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A Model for Estimating Future Emissions of Sulfur Hexafluoride and Perfluorocarbons

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Abstract

Sulfur hexafluoride (SF_6), perfluoromethane (CF_4) and perfluoroethane (C_2F_6) are strong greenhouse gases[1,2,3,4] with long atmospheric residence times.[5,6,7] Under the Kyoto Protocol to the Framework Convention on Climate Change adopted in December 1997, industrialized nations agreed to regulate their emissions of these gases. Here we present a simple spreadsheet model that is useful for projecting future emissions and analyzing compliance with regulatory commitments. We use atmospheric measurements[8,9,10,11,12] of these gases and engineering studies to derive emission factors and scenarios for each of the major anthropogenic sources (leakage from electrical equipment, magnesium casting, aluminum smelting and semiconductor fabrication).[13] Our model is useful for policy analysis because it divides the world into regions of nations that correspond with the political coalitions that dominate the international negotiations through which regulatory commitments are adopted. We show that although firms in many industrialized countries are already limiting emissions, [13,14,15] without further policy intervention global emissions will rise 150% (CF_4 and C_2F_6) and 210% (SF_6) between 1990 to 2050; radiative forcing will increase 0.026 W m^{-2}. Full application of available low- and negative-cost policies in industrialized nations would cut that radiative forcing by one-quarter. We also quantify plausible future manipulations to governmental data and show their possible effect on compliance with the targets of the Kyoto Protocol. West European nations can “cut” their emissions of these gases by half by 2010 simply by manipulating emission factors within the current bounds of uncertainty. The need for more complete and transparent data on these gases is urgent.

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A Model for Estimating Future Emissions of Sulfur Hexafluoride and Perfluorocarbons

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Introduction

Prior studies of SF_6, CF_4 and C_2F_6 have not developed scenarios that are useful for policy analysis. Cook's cogent and comprehensive analysis detailed the policy actions and options for limiting these gases,[13] but her study did not include projections. Many studies have quantified the technological options for limiting individual sources—for, example, the reviews in refs. 16 and 17—but none has made an integrated projection. The few extant global scenarios for these gases are mainly simple extensions of past growth, or purely hypothetical, and exclude potential policy effects.[3,16,18] The only regional analysis of these gases has been hemispheric because such long-lived gases are scientifically useful as tracers of the rate of atmospheric mixing between hemispheres.[8] No projections have been made for regional political groupings. Yet regional analysis is needed because political decisions to regulate these substances within the treaty framework for slowing global warming—the Framework Convention on Climate Change (FCCC)—are dominated by political groupings that often follow regional lines.

Only four industrialized countries have officially reported emissions for each of the two PFCs and SF_6.[19] Thus it is not yet possible to build aggregate regional and global projections from the "bottom up" using national data, except in North America where data are available for both Canada and the United States. Nor has this scant national data been compared with a "top down" method based on the measured increase in atmospheric concentration of these gases. The model and results we report here are a first effort to fill all of these omissions in the existing literature.

We develop scenarios for the globe in total and for each of the three main political groupings that are active in negotiations to strengthen the legal commitments in the FCCC: (1) industrialized countries that are members of the Organization for Economic Cooperation and Development (OECD); (2) the industrialized countries that are now "reforming" after decades of central planning; and, (3) developing countries. The first two groups are listed in "Annex I" of the FCCC and are the only countries under the FCCC and the Kyoto Protocol with regulatory commitments that require them to demonstrate that they are "taking the lead" in slowing global warming. Reforming countries have been given special leniency under the FCCC and the Kyoto protocol, and thus current policy attention is most intensely focused on the first category—the OECD countries. To allow finer resolution, we further divide this first group into Pacific rim (Australia, Japan and New Zealand), Western Europe, and North America. Especially Western Europe and North America often act as a cohesive political coalition and adopt some policies in unison. (We follow the approach in "Annex I" of the FCCC and the Kyoto Protocol and classify Korea and Mexico as developing countries and the

Czech Republic and Poland as reforming countries, although all have recently joined the OECD.)

For each gas we compute the annual global source from the observed increase in atmospheric concentration. (We ignore sinks because the lifetime for each gas is long.) We then attribute that source to the industrialized activities that are known to yield these emissions and derive emission factors for 1994 (SF_6) and 1995 (PFCs), the most recent years for which the most reliable data are available. Table 1 summarizes that attribution process, which is described in additional detail below. We make a baseline projection that incorporates existing and likely policies. And we also project the likely impact of policies that could be easily adopted in OECD nations. All policy action is focused on the industrialized nations; developing countries have adamantly refused to adopt commitments to regulate their emissions. Elsewhere we have analyzed the impact of a worldwide effort to regulate these gases.[20]

We consider the policy scenario most likely if the Kyoto Protocol enters into force. But the baseline scenario is likely if the Protocol is discredited and founders politically as every nation considers whether to “ratify” thus formally confirm that it will adhere to the Protocol. Which course will be followed remains unclear; one reason for policy analysis such as the present paper is to help reveal what is at stake.

For each region we make projections of the future levels of the four industrial activities that cause emissions of SF_6 and PFCs—electricity production and transmission, magnesium foundry operations, aluminum smelting, and semiconductor production (see figures 1 & 2). For electricity we use the authoritative scenarios of the International Institute for Applied Systems Analysis (IIASA)/World Energy Council (WEC) “middle course” (B) scenario.[21] We make projections based on historical data and industry trends for magnesium,[22] aluminum[23] and semiconductor production.[24] (For additional detail, see the captions to figures 1 & 2; we do not use industry scenarios, which typically do not extend beyond two decades.) None of the policies envisioned would significantly affect these industries. Thus our model uses only a single projection for each of the industrial activities. We produce multiple scenarios by varying only the emission factors.

SF_6

Maiss *et al.*,[8] using methods confirmed in other studies,[9,25] reported that in 1994 the mean rise in tropospheric SF_6 concentrations was 0.225 pptv yr^{-1} (5800 $tons_{SF6}$ yr^{-1}). All studies agree that the entire source is anthropogenic. Early assessments[3] focused on usage of SF_6 as an insulator and for other purposes in heavy electrical equipment such as high voltage transformers. We assume that is the main source. But we follow Maiss *et al.*[8] and Stordal *et al.*[26] who suggest that approximately 20% of world SF_6 emissions (1200 tons yr^{-1}) are presently (1990s) from magnesium foundries. SF_6 is also used to degas molten aluminum, but the SF_6 reacts with aluminum and little or no net SF_6 gas is released to the atmosphere. Other applications of SF_6 include as a tracer gas and as an insulator in some windows; it is also present in waste streams where reactive sulfur and fluorine exist, such as from semiconductor cleaning chambers. However, we doubt that these other sources are a significant (>1-2%) source of worldwide emissions.

Emission Factors: Electricity Production

SF_6 is an insulating gas in heavy electrical equipment, such as high voltage cables and circuit breakers and compact substations. Alternative insulating gases and methods are inferior, especially for the highest voltage applications.[27] Some SF_6 leaks to the atmosphere through imperfect seals, but most is vented during testing and maintenance.[16] Projections are difficult to make because emission factors probably vary widely with equipment and servicing practices, for which data are limited. Ideally, a projection should disaggregate activities that yield SF_6 (high voltage and compact applications) from those that don't. But global data on those activities is scarce and projections do not exist. Thus we take a cruder approach and assume that SF_6 emissions are scaled to electricity production.

Our simplified approach introduces several potential errors. We may under-estimate the future source of SF_6 because measured concentrations of SF_6 are presently (late 1994) growing at approximately 6.9% per year,[8] but electricity demand has grown on average 4.2% per year since 1971.[28] Most likely, the difference reflects that SF_6 applications (high voltage switching and compact substations) have diffused into markets in industrialized nations only recently (since the 1970s) and into developing countries even more recently (since the 1980s). The growth of SF_6 consumption and emissions is the compound of those diffusion rates and the growth in electricity demand. (A rising fraction of magnesium-derived SF_6, discussed below may also explain part of the discrepancy between the measured rise in atmospheric SF_6 and the rise in electricity production, but the magnesium source is probably too small to account for the full difference.)

A refined model might also need to account for SF_6 banking in electrical equipment. Production capacity of SF_6 is expanding rapidly; exact statistics are commercial secrets, but current world production may be as high as 10000 tons yr^{-1}.[26] The observed atmospheric increase (5800 tons yr^{-1}) is much lower. Part of the discrepancy is the consequence of SF_6 that is destroyed in some applications, such as in degassing of molten aluminum. But the principal explanation is the accumulating of SF_6 stocks inside heavy electrical equipment. Such leaks may be a small (and declining) portion of the current SF_6 source, and thus incomplete modeling of this source is also likely to introduce only a small uncertainty to the projections. However, special policy attention may be needed to the recovery and management of banked SF_6 if, for example, production of new SF_6 is sharply curtailed and the remaining banked SF_6 must be allocated or destroyed. The vast quantities of banked SF_6 also requires that even if SF_6 production data are released from commercial secrecy that additional efforts will be needed to quantify what fraction of production is actually released to the atmosphere.

For our baseline scenario we assume that the emission factors decline by one-quarter over one lifetime of the capital stock (30 years) and improvement continues at the same rate thereafter. Industry experience suggests that most SF_6 leaks are due to old equipment.[16] Specifications for new equipment require leakage below 1% to 2% yr^{-1}, and field experience suggests that actual leakage is lower.[16] Continued improvement is likely; even without global warming policy signals, SF_6 costs approximately $9000 per metric ton and thus there are benefits to recovery and reuse. We assume that emissions due to service venting are mostly unaffected; only for highly concentrated service activities would it be cost-effective to flush, recover and recycle SF_6.

For our policy scenario we assume that industrialized countries engage in policies that are equivalent to a very small price signal to limit emissions. An extremely modest global warming policy might apply a tax equivalent to \$1 per ton of CO_2, which would have little effect on carbon emissions. But such a tax, weighted by the global warming potentials (GWPs) that many nations have adopted would nearly quadruple the cost of SF_6 emissions. We assume that such signals would reduce the emission factor by 50% over the next decade and a total of 80% within the 30 year turnover of the existing capital stock. Recovery units would be used by maintenance crews when servicing all SF_6-insulated substations and most other SF_6-insulated switching equipment. Atmospheric venting due to remote and irregular servicing would still occur as equipping every service team with the equipment needed to eliminate service venting would be expensive. We are mindful that some firms have already begun some recovery, partially in anticipation of global warming regulation and public concern.[16] Thus the present moment in time, with the Kyoto Protocol freshly adopted, marks a potential shift from our baseline to the policy scenario.

Emission Factors: Magnesium Production

Magnesium foundries use SF_6 blended with inert gases as a “cover gas” to prevent oxidation of the molten metal. Ideally, our scenarios should project the quantity of magnesium processed in foundries in each region and then estimate SF_6 emissions. However, comparable worldwide data are available only for magnesium primary production (figure 1), which we use as a proxy for the quantity of magnesium processed by foundries. This approach is not unreasonable since the distribution of world foundry capacity is roughly similar to world magnesium production. At present, North America dominates both, and it is plausible to expect that the relative shift in production to developing countries (principally China) will be accompanied by a similar shift in foundry operations.

World magnesium production figures and the 1160 tons of SF_6 attributed to this source suggest that the average world emission factor would be 3.3 kilograms SF_6 per ton Mg production in the 1990s. Because SF_6 is used in more advanced foundries, we assume that the emission factors are slightly higher in OECD nations (3.5 kg per ton) and lower in reforming and developing countries (1.5 kg per ton) where SO_2 is still used instead of SF_6 in cover gases. At present developing countries only account for 17% of world magnesium production; using our emission factors they thus account for only 10% of the annual SF_6 emissions attributed to magnesium.

In our baseline scenario, no effort is made to limit SF_6 emissions. However, emission factors rise because our projections are based on primary production of magnesium, and the emission factor for each region must therefore be adjusted to reflect that only some uses of magnesium production result in emissions of SF_6. In 1996 in the United States, for example, approximately 84% of magnesium consumption was in aluminum alloys (51%), iron and steel desulfurization (13%) and other uses that did not yield SF_6 emissions. Only 16% was processed in foundries (cast), resulting in emissions of SF_6. (See ref. 22.) If this fraction remains constant then it would be appropriate to assume that the emission factor (SF_6 per unit of Mg primary production) would remain constant in the absence of changes in industrial practice. However, demand for magnesium in automotive applications is growing at ~15% per year; it is a strong, lightweight replacement for steel (e.g., in steering columns, dashboards and seat frames). If this growth continues as expected, the fraction of total magnesium production that is cast and emits SF_6 will grow and thus the emission factor should also rise. Because this shift in magnesium consumption is already clearly and strongly under way and not likely to saturate soon, in the baseline scenario we assume that the emission factors in 2050 will be three times the level in 1995. We assume that the emission factor in developing and reforming countries will increase to OECD levels over the same period because magnesium is traded on world markets and final cast products are also increasingly traded worldwide; thus foundries worldwide will respond to similar world demand patterns and adopt similar practices in a competitive market. This assumption may nonetheless substantially under-estimate potential growth in SF_6 emissions. If demand for cast magnesium continues at present rates then by 2050 virtually all magnesium production will be cast and, *ceteris paribus*, the emission factor would be six times the present level. (Such a scenario would also require revising upwards the growth rate for total magnesium production, which would further increase the projected SF_6 emissions.)

For the policy scenario, we assume that other cover gases are introduced into OECD nations with the turnover of capital stock (~20 years for specialized foundries) starting in 2000. Thus by 2020, the emission factor in OECD nations is zero.

Figures 3 show the projected emissions from the combination of the electricity and magnesium sources.

Perfluorocarbons (CF_4 and C_2F_6)

Time series atmospheric measurements of PFCs are relatively short. Rasmussen *et al.*[29] reported the first accurate measurements of CF_4 concentrations in the atmosphere in 1979. Khalil and Rasmussen[30] measured the average increase in tropospheric CF_4 concentration of 1.3 pptv yr^{-1} (2% yr^{-1}) for 1978 to 1984. Fabian *et al.*[10] estimated the rise in CF_4 for the early 1980s at 1.9 pptv yr^{-1} . More recently, Harnisch *et al.*[11] have used stratospheric profiles to estimate that CF_4 rose 1.00 pptv yr^{-1} (1.46% yr^{-1}) from 1982 to 1995.[31] These results are consistent with, but slightly lower than, space-based measurements of the stratosphere which suggest an exponential increase in CF_4 concentrations of 1.6 ± 0.6 % yr^{-1} between 1985 and 1994.[12] We adopt the lowest of all these values (1.00 pptv yr^{-1}, equivalent to 15500 $tons_{CF4}$ yr^{-1}) to minimize the possibility that our projections will overstate current and future emissions.

Reliable time series data for C_2F_6 concentrations are even less abundant than for CF_4; the first measurements were reported by Penkett *et al.*[35] in 1981. Using vertical profiles taken in the stratosphere, Fabian *et al.*[10] reported that the C_2F_6 concentration was rising at approximately 0.13 pptv yr^{-1} (6.4% yr^{-1}) in the 1980s. More recently, Harnisch *et al.*[11] reported an average rise in atmospheric concentration of 0.084 pptv yr^{-1} (4.1% yr^{-1}) from 1982 to 1995.[32] We adopt the lowest plausible measured increase (0.084 pptv yr^{-1}, equivalent to 2000 $tons_{C2F6}$ yr^{-1}). Such values suggest a 12:1 (by volume) ratio in the increase of atmospheric $[CF_4]:[C_2F_6]$, which is consistent with studies of individual aluminum smelters that report an approximately 10:1 ratio.[33]

Essentially all sources of CF_4 and C_2F_6 are anthropogenic industrial activity. Only CF_4 has a known natural geologic source, which is very small ($\leq$10 tons_{CF4} yr^{-1}).[10,34] All studies agree that production of aluminum is the largest source of both CF_4 and C_2F_6. In 1981 Penkett *et al*.[35] reported elevated concentrations of these gases in the plumes downwind of aluminum smelters and concluded that these gases were probably entirely the byproduct of aluminum production. However, in the period since their study both of these gases have been manufactured for specialized use, notably in etching and for cleaning chemical vapor deposition chambers during the production of semiconductors.[13,38,42] In addition, some PFCs are used to replace substances that have been regulated due to their impact on stratospheric ozone, as a byproduct in the production of HCFC-22 (which is also regulated due to ozone depleting effects) and other halocarbons, and during the production of Teflon®. PFC producers have expanded capacity and sales for some of these applications,[36] which suggests that these sources could grow in the future. PFCs have also been used as a replacement (and testing agent) for Halon fire-suppression systems; this use probably causes relatively small atmospheric releases but needs more investigation. (Halons are strong ozone-depleting substances and are being eliminated under the Montreal Protocol on Substances that Deplete the Ozone Layer.) Cicerone[5] has also suggested that electrolytic generation of F_2, reduction of UF_4 and UF_6, the use of fluorospar in steelmaking, and rocket fuel combustion may be additional sources.

We follow expert consensus[13,37] and attribute the main source to aluminum production, with a smaller source related to semiconductor production. Exact attribution is difficult because neither source is easy to quantify. For aluminum, emission factors for PFCs produced during smelting vary by plant. The source of manufactured PFCs that leak from semiconductor operations is especially difficult to quantify because emissions depend on production methods, which are commercial secrets; sales of PFCs are also commercial secrets. Our approach is to tune the model to reproduce data for the United States. Although imperfect, this approach is the only one feasible with data that are at present publicly available—the United States is the only large economy for which it is possible to estimate data for both PFC sources—aluminum and semiconductors. We ran our model with the assumption that aluminum production was the only source; that allowed an initial computation of emissions for North America in the middle 1990s (1995). Publicly available data from the United States suggests that perhaps 5-10% of total annual PFC emissions in ~1995 were due to semiconductor production.[38] (We adopt the 10% figure, which may result in a small underestimation of future PFC emissions because conventional semiconductor production declines after 2010—see figure 1.) Those data, which are incomplete and aggregated to protect confidentiality, do not distinguish between the two PFCs. US inventories for 1994 show total PFC emissions of 2400 tons (see ref. 39, table 33). Thus US PFC emissions from semiconductors were 240 tons; however, the same source for the 5-10% figure also suggests that semiconductors were responsible for perhaps 600 tons of US annual PFC consumption. If the latter figure is true then our semiconductor emission factors are low by a factor of two. (Available scant data would be more useful if estimates for gases were disaggregated and if definitions were used consistently; in the semiconductor industry the term “PFC” often includes other gases, notably SF_6, that are not strictly PFCs)

Detailed measurements from aluminum production suggest that that source yields a 10:1 (by volume) ratio of CF_4 to C_2F_6, but no such ratio has been published (nor is likely to exist) for these effluents from semiconductor production. It is plausible that the fraction of

C_2F_6 is larger in semiconductor effluents because that gas is the main PFC cleaning agent for chemical vapor deposition chambers. Absent better information, we assume that a 5:1 volume ratio (3:1 by mass) prevails for semiconductor-related emissions. Thus for the United States the semiconductor sources would be 180 tons_{CF4} and 60 tons_{C2F6}. It is possible that the ratios could be inverted—that C_2F_6 is by volume (and mass) a larger fraction of semiconductor PFC emissions—because C_2F_6 is the gas of choice for cleaning chemical vapor deposition chambers. But the semiconductor source is sufficiently small that measurement and aggregation errors allow consistency with a wide range of ratios. In the next few years the atmospheric record should be able to resolve whether the semiconductor ratio is substantially different from that of aluminum production. Release of disaggregated emission estimates from the industry would also aid in unraveling this puzzle.

Semiconductor Production

The approach for estimating the semiconductor source is very crude because scant available data force us to estimate emission factors per unit value of semiconductor production, whereas emissions are the result of particular technologies and practices. Luckily, the semicondctor source is a small part of total PFC emissions.

In 1995 North American semiconductor production was 47 BUSD. (1 BUSD = 10^9 US Dollars.) From the estimated semiconductor-related emissions of PFCs for that year we estimate emission factors of 4 tons_{CF4} BUSD^{-1} and 1.3 tons_{C2F6} BUSD^{-1}. For the baseline scenario scenario we assume that emission factors in industrialized countries are cut in half in ten years, starting in 1995. Starting in the early 1990s DuPont required its customers to account for and reduce emissions of PFCs; other suppliers and customers are under pressure to do the same, and the semiconductor industry has launched a voluntary partnership to account for and reduce its emissions.[38,40] For the policy scenario we assume that OECD nations cut the emission factor to 10% of 1995 levels between 2000 and 2005.[41] Technologies are already available that can virtually eliminate these emissions through recovery and recycling at little or no cost;[42] use of such technologies and other process changes should be profitable in virtually every semiconductor fabrication plant even if price and other policy signals to limit emissions are relatively small. The fast turnover of semiconductor capital stock allows rapid full diffusion of such new technologies into the marketplace.

Emission Factors: Aluminum Production

The aluminum source of CF_4 and C_2F_6 is due to “anode effects” during the smelting of alumina (Al_2O_3) to produce aluminum (Al).[43,44,45] (For compact reviews see refs. 13, 18 and especially ref. 17.) The smelter pot contains alumina dissolved in an electrolyte, which mainly consists of molten cryolite (Na_3AlF_6); when alumina levels drop, excess voltages allow formation of PFCs from carbon in the anode and fluorine in the salts. (For experimental results that confirm that PFCs are produced only during “anode effects” and not continuously during smelting, see ref. 46.) Tighter control of alumina content and other process parameters can limit the number of anode effects, often at negative cost because improved processes also yield higher energy efficiency. Anode effects depend on cell design and operational procedures during the smelting process and thus probably vary considerably across smelters and regions. Comparable worldwide data on the incidence of anode effects and PFC emissions do not exist; measurements of emission factors are numerous but have been conducted mainly under laboratory rather than field conditions; and no study has documented emissions due to anode effects in developing countries.

Worldwide production of aluminum averaged 17400 thousand metric tons (tmt_{Al}) yr^{-1} over the period of the Harnisch *et al.* study (1982 to 1995), which is the source of our atmospheric PFC measurements. If aluminum were the only source then the worldwide emission factor would be 0.898 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$ and 0.115 $\text{tons}_{\text{C2F6}}$ $\text{tmt}_{\text{Al}}^{-1}$. (We report these values to allow comparison between our results and earlier studies, many of which attributed the entire PFC source to aluminum production.) However, in our model we adopt lower emission factors to allow for the semiconductor source and because actual aluminum production in 1995 was higher (19900 tmt_{Al} yr^{-1}) than during the 14 year average of the Harnisch *et al.* study. Our global average factors for 1995 are: 0.750 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$ and 0.092 $\text{tons}_{\text{C2F6}}$ $\text{tmt}_{\text{Al}}^{-1}$. Although uncertain, we adopt this approach so that if our factors are erroneous that our model will under-estimate current and future emissions.

For our baseline scenario, we assume this average emission factor remains constant in reforming and in developing countries. In North America we assume that the factor declines by 50% from 1995 through 2005, which is consistent with optimistic expectations for industry-government partnerships and other industry actions to reduce PFC emissions at smelters in the United States.[47] After 2005, the emission factor continues to decline by 2% per year with the turnover of capital stock. Such continuous reduction in PFC emission factors is consistent with already evident improvements such as control of alumina feeding and computerized monitoring of anode effects that have demonstrably limited anode effects and PFC emissions from both types of smelting technologies (Söderberg and prebake) that are used in the industry.[17,18] By 2050, *average* emission factors in North America are 20% of current levels (i.e., 0.150 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$ and .02 $\text{tons}_{\text{C2F6}}$ $\text{tmt}_{\text{Al}}^{-1}$).

For comparison, emission factors for the "prebake" cell technology that is typical of new smelter applications have been measured at .2 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$ (ref. 46). The best prebake technology limits the number of anode effects to 0.1 per day (from 2 to 3 per day in older Söderberg and prebake cells).[17,48] Operational studies in Norwegian smelters have measured the average emission factor for Söderberg cells at 0.8 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$ and modern prebake cells at .06 tons_{CF4} $\text{tmt}_{\text{Al}}^{-1}$; and proportional reductions in C_2F_6 emissions have also been measured in the same studies (ref. 48). Other studies,[17] including controlled studies of old and new technology at commercial smelters,[49] suggest similar or even lower emission factors are possible in the newest operational plants. Reductions in anode effects and other process changes also allow lower energy consumption and thus lower operating costs, which explains why these processes were under way in the Aluminum industry even prior to widespread concern about global warming. PFC emissions from smelting could be eliminated with the development of non-carbon anodes.

In Western Europe, voluntary industry-government agreements similar to those in North America already exist in France, Germany, Norway and the United Kingdom (63% of West European production).[50] Similar actions are likely throughout Western Europe. (The only significant uncertainty is Iceland, which is planning large new aluminum smelters but will also face economic and political pressure to employ less PFC-intensive technologies for its new smelters and to retrofit existing smelters.) Thus we expect that the average West European emission factor will drop by half—the same decline as in North America—but over a slightly longer period (15 years). We assume the same decline for the Pacific OECD nations, where similar forms of voluntary regulation and industry reforms are being considered but not presently widespread. In both Western Europe and Pacific OECD nations, the average factor declines 2% per year after 2010.

For our policy scenario we assume that emission factors in OECD nations all decline to one-tenth of current levels over 15 years starting in 2000. (Until 2000 the BAU scenario is followed.) This is consistent with the availability of technologies that can reduce PFC emissions from anode effects to less than 10% of current levels.[13,18] Additional work is needed to perfect the methods and to diffuse them into use. Although emission factors for new plants might be quite low, some smelters would be too costly to retrofit. Emission factors in reforming and developing countries are unchanged.

Figures 4 and 5 show our scenarios for CF_4 and C_2F_6 emissions from the combination of the semiconductor and aluminum sources. Table 2 reports emissions for each gas and region for the baseline scenario; table 3 presents the three OECD regions in detail. Table 4 shows OECD emissions under the policy scenario.

Radiative Forcing and Global Warming Potential

Figure 6 shows the increase in radiative forcing (above 1990 levels) due to these gases; table 5 shows the fraction of global forcing due to each gas.

Following others,[51,52] we discourage use of global warming potentials (GWPs) for converting emissions of different greenhouse gases into common units (e.g., tons of carbon dioxide). GWP-based comparisons are highly sensitive to the arbitrary choice of the time horizon over which forcing is integrated. Seductively simple, the GWP concept ignores the time path of forcing and thus misrepresents the tradeoffs between abatement of gases of with markedly different atmospheric lifetimes. Moreover, GWPs make intransparent that emissions of SF_6 and PFCs are practically permanent in the atmosphere, unlike all other gases included in the Kyoto Protocol (CO_2, N_2O, CH_4, and hydrofluorocarbons). Nonetheless, the GWP method is unwisely used in the FCCC and in most national governments, and thus tables 2-4 also report our findings in million metric tons of CO_2-equivalents (mmt CO_2-equiv), weighted by GWP.

A verification tool?

The Kyoto Protocol to the FCCC specifically lists SF_6 and PFCs in the basket of gases that OECD and reforming countries must reduce. National reports of emissions of these gases will be used to verify compliance with the Protocol’s commitments. Yet so far only four countries (Canada, Germany, Norway, United States) have officially reported emissions for SF_6 and both of the PFCs for 1990 as part of their “national communications” under the

FCCC.[19] Elsewhere[20] we show that our estimated emissions for three of those four countries (all but Germany) are approximately twice the reported levels.

We expect that all countries, especially those that have not already reported inventories for these gases, will evaluate which emission factors will best serve their interests. They will find it easiest to comply with commitments to regulate these gases if they report high emissions for the base year while employing low emission factors for subsequent control years. Such manipulation of factors must be within the bounds of plausibility since no country wants to be exposed cooking its books. For simplicity, here we focus on the base year 1990 and the control year 2010. However, we are mindful that the Kyoto Protocol allows countries to choose between 1990 and 1995 as the base year for these gases (along with the hydrofluorocarbons). We also note that the control period in the Kyoto Protocol is actually the average annual emissions during a five-year period centered on 2010 (i.e., 2008 to 2012).

We illustrate numerically what is at stake with a thought experiment involving data for Western Europe. The European Union (EU), which is the largest political grouping in the region, has not yet reported emissions for SF_6 and PFCs; thus it has considerable scope for manipulating the emission factors it uses when it reports data. What if the EU and other West European nations systematically used high emission factors for the base years and low factors for the control years, within the plausible bounds of uncertainty?

Suppose that the West European nations use our emission factors for the base year. If they do, West European emissions in 1990 were 49 mmt CO_2-equiv, and we project that in 2010 West European emissions of SF_6 and PFCs in 2010 would be 42 mmt CO_2-equiv (see table 3). Suppose, however, that after reporting their base year data that these nations adopt emission factors at the lower bound of plausibility. To illustrate the consequences, we revised downwards the emission factors in our model so that our emissions estimates for 1990 are consistent with the actual reported 1990 emissions estimates for North America. (We conduct this “thought experiment” by tuning the model to actual reported data from North America because that is the only region for which all nations—Canada and the United States—have reported data for 1990.) Collectively such a revision makes no sense because it violates the fundamental principle of our model—that the estimated regional emissions must sum to the observed global rise in atmospheric concentration. But for any individual nation the incentive to make such changes could be high. These revised emission factors yield a baseline projection for Western Europe in 2010 of 24 mmt CO_2-equiv. In other words, it is possible to yield a “reduction” in West European emissions in 2010 simply with a highly plausible manipulation of emission factors. For comparison, this false reduction in emissions—half of the 1990 level—was approximately 3% of all CO_2 emissions from passenger and freight transport in the European Union.

We intend this calculation merely as an illustration of the need for better data and plausible manipulations when there is an incentive to do so. We are mindful that the emission factors are not well known in general, and even less well known for particular situations; our approach is highly aggregated, but national data must reflect factors that are appropriate for local technologies and practices. The possibility of strategic manipulation suggests that an urgent policy need is to build a good data set. Yet the 1990s is an especially difficult time to do so because the industrial processes that cause these emissions are changing rapidly (mostly with the result that emissions will not be as high in the future as might be expected by simple extrapolation of past trends). From a policy perspective, that already challenging task has been made more difficult because just at the time when data sets are being assembled (including crucial base year data) policy makers are also setting targets that have financial and legal implications. Elsewhere we have argued that putting data first, even by a few years, would better serve both the data and the future effectiveness of regulation.[14,51] The need for improved inventories will be especially acute if these gases are incorporated into highly quantified legal instruments, such as emissions targets or tradable emissions permits.

Conclusion

SF_6, CF_4 and C_2F_6 belong to a class of atmospheric pollutants that merit special policy attention because their environmental effects persist for thousands of human generations.[13,14,15] Other PFCs (e.g., C_3F_8) as well as NF_3 also belong to this class, but at present they are substantially less abundant in the atmosphere and less widely used than the three gases examined here.

On the basis of observed increases in the atmospheric concentration of SF_6, CF_4 and C_2F_6 we have derived average emission factors for the activities that release these potent greenhouse gases to the atmosphere. Our approach is highly aggregated but ensures consistency between our emission estimates and the few known facts related to these gases—their measured increase in the atmosphere. We have projected future emissions, concentrations and radiative forcing for two scenarios that illustrate a likely future without additional policy efforts as well as a plausible policy scenario for OECD nations.

Our results point to four conclusions. First, full application of the policies already being implemented in several OECD nations can cut emissions from these countries in half or more from the levels of the 1990s. At least this level of abatement is likely. Second, despite these policies, world emissions of each of these gases rise substantially in the baseline scenario.

Third, over the period of our projection the radiative forcing from these gases grows substantially but remains small relative to CO_2. To illustrate the relative shares, we have used Wigley's carbon cycle model[53] and Wigley and Raper's[54] simplified climate model (MAGICC) to estimate the increase in greenhouse forcing due to industrial CO_2 emissions in the IIASA/WEC "middle course" scenario. The result (~1.6 W m^{-2} over 1990 levels by 2050) suggests that SF_6 and PFCs will grow to 1.6% of the radiative forcing of CO_2 by 2050. At present, these long-lived gases account for only 0.2% to 0.6% of the increase in greenhouse forcing since pre-industrial times.[55] (For comparison, using the same carbon and climate model we estimate that industrial CO_2 emissions in the IS92a baseline scenario[56] of the Intergovernmental Panel on Climate Change result in ~2.1 W m^{-2} of increased forcing by 2050.) A logical next step for analysts would be to add these gases, and estimates of the marginal costs for different abatement options, to models of the economics of global warming to evaluate how controlling these gases compares with other policy options. The case for policy action on these gases is not that they are major causes of global warming—such as carbon dioxide—but rather that low- or negative-cost policies are available, and their impact on the atmosphere would be permanent on the timescale of human civilization.

Fourth, we have also shown that plausible manipulations to emission factors can yield large artificial “reductions” in emissions. For this reason, and because our method for projecting emissions of these gases remains crude, several improvements to data sets and modeling methods are urgently needed. In order of importance, three command particular attention:

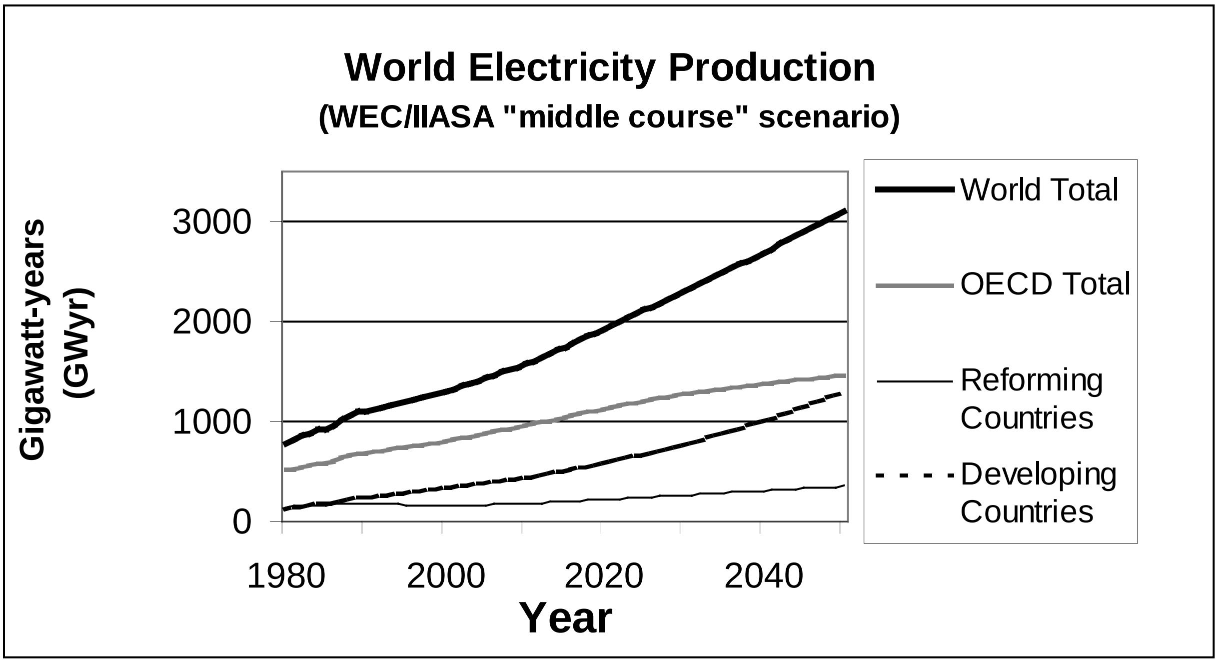
(1) quantifying and projecting SF_6 use in electrical equipment, including the amount banked in existing equipment;
(2) properly attributing the observed rise in SF_6 between electrical equipment and magnesium casting (and other sources, if they exist); and
(3) quantifying the semiconductor source of PFCs. Our method of using estimated US data for allocating the world PFC emissions is highly imperfect, especially because we have only incomplete aggregated data for 1995. Moreover, the middle 1990s was a time of radical change in the semiconductor industry and small errors in estimating sources can propagate into larger improper estimates for average emission factors.

Improvements to the SF_6 emission factors and projections are most urgent because SF_6 is the largest contributor to increased radiative forcing in both scenarios (see table 5), and our method for projecting emissions of that gas are especially crude. Some of these obstacles can be overcome with release of data currently regarded as confidential—a problem that has been solved in other regulatory regimes. A useful method for improving the existing inventories and modeling methods would be an international data project to give independent scientific scrutiny to the current and future inventories of these gases reported under the FCCC and the Kyoto Protocol.

Figures

Figure 1 Past and Future Levels of Industrial Activity that yield SF_6. Electricity production is shown in panels (a) and (b). Magnesium production is shown in panels (c) and (d).

Panel(a)



Electricity production is the IIASA/WEC "middle course" (B) scenario.[21] World electricity production rises to three times 1990 levels by 2050; growth is most rapid in developing countries whose electricity production nearly equals that of western industrialized countries in 2050. Historical data in the figure are from the International Energy Agency.

Panel (b)

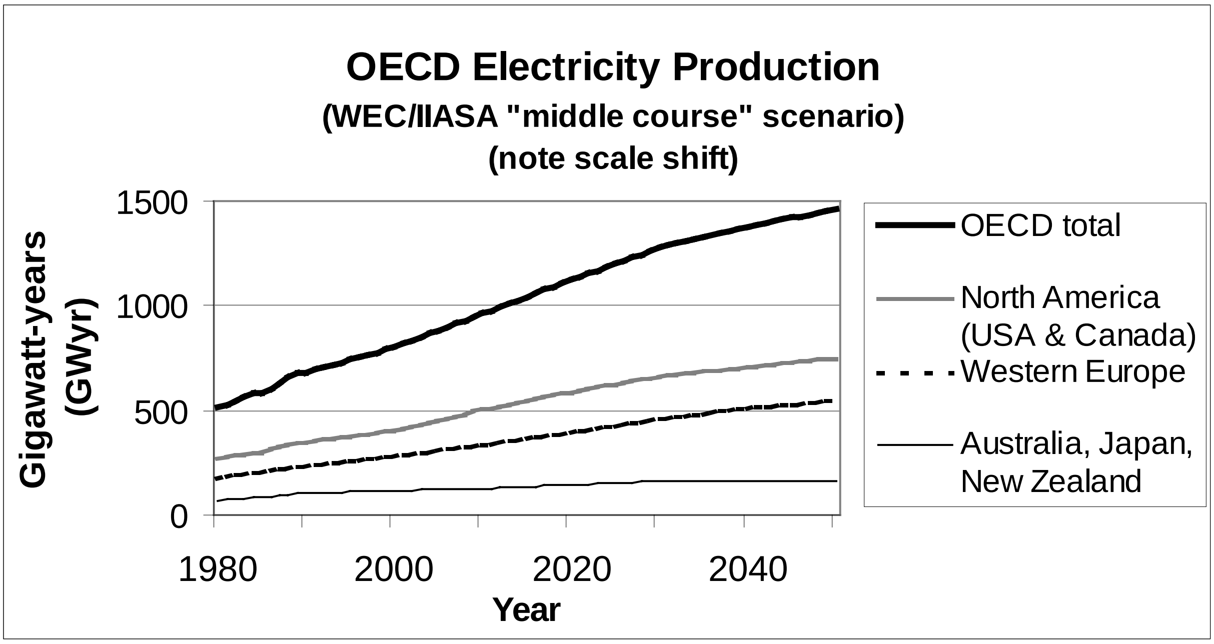
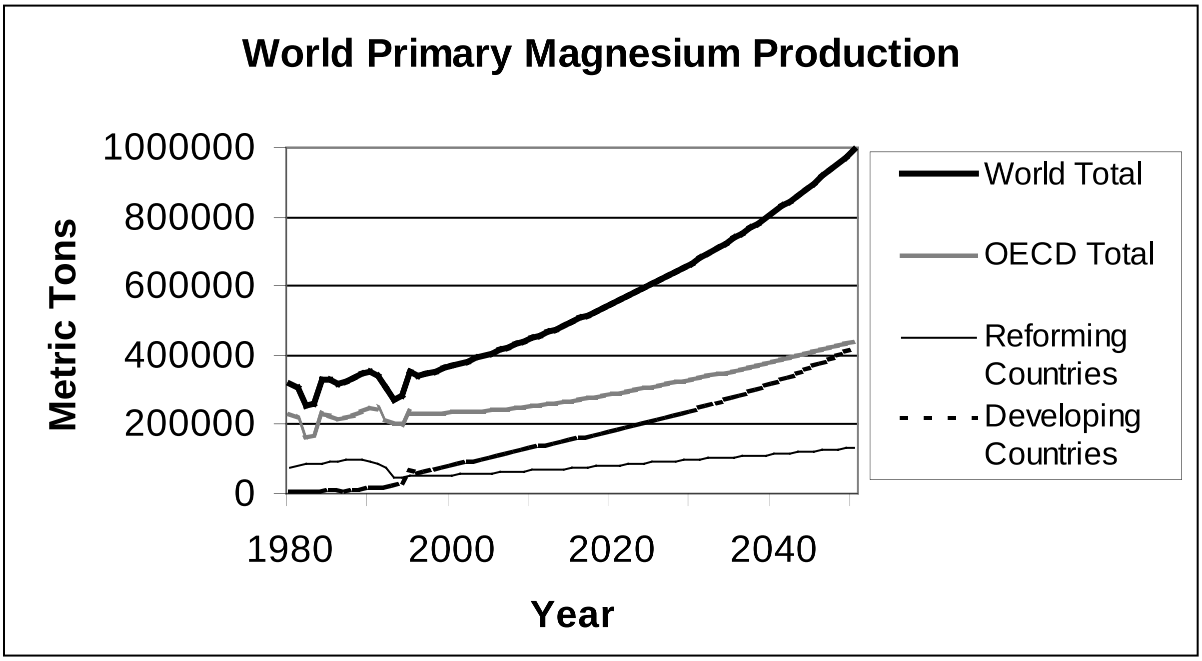


Figure 1 (cont.) Past and Future Levels of Industrial Activity that yield SF_6. Magnesium production is shown in panels (c) and (d).

Panel (c)



Magnesium projection is based on comprehensive historical data compiled by the US Geological Survey.[22] Consistent with historical experience, we project a global increase in demand of 2% yr^{-1}. In the OECD nations, production is concentrated in North America, where we project that growth will rise 1.5% yr^{-1}. US production has been flat since the 1980s, but Canadian has expanded fivefold since the middle 1980s. In pacific OECD nations production has been zero since Japanese production ceased in 1994. In Europe, Italy has ceased production; French output is roughly flat, and Norwegian annual production has declined to approximately half the level of the 1980s. We project that European production will continue to decline at 5% per year and stabilize at half current levels. In the reforming countries, production (mainly in Russia, Ukraine and Serbia & Montenegro) fell sharply during the collapse of central planning but has regained growth. We project a 2% yr^{-1} growth until the pre-collapse levels are achieved, after which production expands at the same rate as in North America (1.5% yr^{-1}). Developing countries supply all other production and thus grow at approximately 3.4% yr^{-1} on average.

Panel (d)

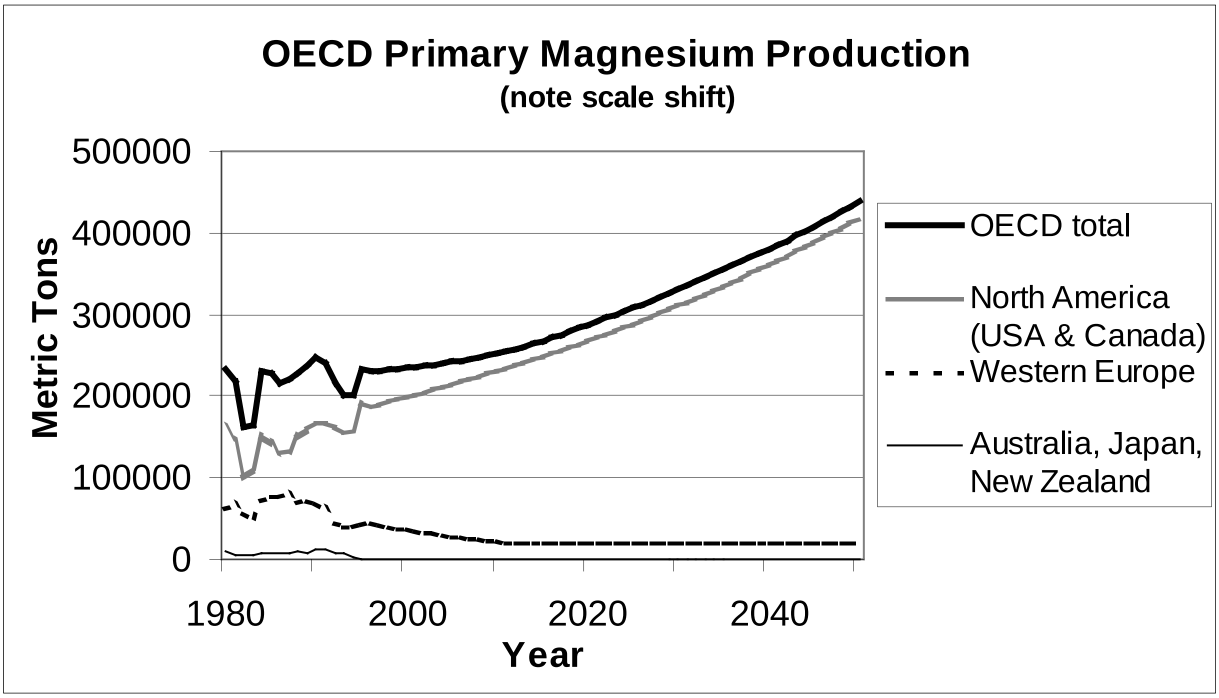
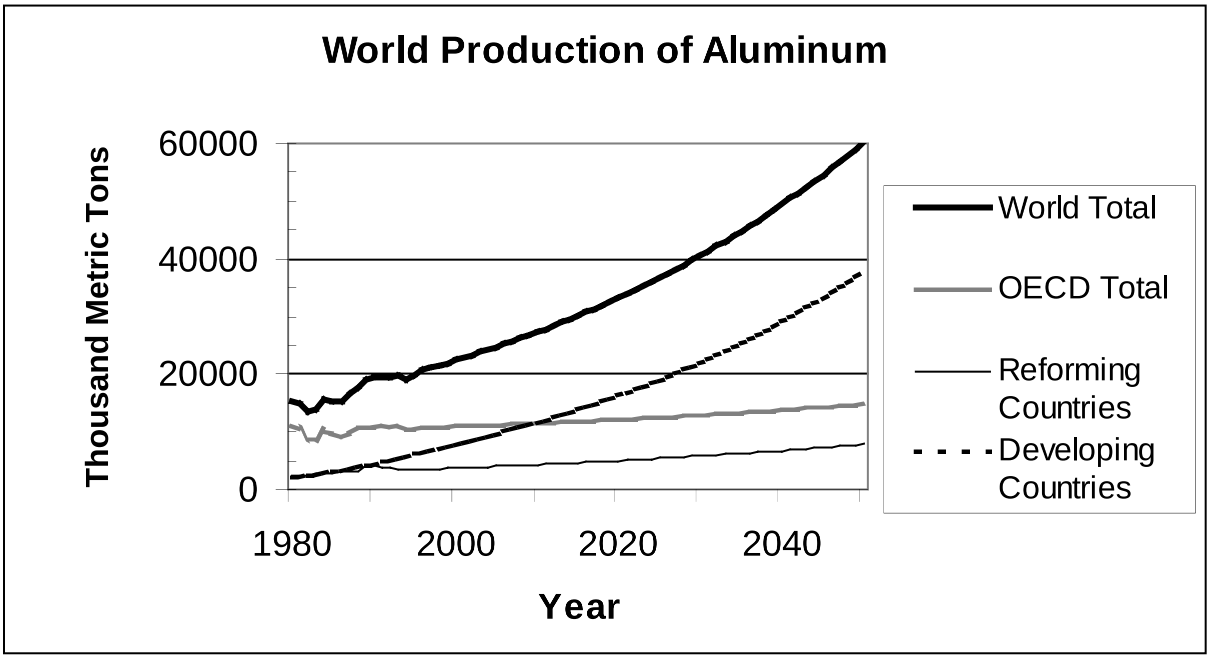


Figure 2 Future Levels of Industrial Activity that Yield PFCs. Aluminum production is shown in panels (a) and (b). Semiconductor production is shown in panels (c) and (d).

Panel (a)



Aluminum production is based on historical data available from the US Geological Survey.[23] We assume that future world production rises 2% per year, which is consistent with the average observed growth since 1980. For North America, we assume growth of 1% per year, which is based on the assumption that Canadian production continues its rise (at a slower pace than during the last decade), and US production remains stagnant as during the last decade. For the Pacific OECD nations (Australia, Japan, New Zealand) we also assume 1% per year growth. During the last 15 years production in this region has been stagnant overall—Japanese production has dropped 98%; output has risen dramatically in Australia (+280%) and New Zealand (+77%) over the period, but production in these two countries has been flat for the last 5 years. In Western Europe, production has declined 10% over the last 15 years; we project that the decline will continue at 1% per year. In the reforming countries production declined significantly with the collapse of central planning but has since stabilized; we project 1.5% per year average growth in the future. Developing countries contribute the remaining share of world production and thus grow at more than 2% per year. Developing country production of aluminum has steadily grown over the last 15 years; in 1996, estimated production of aluminum in developing countries was more than three times the 1980 level.

Panel (b)

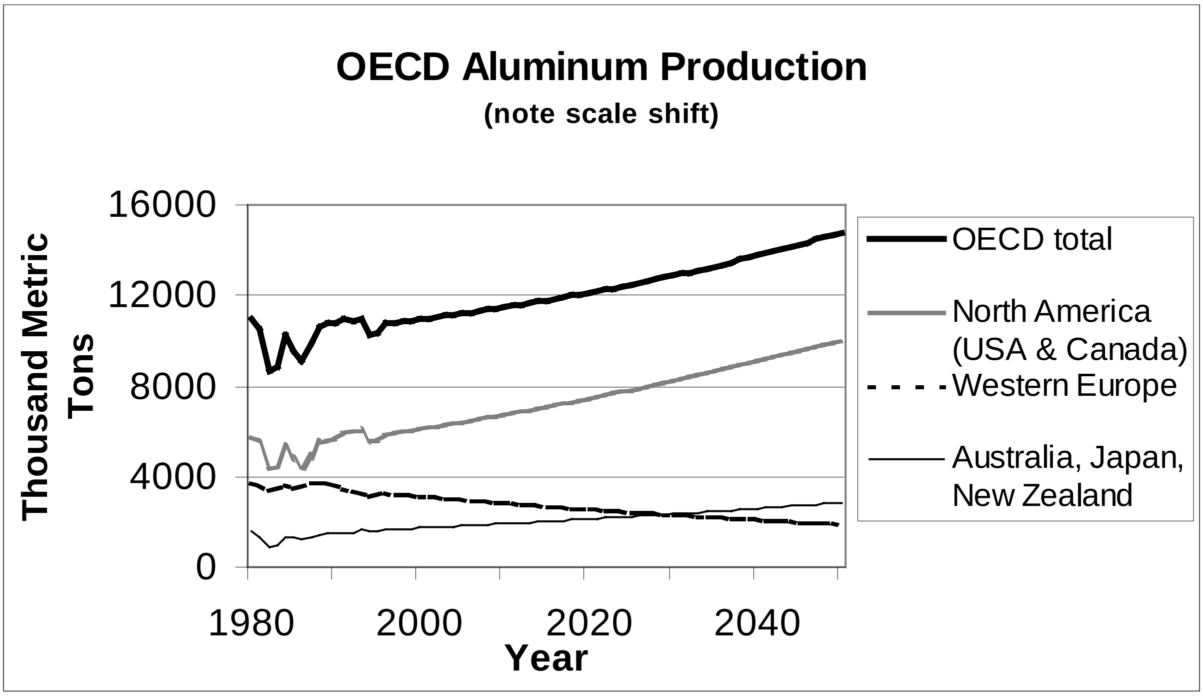
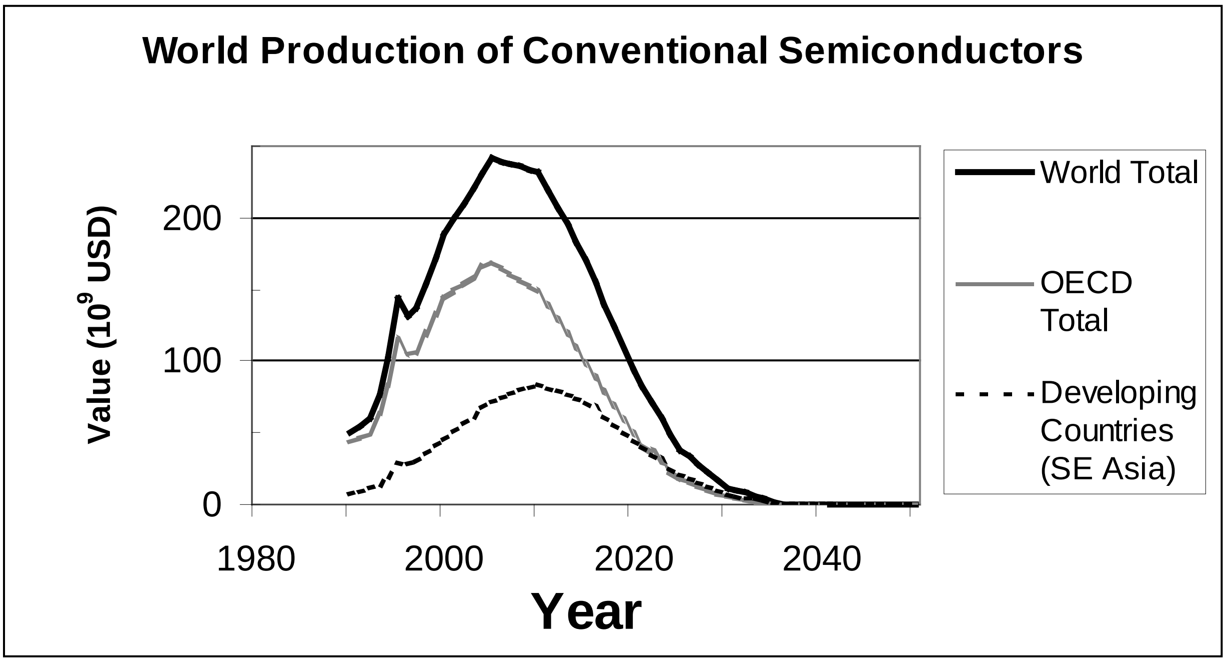


Figure 2 (cont.) Past and Future Levels of Industrial Activity that Yield PFCs. Semiconductor production is shown in panels (c) and (d).

Panel (c)



Our semiconductor projection is based on the global sales data of the Semiconductor Industry Association,[24] the only integrated global and regional historical data set. We fit curves for each of four regions (Americas, Europe, Japan, Asia/Pacific) through non-linear optimization under the constrain of a maximum in the period 2010-2020. The projection envisions conventional semiconductor production declining sharply after 2010, to be replaced presumably by new methods that perhaps are unlike current approaches (including in their use of PFCs).

Panel (d)

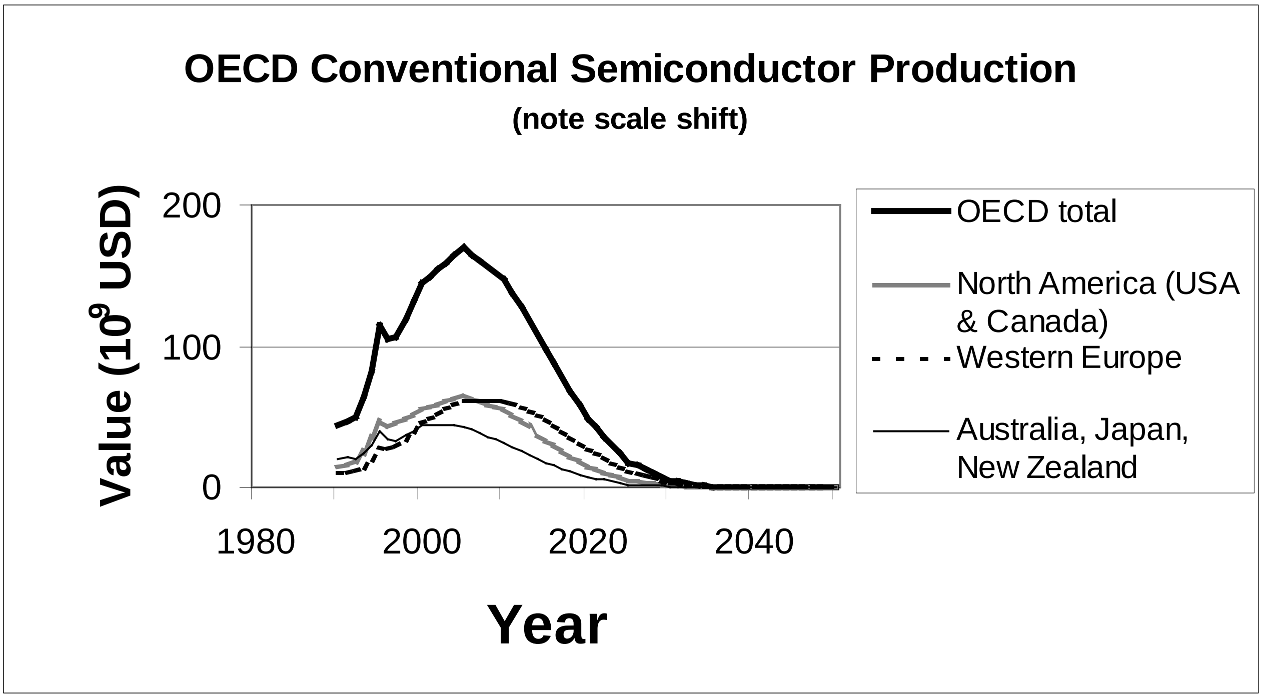
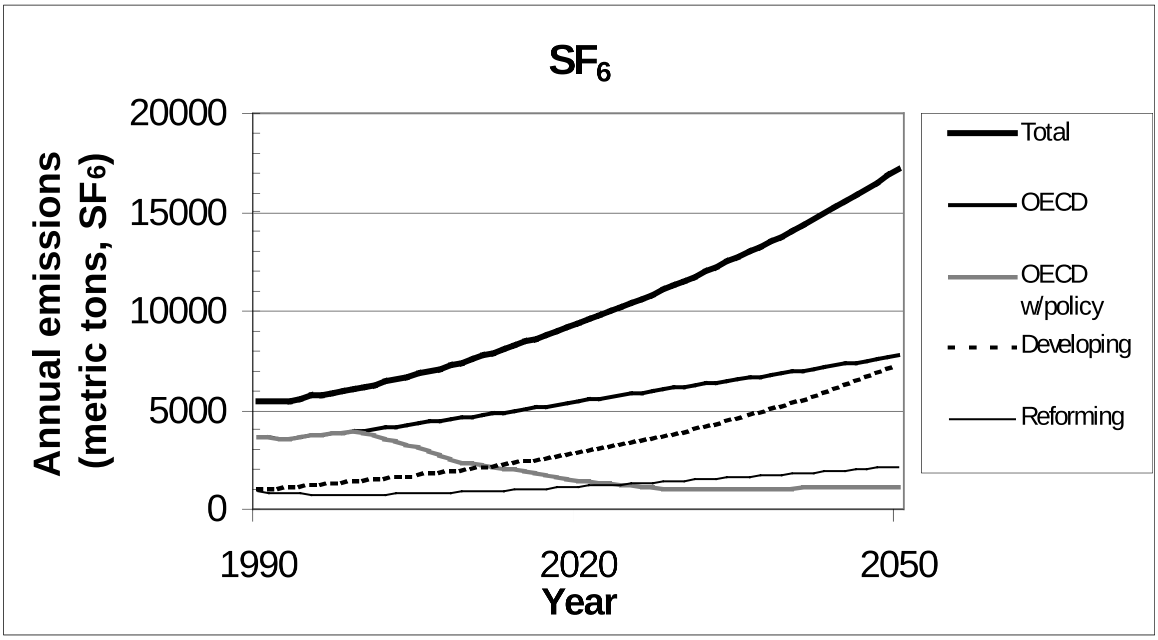


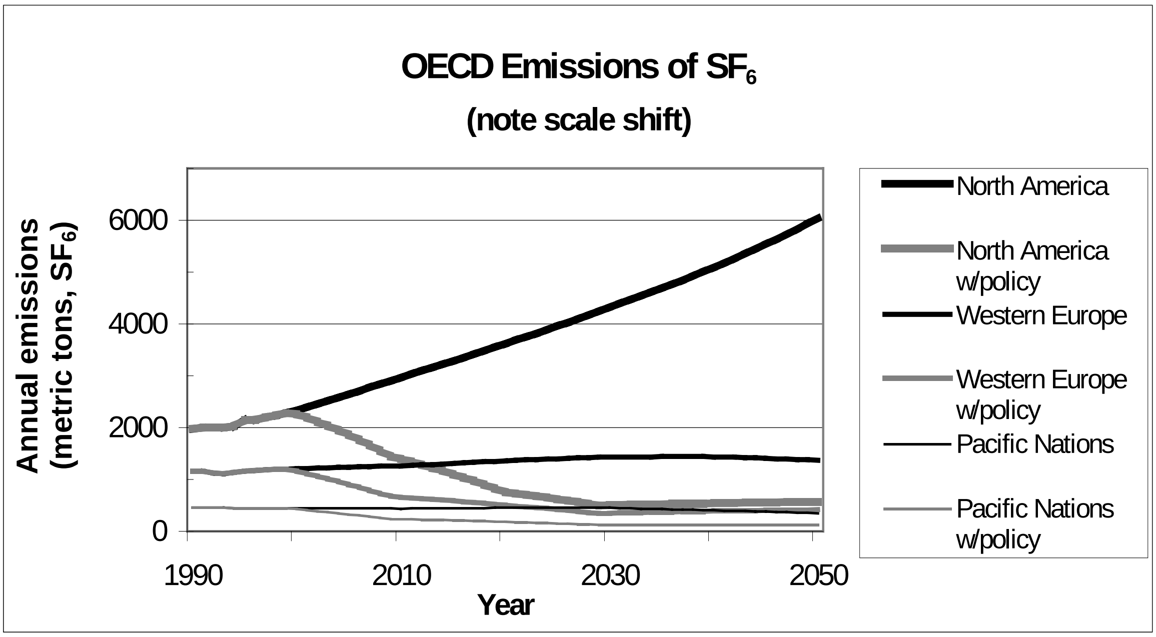
Figure 3 Emissions of SF_6.

Panel (a)



Shows global emissions for our baseline and policy scenario.

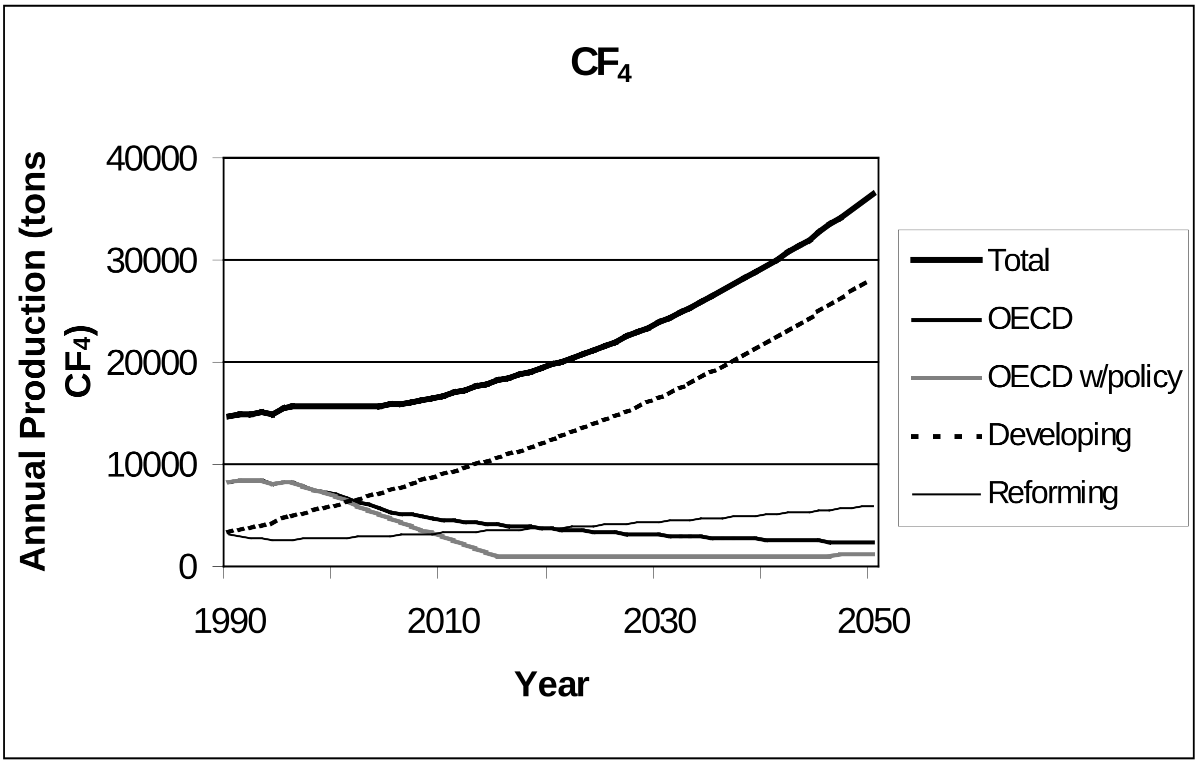
Panel (b)



Shows emissions from three OECD regions for baseline and policy scenarios.

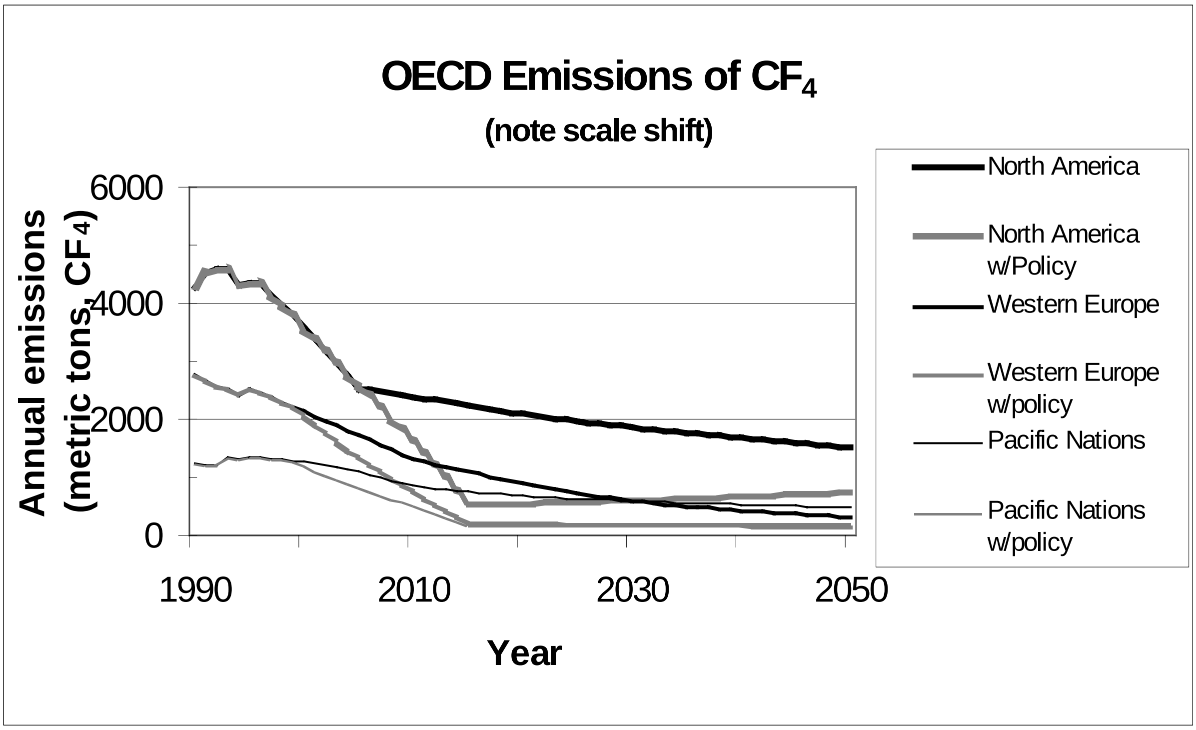
Figure 4 Emissions of CF_4.

Panel (a)



Shows global emissions for our baseline and policy scenarios.

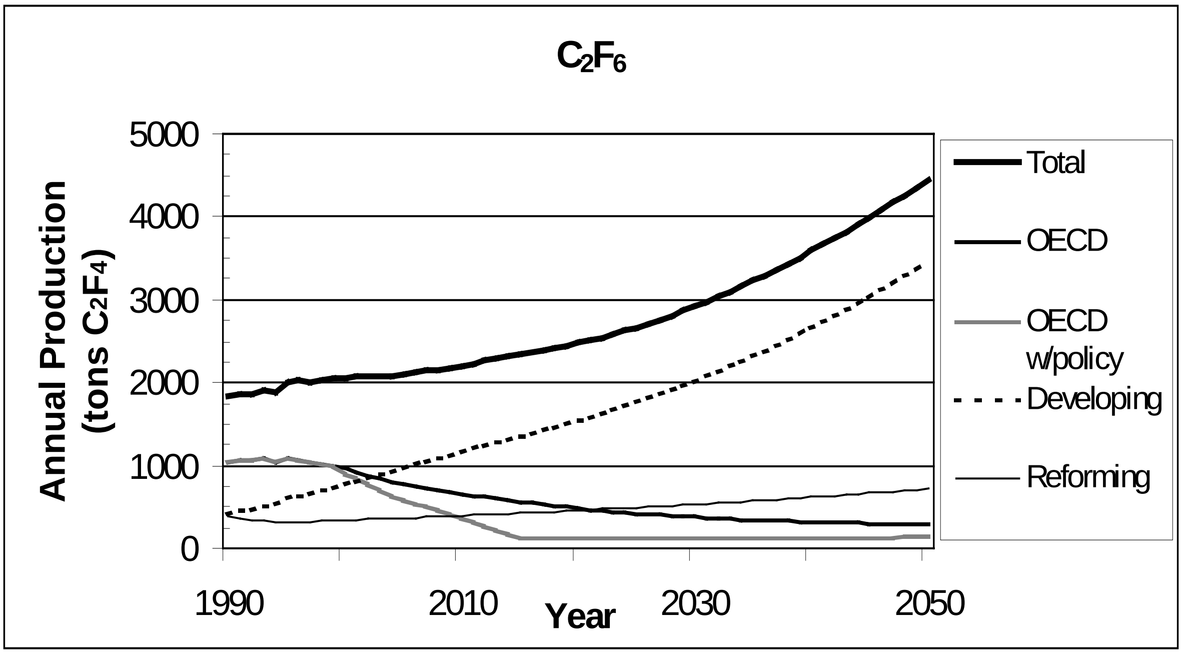
Panel (b)



Shows emissions from three OECD regions for baseline and policy scenarios.

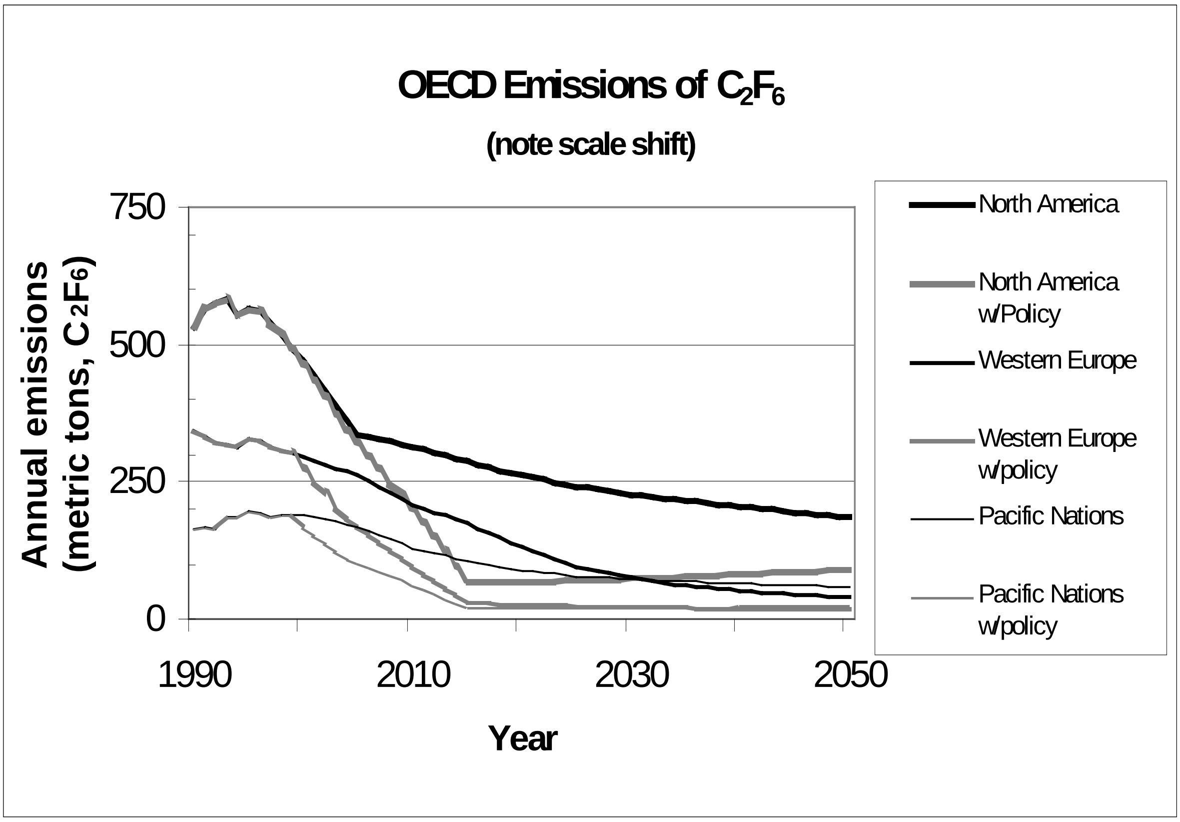
Figure 5 Emissions of C_2F_6.

Panel (a)



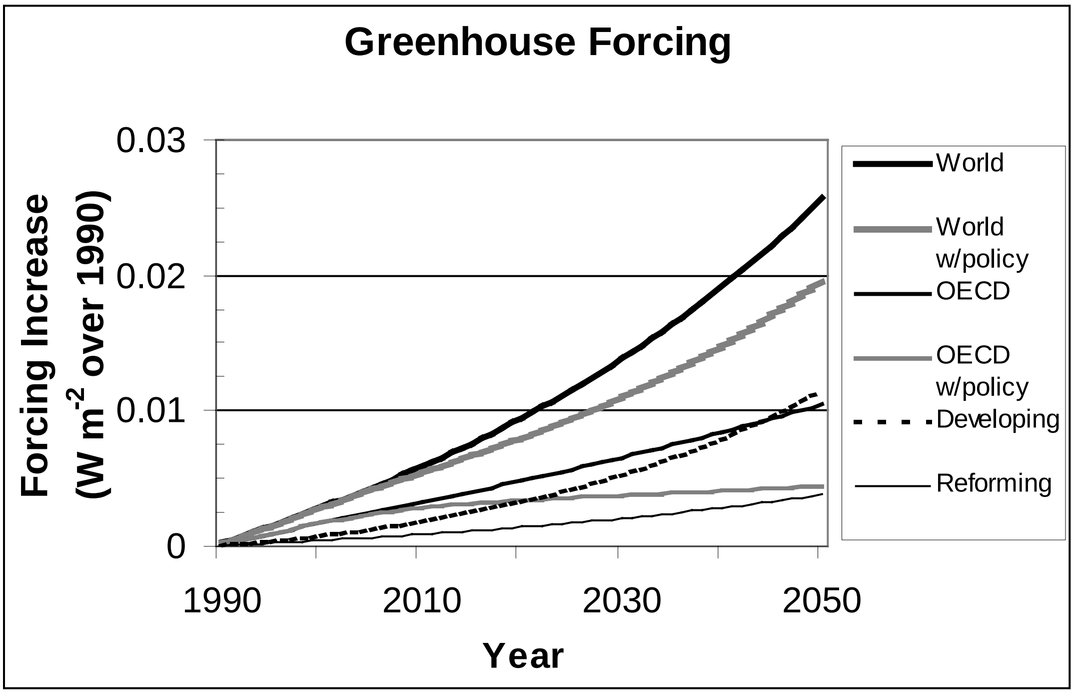
Shows global emissions for our baseline and policy scenarios.

Panel (b)



Shows emissions from three OECD regions for both scenarios.

Figure 6 Radiative Forcing Due to SF_6 and PFCs.



Curves show total forcing due to the accumulated emissions of these gases (emissions reported in table 2). We use the forcing coefficients summarized by the Intergovernmental Panel on Climate Change (table 2.2 of ref. 7) and ignore band saturation, which is not significant at such low concentrations.

TABLES

Table 1 Observed increase in SF_6 and PFCs, attribution of sources, and emission factors for middle 1990s.

Gas	Observed rise	Source Activity	Gas attributed to source	Level of activity	Emission factor
SF_6	5800 tons_{SF6} yr^{-1}	Electricity Supply (leakage from circuit breakers and compact substations)	4600 tons_{SF6} yr^{-1}	1180 Gwyr yr^{-1}	3.9 tons_{SF6} Gwyr_{elec}^{-1}
		Magnesium (SF_6 as cover gas during casting)	1200 tons_{SF6} yr^{-1}	300 tmt_{Mg} yr^{-1}	3.5 ton_{SF6} tmt_{Mg}^{-1} (OECD countries) 1.5 ton_{SF6} tmt_{Mg}^{-1} (developing countries)
CF_4	15500 tons_{CF4} yr^{-1}	Aluminum production ("anode effects")	15000 tons_{CF4} yr^{-1}	19900 tmt_{Al} yr^{-1}	0.75 tons_{CF4} tmt_{Al}^{-1}
		Semiconductor production (waste stream from etching and cleaning of deposition chambers)	570 tons_{CF4} yr^{-1}	140 BUSD yr^{-1}	4 tons_{CF4} BUSD^{-1}
C_2F_6	2000 tons_{C2F6} yr^{-1}	Aluminum production (see above)	1800 tons_{C2F6} yr^{-1}	19900 tmt_{Al} yr^{-1}	0.092 tons_{C2F6} tmt_{Al}^{-1}
		Semiconductor production (see above)	180 tons_{C2F6} yr^{-1}	140 BUSD yr^{-1}	1.3 tons_{C2F6} BUSD^{-1}

Notes: tmt = thousand metric tons (10^9g); BUSD = billion (10^9) US Dollars; Gwyr = gigawatt-years.

Our model is based on emission factors derived from the measured rise in atmospheric concentration and a proxy for the activities that cause that rise. The factors for magnesium casting have been adjusted to account for differences between industrialized and developing countries (see text). The PFC factors were adjusted to reproduce the likely ratio of emissions in North America for 1995 (see text). Because of rounding errors in that process the values in column 4 do not sum exactly to the total PFC sources given in column 2.

Table 2 Regional and global emissions of SF_6, CF_4 and C_2F_6 for the baseline scenario

	1990		2010				2050			
		GWP-weighted			GWP-weighted				GWP-weighted	
	emiss/yr tons/yr	emiss/yr mmt CO_2	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2
OECD total										
SF_6	3590	86	4669	30%	112	602	7760	116%	185	7976
CF_4	8243	54	4543	-45%	30	284	2309	-72%	15	1741
C_2F_6	1041	10	652	-37%	6	55	282	-73%	3	325
total		149			147	941			203	10042
Reforming										
SF_6	870	21	883	1%	21	224	2170	149%	52	1816
CF_4	3173	21	3242	2%	21	161	5880	85%	38	1554
C_2F_6	387	4	395	2%	4	33	717	85%	7	268
total		45			46	418			97	3639
Developing										
SF_6	974	23	2007	106%	48	2024	7249	645%	173	4752
CF_4	3260	21	8970	175%	58	921	28268	767%	184	5354
C_2F_6	403	4	1162	188%	11	176	3449	755%	32	939
total		48			117	3121			389	11045
World										
SF_6	5433	130	7558	39%	181	393	17179	216%	411	14545
CF_4	14676	95	16755	14%	109	394	36457	148%	237	8650
C_2F_6	1832	17	2210	21%	20	68	4448	143%	41	1531
total		242			310	855			688	24726

Also shown are values weighted by global warming potentials (GWPs). GWPs indicate the net radiative forcing due to emission of 1 kg of a gas over a specific time horizon, relative to the forcing caused a 1 kg emission of CO_2 over the same period. We use the mass GWP values (100 year time horizon) adopted by the Intergovernmental Panel on Climate Change (IPCC) in 1996 (ref. 7): 23900 (SF_6), 6500 (CF_4), and 9200 (C_2F_6). Due to changes in the modeling of the carbon cycle and revised measurements of the infrared strength of the PFCs, those values vary from the GWPs used in the “national communications” by which several countries have reported emissions of these gases to the FCCC (ref. 19). Where necessary, we have revised the FCCC data so that all numbers in this paper reflect the 1996 GWP values. For no good reason, 100 years is the most common time horizon; one failing of the GWP concept is that it requires policy makers to make this arbitrary but significant choice. If a 500-year time horizon were used, for example, the GWPs for SF_6 and PFCs would rise by approximately 50%. In addition to annual emissions, we show cumulative emissions (since 1990) because the absolute level of greenhouse warming depends on the accumulation of gases.

Table 3 OECD emissions of SF_6, CF_4 and C_2F_6 for the baseline scenario.

	1990		2010				2050			
		GWP-wtd			GWP-weighted				GWP-weighted	
	emiss/yr tons/yr	emiss/yr mmt CO_2	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2
North America										
SF_6	1970	47	2969	51%	71	1198	6038	206%	144	5415
CF_4	4269	28	2393	-44%	16	477	1515	-65%	10	967
C_2F_6	533	5	314	-41%	3	87	185	-65%	2	173
total		80			89	1763			156	6555
Western Europe										
SF_6	1157	28	1262	9%	30	602	1371	18%	33	1931
CF_4	2750	18	1305	-53%	8	284	315	-89%	2	456
C_2F_6	343	3	209	-39%	2	55	38	-89%	0	89
total		49			41	941			35	2476
Pacific OECD										
SF_6	462	11	438	-5%	10	224	351	-24%	8	630
CF_4	1224	8	846	-31%	5	161	479	-61%	3	319
C_2F_6	165	2	129	-22%	1	33	58	-65%	1	62
total		21			17	418			12	1011
OECD total										
SF_6	3590	86	4669	30%	112	2024	7760	116%	185	7976
CF_4	8243	54	4543	-45%	30	921	2309	-72%	15	1741
C_2F_6	1041	10	652	-37%	6	176	282	-73%	3	325
total		149			147	3121			203	10042

Table 4 OECD emissions of SF_6, CF_4 and C_2F_6 for the policy scenario.

	2010				2050			
			GWP-weighted				GWP-weighted	
	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2	emiss/yr tons/yr	increase 1990 level	emiss/yr mmt CO_2	cum emiss mmt CO_2
North America								
SF_6	1395	-29%	33	986	574	-71%	14	1643
CF_4	1616	-62%	11	464	752	-82%	5	641
C_2F_6	200	-62%	2	83	92	-83%	1	114
total			46	1533			19	2398
Western Europe								
SF_6	659	-43%	16	514	416	-64%	10	936
CF_4	747	-73%	5	258	142	-95%	1	311
C_2F_6	95	-72%	1	47	17	-95%	0	56
total			21	819			11	1303
Pacific OECD								
SF_6	235	-49%	6	193	126	-73%	3	339
CF_4	506	-59%	3	144	215	-82%	1	195
C_2F_6	64	-61%	1	28	26	-84%	0	37
total			9	365			5	571
OECD total								
SF_6	2289	-36%	55	1693	1116	-69%	27	2918
CF_4	2870	-65%	19	865	1108	-87%	7	1147
C_2F_6	359	-66%	3	158	135	-87%	1	207
total			77	2716			35	4272

Table 5 Absolute level and fraction of radiative forcing due to SF_6, CF_4 and C_2F_6 for baseline and policy scenarios.

	Baseline		Policy	
	2010	2050	2010	2050
SF_6 (W m^{-2})	0.003	0.015	0.003	0.010
percent of total	56%	59%	54%	50%
CF_4 (W m^{-2})	0.002	0.009	0.002	0.008
percent of total	37%	35%	39%	42%
C_2F_6 (W m^{-2})	0.000	0.002	0.000	0.001
percent of total	7%	6%	7%	7%
Total (W m^{-2})	0.006	0.026	0.005	0.020

Notes

[1] Wang, W.C., Pinto, J.P., Yung, Y.L, 1980, “Climatic Effects Due to Halogenated Compounds in the Earth’s Atmosphere,” *Journal of the Atmospheric Sciences*, **37**, 333-338.

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[32] The same discussion above (note 31) applies here.

[33] Schiff *et al.*, cited in Cook (ref. 13) at note 19. See also Tabereaux (ref. 17) at p. 34. Because the molecular weight of C_2F_6 is higher than of CF_4, the *mass* emission ratio of C_2F_6 would be 15% that of CF_4 if the volume rate is one-tenth.

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