will introduce the time dimension via the carbon intensity; an examples is: (hectares planted in some crop)-(carbon emissions *per year* per hectare planted in that crop).

SECTION 3. THE DECARBONIZATION OF ENERGY SUPPLY

The Stabilization Triangle reduces carbon emissions from fossil fuel in 2054 to 7 GtC/y from 14 GtC/y. In addition to the energy efficiency strategies discussed in the previous section that can bring about such emissions reductions, there are also many supply strategies.

In recent years, fossil fuel extraction and use has resulted in the transfer of between six and seven billion metric tons of carbon per year (GtC/y) from fossil fuels to the atmosphere. At the next level of detail, where data are disaggregated in various ways (by part of the world, fuel, end-use, etc.), disagreements among available references reflect a variety of uncertainties in the data. Such uncertainties arise from poor reporting from some countries, variable and unknown carbon content of fuels (especially, across coals), and incomplete knowledge of the timing of the delayed carbon emissions from the world's many long-lived petrochemical products, like plastics and asphalt (the "non-energy uses" of fossil fuels). Unless otherwise noted, we use CO_2 emissions data from the International Energy Agency's *World Energy Outlook 2002* (S32, p. 413). We also use the energy-to-carbon conversion ratios recommended at the BP website (these are lower heating values); for natural gas, oil, and coal, in units of kgC /GJ, these are, respectively: 15.29, 20.07, and 25.80[6].

In Table S3, a 3x3 matrix, we display a disaggregation of the 6.2 GtC/y global carbon emissions in 2000 (S33). The columns of the matrix are fuels (gas, oil, coal), and the rows are category of use (power, transportation, direct fuel use)[7]. The same information is also shown in Fig. S2, top. Coal dominates the electricity market. Coal and gas compete in markets for electricity and process heat. A significant amount of coal is used directly for space heat in developing countries. Oil emissions account for almost all transportation emissions. Almost half of oil emissions come from sectors other than transportation.

In 2054, it is reasonable to assume that natural gas, oil, and coal will all continue to be produced, and that many current features of energy demand will be intact. In keeping with the spirit of our analysis, where we seek to specify as little as possible of BAU, we adopt a deliberately oversimplified view of BAU carbon emissions in 2054, in the form of another 3x3 matrix, with the same structure as the 2000 matrix. It is shown in Table S4 and Fig. S2, bottom left.

The BAU in Table S4 is deliberately rough hewn, but it is consistent with general expectations and it can help guide our thinking. We have confined ourselves to integer emissions, in units of GtC/y. The total of 14 GtC/y emissions in the baseline is split: 5 GtC/y natural gas, 3 GtC/y crude oil, and 6 GtC/y coal[8]. All crude oil is used in the transport sector. To promote attention to the potential for competition in 2054 in the transport sector between fuels derived from crude oil and from coal, emissions for transport from oil-derived fuels and coal-derived synfuels are 3 GtC/y and 1 GtC/y, respectively. The power sector emissions are 2 GtC/y from natural gas and 3

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[6] The BP Tables (S34) state the conversion units in tC/toe: 0.64, 0.84, and 1.08, respectively. We use 1 toe = 41.86 GJ (10 Gcal).

[7] What we are calling Direct Fuel Use is the sum of two categories in *World Energy Outlook – 2002*: "Industry" and "Other" (S33). Industry will be dominated by process heat, since electricity is accounted for separately. "Other" will be dominated by space and water heating in buildings.

[8] A substantial fraction of the natural gas and oil will be what is today called, "unconventional," (tar sands, for example). The use of lower quality oil and gas resources may not alter the deep structure of energy markets expressed in our 2054 matrix.

GtC/y from coal. Emissions associated with direct use of fuel elsewhere than in transport are 3 GtC/y from natural gas and 2 GtC/y from coal; these fuels are used largely for industrial process heat and residential and commercial building space and water heating. Carbon emissions arise about equally, as today, from providing electricity, transportation, and heat for industry and buildings.

To cut 2054 carbon emissions by half, both the power system and the fuels system must be aggressively decarbonized. Below, we examine the decarbonization of power first, then the decarbonization of fuel.

I. The Decarbonization of Power

To decarbonize electricity production the principal target will be the coal power plant, and the secondary target will be the natural gas power plant. How much coal electric power is associated with 1GtC/y entering the atmosphere?

As in Section 2 of the Supporting On-Line Material, we choose a reference baseload coal plant, for 2054, that operates at 50% lower-heating-value efficiency, and hence with a carbon intensity of 186 gC/kWh. We now add that it has a capacity of 1 GW and operates with 90% capacity factor. Each year, therefore, it produces 8 TWh of electricity and emits 1.5 MtC. Our answer, then, is that 700 GW_e of vintage 2054 baseload coal capacity emits 1 GtC/y.

A carbon-emission rate from coal plants of 1 GtC/y is accompanied by coal consumption, in energy units, of 40 EJ per year, and 5400 TWh per year of electricity[9]. The electricity output is nearly as large as (90% of) today's total electricity output from coal, 6000 TWh in 2000, according to the World Energy Outlook (S33, p. 411). The coal input is about 60% of total coal input to power plants in 2000, 65 EJ (S33, p. 410). The second percentage is smaller, because the average efficiency of coal plants today is considerably less than the efficiency we are assuming for 2054.

Because we make much use of the equivalence of 700 GW of coal power plant capacity and 1 GtC/y of carbon emissions, it is important to understand the underlying assumptions. The carbon intensity we assume for the coal plants in 2054 far exceeds the average carbon efficiency today: Combining a 50% lower-heating-value efficiency with our lower-heating-value carbon intensity for coal, 25.80 kgC/GJ, yields an average carbon intensity of coal plants in 2054 of 185 gC/kWh, compared to 290 gC/kWh in 2000[10]. Combining these assumptions with a plant assumed to run 90% of the year, the emissions from each plant are 1.47 MtC/y, and therefore 1 GtC/y is emitted from 680 plants, which we round off to 700 plants.

A smaller number of 1 GW coal plants will emit 1 GtC/y when the efficiency is less, and a larger number when the plant runs less often. Combining two data one year apart, 1.712 GtC/y emissions from coal plants in 2000 and 1056 GW of installed coal capacity in 1999 (S33, p.413 and p. 412), one finds that 620 GW of recent coal plant capacity is associated with 1 GtC/y of recent emissions; evidently, the effects of much lower efficiency and much lower capacity factor nearly cancel.

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[9] 1 TWh = 10^9 kWh.

[10] Year 2000 carbon in and electricity out for coal-based power plants were, respectively, 1712 MtC/y and 5989 TWh/y (S33, p. 411 and p. 413).

The average carbon intensity of electric power from natural gas in 2000 was 172 gC/kWh,[11] about 60% of the average carbon intensity of electric power from coal in 2000, 290 gC/kWh, just cited. The average efficiencies of conversion of natural gas and coal to electricity are both about 32%[12]. Much of the natural gas is consumed in peaking plants, which are not as efficient as baseload plants. Correcting for this by assuming 60% lower-heating-value efficiency for the reference 2054 baseload natural gas plant, natural gas in 2054 will emit about half as much carbon per kWh as baseload coal plants.

It follows that a strategy that builds the capability, by 2054, to avoid the production of electricity from 1400 GW of baseload natural gas plants is a wedge. Equivalently (referencing the output instead of the capacity), a strategy that builds the capability to avoid the production of 10,800 TWh of electricity from vintage 2054 natural-gas-based power plants is a wedge. A wedge of natural-gas-based electricity avoided is approximately equal to four times the Year 2000 global production of electricity from natural gas (2700 TWh) (S33, p.411).

Four distinct approaches to the decarbonization of power will compete with one another:

A) Fuel shifting: Coal can be displaced by natural gas.

B) Carbon capture and storage: The CO_2 in the coal or natural gas can be captured and stored instead of vented to the atmosphere.

C) Nuclear energy: Coal or natural gas can be replaced by nuclear energy.

D) Renewable energy: Coal or natural gas can be replaced by renewable energy

We discuss each of these four options below.

A. Fuel Shifting: Substituting Natural Gas Power for Coal Power

From the data just presented, it follows that a wedge is available from using natural gas instead of coal at 1400 GW of baseload power plants by 2054. The pace associated with this wedge is 28 GW of new natural gas power displacing 28 GW of new coal power every year. Equivalently, a wedge results from producing10,800 TWh of electricity from natural gas instead of coal by 2054. At these power plants, 1 GtC/y will be emitted from natural gas instead of 2 GtC/y from coal. The 3x3 matrix for 2054 above would read, after one such wedge: 1 GtC/y from coal to electricity and 3 GtC/y from natural gas to electricity, for a total 2054 emission of 4 GtC/y associated with electricity production, instead of 5 GtC/y. A full second wedge of this kind would not be available.

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[11] Year 2000 carbon in and electricity out for natural-gas-based power plants were, respectively, 461 MtC/y and 2676 TWh/y (S33, p. 411 and p. 413).

[12] Inputs of coal and natural gas to electricity in 2000 were, respectively, 1555 Mtoe/y (65.1 EJ/y) and 725 Mtoe/y (30.3 EJ/y) (S33, p. 410), resulting in average Year 2000 efficiencies (electricity out/fuel in) of 33% for coal and 32% for natural gas.

Materials flows equivalent to one billion tons of carbon per year are huge. We assume a reference coal which is 70.7% carbon[13]. Then, a flow of 1.4 billion tons of coal per year carries 1 GtC/y. The flow of natural gas, which is about 75% carbon (since natural gas is mostly methane, and methane is CH_4), is 1.3 billion tons per year. However, flows of natural gas are usually measured as volume flows, for example in units of billions of standard cubic feet per day (Bscfd). We find that 1 GtC/y is a flow of 190 Bscfd of natural gas.[14] Therefore, 1 wedge is a program of development of natural-gas-based power that displaces coal and grows from zero to 190 Bscfd in 50 years, emitting 1 GtC/y, but backing out coal that is twice as carbon intensive in producing electricity, and so would have emitted 2 GtC/y.

We can relate a wedge of natural gas to flows through specific large pipelines and LNG tankers:

> The Alaska natural gas pipeline currently under negotiation is to carry about 4 Bscfd. A wedge of flowing natural gas (190 Bscfd, or 1 GtC/y) is equivalent to bringing one Alaska pipeline on line every year for 50 years[15].
>
> A wedge of flowing natural gas (190 Bscfd, or 1 GtC/y) is equivalent to 50 large LNG tankers docking and discharging every day[16]. Current LNG shipments create about one-tenth as large a flow of carbon.

B. Electricity with Carbon Capture and Storage (Carbon Sequestration)

When energy is extracted from fossil fuels or biofuels by oxidizing its carbon to CO_2, there is no fundamental reason why that CO_2 should end up in the atmosphere. It is possible to capture the CO_2 at the energy conversion facility instead of venting it, and to store the captured CO_2 to prevent it from reaching the atmosphere for a long period of time. This strategy, carbon capture and storage (CCS), also known as fossil carbon sequestration, is being widely studied as a carbon mitigation strategy. The 2002 National Academy of Engineering symposium proceedings (S36) is a good source of introductory essays on many of the major issues; for more detailed information, we recommend the collection of papers prepared for a 2002 international conference in Kyoto, in two volumes (S37). The website of the International Energy Agency's Greenhouse Gas R&D Programme, www.ieagreen.org.uk, is particularly useful.

A wedge is CCS applied by 2054 to 800 GW of baseload coal power or 1600 GW of baseload natural gas power – when we take into account less than perfect capture and storage (both CO_2 not captured and extra energy to power the capture and storage). Biomass can also be used with CCS, leading to a net withdrawal of CO_2 from the atmosphere. Biomass may be able to be used

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[13] "70.7 percent carbon describes coal equivalent within +/- 2%," according to G. Marland, et. al. (S35) . This percentage is consistent with the bituminous coal atomic ratios of $CH_{0.8}O_{0.1}$, if the coal is 85%($CH_{0.8}O_{0.1}$) and 15% "other", by weight. "Other" might be ash.

[14] We assume that the volumetric carbon content of natural gas is 538 gC/Nm^3, where Nm^3 is "normal cubic meter." We use the equivalence of two gas volumes, both defined at atmospheric pressure, but defined at different temperatures: 1 Nm^3 = 37.24 scf, where scf is "standard cubic foot." (The scf is at 60 degrees F, and the Nm3 is at 0 degrees C.) The arithmetic, then, is that 1 GtC/y is $37.24/(538*10^{-6}*365)$ Bscf/d = 190 Bscf/d. Here, both G and B are one billion, or 10^9.

[15] Another large natural gas pipeline is being built across China, from Kovyktinskoye, "Kovykta," in eastern Siberia, to Beijing. It is similar in size to the Alaska pipeline.

[16] We assume the LNG tanker has 200,000m^3 capacity. The density of LNG is 610 times the density of standard natural gas.

in dedicated facilities, and it also can be "co-fired" with coal, followed by CCS, increasing the mitigation effect of CCS per kWh.

To achieve the objectives of CCS, several commercial technologies must be combined in new ways. Key carbon capture technologies are well known from their use in industrial hydrogen production at refineries and ammonia plants. Key carbon storage technologies are well known from their use for enhanced oil recovery (EOR). We consider carbon capture and carbon storage separately.

Carbon capture Carbon capture is possible as end-of-pipe technology ("post-combustion capture"): CO_2 is separated from the flue gases exiting a power plant or other industrial facility, for example by chemical absorption or adsorption. Alternatively, CO_2 may be captured at an early stage, prior to most of the energy generation ("pre-combustion capture"). Post-combustion capture is less disruptive of already established technological practice. However, in many cases, pre-combustion capture is less costly, because the key step of separating CO_2 from other gases may be accomplished at much higher partial pressure.

Pre-combustion CO_2 capture shares many technologies with the gasification of solid fuels (coal, petroleum coke, and various biofuels). The synthetic gas (syngas) exiting the gasifier contains, principally, CO and H_2, at high temperature and pressure, but it also contains impurities, like sulfur. For a gasification plant to become a pre-combustion capture plant, the CO and H_2 mixture must be converted to a CO_2 and H_2 mixture, via a shift reactor ($CO + H_2O \rightarrow CO_2 + H_2$). The technologies to remove impurities from syngas are similar to the technologies to remove CO_2 from a mixture of CO_2 and H_2.

When gasification is the first step in power production, if there is no CO_2 capture, the CO-plus-H_2 syngas goes to a turbine, whereas if there is CO_2 capture, a much more H_2-rich syngas goes to the turbine. The incremental cost of CO_2 capture in power production, if gasification becomes established as the power conversion system of choice, is relatively low. Thus, the competition within coal-based power between steam power and power from gasification strongly affects and is affected by any requirement for carbon mitigation. The more gasification-based power is competitive, the less costly CO_2 capture will be, and the greater the societal demand for CO_2 capture, the more competitive gasification-based power will be.

Pre-combustion CO_2 capture also shares many technologies with H_2 production from coal or natural gas. Here, both a shift reactor to produce a mixture of CO_2 and H_2, and subsequent separation of the H_2 from the CO_2, are necessary to obtain a high-purity H_2 stream. The current scale of production of H_2, therefore, provides useful reference values for the task required to produce the "capture" part of a wedge of "capture and storage."

Hydrogen is currently produced from fossil fuels at a rate of about 40 million tons per year. Most production is associated with two industries, ammonia fertilizer and petroleum refining, and, in both cases, H_2 is produced and used in the same complex. At 120 GJ/t (lower heating value) for H_2, the flow of secondary energy as H_2 is approximately 5 EJ/y. As a result, taking into account losses in conversion of primary energy to H_2, roughly two percent of the 400 EJ/y of global primary energy is used to make H_2. Since, at any plant where H_2 is produced from fossil fuels, a nearly pure stream of CO_2 can be captured at some stage, we estimate that 0.1 GtC/y of capturable CO_2 is generated at H_2 production plants (S38**)**. Today, in every case, this CO_2 is vented, but only small changes could lead to capture. The scale of H_2 production today is only ten times smaller than the scale of a wedge of carbon capture in 2054.

We return to H_2 production later in this section, when we consider the decarbonization of fuels and the hydrogen economy.

Carbon storage The capture part of "capture and storage" results in a stream of relatively pure CO_2 at a plant gate, ready to be taken away. The CO_2 must be at high pressure, if it is to leave via gas pipeline, and the compression step is often the most expensive and energy-intensive step in the whole process. But, where can it be stored, and in what chemical form? Many novel proposals are receiving much attention, including storage in minerals and storage in the deep ocean, but, in the spirit of this paper, we consider only "geological storage," because this is the one storage strategy for which there is already substantial relevant experience. The oil industry moves large quantities of CO_2 into underground formations for enhanced oil recovery (EOR), by far the largest industrial use of CO_2. The CO_2 is injected as a supercritical fluid, and much has been learned via EOR about migration of the fluid, dissolution into hydrocarbons and brine, and chemical interaction with host rock. The scale of current EOR provides useful reference values for the task required to produce the "storage" part of a capture-and-storage wedge.

In EOR, much of the CO_2 injected into a hydrocarbon formation reemerges with the oil it has helped produce, and it is then separated and reinjected. We choose to describe EOR experience with CO_2 in terms of the total flow of new CO_2 brought to EOR sites, rather than the total flow of CO_2 injected at EOR sites, which includes recycled CO_2. About 10 MtC/y is brought to EOR sites in the U.S. today. Most of these sites are in the Permian Basin, West Texas, and most of the world's EOR is in the U.S. Therefore, a wedge of the storage part of capture-and-storage is a flow of CO_2 about 100 times larger than the current flow of CO_2 to EOR sites.

EOR today only rarely uses CO_2 captured from fossil fuels. Rather, most of the CO_2 used in EOR is drawn from *natural* CO_2 reservoirs. A large part of the CO_2 used for EOR in the Permian Basin is tied to the huge McElmo CO_2 reservoir in southwest Colorado via a 800-km-long CO_2 pipeline that runs across New Mexico. This pipeline carries somewhat more than 1 billion standard cubic feet per day (Bscfd) of CO_2, or about 5 MtC/y[17]. Thus, a wedge is an activity that, during each of the next 50 years, adds a flow of carbon equal to the flow through four pipelines like the pipeline from McElmo Dome to the Permian Basin.

Much work remains to be done before there are good estimates of the total storage capacity for geological storage of CO_2, and before storage integrity and leakage are well understood. The storage part of a capture-and-storage wedge requires the storage of 25 GtC over the next 50 years. The global storage capacity in oil and gas reservoirs is estimated at 10 to 20 wedges. Estimates of the global storage capacity in large unconfined saline aquifers range from only four wedges to one hundred (S39).

Carbon storage has not been the objective of EOR. In the past ten years, however, demonstration projects designed to gain experience with geological sequestration have begun to come on line.

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[17] Note that, as a manifestation of the universal properties of gases at low pressure, a flow of 190 billion standard cubic feet of gas per day (Bscfd) is a carbon flow of 1 GtC/y, the carbon flow associated with a wedge, *whether the gas is* CH_4 *or* CO_2.

The first three of these are: 1) the Sleipner project, offshore Norway; 2) the Weyburn project, Saskatchewan, Canada; and 3) the In Salah project, Algeria. The Sleipner project demonstrates storage in a huge unconfined aquifer; the Weyburn project demonstrates storage associated with EOR; and the In Salah project demonstrates storage in the water leg beneath the same natural gas field from which the natural gas is being produced. All three projects involve approximately the same storage rate: one million tons of carbon dioxide per year (0.3 MtC/y). Thus, a wedge of storage is 3000 Sleipners, or 3000 Weyburns, or 3000 In Salahs.

It is possible that storage of CO_2 will be routinely accompanied by the storage of pollutants, like sulfur, as a single fluid mixture. For the past 15 years, “acid gas” (a mixture of CO_2 and hydrogen sulfide, or H_2S, obtained from the desulfurization of “sour gas,” or gas with high sulfur content) has been disposed of in geological media in Western Canada. This method, which we call co-capture and co-storage, is being adopted increasingly as the preferred strategy for sulfur management for many sour natural gas fields in western Canada and the U.S. The 2003 injection rate, summed over 41 active sites, was about 0.45 $MtCO_2$/y (0.12 MtC/y) and 0.55 MtH_2S/y. The cumulative storage through 2002 was 2.5 $MtCO_2$ (0.7 MtC) and 2.0 MtH_2S (S40).

Natural gas is stored in geologic reservoirs to buffer demand, providing further relevant experience in moving gases into and out of reservoirs below ground. In the U.S. alone, total gas in storage in 1999-2002 ranged, approximately, between five and seven trillion standard cubic feet, the minimum in March and the maximum in October (S41). The six-month-average flow in and out, therefore, is about 10 billion standard cubic feet per day (Bscfd). As noted above, a carbon flow of 1 GtC/y, whether as methane or CO_2, is a flow of 190 Bscfd. Therefore, ramping up the gas flow currently associated with seasonal natural gas storage in the U.S. to twenty times its current rate over the next fifty years is the storage part of a wedge of CO_2 capture and storage.

C. Nuclear Power

A wedge from nuclear power is power production by 2054 at a rate of 5400 TWh/y that displaces electricity from coal or 10,800 TWh/y that displaces electricity from natural gas. Assuming that 2054 nuclear plants have the same 90% capacity factor as we earlier assumed for 2054 coal and natural plants, a wedge is 700 GW of additional installed nuclear capacity by 2054 that displaces coal, or 1400 GW that displaces natural gas.

In 1999, 351 GW of nuclear capacity were installed, and in 2000, the rate of production of nuclear electricity was 2586 TWh/y, for an average capacity factor (neglecting the one-year interval) of 84% (S33). Assuming that the wedge envisioned here is added to existing capacity which remains unchanged, we see that a wedge of nuclear power displacing coal requires approximately tripling, by 2054, both the installed nuclear capacity (adding 700 GW to 350 GW) and nuclear power output (adding 5400 TWh/y to 2600 TWh/y). The current challenge of nuclear waste disposal, in terms of mass of fission products, also grows by a factor of three.

The world’s nuclear capacity today is far below what was expected in the 1960s, when nuclear power’s promise as a substitute for coal was most highly regarded. Round numbers were used to project an installed nuclear capacity in 2000 of 1000 GW in the U.S. and 1000 GW in rest of the world. Problems of plant siting, uranium resource availability, and waste management were all addressed in that period, and no technical obstacles were identified. The U.S. currently has about ten times less nuclear capacity than then envisioned and the world as a whole has about six times less. Were the incremental 1600 GW to be built through steady construction over the next 50 years and be credited against baseload coal, this would account for roughly two wedges. Nuclear fusion reactors could account for some of this capacity, if fusion were to arrive on the scene faster than is now anticipated.

Nuclear fission power generates plutonium, as neutrons are absorbed by U^{238}. The rate of generation of plutonium depends on the reactor type and its operation. A light water reactor running on low-enriched uranium (the dominant reactor today) generates about 35 kg Pu per TWh of electricity[18], or 250 kgPu/y per installed GW, at 80% capacity factor. If our 2054 reactor has the same plutonium production rate per unit of thermal energy, but 50% efficiency and 90% capacity factor, it generates 180 kgPu/y. A wedge from nuclear power (700 GW) generates, in 2054, 130 tPu per year[19].

To estimate the quantity of plutonium produced over the fifty years by the nuclear power plants that fill the wedge, we assume a linear ramp, so that, each year, 14 GW of new nuclear capacity are installed. Over 50 years, there are 17,500 GW-years of nuclear reactor operation. We can bracket the Pu produced while filling the wedge by observing that if all the reactors generated plutonium at today's estimated rate of 250 kgPu/GW-year, 4400 tPu would be produced, and if all the reactors generated plutonium at the rate we are estimating for reactors built in 2054, 180 kgPu/GW-year, 3200 tPu would be produced[20]. This addition of several thousand tons of plutonium to the world's stock can be compared with: 1) 1000 tPu, the current inventory in all the world's spent fuel; 2) 100 tPu, the current inventory in U.S. weapons; and 3) 10 kgPu, the critical mass of plutonium.

D. Power from Renewables

The list of renewable power sources is long. It includes power from renewable energy in the form of heat that is then converted to electricity in a power cycle, as well as power that has been generated directly from an organized renewable energy source. In the first category, the heat may originate in focused sunlight or geothermal energy or the combustion of biomass. It is possible for such heat to supplement the heat from the combustion of fossil fuels, as in the co-firing of biomass and coal, mentioned briefly earlier under carbon capture and storage. In the second category, organized renewable energy, capable of being converted to electricity without an intervening thermal power cycle, can take the form of hydropower, photovoltaics (PV), wind, waves, and tides.

Here, we arbitrarily focus on the displacement only of coal and only by wind or PV. Given the assumptions in this paper, a wedge of wind must displace 700 GW of baseload coal (5400

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[18] We estimate this production rate from two inputs: 1) a ton of enriched uranium fuel generates about 35 GW_t-days of *thermal* energy before replacement (this is the "burn-up" of the fuel, expressed in its usual units), and 2) at replacement the spent fuel is about 1.0% plutonium (S42, Table 7.1, p. 109). Thus, the production of 10 kg Pu accompanies the production of 0.84 TW_th of thermal energy. At 32% efficiency converting thermal energy to electricity, the plutonium generation rate is 37 kgPu/TWh of electricity.

[19] Such a calculation is at best illustrative, because reactors in 50 years are unlikely to resemble today's light water reactors. They could produce either substantially more or substantially less plutonium than we have estimated.

[20] One way to model our conjectured improvements in nuclear reactor efficiency and capacity factor would be to assume that the plutonium production per reactor-year depends linearly on the year that the reactor begins operation, falling linearly from 250 kgPu/GW-year to 180 kgPu/GW-year over the 50 years. For this simple model, 3500 tPu are produced while filling the wedge – indeed bracketed by 4400 tPu and 3200 tPu.

TWh/y). Assuming a linear ramp, an increment of 100 TWh/y of either new wind energy or new PV each year for 50 years would be a wedge.

But wind blows intermittently, and PV cannot be collected at night; both are intermittent energy sources. The capacity of intermittent renewable energy to displace fossil fuel power depends on the availability of stand-alone storage and hybrid storage. A wedge is sufficiently large that it will require the wind or PV energy to be embedded in a system with sufficient storage to compensate for intermittency.

An example of hybrid storage is compressed-air wind-energy storage for remote wind farms, where the challenge is to gain maximum value from transmission lines by keeping them full. On very windy days, instead of spilling the wind at the site, the excess wind is stored in some geological formation as compressed air. Then, when winds are low, supplementary turbine power is produced by the compressed air, after its enthalpy is boosted by the burning of natural gas (S43).

For both wind and PV, deployment is measured in peak watts (W_p), a measure of the power output at the cutoff wind speed for wind and in direct sun normal to the surface for PV. We are assuming a present wind capacity of 40 GWp, based on data showing that at the end of 2002, the global installed wind capacity was 32 GW_p and had increased 29%, or 7.2 GW_p, over 2001. In 2002, 65 TWh were produced from wind, 0.4 % of total global electricity consumption (S44). Assuming the same 26% capacity factor relative to peak capacity in 2001 as in 2002,[21] wind energy in 2002 exceeded wind energy in 2001 by 16 TWh, one-sixth of the linear rate of increase required for 50 years for a wedge of wind-for-coal.

A simple way to estimate intermittency, for both wind and PV, is to match peak watts to baseload watts by dividing by three. (As we have just seen, a typical capacity factor for wind or PV is about one quarter, as compared to somewhat more than three-quarters for a baseload plant. In 2054, we imagine a 30% capacity factor for PV and wind and a 90% capacity factor for baseload plants.) Thus, a wedge is about 2000 GW_p of peak wind or PV power displacing coal by 2054, or 4000 GW_p displacing natural gas. The rate of deployment, for a linear ramp, is 40 GW_p per year if coal is displaced and 80 GW_p per year if natural gas is displaced. The current global deployment of PV is about 3 GW_p. For the past several years, installed global PV capacity, like wind capacity, has been growing at 30% per year (say, 0.7 GW_p/y). Thus, a wedge of PV-for-coal requires increasing the deployment of PV by a factor of 700 by 2054, or increasing the current deployment rate by a factor of 60.

To estimate the spatial demands of future wind farms on land or in the sea, we use data for Denmark's new 160 MW Horns Rev wind farm off the west coast of Jutland (S45). This offshore wind farm has 80 turbines in an 8x10 rectangular array, each with 80m-diameter blades and 2-MW_p output. The turbines are seven blade-diameters apart both in the prevailing wind direction and transverse to it. Thus, each of the inner 2-MW_p turbines "occupies" 310,000 m^2, and its power density is 6 W_p/m^2, from the perspective of surface area required[22]. A wedge in the form

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[21] To produce 65 TWh from wind in 2002 would require 2300 hours of operation at peak capacity, or operation for 26% of the year, assuming 28 GW_p average installed peak wind capacity.

[22] The area occupied by the entire Horns Rev wind farm is reported as 20 km^2 (S45), which results in a ratio of peak-power production to wind farm area of $8 W_p/m^2$. The area reported is equal to nine times seven inter-windmill spacings, rather than ten times eight, as if no surface were "occupied" beyond the perimeter of the wind farm.

of 2000 GW_p of wind-for-coal would then require 30 million hectares of surface. If all were on land, this would be between one and two percent of the world's 1800 million hectares of land estimated to have winds of Class 4 and above (S46). Thirty million hectares is also 3% of the land area of the United States. Land from which wind is harvested can be used for many other purposes, notably for crops or pasture.

The land demand for PV is inversely related to the conversion efficiency of sunlight. Here we choose 100 W_p/m^2 for the peak power output from PV divided by the area of the collection site[23], 15 times greater than for wind. Then, a wedge in the form of 2000 GW_p of PV-for-coal requires two million hectares, or 20,000 km^2, of site surface, either dedicated land or multiple-use surfaces such as the roofs and walls of buildings.

Note that in quantifying the wedges of renewable electricity, here, we have not needed to take into account the mix of centralized and distributed generation. Hundred-square-kilometer regions devoted to arrays of photovoltaics or wind farms have been treated as equivalent to large numbers of rooftop PV units or isolated wind turbines.

Greater Electrification as a Consequence of Decarbonization

In searching for wedges, it is important to keep in mind that, in a carbon-constrained world, electricity may displace fluid fuels, especially in distributed uses of energy. Today, when electricity competes as a secondary energy carrier with hydrocarbons in distributed energy markets, such as the markets for vehicle fuel and space heating, it does poorly. Distributed hydrocarbons offer portability in the first instance and thermodynamic efficiency in the second. The electric battery car has not displaced the car powered by gasoline or diesel fuel. The electric resistive heater has not displaced the natural gas furnace. In the future, however, distributed hydrocarbons will carry new costs associated with carbon emissions to the atmosphere: once hydrocarbons are distributed to small users, their carbon cannot be captured and stored. It should become more attractive to charge the battery on a hybrid vehicle at home from the grid between uses. The electric heat pump should become competitive in a larger range of climates.

We judge that, overall, the alternatives for the decarbonization of electricity discussed in this section will enter the market under a weaker carbon constraint than the alternatives for the decarbonization of fuel discussed in the next section. The result will be accelerated electrification: a greater fraction of primary energy used to produce electricity under a carbon constraint than in its absence.

II. The Decarbonization of Fuel

To decarbonize fuels production, there are major targets at both large and small unit scale. At large unit scale, fossil fuels today are used directly to provide industrial high-temperature heat. Under a carbon constraint, fossil fuels may continue to provide this service, while CO_2 is captured and stored. Or, carbon-free or low-carbon hydrogen, produced at large scale, may substitute for fossil fuels.

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[23] On a clear day, the flux of sunlight is 1kW/m^2. Assuming 10% site conversion efficiency (inevitably less than device conversion efficiency), the peak power output per unit of site area is 100 W_p/m^2, and, using our factor-of-three approximation, average power output is 33 W/m^2.

At small unit scale, the principal targets are fuels for transportation and fuels to provide low-temperature heat to buildings. In 2000, as we saw in Table S3, about 3.6 GtC/y of CO_2 emissions were associated with fuels production, and 2.6 GtC/y of CO_2 emissions were associated with electricity production. Of the 3.6 GtC/y, 1.4 GtC/y was associated with oil for transportation. The remaining 2.2 GtC/y, divided remarkable equally between emissions from coal, oil and gas, is associated with direct uses of fuel, but we do not know how much is associated with centralized use by industry and how much with decentralized use in buildings. If we assume that two-thirds is associated with buildings, then on-site dispersed use (buildings and transportation) would account for almost half of carbon emissions. Continuing to use fossil fuels for such uses, but capturing and storing the carbon, is almost surely too costly. Carbon mitigation, instead, is likely to take the form, principally, of the distribution of carbon-free and low-carbon fuels, or the substitution of electricity.

Not only does fuels use come at large and small unit scale, but so, too, does fuels production. This leads to three possibilities: 1) large unit scale in both fuels production and fuels use, as in a steel plant; 2) small unit scale in both fuels production and fuels use, as in home heating from local woodlots; and 3) large unit scale in fuels production connected via infrastructure to small unit scale consumption, as in gasoline for vehicles and natural gas for home heating. The same four approaches that we explored while searching for wedges in the decarbonization of power also span the options for the decarbonization of fuels:

A) Fuel shifting: Natural gas can replace coal as a source of industrial and domestic heat.

B) Carbon capture and storage: There is a large quantity of residual carbon when coal or natural gas is transformed into hydrogen fuel, or when coal is transformed into hydrocarbons. In both cases, the residual carbon can be captured and stored as CO_2.

C) Nuclear energy: Fuels derived from fossil fuels can be replaced by nuclear hydrogen.

D) Renewable energy: Fuels derived from fossil fuels can be replaced by biofuels, renewable electrolytic hydrogen, or solar heat.

All four options compete to provide decarbonized fuels for centralized and decentralized use, but only the fourth option can provide dispersed fuel without an elaborate infrastructure.

Much of what we have written above about decarbonization of electricity in each of these categories applies to fuels as well. Below, for each of these four options we introduce only supplementary material.

A. Fuel shifting: Substituting Natural Gas for Coal in Domestic Heating and Industrial Processes

Coal is widely used for space heating and cooking in many developing countries. Although the extent of this direct use of coal is poorly documented, here may be one of the most important opportunities to have a large positive impact on carbon mitigation and to attack other environmental and public health problems at the same time. Both the indoor pollution associated with poorly ventilated combustion and the outdoor pollution in villages, towns, and cities associated with low-efficiency decentralized coal burning are notorious. Burning the coal more efficiently, more cleanly, and with better ventilation can improve the situation, as can burning coal-derived liquids and gases (synfuels). Given time for natural gas networks to develop, it is also possible to displace coal with natural gas. There may well be a wedge available in the displacement of decentralized coal burning by natural gas in the cities and towns of the developing world, though it may be hard to argue that the wedge is available as a difference between two credible scenarios. A wedge is not available if, over the next 50 years, the elimination of decentralized coal burning is regarded as near certain, even in a world where global carbon does not become a pressing concern.

Coal is also used directly in large centralized applications, notably in steel plants and other metallurgical plants. Displacing such coal is likely to be one focus of decarbonization. Available savings available may well be of the scale of a wedge, through a combination of remaining with coal but capturing and storing the CO_2 produced on the site, substituting hydrogen for coal, and substituting natural gas for coal.

The potential for carbon mitigation via modifications of the energy system where coal is used directly, as best we can determine, is largely unexplored.

B. Synfuels Production and Hydrogen Production with Carbon Capture and Storage:

We discuss two topics in this subsection. We first contend with the possibility that by 2054 oil no longer dominates the transportation sector, presumably for a combination of geophysical and geopolitical reasons, and that coal becomes a substantial source of synthetic carbon-bearing fuels. The impact of such a change in the global energy system for carbon emissions is inherently negative, but we will see that carbon capture and storage offers the promise of undoing some, if not all, of this impact. We then introduce hydrogen, first in general and then with specific reference to hydrogen as a vehicle fuel. This material is intended to serve the two subsequent subsections as well: nuclear hydrogen and renewables hydrogen. We conclude this subsection with a discussion of hydrogen vehicle fuel produced from fossil fuels, with the capture and storage of the accompanying CO_2.

Synfuels with Carbon Capture and Storage

Looming over the 2054 energy scene is the possibility that liquid fuels from petroleum will have become substantially more costly than today, not because of imperfect markets but because of geophysical factors: the cheaper oil may have been largely extracted. For each 100 GtC of carbon emissions from oil, 860 billion barrels of oil are extracted from the ground. By 2000, the world had extracted almost exactly this amount. Estimates of ultimately recoverable conventional oil currently still in the ground are in the range of 2000 ± 1000 billion barrels[24].

It is therefore likely that by 2054 a significant fraction of the fuels used at small unit scale in vehicles and buildings will not come from conventional oil, but from unconventional oil and coal. We specifically identify synthetic fuels (synfuels) from coal here. A synfuel, chemically,

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[24] A good discussion of oil reserve estimates can be found in reference S47, chapter 3. Cumulative consumption by 2000 is estimated as “close to 900” billion barrels (S47, p. 43).

can be any of the current fuels produced from crude oil and natural gas, or a new “tailored” fuel. If large-scale synfuels production from coal occurs, the challenge of global carbon management will become more difficult, because obtaining fuels from coal is significantly more carbon intensive than obtaining fuels from crude oil. However, CCS provides a way to cancel much of the extra carbon intensity of coal-based-fuels, relative to oil-based-fuels (S48). The reason is that in the conversion of coal to synfuels, abundant CO_2 will be produced.

In a modern plant, we estimate that, for each two carbon atoms in coal, one will appear as CO_2 and one in the synfuels. Given that assumption, how much synfuels production is associated with a wedge, when one considers the alternatives of CCS and its absence? A flow of 23.56 mbd of reference crude oil carries a carbon flow of 1 GtC/y.[25] If we assume that synfuels and reference crude oil have approximately the same carbon content and specific gravity, then 1 GtC/y is also 23.56 mbd (rounding off, say, to 25 mbd) for synfuels. We make the rough assumption that, at a 2054 synfuels plant, carbon will leave in equal amounts as vented CO_2 and as product. In that case, a carbon flow of 1 GtC/y in synfuels leaves behind at the coal-to-synfuels plant an equal 1 GtC/y flow of capturable and storable carbon. It follows that applying CCS rather than venting the CO_2 emitted at 25 mbd of synfuels plants is a wedge, if the CCS captures all the carbon, and a wedge is more like CCS deployed at 30 mbd of synfuels plants with less than perfect capture.

Currently, Sasol produces 165,000 barrels per day of synfuels and chemicals from coal in Secunda, South Africa, east of Johannesburg (S49). This is the world’s largest synfuels facility, and it is similar in scale to a typical large refinery. Assuming the average specific gravity and carbon content of these synfuels is the same as reference crude oil, there is a carbon flow of 7 MtC/y in the synfuels leaving the Sasol plant. The Sasol plant is the largest point source of atmospheric CO_2 emissions in the world.

Comparing 165,000 barrels per day synfuels production from Sasol’s plants with our estimate that 1 GtC/y will be available for capture in 2054 from 30 mbd of coal-to-synfuels production, a wedge is an activity that, over 50 years, achieves the ability to capture the CO_2 emissions from 180 Sasol-scale coal-to-synfuels plants.

A synfuels plant can be designed to “polygenerate” both electricity and synfuels from coal, and, as well, to capture and store as CO_2 the carbon not in the synfuels product. Over time, polygeneration could evolve to include a greater proportion of hydrogen production (S48).

An orientation to hydrogen fuel

Today, the two-way competition between electricity and secondary hydrocarbon fuels plays out in arenas as disparate as the home water heater and the steel furnace. It is plausible that this two-way competition will become a three-way competition, with the inclusion of hydrogen fuel. Like electricity, hydrogen is a *secondary* fuel. It has to be made from something else, and it can be made from everything else. Much work is being done to examine how hydrogen may enter the

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[25] The equality of these two carbon flows, 1 GtC/y and 23.56 million barrels of reference crude oil per day (mbd) links the unit of our carbon discussion with perhaps the world’s most widely used unit of bulk energy flow. This equality requires only two assumptions about reference crude oil: Its specific gravity is assumed to be 0.860 (API^{o} = 33.0^{o}), and it is assumed to be 85.0% carbon by weight. Also, 1 barrel = 42 gallons = 159 liters. Multiplying by 365.24 days per year, an alternate form of this equality is that 1 GtC is the carbon in 8.605 billion barrels of reference crude oil.

energy economy. A recent reference is the National Research Council (NRC) report, *The Hydrogen Economy: Opportunities, Costs, Barriers, and R&D Needs* (S38).

Hydrogen is already in widespread use, but as a chemical, not a fuel. Adding hydrogen at a petroleum refinery improves the product mix, and making hydrogen is a necessary first step in making ammonia (NH_3) and nitrogen fertilizer. Currently these two uses, between them, elicit an annual production of 40 MtH_2. Almost all this hydrogen is made from fossil fuels, because it is cheaper than hydrogen produced from nuclear energy or renewable energy; production from fossil fuels does not require the costly intermediate step of electrolysis of water.

The second output when hydrogen is produced from fossil fuels is CO_2. In a carbon constrained world, this will disadvantage fossil fuels as the source of hydrogen, relative to hydrogen produced from nuclear or renewable energy. Currently, at least 100 MtC is vented annually as CO_2, often at high purity, at H_2 production sites (S38, Chapter 7). Hydrogen produced with capture and storage of CO_2 (CCS hydrogen), discussed above because of the overlap with low-carbon coal-based power via gasification and CO_2 capture, will compete with nuclear hydrogen and renewable hydrogen. A 1 GtC/y carbon flow to the atmosphere in hydrogen production from fossil fuels is associated with only a ten-fold increase, relative to today, in hydrogen production. And the technology exists to capture and store this carbon.

CCS hydrogen and nuclear hydrogen can only be produced at large unit scale. Hydrogen produced at large scale can serve distributed users, like light-duty vehicles and buildings, only if there is a hydrogen infrastructure connecting the large with the small. Such an infrastructure does not now exist, and it may be more difficult to create than many other infrastructures. The reason is that a hydrogen infrastructure to provide fuel to dispersed users is in competition with small-scale hydrogen production downstream from two other already existing infrastructures: 1) the electricity infrastructure that facilitates local hydrogen production in small electrolyzers, and 2) the natural gas infrastructure that facilitates local hydrogen production in small methane reformers. If the second of these – the small methane reformer – dominates hydrogen production, the CO_2 generated at such dispersed sites is unlikely to be captured and stored, because of the diseconomies of CCS at small scale, and hydrogen production will not serve the goals of carbon mitigation.

An orientation to hydrogen vehicles

As we already saw in Section 2 of the Supporting On-Line Material (Energy Efficiency and Conservation), a wedge is available from more efficient light-duty vehicles. Specifically, we considered cars on the road in 2054, driven 10,000 miles per year, and achieving either 60 mpg or 30 mpg. As in Section 2 of the Supporting On-Line Material, we attribute 3 kgC of carbon emissions to each gallon of conventional fuel, thereby including a 25% overhead on a fuel carbon intensity of 2.4 kgC/gallon. Then, these cars emit, annually, either half a ton of carbon (at 60 mpg) or a full ton of carbon (at 30 mpg). A strategy that puts on the road in 2054 two billion 60 mpg cars, instead of two billion 30 mpg cars, is a wedge. Clearly, a second wedge can be obtained if these two billion 60-mpg cars run on hydrogen, as long as the carbon emissions associated with the hydrogen production are negligible.

Let us first assume that the substitution of energy as hydrogen for energy as gasoline is one-for-one. Invoking the useful fact that the energy content (lower heating value) of 1 U.S. gallon of gasoline and 1 kg of hydrogen are both almost exactly the same (120 MJ), the one-for-one assumption, therefore, means one ton of hydrogen fuel backs out three tons of carbon emissions at the tailpipe. The hydrogen vehicle gets 60 miles per gallon of gasoline equivalent and is driven 10,000 miles per year, so it requires 170 kg of hydrogen fuel per year and backs out 500 kg of carbon per year in conventional fuels. Two billion cars require 330 million tons of hydrogen per year and back out 330 billion gallons of gasoline or diesel fuel (containing 1 GtC) per year.

Treating the energy stored in hydrogen and stored in gasoline as equivalent leaves out many critical issues. Hydrogen scores less well than gasoline from the perspective of safety and storage. Hydrogen scores better than gasoline, if the full promise of fuel cells can be realized. The NRC Report postulates that fuel cells deliver a 67% premium in energy efficiency for hydrogen, relative to hybrid vehicles running on hydrocarbons (S38, Chapter 4); 100 mpg-equivalent fuel cell cars would displace 60 mpg gasoline or diesel cars, for example[26]. Then, each kilogram of hydrogen fuel backs out five kilograms of carbon in conventional fuel, and each 100-mpg-equivalent hydrogen car requires 100 kgH_2 per year and prevents 500 kgC/y of tailpipe emissions. Where two billion 60-mpg-equivalent cars required 330 million tons of hydrogen per year, two billion cars with a fuel economy of 100-mpg-equivalent require 200 million tons of hydrogen per year.

For the remainder of this section, we will assume the hydrogen fuel cell cars achieve 100 mpg-equivalent, and we will identify several wedges, each associated with a different way of producing, annually, 200 MtH_2 of carbon-free hydrogen, or an appropriately larger amount of low-carbon hydrogen.

CCS hydrogen and CCS-hydrogen vehicles

The NRC report provides flow sheets for a "current" coal-to-hydrogen plant without and with CCS. For each ton of hydrogen produced, if CO_2 is not captured, 5.1 tons of carbon as coal flow through the plant and are vented; if CO_2 *is* captured, 5.2 tons of carbon as coal flow through the plant, of which 4.4 tons of carbon are captured and 0.8 tons of carbon (16%) are vented (S38, Appendix E). Thus, if over the next 50 years, we move to a hydrogen economy with coal as the workhorse for hydrogen production, for each ton of hydrogen produced, the venting of 4.3 tons of carbon is at stake in the decision to deploy CCS technology, rather than to vent the CO_2, at coal-to-hydrogen plants. For each 230 million tons of hydrogen produced from coal in 2054, a wedge is at stake in the decision to deploy CCS technology. The NRC plants are large: the hydrogen production rate is 1200 tH_2/day. A wedge is at stake in the decision to deploy CCS at 500 of these plants.

The NRC report also provides flow sheets for "current" natural-gas-to-hydrogen plants without and with CCS. The NRC data can be anticipated knowing only that half as much CO_2 is produced per unit of energy from natural gas as from coal: For each ton of hydrogen produced, if CO_2 is not captured, 2.5 tons of carbon as coal flow through the plant and are vented; if CO_2 *is* captured, 2.8 tons of carbon as coal flow through the plant, of which 2.3 tons of carbon are captured and 0.4 tons of carbon (16%) are vented (S38, Appendix E). Continuing the reasoning of the previous paragraph, if over the next 50 years, we move to a hydrogen economy with *natural gas* as the workhorse for hydrogen production, for each ton of hydrogen produced, the

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[26] The fuel economies of the NRC hybrid and fuel cell vehicles in 2050 are somewhat less: 50 and 83 mpg, respectively (S38, Chapter 4).

venting of 2.1 tons of carbon is at stake in the decision to deploy CCS technology, and for each 480 million tons of hydrogen produced, a wedge is at stake in the decision to deploy CCS technology. The NRC natural-gas-to-hydrogen plants also have a 1200 tH_2/day capacity. A wedge is at stake in the decision to deploy CCS at 1100 of these plants.

Although, under the assumptions above, 200 MtH_2 of *carbon-free* hydrogen can create a wedge by backing out conventional hydrocarbon vehicle fuel in two billion 60-mpg cars in 2054, how much more hydrogen needs to be produced, for how many additional vehicles, when one takes into account that CCS hydrogen is not completely carbon free?

Annually, each 100 mpg car requires 100 kgH_2, and 80 kgC is emitted at the coal plant when this hydrogen is produced. Then, the net atmospheric carbon emissions reduction in displacing a 60 mpg gasoline car with a 100 mpg-equivalent hydrogen is 420 kgC/y. To eliminate 1 GtC/y of emissions, therefore, requires changing not two billion, but 2.4 billion cars. A flow to the atmosphere at tailpipes of 1.2 GtC/y is replaced by a flow of carbon into CCS coal plants of 1.4 GtC/y, a flow into the atmosphere at CCS coal plants of 0.2 GtC/y, and a flow from the CCS coal plants into storage of 1.2 GtC/y. The net flow to the atmosphere is 1 GtC/y less.

The objective of hydrogen production from fossil fuels is to transfer as much of the energy content of the fossil fuel to the hydrogen as is consistent with optimizing the plant economics. Adding the objective of CO_2 capture complicates the optimization and increases the costs. However, most of the plant components required to capture CO_2 are already required to produce hydrogen. For example, the shift reactor (see Section IB, above) required for CCS is needed for hydrogen production without CCS, but not for power production without CCS. As a result, the fractional cost increment for CCS is substantially smaller in hydrogen production than in electricity production (S38, Chapter 8 and Appendix E).

C. Nuclear electrolytic hydrogen

An orientation to carbon-free hydrogen, applicable to both nuclear and renewable primary sources

Non-carbon energy offers opportunities to carve wedges out of the 2054 carbon economy not only by producing electricity that displaces fossil-energy-based electricity (discussed earlier), but also by producing hydrogen that displaces fossil-energy-based fluid fuels. The non-carbon energy can be either nuclear energy or renewable energy. In both cases, there are two ways of producing hydrogen: 1) via chemical cycles that require high-temperature heat, after first producing that high temperature heat, and 2) by the electrolysis of water, after first producing electricity.

The nuclear power plant capable of delivering heat at sufficiently high temperatures to run the chemical cycles identified thus far (roughly, 900^oC) is not yet proven, nor has high-temperature heat from focusing solar collectors been shown to lead to competitive hydrogen. A good, recent review of nuclear hydrogen, including hydrogen via high-temperature cycles, is available (S38, Chapter 8). If high-temperature nuclear reactors can be developed, they will be capable of producing hydrogen at higher efficiency (hydrogen out divided by nuclear power in) than the route to hydrogen via electrolysis.

Like CCS hydrogen, nuclear thermal hydrogen will be produced only at large unit scale. By contrast, if hydrogen is to be made electrolytically from electricity on the grid, the unit scale of the electricity generator does not determine the unit scale of production of hydrogen. Instead, the unit scale of production of hydrogen will be determined by the unit scale of the electrolyzer. The scale for which the NRC Report develops flow sheets for electrolysis is 480 kilograms of hydrogen per day, 2500 times smaller than the scale of production of hydrogen from coal plants with CCS.

The "present" electrolyzer in the NRC Report is assumed to produce 1 kg of hydrogen from 52.5 kWh of electricity, or 19 grams of hydrogen per kWh, an efficiency of 75% based on the higher heating value of hydrogen, or 63.5% based on its lower heating value. Then, in the vehicle substitution strategy that we have been considering where 1 kg of carbon-free hydrogen backs out 5 kg of carbon, each 1 kWh of carbon-free electricity backs out 95 g of carbon.

Given carbon-free electricity, can carbon emissions be reduced more by directly backing out coal in a power plant or by making hydrogen and backing out gasoline or diesel?

The same kWh of carbon-free electricity just considered, which we directed toward hydrogen production for a fuel-cell car, instead could have backed out coal power. Which strategy backs out more carbon: Using a carbon-free kWh to make hydrogen for a 100 mpg fuel-cell car that removes a 60 mpg vehicle from the road, or using a carbon-free kWh to make electricity that keeps a coal power plant from running?

Suppose the same carbon-free kWh had been used to back out a kWh produced in one of the reference 50%-efficient coal power plants discussed above. Earlier, we worked out that each kWh at the coal plant produced 186 g of carbon emissions, so each carbon-free kWh used to produce electricity avoids 186 g of carbon emissions that would have been emitted at a coal plant. Here, we just worked out, each carbon-free kWh used to produce hydrogen avoids 95 g carbon that would have been emitted by a gasoline engine. Thus, we have the intriguing result that carbon-free electricity reduces carbon emissions twice as effectively when directed toward the displacement of coal-based electricity than when directed toward the displacement of gasoline fuel via electrolytic hydrogen.

The factor of two advantage of the coal-substitution strategy over the gasoline-substitution strategy for carbon-free electricity is the result of three assumptions: coal power plant lower-heating-value efficiency (C), electrolyzer lower-heating-value efficiency (E), and premium for hydrogen fuel, expressed as the number of kg C displaced by 1 kg H (R), all dimensionless numbers. The relative advantage of the coal strategy over the gasoline strategy in reducing carbon emissions – let's call it, the "electricity preference factor" – turns out to be 3.1/(CxExR). For our particular assumptions, C = 0.5, E = 0.635, and R = 5, the electricity preference factor is 1.9, or, approximately, two.

The electricity preference factor is *more* than a factor of two, if either C or E or R is less, relative to our inputs, while the other two are unchanged. The electricity preference factor is more than two, if C is less than 0.5, i.e., if the coal plant is less than 50% efficient, because then more coal is backed out. The electricity preference factor is more than two, if E is less than 0.635, because, with a less efficient electrolyzer, less hydrogen fuel is made. The electricity preference factor is more than two, if the multiplier is less than five for hydrogen in a fuel-cell vehicle relative to a gasoline vehicle, which would result, for example, if the fuel cell car is less spectacular.

We turn this comparison into a comparison of alternative wedges. We have considered three wedges that could be achieved starting from carbon-free electricity: 1) a wedge via carbon-free electricity displacing coal-based electricity; 2) a wedge via carbon-free electricity displacing natural-gas-based electricity; and 3) a wedge via carbon-free electrolytic hydrogen displacing conventional vehicle fuel. The first wedge is the most effective, requiring 5400 TWh/y. The second and third wedges are about equally demanding: the second wedge requires 10,800 TWh/y. The third wedge requires 100 kgH_2 per car per year in two billion cars, or 200 MtH_2/y. To produce such a wedge using our electrolyzer requires about 10,000 TWh/y of carbon-free electricity.

Nuclear electrolytic hydrogen is carbon-free hydrogen, except to the extent that fossil energy is used in the nuclear fuel cycle, in plant construction, etc. Assuming such “net carbon” issues can be neglected, all of the calculations above for carbon-free hydrogen apply. A wedge via nuclear electrolytic hydrogen used in very efficient fuel cell cars requires 10,000 TWh of annual nuclear power by 2054. This is four times the rate of production of nuclear power in 2000, 2600TWh/y, a statistic quoted earlier (S33, p. 411). Assuming nuclear plants with 90% capacity, a wedge requires the hydrogen produced from 1300 1 GW plants.

Compare with our earlier result that a wedge is 700 1 GW nuclear plants displacing coal power. We see the factor of two advantage of coal displacement relative to gasoline displacement at work here: it takes twice as much nuclear power to achieve a wedge via electrolytic hydrogen for fuel cell cars as via direct substitution for coal power.

Carbon emissions when grid-based electricity produces hydrogen

One can make hydrogen from coal either by the thermochemical processes discussed above or by electrolysis. The thermochemical route from coal to hydrogen yields 1 kgH_2 from 5 kgC in coal. The electrolysis route from coal to hydrogen produces 1 kWh from 186 gC in coal, and then requires 52.5 kWh for the electrolyzer to produce 1 kgH_2; as a result, the electrolytic route yields one kg H_2 from 10 kgC in coal. Thus, the thermochemical route from coal to hydrogen is twice as efficient as the electrolysis route.

Suppose we use grid electricity, rather than carbon-free electricity, to power the electrolyzer. Grid electricity averages over *all* sources. In 2000, 15,400 TWh of electricity were produced from all sources, and a total of 2.36 GtC was emitted to the atmosphere from all plants with fossil fuel sources (S33, pp. 410 and 411), resulting in an average carbon intensity for the current grid of 153 gC/kWh. Our electrolyzer, which uses 52.5 kWh to produce 1 kgH_2, results in the emission of 8.0 kgC when it produces 1 kgH_2 from grid electricity. This is *more* carbon than the 5 kg of tailpipe carbon displaced by 1 kg H_2 as fuel (for our strategy where 100 mpg-equivalent hydrogen fuel cell cars replace 60 mpg gasoline cars). Globally averaged grid electricity at present is too carbon rich to be a source of carbon savings via electrolytic hydrogen and fuel cell cars. Of course, there will be many local situations where completely carbon-free or relatively carbon-free electricity is available.

D. Renewable Fuel: Renewable Hydrogen, Solar Heat, Sustainable Biofuels

We discuss three ways in which renewable energy can produce wedges by decarbonizing fuel. Hydropower, wind power, and photovoltaic electricity can produce hydrogen via electrolysis. Direct sunlight can provide heat that backs out fossil fuels used for space and water heating in buildings. And, plant matter (biomass) can be converted into fuels.

Electrolytic hydrogen from renewables

Electrolyzers producing hydrogen do not know the difference between renewable electricity, nuclear electricity, and other sources of electricity. Thus, the result above, that 1 kg of hydrogen can be produce from 52.5 kWh of electricity, based on the NRC electrolyzer, holds for renewable energy as well. A wedge from our car substitution strategy requires 10,000 TWh/y of renewable electricity. This may be compared to the 2002 global rate of production of electricity from hydropower, 2650 TWh/y, four times less and almost exactly the same as the rate of production of electricity from nuclear energy (S33, p. 411).

While nuclear electricity comes only at large unit scale and must be grid-connected, renewable electricity comes at all scales. It can produce distributed power, and it can produce grid-independent power. A wedge from 10,000 TWh/y of renewable electricity making hydrogen that eliminates tailpipe carbon emissions could be produced by four million 1 MW_p windmills or four hundred million 10 kW_p photovoltaic arrays, operating at 30 percent capacity factor.

Solar heat

One can associate each use of fuel with a temperature required to meet the need that the fuel is serving. Two of the most important uses of fuel, from the standpoint of carbon emissions, are heating of living spaces and heating of water, and both involve supplying heat at a temperature not very different from nearby “ambient” temperatures (the temperatures of nearby outside air or ground water, for example)[27]. The jobs of space heating and water heating rarely involve boosting the temperature, relative to ambient temperature, more than 50^oC. Thermodynamics identifies the combustion of fuels for such purposes as intrinsically inefficient (S50). Wedges are available from displacing carbon emissions from the chimney, just as they are available from displacing carbon emissions from the tailpipe.

We commented earlier in this section that the heat pump, in principle, offers significant carbon savings in space and water heating. We noted in Section 2 of the Supporting On-Line Material that the insulation of buildings offers similarly large savings. Here we note that still a third strategy is to pursue passive and active solar energy management, the domain of solar architecture, to heat buildings in winter and to heat water year round. A full wedge is probably available from judicious combinations of solar design, careful construction, substantial insulation, and broad use of efficient heat pumps. Detailed estimates remain to be done.

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[27] To quantify how “different” one temperature is from another temperature, one must introduce the concept of absolute temperature, which is 273 degrees higher than Celsius temperature. The transfer of heat from outside air at 0^oC to hot water at 50^oC is a fractional increase in its absolute temperature of 50/273, or 18%.

Sustainable biofuels

At least one wedge is probably available from each of two distinctly different strategies involving changes to vegetation. One can enlarge the stock of carbon in vegetation (enlarging the carbon stored in forests, for example), thereby drawing down the stock of carbon in the atmosphere. This topic will be addressed in Section 4 on the Supporting On-Line Material (Forests and Agricultural Soils). It is also possible to replace fossil fuels with fluid fuels produced directly from plant matter (biomass) that is grown sustainably. In the latter case, the use of "biofuels" makes no net addition of CO_2 to the atmosphere; the biofuels oxidized for energy deliberately through technology would have decayed (oxidized) elsewhere anyway (wood on the forest floor, for example). A sustainable biofuel is one obtained from plants that are replaced by new plants at the same rate as they are used.

A hectare of land used to produce biofuels has the potential to have a larger effect on the atmospheric carbon balance than a hectare of land used as a carbon sink. There are two reasons: 1) Most of the new carbon fixed by vegetation each year is allocated to construct short-lived and fast–decomposing tissue, such as leaves and fine roots. Because of its short residence time in ecosystems, such tissue cannot contribute substantially to a carbon sink, but it can be collected and used to produce biofuels. 2) A hectare of land dedicated to biofuels can produce these fuels indefinitely, displacing a stream of fossil carbon indefinitely, whereas a hectare of land used as a carbon sink has a certain capacity to store carbon and then its contribution to carbon accounts "saturates."

Examples of biofuels crops include switchgrass, sugarcane, and corn (S51). A good yield from such annually harvested species is 15 dry tons (dt) per hectare per year. Dry biomass is about 50% carbon by weight, so the carbon yield is 7.5 tC/ha-y, and the yield from 130 million hectares (Mha) dedicated to such biofuels (biofuels plantations) is 1 GtC/y. This is 10 percent of today's 1500 Mha of total cropland.

The energy content of biomass fuel is between 15 and 20 GJ/dt. (The lower value is appropriate for crops, the higher value for wood.) Thus, a good energy harvest is about 200 to 300 GJ/ha-y. This harvest may be restated as 0.7 W/m^2 to 1.0 W/m^2. Comparing this harvest with annually averaged incident sunlight, typically 250 W/m^2, the harvest is seen to convert 0.3 to 0.4 percent of incident sunlight. Such a low conversion rate, even for a high-yield species, is confirmation that the conversion of incident sunlight via photosynthesis has been only one of many objectives of green-plant evolution. Accordingly, there is considerable headroom for genetic engineering to improve substantially on such yields with organisms designed to convert sunlight efficiently into fuel (artificial photosynthesis), greatly reducing the land demands for a future wedge from artificial biofuels, relative to biofuels from nature's plants.

How are biofuels likely to be used? The current energy economy demonstrates clearly that liquid and gaseous fuels that contain carbon are the most valuable forms of energy. We should anticipate that biomass will be transformed preferentially into biofuels, rather than into electricity or hydrogen. As discussed earlier in this Section, biomass conversion into electricity could also become significant, via distributed production and via co-firing with coal. But biomass conversion to hydrogen is unlikely to become important. Hydrogen is not an intrinsically desirable fuel. Its virtue, from a climate perspective is that it does not contain fossil carbon and can be produced with relatively low fossil-carbon emissions. Biofuels already share this virtue[28].

The International Energy Agency estimates that the total energy in biomass providing "primary energy" for human needs in 2000 was 45 EJ, roughly 10% of that year's total primary energy (420 EJ). It further estimates that the non-OECD countries accounted for 85% of this bioenergy (S33, p.411). Most non-OECD bioenergy consumption is "traditional biomass," including firewood, crop wastes, dung, and charcoal. In both the OECD and non-OECD countries, there is a substantial contribution from wood waste in commercial forestry.

Currently, the principal "modern" biofuel is ethanol. In 2002, global fuel ethanol production was 22 billion liters/y, or 380,000 barrels per day, 95% of which was produced in two large national programs: by Brazil (from sugarcane) and by the U.S. (from corn). In both cases, the ethanol is used as automobile fuel, backing out petroleum products. The production rate in Brazil in 2002 for fuel ethanol was 12.6 billion liters/y, or 220,000 barrels per day (S52), about equally in anhydrous and hydrated forms (S53)[29]. The production rate in the U.S. in 2002 was 8.2 billion liters/y (S52), or 140,000 barrels per day[30]. In the U.S., ethanol accounted for about one percent of the energy content of vehicle fuels (S55); it was used in 12 percent of fuel at 10% blend.

Taking 21.1 MJ to be the energy available in a liter of ethanol[31], 0.46 EJ/y is the primary energy production associated with 2002 global ethanol production, which is 1% of all primary biomass energy, and 0.1% of all primary energy. Since ethanol is 52% carbon, a liter of ethanol contains 0.41 kgC,[32] and a gallon of ethanol contains 1.55 kgC, about two-thirds of the volumetric carbon content of gasoline or diesel fuel. The current ethanol flow of 22 billion liters per year is a renewable carbon flow of 9 MtC/y, not much larger than the non-renewable carbon flow in Sasol's coal-derived synfuels (7 MtC/y, see above). The 2002 renewable carbon flows in Brazil's and the U.S.'s ethanol programs were 5.2 and 3.4 MtC/y, respectively.

Ethanol is currently the principal modern biofuel, because in the natural world there are bacteria that can produce ethanol by fermentation with high selectivity. A world with extensive biofuels production can be expected to produce a wide range of biofuels, including methanol, dimethyl ether (DME), and "biodiesel" fuels[33].

What amount of land produces a wedge, when its harvest of fast-growing biomass is converted to ethanol that backs out conventional vehicle fuels? We assume that ethanol is produced from

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[28] Another "driver" of the energy economy toward hydrogen in many countries is hydrogen's ability to reduce dependence on imported oil and gas, when hydrogen is made from domestic energy sources. Biomass shares this advantage too.

[29] Brazil's 2002-2003 total rate of consumption of ethanol, 12.5 billion liters/y, is the sum of: 1) 5.6 billion liters/y as hydrated ethanol, blended into all gasoline sold in Brazil at a percentage in the low 20s, and 2) 7.0 billion liters/y as anhydrous ethanol, used in engines adapted for pure ethanol (S53).

[30] A different source reports that in 2003 U.S. fuel ethanol production was 10.6 billion liters/y (S54), or 180,000 barrels per day.

[31] The lower heating value (LHV) heat of combustion of liquid ethanol is 26.8 MJ/kg, and its specific gravity is 0.789. Then, the heat released (LHV) in the ethanol combustion 21.1 MJ/liter; equivalently, the combustion of 48 liters of ethanol release 1 GJ.

[32] We again use the specific gravity of ethanol, 0.789.

[33] The term "biodiesel" is confined to esters of natural vegetable oils. Biodiesel production is expanding rapidly in Europe. An annual biodiesel production capacity of 1.4 billion liters in Europe and 1.5 billion liters globally was in place in 2002 (S52).

biomass with 50% energy conversion efficiency. Then, 100 to 150 GJ of ethanol, or 5000 to 7000 liters of ethanol, are produced per hectare[34]. We further assume that engines designed for ethanol, taking advantage of its high octane rating, can convert fuel energy into energy for driving 25% more efficiently than engines designed for conventional fuel, at the same level of engine engineering. Our reference fuel-efficient conventional vehicle, again, is driven 10,000 miles per year with 60 mpg fuel economy, and so uses, annually, 167 gallons of gasoline. The energy content of this gasoline is 20 GJ. Then, annually, the ethanol car will use 16 GJ of ethanol, produced from 32 GJ of biomass. Assuming an average value of 250 GJ biomass yield per hectare, one-eighth of a hectare of dedicated land will be required for each car[35].

Using, as above, 3 kgC/gallon for conventional fuels (which includes 25% carbon overheads in fuels production), the carbon saved annually per car is half a ton. A wedge is the replacement, by 2054, of a fleet of 2 billion reference cars running on conventional fuels by cars fueled by ethanol. The ethanol for a wedge is produced from high-yield energy crops grown on 250 million hectares, an area equal to one-sixth of the world's cropland. It is an ethanol program producing 1000 billion liters of ethanol per year, which is roughly 100 times larger than the current Brazilian or U.S. program, or 50 times larger than the total global program.

Much of the land that would have to be dedicated to annually harvested biofuels crops to gain a wedge would also be suitable for conventional agriculture. Land resources can be stretched by obtaining biofuels from residues of commercial crops (examples include bagasse from sugarcane, corn stover, and rice husks) and from harvest and mill residues of forest plantations.

Not included here are CO_2 emissions associated with fossil-carbon inputs accompanying ethanol production (inputs for feedstock production and for conversion of feedstock to ethanol). The ratio of fossil fuel input to ethanol output currently ranges from about 10% for Brazilian sugar to near unity for U.S. corn (S52).

Biofuels production has one special feature often mentioned in connection with carbon management: If biomass is co-fired with coal in coal power plants with CCS or in coal-to-hydrogen plants with CCS, the carbon removed from the atmosphere during biomass growth ends up below ground. Via biomass, the atmosphere is scrubbed of CO_2. Atmospheric scrubbing via biomass conversion with CCS is likely to remain a small activity, however, if one accepts that biofuels, not electricity or hydrogen, are the preferred products of biomass production, and that most biomass energy conversion is likely to be at a smaller scale than is required for CCS.[36]

Large-scale scrubbing of CO_2 from the atmosphere may be feasible someday, not via storage of CO_2 containing the carbon "captured" by biomass, but via storage of CO_2 captured directly from

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[34] This value of ethanol production per hectare per year is similar to Brazil's today from sugarcane, and twice the value in the U.S. today from corn (S52).

[35] The annual carbon flow per car is as follows: one-eighth of a hectare of biomass is, equivalently, 30 GJ, 2 tons, or 800 kgC. From the 800 kgC in biomass we produce 300 kgC in ethanol which backs out 400 kgC in gasoline. Including carbon overheads on the gasoline, 500 kgC of gasoline-related fossil-carbon are not emitted to the atmosphere. (Here, gasoline is 85% carbon, its LHV heat of combustion is 43 GJ/t, and its specific gravity is 0.74.)

[36] If the biomass feedstock has a higher C/H ratio than the biofuel product, there may be a CO_2 coproduct. For example, the C/H ratio of biomass – approximately, CH2O – is 0.50, which is higher than the C/H ratio of ethanol (C_2H_5OH), which is 0.33. A simplified ethanol production reaction produces excess CO_2: $3\ CH_2O \rightarrow C_2H_5OH + CO_2 + H_20$. Therefore, biofuels production at very large scale could provide be an opportunity for carbon capture and storage.

the air at large dedicated chemical absorption facilities (S56, S57). Such air scrubbing technology, like nuclear fusion electricity, nuclear thermal hydrogen, and artificial photosynthesis, may provide “second-period wedges” in the second half of the century. All of these technologies have the potential to reduce 2104 carbon emissions by 1 GtC/y or more, and to reduce carbon emissions over the interval 2054-2014 by 25 GtC or more, relative to some plausible BAU for 2054-2104. But they probably do not have the potential to provide “first-period wedges” in 2004-2054, the subject of this paper. Assigning technologies to “first-period wedges” and “second-period wedges” may be a fruitful exercise.

Putting It All Together

The emissions profile of any specific carbon-responsive global economy can be described by a 3x3 carbon emission matrix for 2054 (three fuels, three sectors of the energy economy), like the two matrices presented at the beginning of this section (Tables S3 and S4). In particular, if the Business As Usual world in 2054 is chosen to be the 14 GtC/y matrix displayed in Table S4, then the carbon-responsive world is found by removing seven GtC/y from the entries in that matrix. The sum of the entries in the new matrix (all in GtC/y) will be seven[37].

We have introduced a large number of wedges that might be developed over the next fifty years as global carbon mitigation strategies. The number of different ways of choosing the seven wedges to fill the stabilization triangle is very large. Some strategies capable of providing one wedge may be able to provide two wedges. Some wedges included in one person’s Stabilization Triangle will be considered part of Business As Usual by another person.

To stimulate discussion, we introduce a carbon-responsive matrix here, displayed in Table S5 and in Figure S2, bottom right. Here, as before, we restrict ourselves to integer entries. Relative to Table S4, of the three fuels, it is coal whose emissions we have most sharply reduced. Of the three sectors, it is transportation whose emissions we have least sharply reduced. Natural gas continues to provide fuel for high-value distributed uses, where carbon emissions are at too small a unit scale to be captured and stored. The extensive use of decentralized coal in developing countries for space heating has come to an end.

Many combinations of wedges to decarbonize the electricity sector are compatible with the top row of this 3x3 matrix. From the entries in the first row, one cannot infer the relative contributions of end use efficiency, nuclear power, renewable power, and CCS technology. Similarly, from the entries in the third row, one cannot discern the relative roles of efficiency, solar architecture, and industrial hydrogen in reducing carbon emissions from direct fuel use.

One can easily argue the merits of a transfer of one unit of emissions from one matrix element to another in Table S5. We note in particular that by placing a *1* where coal intersects transportation we are asserting that synfuels will be used extensively for transportation. Here, we are being consistent with the 14 GtC/y 3x3 BAU matrix proposed at the beginning of this section, where the same assumption was made. A world where synfuels from coal are not a significant source of

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[37] An exception arises if one wedge or more is obtained by the storage of carbon in the biosphere, as discussed in the Supporting On-Line Material, Section 4. In this case, the sum of the entries in the matrix of 2054 carbon emissions can be more than seven. Each wedge of carbon storage in the biosphere allows an additional 1 GtC/y of emissions in 2054.

vehicle fuel would have a *3* where oil and transportation intersect and a blank entry where coal and transportation intersect.

Table S5, and any corresponding table the reader may propose, says nothing about *how* such wholesale decarbonization is to be accomplished. Industrial structures, carbon policies, targeted subsidies, international relationships, geophysical realities, research and development priorities, changes in behavior and values, and other crucial factors remain unspecified.

SECTION 4: FORESTS AND AGRICULTURAL SOILS

When evaluating methods of biological carbon sequestration, it is important to remember that ecological carbon reservoirs are dynamic. Each carbon atom taken from the atmosphere by the growth of a newly planted forest will eventually return to the atmosphere when the tissue that contains it dies and decomposes. Thus, biological sequestration occurs only if the size of an ecological carbon pool is permanently increased by a net transfer of carbon from the atmosphere to an ecosystem. For example, suppose that a region of cropland is converted into a mosaic of periodically harvested plantation forests, with an even age distribution of forest stands ranging from those newly harvested to those just before harvest. This conversion will remove carbon from the atmosphere because the total mass of carbon (living and undecomposed organic matter) in a mosaic of plantation forests is larger than the mass of carbon in cropland. The difference in carbon mass (plantation mosaic minus cropland) represents a one-time net transfer of carbon from the atmosphere to the land, even though each patch of forest in the plantation mosaic is periodically harvested.

The dynamic nature of ecological carbon pools also implies that options of biological sequestration cannot be relied upon indefinitely, simply because the sizes of ecological carbon pools cannot be increased forever.

Reduced Tropical Deforestation

The 1.5 billion hectares of tropical forests contain 7-10 wedges worth of carbon in living trees and another 5-9 wedges in soils (S10, S58-S61). When primary forest (forest that has never been logged) is converted to permanent cropland, all of the 120-165 tC/ha in living trees (S10, S59, S60) and up to one third of the 83-150 tC/ha in the top 1 meter of soil is emitted to the atmosphere (S10, S59, S60, S62, S63). Conversion to pasture emits the carbon in trees, but may actually increase soil carbon by up to 10% (S64).

Section 1 of the Supporting On-Line Material and (S10) review the current controversy about the size of the carbon source caused by tropical deforestation. Briefly, a recent satellite survey concludes that a net of ~ 6 million hectares of tropical forest were lost per year in the 1990's (S11 and see S12), whereas surveys based on FAO statistics (S65) conclude that loss rates were twice this high. This leads to a factor of two difference in emissions to the atmosphere: ~1 vs. ~2 GtC/y (S10).

We make the conservative assumption that deforestation emissions are ~1GtC/y and that they will decrease linearly by one half in fifty years (see Section 1, above). Thus, half a wedge could be achieved by cutting deforestation to zero in fifty years. On the other hand, if deforestation losses were 2 GtC/y, then elimination of deforestation by 2054, relative to elimination of half of deforestation by 2054, would create a full wedge. Previous studies that rely on relatively large estimates of deforestation losses (S62, S63) have also concluded that approximately one wedge could be filled by reduced tropical deforestation by 2050.

Approximately 40% of current tropical deforestation is in Latin America, and approximately 30% each in Africa and Asia (S63). According to S66, the primary causes of deforestation differ among the continents, with pasture for cattle dominating in Latin America, fuel wood and cropland co-dominating in Africa, and cropland dominating in Asia. Thus, future decreases in deforestation would imply reduced future land area in food production.

Temperate and Boreal Forest Sink

Forest clearance, primarily for cropland, was responsible for 87% of the net of 136±55 GtC transferred from the terrestrial biosphere to the atmosphere from 1850 to 1998 (S62). A small portion of these net emissions is now being reclaimed because of changes in land use in the temperate and boreal zones. The forest sink in the United States, Canada, Russia, and Europe is approximately 0.7 GtC/y, but with wide uncertainty (S8). The largest contributor is the United States (0.3 GtC/y), where the sink is caused primarily by land use change (S14, S67, S68). For example, over the last 50 years in the eastern United States, the annual increase in above-ground carbon in wood (0.3 GtC/y) was larger than harvest by 0.1 GtC/y (S67). Growth rates do not appear to have increased because of CO_2 fertilization in these forests (S14). Even if models of CO_2 fertilization were correct (see S69), the few percent increase in growth predicted because of CO_2 fertilization would not be enough to overturn the conclusion that the sink is caused overwhelmingly by agricultural abandonment and harvest practices. Although increasing growth rates are observed in some European forests, these are also probably due to changes in management (S70).

There are three ways to increase the northern forest sink. One could increase the carbon gain rate of existing forests, decrease the carbon loss rates, or increase forest area. The IPCC (S62, S63) proposes all three, and estimates that 60% of a wedge could be obtained from northern forests. However, a large fraction of this increase would come from controlling fire and insect pests to decrease carbon loss rates (see Figure 4.8 in S63). Although it is feasible to increase carbon storage in this way, the option is unusual, in that fire and pest control would have to continue effectively forever. By simply relaxing effort, all of the newly stored carbon would return to the atmosphere. (Other options, such as reforestation, could also be reversed, but only if an action, clear-cutting, were taken.) For this reason, we do not include pest and fire management in our analysis, and we conclude that substantially less than a wedge is available from changing the management of temperate and boreal forests, at least using technology that is already deployed at large scale today.

The half wedge mentioned in the text from reforestation or afforestation is calculated from the following simple model of the build-up of carbon in forests after planting:

$$C'(t) = S - C(t)/R,$$

where $C(t)$ [tC/ha] is the wood carbon stored per forest area at a time t [years] after planting, $C'(t)$ [tC/ha-y] is its rate of change, S [tC/ha-y] is the rate of wood carbon gain per forest area, and R [years] is the residence time of carbon in the ecosystem. We assume the forest gains carbon at a constant rate, so S is independent of time. Then, the wood carbon climbs to a plateau, $C(t) \sim RS$, after many multiples of R. The net increase in stored wood declines steadily:

$$C'(t) = Se^{-t/R}.$$

We define the sink at the end of the period of interest, T [years], to be K [tC/y]. (For a half wedge, T = 50 years and K = 0.5 GtC/y.) We further define $A(t)$ [ha] to be the amount of land in forest at time t, and $P(t)$ [ha/year] to be the rate of planting: $P(t) = A'(t)$. We find the rate of planting by requiring the total sink to grow linearly at all intermediate times: at time t, the sink is $(K/T)t$.

Equating the total sink at time t to the integral over the contribution to the sink from all previous times of planting (y):

$$Kt/T = \int_0^t [P(y) \text{ x } C'(t-y)]dy,$$

or, $$(K/ST)te^{t/R} = \int_0^t [P(y) \text{ x } e^{y/R}]dy,$$

Differentiating both sides yields the planting rate at time t:

$$P(t) = (K/ST)[1 + t/R]$$

The planting rate increases, to compensate for the older average age of the forests already established. The planting rate increases linearly. The total area planted by time T is:

$$\mathrm{A(T)} = \int_0^T P(t)dt = (K/S)[1 + T/(2R)]$$

Typical values for the tropics are R = 50 years and S = 3 tC/ha-y; typical values for the temperate zone are R = 100 years and S = 1.5 tC/ha-y. Inserting T = 50 years and K = 0.5 GtC/y, we find that a half-wedge can be obtained by reforestation and afforestation of 250 Mha of tropical forest by 2054: the initial planting rate is 3.3 Mha/y, by 2054 the planting rate is 6.7 Mha/y, and over the 50 years the average planting rate is 5 Mha/y. A half-wedge can also be obtained by reforestation and afforestation of 417 Mha of temperate forest by 2054: the initial planting rate is 6.7 Mha/y, by 2054 the planting rate is 10 Mha/y, and over the 50 years the average planting rate is 8.3 Mha/y.

The half wedge mentioned in the text from storage of carbon on new plantations is calculated as follows. We assume that plantations gain carbon at a roughly constant rate, Z, [tC/ha-y], from planting through harvest, and that the number of years between harvests is r [y]. We assume a mosaic of plantations of area A [ha], with a uniform age distribution, so the mosaic contains a $AZr/2$ tons of carbon. By 2054, these plantations need to store 12.5 GtC to contribute half a wedge. This requires $25/Zr$ billion hectares of new plantations to be established by 2054. Note that the product, Zr, is simply the yield at harvest. If the yield at harvest is 80 tC/ha, then 313 million hectares of plantations have to be established by 2054 to achieve the half wedge. The current rate of formation of new plantations, 3.2 million hectares per year (S62), if continued for 50 years on previously unforested land, is already sufficient to create one quarter of a wedge. Also, 313 million hectares is approximately five times larger than the current 61 million hectares in plantations (S62, S65).

Agricultural Soils

Conversion of natural vegetation to annually tilled cropland results in the loss, on average, of one third of the soil carbon if the land was formerly forested, and of one half of the soil carbon if the land was formerly in grassland or pasture (S62, S64). Over historical time, approximately 55 Gt of carbon has been lost on the 1600 million hectares of cropland (S58, S63).

Soil carbon loss can be reversed by techniques that increase the rate of carbon input into agricultural soils or decrease the rate of carbon loss. The former include techniques to reduce the period of bare fallow and the planting of cover crops. The latter include conservation tillage practices that reduce aeration of the soil, such as no till, ridge till, or chisel plow planting (S62, S71). Experiments have shown that it is possible to reverse the loss of soil carbon on croplands with these techniques (S71- S73) and to store carbon at an average rate of 0.3-0.6 t/ha-y over a period of several decades (S62, S72-S74). The lower storage rate, if it could be continued for 50 years, would store the 25 GtC required to contribute a wedge if it were applied to all cropland.

Soil management strategies that increase soil carbon are already widely adopted. Conservation tillage alone had been adopted on 110 million hectares by 1995 (S74). The IPCC estimated that up to a wedge (up to 22-29 GtC) could be filled by management of existing agricultural soils (S63, S75).

Figure S1 (A)

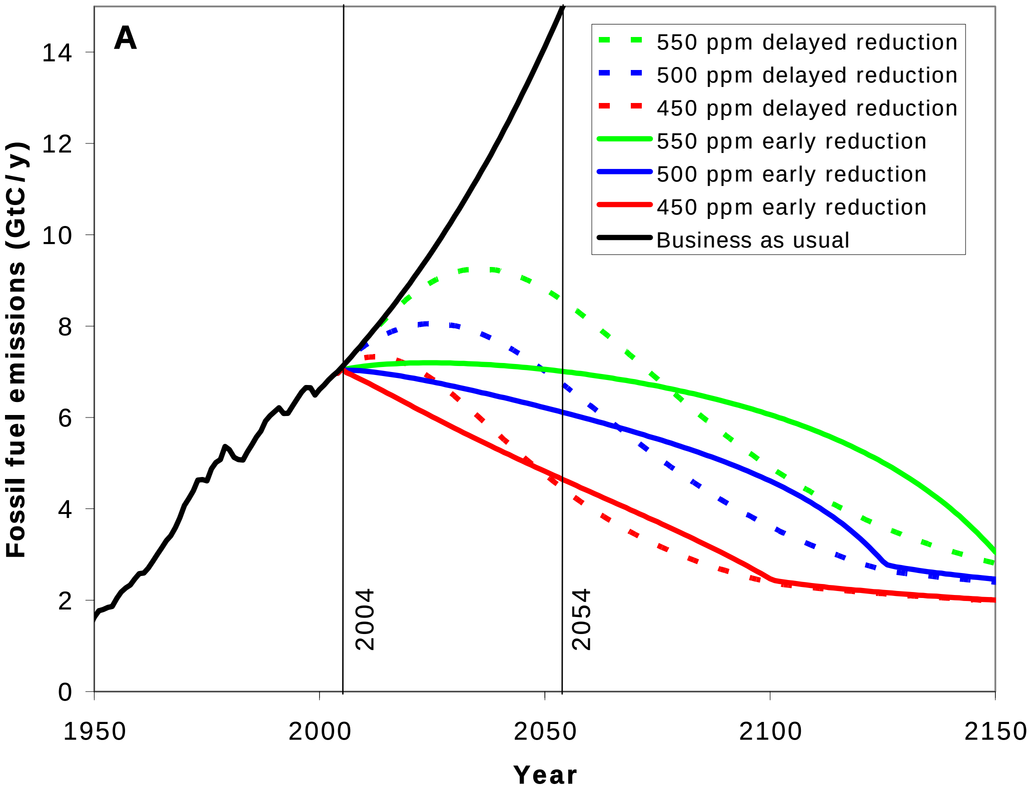


Figure S1 (B)

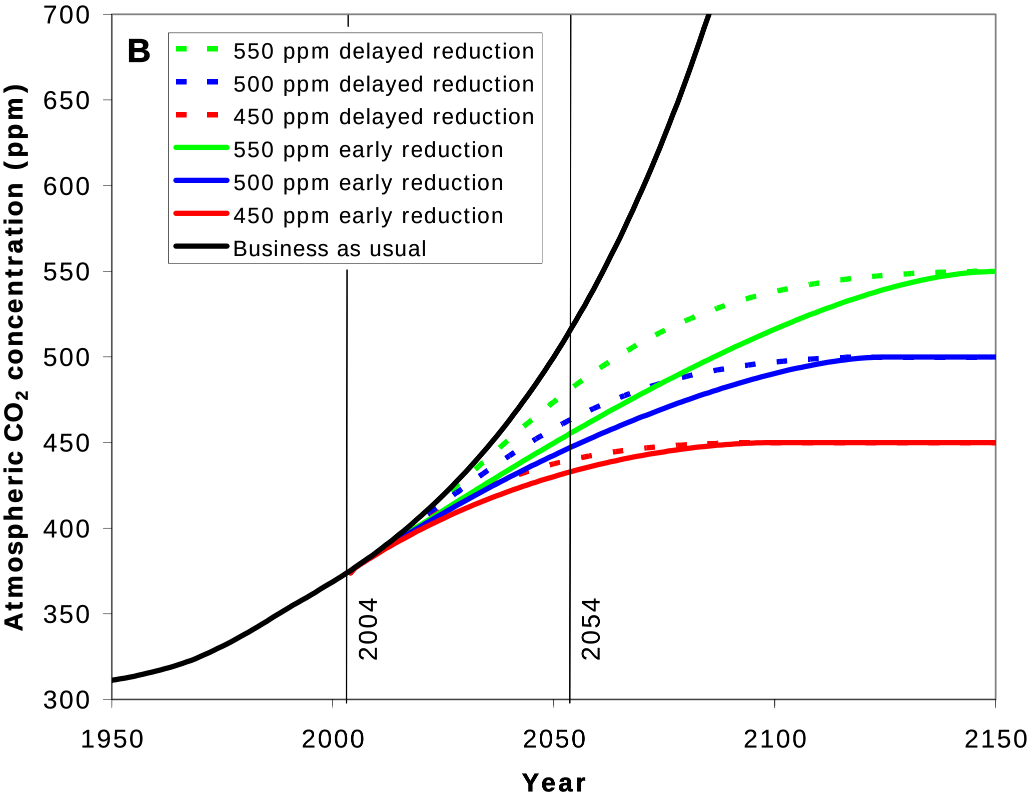
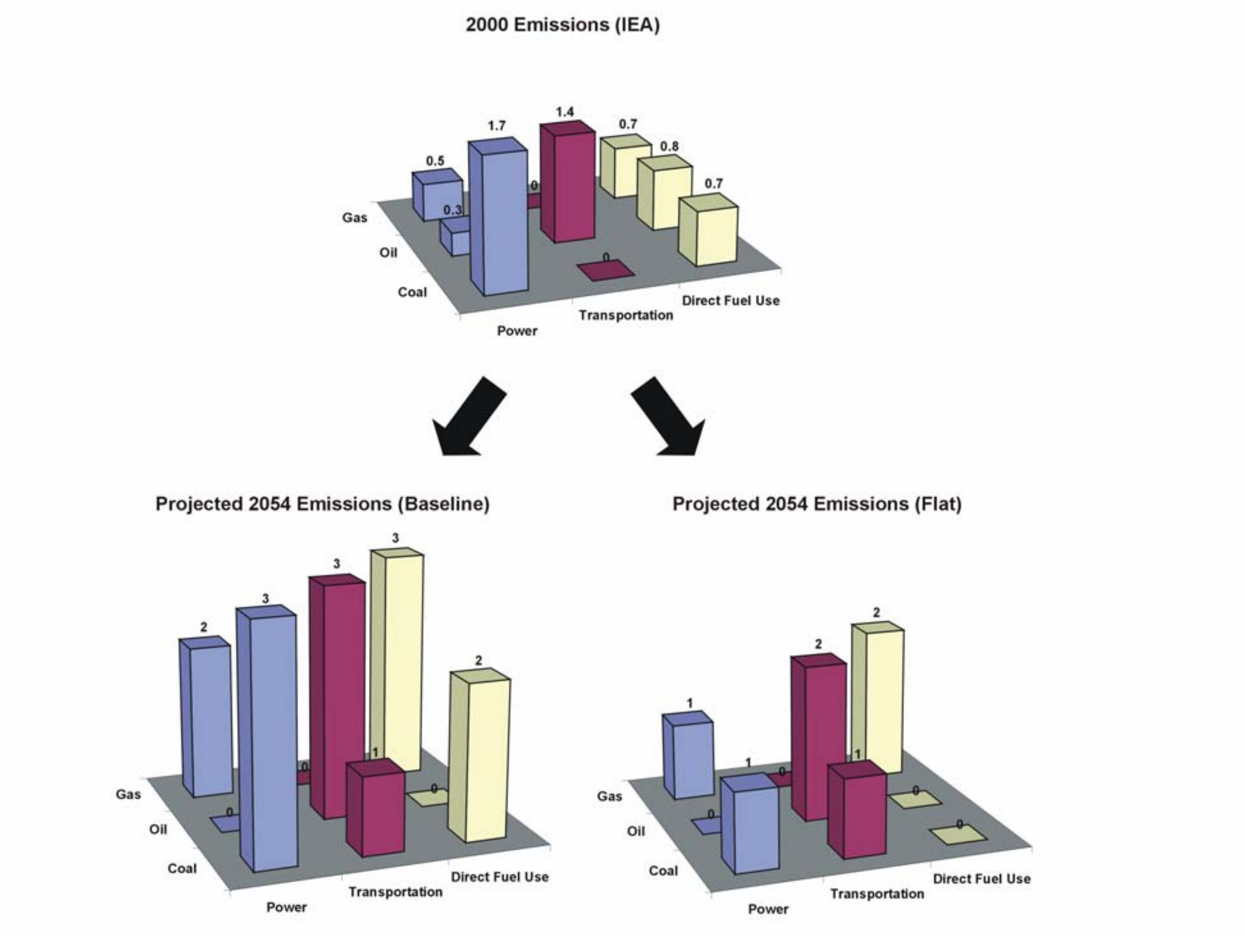


Figure S1. (A) The six stabilization emissions scenarios, and the Business As Usual (BAU) emissions scenario used in this study. The “delayed reduction” scenarios depart from BAU emissions between 2005 and 2010; they are identical to the “WRE” series stabilization scenarios (S19-S21) except that they follow historical and BAU emissions that have been updated since those scenarios were constructed, and the imposed atmospheric CO_2 concentrations in 2050 have been lowered by 5 ppm (for the 450 ppm scenario) or 10 ppm (for the 500 and 550 ppm scenarios), in order to keep emissions below those of the BAU scenario. The “early reduction” scenarios depart from historical emissions starting in 2004; they are otherwise identical to the “S” series stabilization scenarios described in (S21), which departed from historical emissions in 1990. The delayed reduction (WRE) 500 ppm scenario has been selected from this set to appear in Fig. 1A as an example stabilization emissions scenario. **(B)** Atmospheric CO_2 concentration trajectories corresponding to the six stabilization scenarios and the Business As Usual (BAU) emissions scenario.

Figure S2


2000 Emissions (IEA)

Projected 2054 Emissions (Baseline)

Projected 2054 Emissions (Flat)

Figure S2. Graphical representations of Table S3 (top), Table S4 (bottom left), and Table S5 (bottom right). Carbon emissions are disaggregated by fuel and end use. In 2000, fossil-fuel-based global emissions of carbon to the atmosphere as CO_2 were 6.2 GtC/y (top, Ref. S33). The challenge of global carbon management is idealized by displaying a pair of worlds in 2054, one with 14 GtC/y emissions (bottom left), the other with 7 GtC/y emissions (bottom right). The difference between these two worlds is seven wedges of carbon-mitigation activity. The specific pair of 2054 worlds shown here is arbitrary; many other pairs are consistent with the wedges analysis.

TABLE S1. The six stabilization emissions scenarios and Business As Usual (BAU).

Scenario	Stabilization target (ppm)	Cumulative emissions from 2004-2054 (GtC)	Cumulative avoided emissions from BAU 2004-2054 (GtC)	Number of wedges	Emissions in 2054 (GtC/y)	Emissions rate of change in 2054 (%/y)
Business As Usual	–	525	–	–	15.0	+1.5
Delayed reduction (similar to IPCC “WRE” series)	450	315	210	8.4	4.4	–1.7
	500	382	143	5.7	6.7	–1.1
	550	433	92	3.7	8.6	–0.8
Early reduction (similar to IPCC “S” series)	450	294	231	9.2	4.6	–1.0
	500	335	189	7.6	6.1	–0.4
	550	359	166	6.6	7.0	–0.2

TABLE S2. Parameters used to generate the stabilization atmospheric CO_2 concentration curves in Fig. S1(B). See S21 for more information.

Scenario timing	Stabilization concentration (ppm)	Stabilization year	Departure year from BAU	Departure concentration (ppm)	Departure rate of change (ppm/y)	Tie-point year	Tie-point concentration (ppm)
Delayed reduction (similar to IPCC “WRE” series)	450	2100.5	2005.5	377.9	1.74	2050.5	438.0
	500	2125.5	2008.0	382.4	1.83	2050.5	454.0
	550	2150.5	2010.5	387.1	1.92	2050.5	475.0
Early reduction (similar to IPCC “S” series)	450	2100.5	2004.5	376.1	1.71	2051.0	431.0
	500	2125.5	2004.5	376.1	1.71	2061.0	455.6
	550	2150.5	2004.5	376.1	1.71	2071.0	480.2

Table S3: Allocation of emissions in 2000 among fuels and end-use sectors
Source: S33, p. 413.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	0.5	0.3	1.7	*2.6*
	Transportation	--	1.4	--	*1.4*
	Direct Fuel Use	0.7	0.8	0.7	*2.2*
	Total	*1.3*	*2.5*	*2.4*	*6.2*

Note: 0.3 GtC/y for "transformation, own use and losses" has been distributed in proportion to the magnitude of each end use, for each fuel, and 0.1 GtC/y for non-energy uses has been distributed among the fuels within "Direct Fuel Use."

Table S4: Allocation of 14 GtC/y emissions in 2054 among fuels and end-use sectors in Baseline Scenario. Unit of Table entries: GtC/y.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	2	--	3	*5*
	Transportation	--	3	1	*4*
	Direct Fuel Use	3	--	2	*5*
	Total	*5*	*3*	*6*	*14*

Table S5: One possible allocation of 7 GtC/y emissions in 2054 among fuels and end-use sectors. Unit of Table entries: GtC/y.

		FUEL			
		Gas	Oil	Coal	*Total*
END-USE SECTOR	Power	1	--	1	*2*
	Transportation	--	2	1	*3*
	Direct Fuel Use	2	--	--	*2*
	Total	*3*	*2*	*2*	*7*

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