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Implications for the USA of stabilization of radiative forcing at 3.4 W/m^2

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Stabilization presents a daunting challenge for all countries of the world, regardless of their stage of development, institutions or technological capabilities. This article explores the implications for the USA of climate stabilization at 3.4 W/m^2. Stabilization at this level, even under idealized conditions of nearly immediate global cooperation, will require a transformation of the USA's energy system, beginning almost immediately and extending throughout the century and beyond. This transformation will need to be even more rapid and extensive if the emissions reduction regime encompasses only a portion of the global economy. The availability of advanced technologies such as CCS, sustainable bioenergy production, wind and solar, nuclear energy and end-use efficiency improvements will facilitate this transition. Indeed, the degree to which technology advances over the coming century is among the most important determinants of the economic costs of stabilization for the USA and the rest of the world. The scope of the energy system transformation highlights the need to begin deploying technologies that are currently available and to continue to invest in R&D to develop newer, more efficient, and less expensive low- or zero-carbon energy supply technologies and end-use technologies.

Keywords: climate change; climate stabilization; energy; energy systems; low-carbon society; technology

La stabilisation représente un défi grave pour tous les pays du monde, quelque soit leur stade de développement, leurs institutions ou aptitudes technologiques. Ce papier explore les conséquences éventuelles pour les Etats-Unis d'une stabilisation climatique à 3.4 W/m^2. Une stabilisation à ce niveau, même dans des conditions idéalisées de coopération mondiale presque immédiate, nécessitera une transformation du système énergétique des Etats-Unis à commencer dès à présent et se déroulant tout au long de ce siècle et au-delà. Cette transformation devra être d'autant plus rapide et extensive si le régime de réduction des émissions n'englobe qu'une partie de l'économie mondiale. La disponibilité de technologies avancées telles que la CSC, la production durable de bioénergie, l'éolien et le solaire, l'énergie nucléaire et l'amélioration de l'efficacité à utilisation finale faciliteront cette transition. En effet, l'avancée des progrès technologiques au cours du siècle à venir sera un des facteurs les plus déterminants du coût économique de stabilisation pour les Etats-Unis et le monde. L'etendue de la transformation du système énergétique met en valeur le besoin d'amorcer le déploiement des technologies qui sont disponibles actuellement et de continuer à investir dans la recherche et le développement pour le développement de technologies d'énergie faiblement carbonées ou décarbonées et de technologies d'utilisation finale plus neuves, plus efficaces, moins chères.

Mots clés: changement climatique; énergie; société sobre en carbone; stabilisation du climat; systèmes énergétiques; technologie

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1. Introduction

Stabilization is a global challenge: no country can stabilize atmospheric GHG concentrations acting alone. In the long run, stabilization will require the combined efforts of nearly every country around the world. But every country and region is different; in its history, its demographics, its institutions, its economic prosperity, its energy system, its technological capacity and, of course, its GHG emissions. The challenges presented by stabilization in every country are therefore different, but they are also linked because all countries must eventually participate in emissions mitigation.

Limiting anthropogenic climate change requires the stabilization of radiative forcing, a measure of the change in atmospheric energy balance by greenhouse gases (GHGs) and aerosols.[1] This article explores the potential implications of stabilization for the USA within a global context. We explore the US implications within a cooperative global scenario in which radiative forcing from carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6) is limited to 3.4 W/m^2, relative to a pre-industrial state. This radiative forcing level is consistent with stabilizing the concentration of CO_2, the most important GHG released by humans to the atmosphere, at approximately 450 parts per million (ppm), stabilizing the concentration of CH_4 at approximately 1.4 ppm, and stabilizing the concentration of N_2O at 0.36 ppm. There is no scientific consensus that limiting radiative forcing to 3.4 W/m^2 is the ‘right’ target. Nevertheless, limits in this range are of particular interest from the perspective of the low-carbon society and are the subject of this series of papers in this *Climate Policy* supplement.

This article illustrates that stabilization will require substantial changes in the energy sector, changes that will ultimately encompass every country either directly or indirectly. The scenario presented here envisions a world where increasing prosperity results in the majority of global emissions originating from non-Annex 1 countries by 2020. The US economy grows fivefold over the century, leading to emissions increases, without mitigation actions, of only 35%, in large part because of substantial advances in energy supply and demand technologies. Even in an optimal global strategy, stabilization at 3.4 W/m^2 still requires a transformation of the US energy system that needs to begin almost immediately. Delays in emissions reductions by non-Annex 1 countries increase the speed and extent of this transformation (Edmonds et al., 2008).

2. The MiniCAM model

The analysis presented here employs the ObjECTS MiniCAM model (Brenkert et al., 2003; Kim et al., 2006). The ObjECTS MiniCAM is a long-term, global integrated assessment model of energy, economy, agriculture and land use, which considers the sources of emissions of a suite of greenhouse gases (GHGs) emitted in 14 globally disaggregated regions, the fate of emissions to the atmosphere, and the consequences of changing concentrations of greenhouse-related gases for climate change over a time period ranging from 1990 to 2095. The model combines a technologically detailed global energy-economy model, an agricultural land-use model (Gillingham et al., 2007), and a suite of coupled gas-cycle, climate, and ice-melt models: the Model for the Assessment of Greenhouse-gas Induced Climate Change (MAGICC; Wigley and Raper, 1992, 2002; Raper et al., 1996). The MiniCAM is a direct descendent of the energy-sector model described by Edmonds and Reilly (1985). MiniCAM has been used extensively for energy, climate, and other environmental analyses conducted for organizations that include the US Department of Energy (DOE), the US Environmental Protection Agency, the IPCC, and several major private sector energy companies. The model is designed to examine long-term, large-scale changes in global and regional energy, economy, emissions of greenhouse gases, short-lived species, and land-cover, atmosphere, carbon cycle, ocean and climate systems, with special emphasis on the role of energy technology.[2]

3. The reference scenario

The reference scenario serves as a point of departure for exploring the implications for the USA of stabilization of global radiative forcing at a level consistent with a 'low-carbon society'. The reference scenario used in this article is described in detail by Clarke et al. (2007a). It assumes that climate policies that are presently in place throughout the world remain in place until the year 2012, at which time they are assumed to expire and are not replaced or extended by other policies motivated by climate change. Other policies and measures motivated by local and regional environmental quality considerations are assumed to be strengthened and extended. For example, sulphur emissions are assumed to be increasingly limited throughout the world. The assumption that no country takes action on climate for the full century is deliberately unrealistic.[3] The reference scenario is constructed as a contrast to alternative scenarios that limit radiative forcing to specific levels (Clarke et al., 2007a).

The most important assumptions shaping the reference scenario are population and labour productivity growth. We assume both a demographic transition and rapid economic expansion that gradually permeates the presently developing world. A central characteristic of the reference scenario is the increasing importance of the non-Annex I nations. World population is increasingly dominated by these countries (Figure 1). Rates of economic growth well above those in the Annex 1 countries also shift economic output to the non-Annex 1 countries (Figure 2). As a result, the non-Annex 1 countries produce more CO_2 than the Annex 1 countries by 2020 (Figure 3). In total, considering all the GHGs in this study, radiative forcing by the end of the century in the reference scenario well exceeds the stabilization limit of 3.4 W/m^2 considered in this article, and CO_2 takes on an increasing share of the total forcing (Figure 4A).[4]

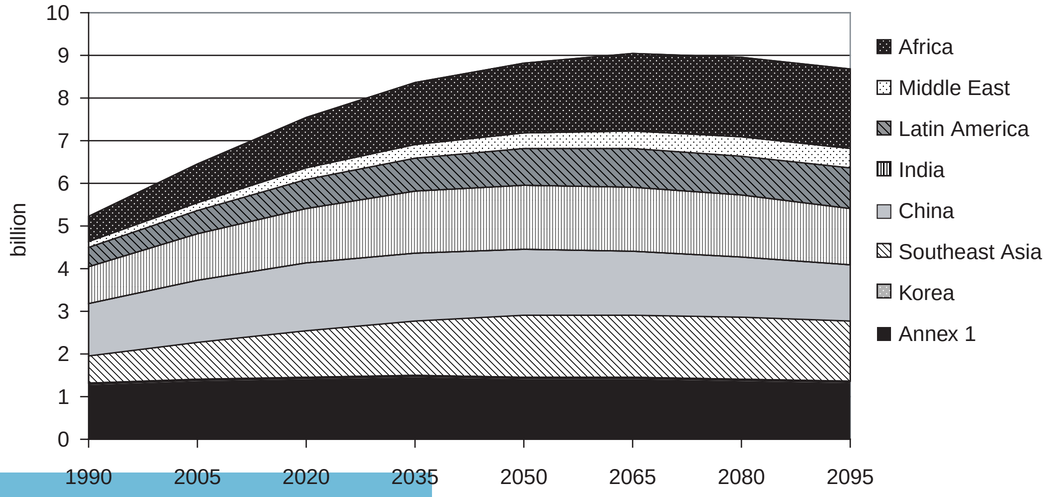


FIGURE 1 Global population in the reference scenario.

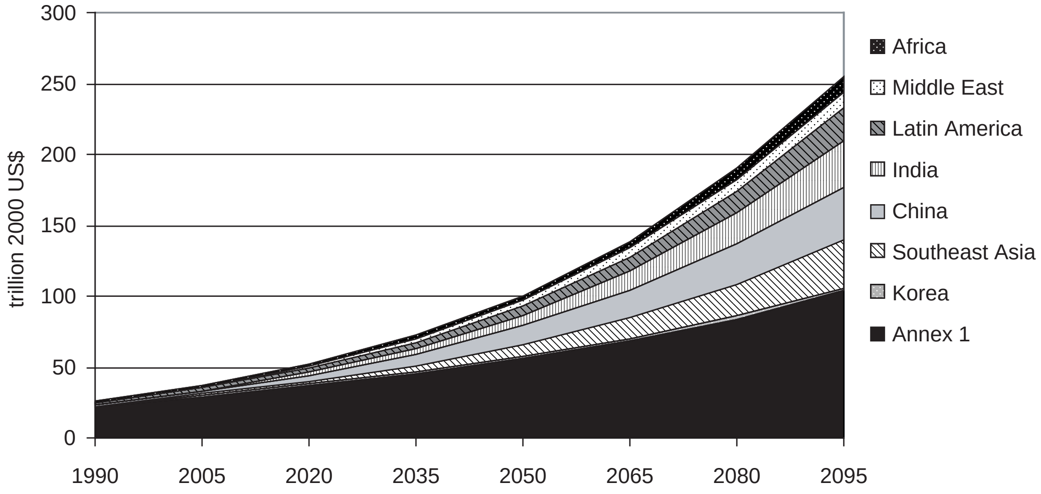


FIGURE 2 Global GDP in the reference scenario.

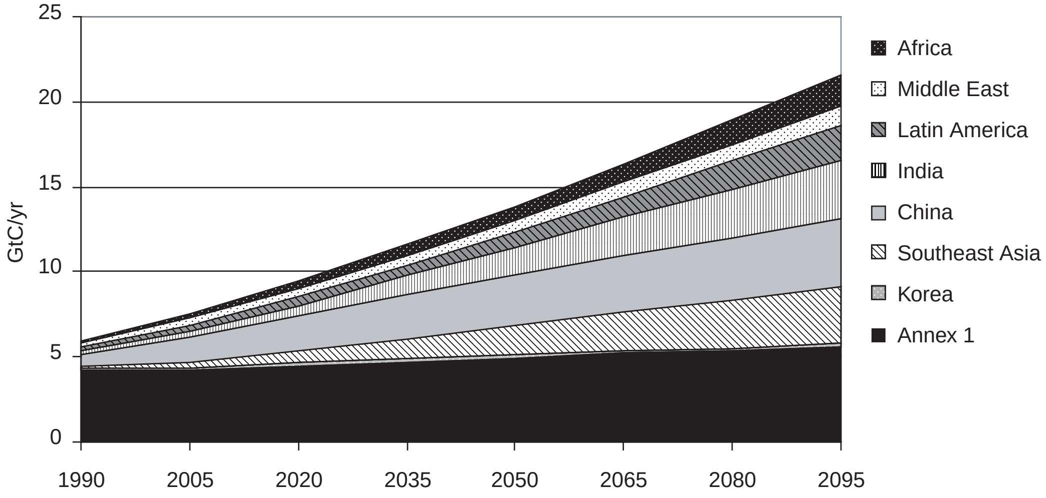


FIGURE 3 Global fossil fuel and industrial carbon emissions by region 2005–2095.

The reference scenario incorporates substantial technological developments and assumes the availability of multiple energy forms. The economic cost and performance of wind and solar power systems are assumed to improve over the course of the century. Nuclear power is assumed to be available and to compete on the basis of cost and performance, and is assumed to successfully address non-economic issues which include nuclear waste, weapons proliferation, energy security, health and safety. Several bioenergy technologies are assumed to be available, including traditional bioenergy fuel use in developing countries, bioenergy based on use of waste and residue products such as bark in the pulp and paper industry, agricultural residues, and dedicated bioenergy crops.

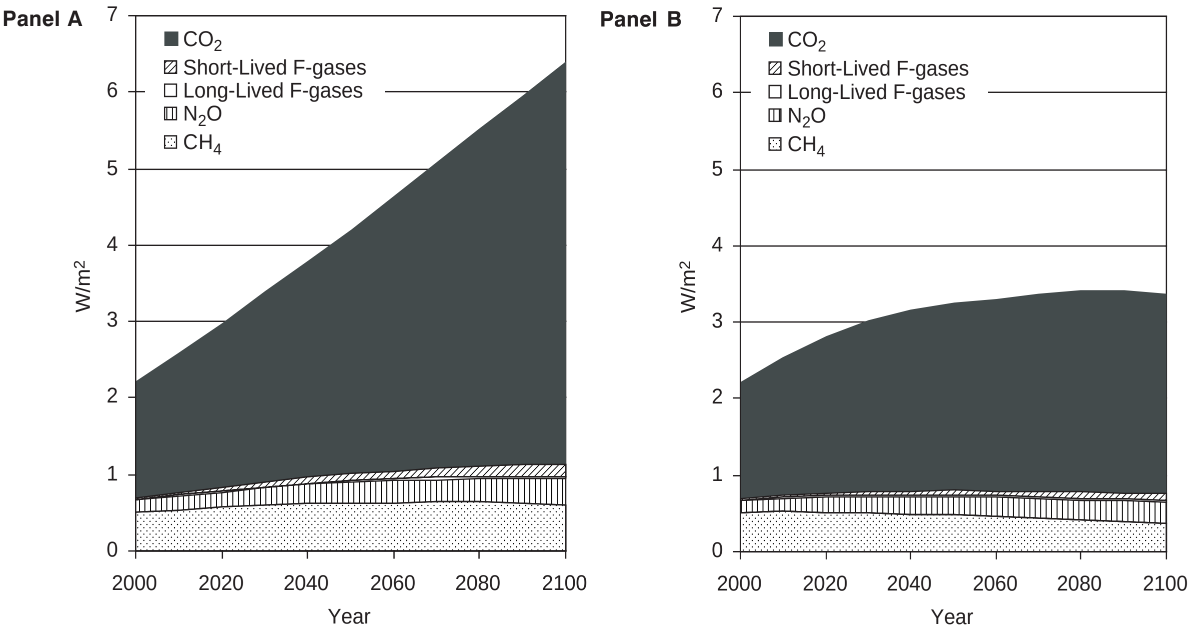


FIGURE 4 Reference case radiative forcing by gas (A) and radiative forcing in the 3.4 W/m^2 stabilization scenario (B).

Despite the fact that dramatic increases in the production and use of non-fossil energy forms takes place in the reference scenario, the global and US energy systems continue to be dominated by fossil fuel use (Figure 5).[5] In addition, because of the availability of these options, along with assumptions of substantial improvements in energy intensity over the century, US energy primary energy consumption increases by only 35% over the century despite a more than fivefold increase in US economic output. Indeed, the USA's primary energy consumption is level or declining over the final four decades of the century. In a sense, the assumptions underlying this reference scenario lead to emissions reductions, even without policy, beyond what would occur if technology were assumed to remain static or advance more slowly over the century. Emissions would be larger if other forces that influence GHG emissions, such as population growth and per-capita energy service demand growth, were to increase at faster rates than assumed in this scenario.

4. Emissions and stabilization of radiative forcing at 3.4 W/m^2

The stabilization scenario assumes that all the world's countries begin, after 2012, to work cooperatively to reduce greenhouse gas emissions. Global economic efficiency is assumed, meaning that emissions reductions are undertaken so as to equalize marginal costs of emissions reductions across regions and GHGs. In addition, the intertemporal allocation of emissions reductions is designed to minimize global costs.

Note that the radiative forcing target here refers to total greenhouse gas forcing only. Forcing from aerosols, tropospheric and stratospheric ozone were not included in the target. The sum of these additional forcings is small by 2100, with positive tropospheric ozone forcing nearly cancelling, on a global average basis, the net negative aerosol forcing, changing the total forcing target by only a small amount.

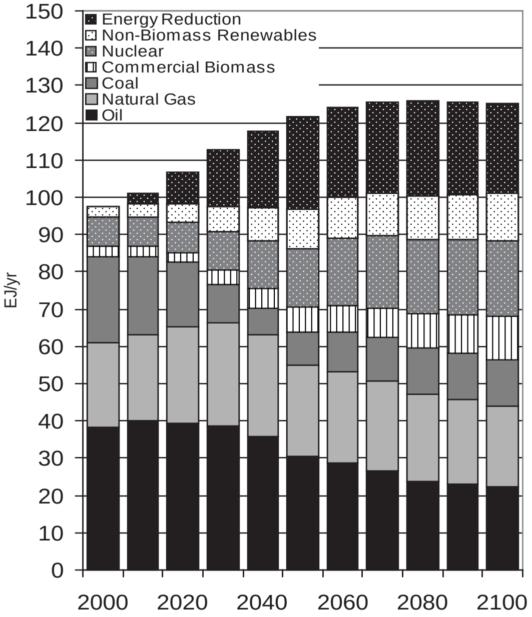


FIGURE 5 The USA's primary energy consumption.

Stabilization of radiative forcing is accomplished by placing an economic value on GHG emissions. In MiniCAM this is accomplished by applying a tax on emissions of GHGs. This tax is uniform across all sources of emissions – industrial, fossil fuel use, and land-use change emissions – and across all regions of the world. Initially, the uniform tax on GHG emissions is assumed to rise at the rate of interest plus the natural rate of removal from the atmosphere (Hotelling, 1931; Peck and Wan, 1996). For example, if the rate of interest is 4% per year and the rate of removal of carbon from the atmosphere is 1% per year, then the price of carbon rises at 5% per year. At the point in time when the concentration of CO_2 reaches the stabilization limit, the price of carbon is set by the physical limit on carbon uptake by natural systems at the steady-state concentration. The time of radiative forcing by gas for the 3.4 W/m^2 stabilization scenario is shown in Figure 4B.

The price of carbon rises exponentially until mid-century, when it reaches approximately \$500/tC (\$136/tCO_2), at which point the concentration of CO_2 approaches its steady-state value (Figure 6). After 2050 the price continues to rise until approximately 2080, but at a slower than exponential rate.[6] The absolute price actually begins to fall at the end of the 21st century as emissions are controlled to maintain the CO_2 concentration at its steady-state value.

Other policy instruments could be employed to achieve the same outcome. However, to minimize cost, an instrument must maintain marginal GHG emissions mitigation costs nearly equal across all regions and emissions sources, and these marginal costs must rise at the appropriate rate over time. Allocating emissions allowances in appropriate quantities creates a market and market price that performs the same signalling function as a tax as long as all carbon is covered in all regions and human activities. Generating the appropriate rate of price escalation could be achieved by managing the supply of allowable permits. Regulatory policy instruments could also be employed to achieve the same end. However, it can be difficult in practice to maintain equality in the marginal value of GHG emissions across sectors employing regulatory instruments alone. Each policy instrument has its own set of advantages and disadvantages and the eventual choice will depend on many factors, including the local institutional history and context, and will probably evolve with time (DOE, 1989).

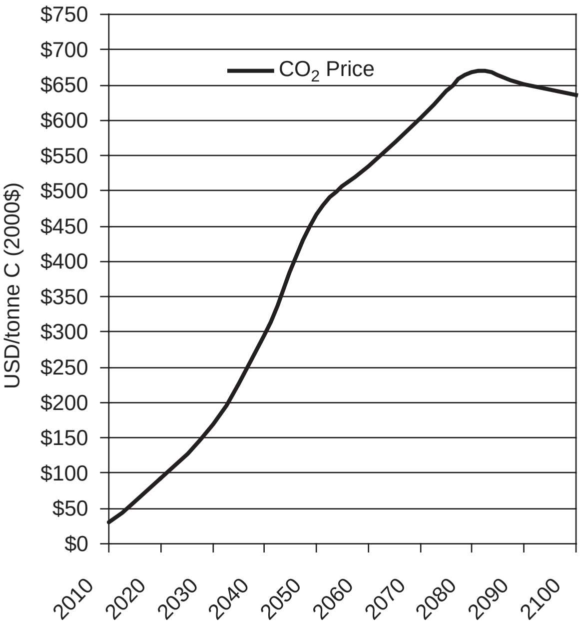


FIGURE 6 Price path for carbon emissions consistent with stabilization of radiative forcing at 3.4 W/m².

Emissions mitigation relative to the reference scenario and relative to the present is substantial in both the USA and globally (Figure 7). By 2050, global emissions are 50% of 2010 levels. By 2100, global emissions have declined by two-thirds relative to 2010 and by almost 90% relative to the reference scenario. The USA's emissions mitigation is somewhat greater relative to 2010 than the global average, with a 58% reduction in 2050 rather than 50%. Because the rate of emissions growth in the USA is slower than for the world as a whole, its emissions mitigation relative to the reference scenario is somewhat smaller than the world average. The degree of emissions mitigation and its timing are, nonetheless, daunting.

5. The US energy system and stabilization at 3.4 W/m²

5.1. Overview of the US energy system

Like the rest of the world, the US energy system is dominated by fossil fuel use at present, and in the reference scenario that dominance persists throughout the century (Figure 5) despite a growing share of energy provided by non-emitting energy sources. In contrast, dramatic changes occur in both the US and global energy systems in the 3.4 W/m² stabilization case. By 2050, fossil fuel use has declined to about half of the USA's primary energy consumption (Figure 8A). In 2050, the USA's primary energy consumption is about 20% smaller than in the reference scenario. These reductions in demand are driven by higher energy prices engendered by the price on GHGs.

By mid-century almost half of all primary energy is provided by non-fossil energy forms, largely nuclear, solar, wind and biomass. Biomass energy is treated as a non-carbon-emitting energy form. The increased use of nuclear energy is particularly striking. Power production from nuclear energy doubles by 2040 and triples by 2070, but its relative contribution remains stable in the final decades of the century. The increase in deployment of non-biomass renewable energy

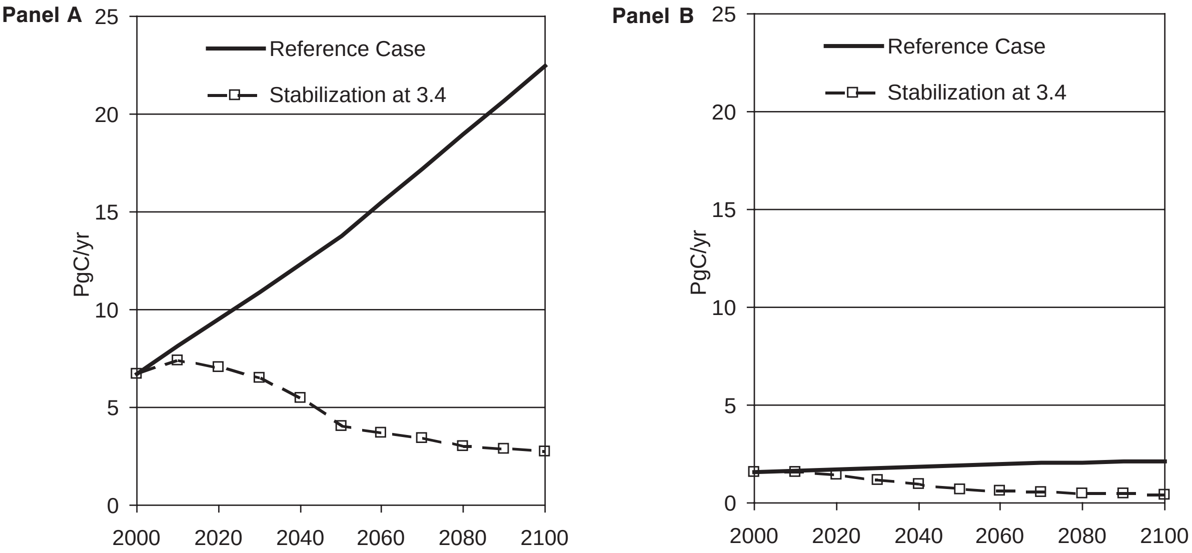


FIGURE 7 Global (A) and US carbon emissions (B) consistent with stabilization of radiative forcing at 3.4 W/m².

production is even more striking. Production more than triples by 2040 and quadruples by 2070, though much of the increase in market share also occurs in the reference scenario. Changes in primary energy consumption are shown in Figure 8B plus fossil fuel energy used in conjunction

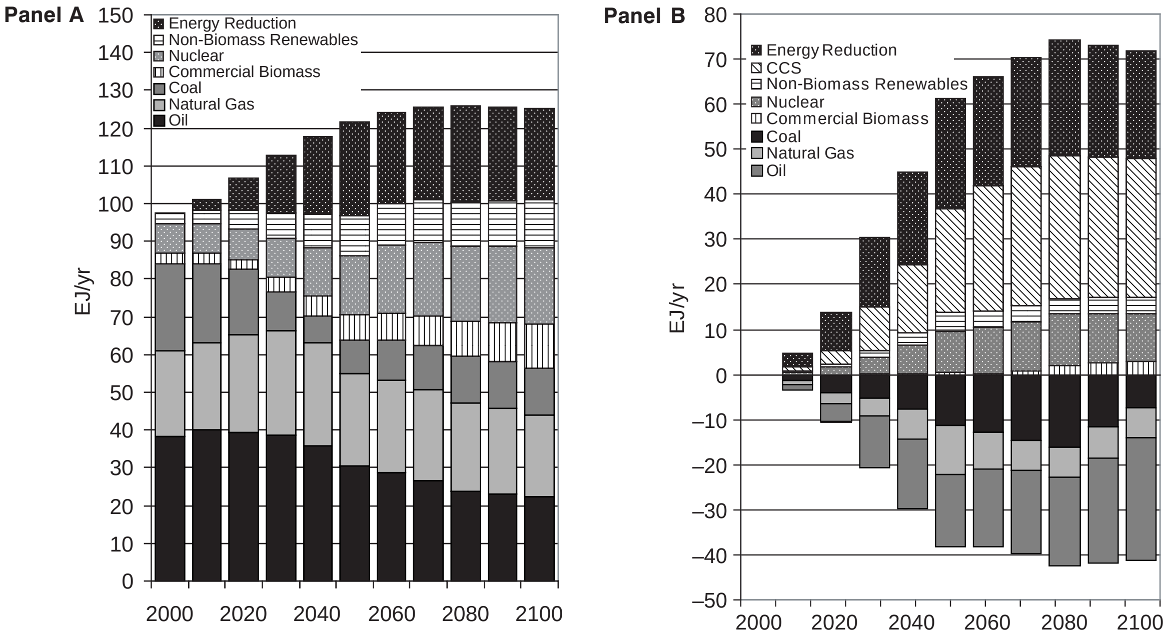


FIGURE 8 The USA's primary energy consumption (A) and associated changes (B) with stabilization of radiative forcing at 3.4 W/m².

with CO_2 capture and geological storage (CCS), and reductions in aggregate energy use. Negative values refer to reductions in energy use by fuel, while positive values are increased primary energy consumption in the stabilization case relative to the reference scenario. (Note that overall reductions in primary energy consumption are shown as a positive value.)

5.2. CO_2 capture and storage

An important technology option that is assumed to be available in the scenario is CO_2 capture and storage technology. Direct use of fossil fuels declines steadily in the stabilization scenario. The use of coal declines precipitously and remaining coal use is increasingly deployed with CO_2 capture and geological storage (CCS) technology. By 2050 all coal use employs CCS, and by 2070 almost all fossil fuel power generation employs CCS technology (see Figure 9).

It is assumed that CO_2 can be scrubbed, transported and permanently stored in geological repositories. Given that all fossil power generation is assumed to be able to employ this technology it is important to acknowledge that many important steps remain to be taken before this can be accomplished. While there is good experience with all of the components of CCS technology, the technology has not been deployed on a large scale. Projects in operation today capture and store approximately 1 TgC/yr (3.67 $TgCO_2$) globally (Dooley et al., 2006). However, in the stabilization scenario 55 TgC/yr are stored by 2020 in the USA alone (Figure 10A) while 267 TgC/yr are stored globally. By the middle of the century, deployment has increased by another order of magnitude (Figure 10B), engendering a further set of challenges in terms of the scale of the necessary technology deployment.

Since CCS is presently not deployed on a large scale, a rapid ramp-up implies addressing important transition issues such as the availability of drilling rigs, site characterizations, manufacture of capture

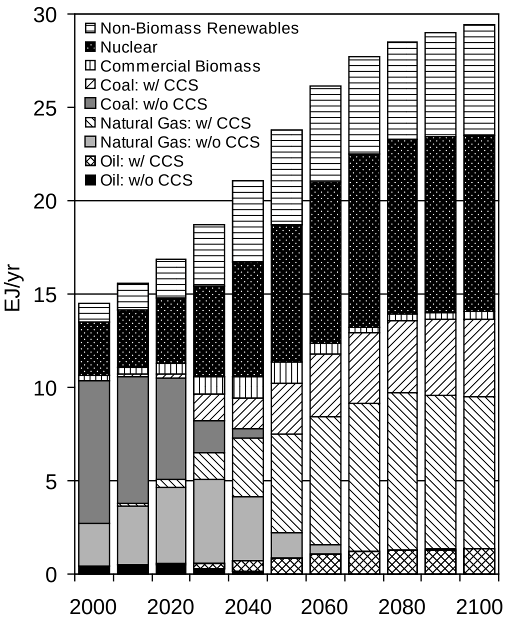


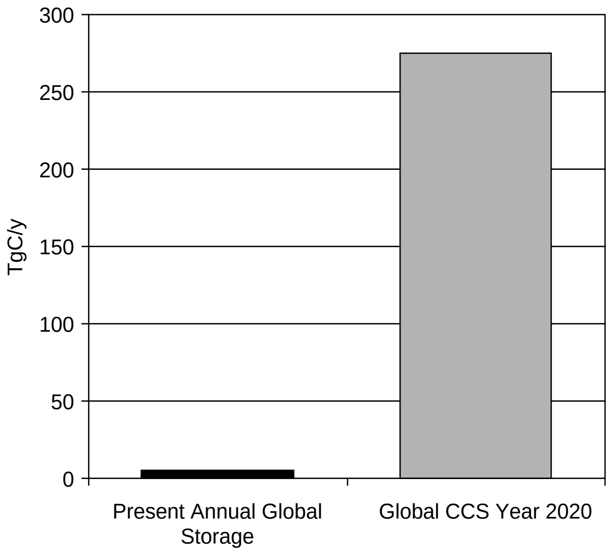
FIGURE 9 The USA's power generation by technology with stabilization of radiative forcing at 3.4 W/m².

and transport systems, and establishment of the institutional mechanisms necessary to facilitate and regulate deployment. At the most fundamental level, CCS technology creates additional costs for any productive activity. Thus, unless carbon takes on a sufficiently high value, either explicitly or implicitly, the technology will not be deployed. In addition, the technology is associated with long-lived capital assets, and therefore it must be possible for investors to form expectations about future values of carbon that are consistent with the path outlined earlier in this article.

Instruments to recognize the emissions reductions that occur if CO_2 is captured and stored need to be developed. We have also assumed that captured carbon that is stored in a geological reservoir remains there indefinitely. Monitoring and verification will be an essential component of successful technology deployment. Finally, no technology can ever be perfect. Thus, instruments will need to be created that allow investors to manage their long-term risks.

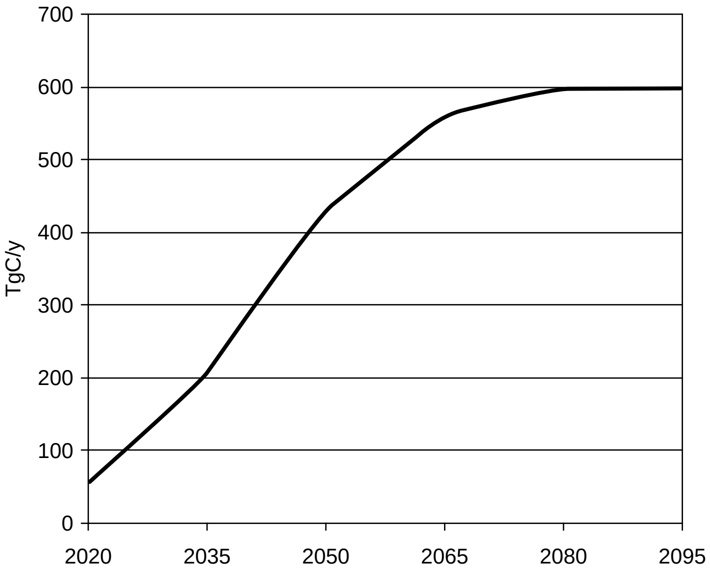
Globally, the challenge of technology development and deployment and the development of associated monitoring mechanisms loom large. Cumulative carbon capture reaches 32 PgC by 2095 in the USA and almost 250 PgC globally. At a coarse scale, this is well within the magnitude of maximum geological storage potential estimated for the USA (>1,000 PgC) and for the world (>2,800 PgC) (Edmonds et al., 2007). However, some regions, such as Japan and Korea, may find limited geological storage potential within their national boundaries. Even within the USA, storage potential is not evenly distributed. Power generators in the Ohio valley will find relatively abundant opportunities. However, power generators in New England may find fewer potentially attractive sites (Dooley et al., 2006).

CCS technology is potentially applicable to many large point-source emitters. The largest application of the technology in the analysis reported here was in electric power generation. However, other point-source emissions are also important, including cement kilns, iron and steel foundries, natural gas processing, petroleum refineries and, potentially, hydrogen production facilities.



Panel A. Present and year 2020 global deployment rates

FIGURE 10 Deployment of CCS with stabilization of radiative forcing at 3.4 W/m^2.



Panel B. U.S. Deployment between 2020 and 2095.

FIGURE 10 The USA's deployment of CCS with stabilization of radiative forcing at 3.4 W/m². (*Cont'd*)

5.3. Bioenergy and terrestrial carbon

Globally there is approximately 1,800 PgC stored in terrestrial ecosystems. For comparison, cumulative carbon emissions in the reference scenario in the 21st century were approximately 1,400 PgC. On balance, terrestrial reservoirs are believed to be accumulating carbon through regrowth and CO_2 fertilization effects (see Figure 11). The net uptake by ecosystems is thought to be more than sufficient to offset present carbon emissions from land-use change, which amount to approximately 1.5 PgC/year.

Figure 11 shows three time-paths for global net terrestrial carbon system uptake (shown as negative emissions in Figure 11), one time-path for the reference scenario, and two alternative time-paths for net terrestrial carbon system uptake for stabilization of radiative forcing at 3.4 W/m². Carbon uptake along the reference time-path is higher for two reasons; the first of which is the CO_2 fertilization effect whereby plant growth is enhanced by higher atmospheric CO_2 levels. The CO_2 concentration is higher in any year along the reference scenario time-path, so plants store more carbon in biomass and soils. Second, the extent of commercial biomass cropping is smaller in the reference scenario, which in turn means that the demand for land is smaller than in the stabilization scenario. The larger demand for land for biomass crops in the policy scenario results in additional carbon releases through deforestation.

Note that these two effects are offset by temperature feedbacks, which are thought to result in a net reduction in carbon storage as temperatures increase. Temperature feedbacks are larger in the reference case; an effect that acts in the opposite direction to CO_2 fertilization and enhanced deforestation, due to increased biomass demand.

The important distinction between the two scenarios that stabilize radiative forcing at 3.4 W/m² is that along the path with higher terrestrial carbon cycle uptake, the line labelled '3.4 W/m²' in Figure 11, a value is placed on terrestrial carbon, while along the line labelled '3.4 W/m² No Carbon Tax on Land-use Change Emissions' in Figure 11 the value of terrestrial carbon is zero.

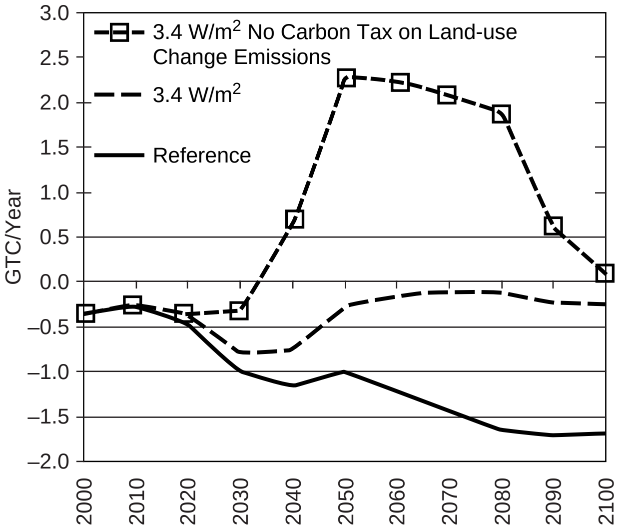


FIGURE 11 Impact on global net terrestrial carbon uptake of a tax on terrestrial carbon emissions.

The reason that the terrestrial reservoirs shift from sink to source between the line labelled '3.4 W/m^2' and the line labelled '3.4 W/m^2 No Carbon Tax on Land-use Change Emissions' can be traced to bioenergy. Bioenergy is treated as non-carbon emitting, because it obtains its carbon from the atmosphere. However, bioenergy derived from purpose-grown crops requires land. As the price of carbon rises, the relative attractiveness of bioenergy relative to fossil fuels grows. If terrestrial carbon is not valued, then excessive land is allocated to the production of bioenergy and insufficient land is allocated to storage of carbon in forests and soils. Figure 11 shows that the failure to value terrestrial carbon can lead to dramatic rates of deforestation to obtain land, especially in the tropics, for bioenergy plantations.

Because the atmosphere treats all carbon equally, the value associated with emissions of carbon to the atmosphere should be the same regardless of the source. Thus, despite the difficulties associated with placing a value on terrestrial carbon, valuing that carbon at zero could potentially lead to substantial negative impacts of climate policies, including increased deforestation, decreased afforestation and reforestation, and decreased provision of ecosystem services.

5.4. End-use energy and electrification

Electricity plays an important role in the stabilization scenario. Even in the reference scenario the ratio of electricity to total end-use energy consumption rises over time, just as it rose historically. However, the ratio rises significantly more rapidly in the stabilization scenario (Figure 12).

As the price of carbon rises, the power sector relies increasingly on non-emitting technologies (Figure 9). End-use sectors, particularly buildings and industry, shift increasingly to electricity and away from the direct use of fossil fuels as the carbon price rises. For example, building sector emissions are driven down by more than 65% in the 3.4 W/m^2 stabilization scenario relative to the reference scenario in the year 2095. Yet, energy use declines only 20%. Forty-five percent of emissions reductions in the buildings sector are the consequence of fuel switching, primarily to electricity. By 2095, electricity is responsible for 80% of energy consumed in the buildings sector in 2095.

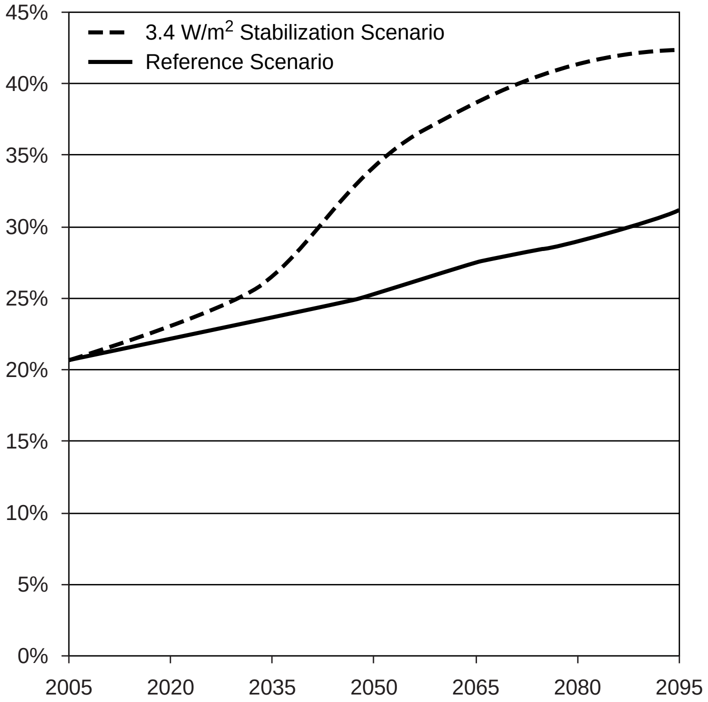


FIGURE 12 Ratio of electricity consumption to total final energy consumption reference and stabilization at radiative forcing at 3.4 W/m²

The role of technology in end-use sectors shifts over time in the 3.4 W/m² stabilization scenario. Initially technologies that conserve electricity reduce emissions dramatically by reducing power production that would have been predominantly generated with fossil fuels. As the power sector decarbonizes, technologies that can substitute electricity for fossil fuels in the provision of energy services become increasingly valuable.

Edmonds et al. (2005) showed that this phenomenon has important policy implications. Policies that value carbon in power generation, but which do not value carbon in end-use sectors, rapidly lead to economic inefficiencies that raise the cost of stabilization. They do so because valuing carbon in power generation raises the price of electric power. If carbon is not valued in end-use sectors, then the price of electricity rises relative to fossil fuels and end-use sectors substitute fossil fuels for electricity and de-electrify. As a consequence, the decarbonizing power sector is employed relatively less in end-use, and carbon-emitting technologies are employed relatively more. This is yet another example of the principle of valuing all carbon equally at the margin throughout the economy, regardless of sector.

5.5. Technology and cost in the near, mid- and long term

The present price of carbon and other GHGs depends on the entire period. In the analysis reported here the relationship is simple and direct. We assumed a price trajectory that minimizes social cost. The price of carbon and all GHGs rises at the rate of interest plus the rate of removal from the stock in the atmosphere. Thus, every future price is determined by the choice of the present price.

Of course, the real world does not work in an ideal manner, nor is the future perfectly predictable. There is no way of knowing either the future or the suite of technologies that will be available in the future. The choice of the present price of carbon depends on expectations about the future which are subject to regular reassessment and revision as the future unfolds.

That having been said, the choice of the initial price depends on expectations about future technology. A more pessimistic outlook for future technology performance and availability implies a higher current price of carbon (and other GHGs). Similarly, an optimistic view of future technology performance and availability implies a lower current price of carbon.

Any mitigation programme begins in the present, deploying the technology that is available. As the stabilization regime moves forward in time, the opportunity exists to improve the present suite of technologies. Investments in present technology and in the creation of incremental improvements in that suite of technologies will be driven not only by the present carbon price, but the expectation that the price will rise with time. Both the existence of a value on carbon and other GHGs and the creation of an expectation for future price increases consistent with stabilization are important elements in stabilizing radiative forcing at 3.4 W/m^2.

As important as near-term prices and expectations are in stabilizing radiative forcing at 3.4 W/m^2, it should be noted that the bulk of emissions mitigation occurs not in the near or mid-term, but in the post-2050 period. Thus, another important element in a technology strategy needs to be investment in basic science that holds the potential to provide the foundation upon which future technologies can be built. Managing technology risk in a world where ‘spillover’ effects are pervasive in technology development (Clarke and Weyant, 2002; Clarke et al., 2006) implies investments in a broad spectrum of scientific inquiry.

The price of CO_2 rises to steadily reduce global carbon emissions (see Figure 13). The rise is exponential until 2050, at which point the concentration of CO_2 has reached 450 ppm and radiative forcing has reached its steady-state level. Thereafter the price of carbon is determined by the commitment to maintain radiative forcing at 3.4 W/m^2. The price of carbon continues to rise until 2080, after which point it begins to decline as technology advance and the declining rate of physical carbon emission reduction requirements finally reduce the marginal cost. Total present discounted costs for the USA to limit carbon emissions amount to approximately 1.2 trillion year 2000 constant US\$, compared with

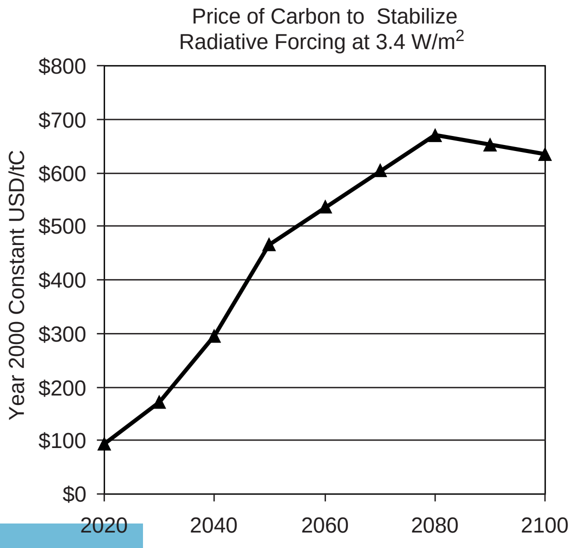


FIGURE 13 Price of carbon to stabilize radiative forcing at 3.4 W/m^2

global total present discounted costs of 9.8 trillion year 2000 constant US$, where costs are discounted at 5% per year. These costs are the lowest potential costs for achieving the long-term stabilization goal and reflect the idealized representation of the policy, namely a world in which carbon emissions are reduced in a globally and intertemporally efficient emissions limitation regime. Relaxation of this assumption raises costs both globally and in the USA, potentially by several orders of magnitude.

6. Delays in participation

The scenario we have analysed, which stabilizes radiative forcing at 3.4 W/m^2, was constructed on the assumption that the world undertakes actions in an economically efficient manner. All regions of the world were assumed to participate in the global emissions control regime beginning in the year 2012, and applied the same price to carbon and other GHGs, with that price rising at the economically efficient rate. Relaxing these assumptions has substantial implications for the USA if the goal of stabilizing radiative forcing at 3.4 W/m^2 is still to be achieved.

As discussed earlier, limiting climate change is inherently a global, not regional, problem. The concentration of GHGs in the atmosphere depends on all GHG emissions everywhere and from all sources. Stabilizing the concentration of CO_2 in the atmosphere also entails limiting cumulative, not annual, carbon emissions everywhere and from all sources. This means that limiting radiative forcing to 3.4 W/m^2 implies a limit in cumulative emissions. Delayed participation on the part of any region means that the emissions mitigation that occurs in the idealized control regime analysed in this article must be made up by other regions.

As shown by Edmonds et al. (2007), there is little room for intertemporal displacement of emissions into the future for a 3.4 W/m^2 target, meaning that delays in the participation of some regions mean substantial increases in near-term emissions reductions for those countries acting first. For example, in Edmonds et al. (2007), if the non-Annex I countries were to delay emissions reductions to 2020 or beyond, the USA might need to reduce emissions by as much as 50% by 2020 to help keep the globe on an emissions pathway that would allow the 3.4 W/m^2 limit to be met. Reductions of such magnitude, while technically not impossible, are so drastic that they would stress the ability of US society to actually accomplish such reductions.

The point is also general and symmetrical. That is, delays on the part of the USA would shift the burden to participating regions, increasing the cost that mitigating regions would experience if the 3.4 W/m^2 goal were to be realized.

Climate change is a public-good problem, and thus there is always an incentive for any party to under-report their desire to reduce emissions and to be a ‘free rider’. The 3.4 W/m^2 limit is so severe that there is little latitude to shift emissions mitigation into the future to compensate for delayed participants.

Limiting the change in radiative forcing to 3.4 W/m^2 is an enormous and unprecedented global and regional challenge. Delayed participation on the part of any major region shifts the burden of emissions mitigation onto regions that are mitigating emissions. And, if the non-participating regions account for a significant share of emissions, a point is rapidly reached beyond which it is physically impossible to limit radiative forcing to 3.4 W/m^2 without first ‘overshooting’ the limit for some period of time.

7. Conclusions

Stabilization presents a daunting challenge for all countries of the world, regardless of their stage of development, institutions or technological capabilities. This article has explored the implications for the USA of stabilization at 3.4 W/m^2. Stabilization at this level, even under idealized conditions of nearly immediate global cooperation, will require a transformation of the US energy system beginning almost immediately and extending throughout the century and beyond. This transformation will need to be even more rapid and extensive if the emissions reduction regime encompasses only a portion of the global economy.

The availability of advanced technologies such as CCS, sustainable bioenergy production, wind and solar, nuclear energy and end-use efficiency improvements will facilitate this transition. Indeed, the degree to which technology advances over the coming century is among the most important determinants of the economic costs of stabilization for the USA and the rest of the world. The scope of the energy system transformation highlights the need to begin deploying technologies that are currently available and to continue to invest in R&D to develop newer, more efficient, and less expensive low- or zero-carbon energy supply technologies and end-use technologies.

The rapid pace of the transition necessary to meet a 3.4 W/m^2 target, particularly in what may be less idealized cases, where coordinated, global action does not immediately occur, raises questions about the ability of even wealthy societies to achieve the requisite widespread changes over a period of just one or two decades. The scale of expansion of CCS technology seen in this scenario is only one example of the technological and institutional changes that will be needed to effect such a transformation. While model results such as this can illustrate a potential path of technology deployment that would lead to a given goal, the process of initial technology development and deployment, in particular, is not explicitly modelled. It is not known, for example, if the roughly 100-fold expansion in global CCS activities projected in this scenario to occur over the next 12 years is even possible. If such a rapid deployment of this particular technology is not possible, then mitigation activities in other sectors would need to be further accelerated to achieve the same goal; other sectors that have their own institutional and logistical barriers. Further work is needed in order to better understand and quantify both the constraints on expansion of mitigation technologies for particular sectors and the methods that could be used to reduce these constraints.

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Notes

1. Radiative forcing could also be changed through direct anthropogenic intervention with incoming solar radiation through geoengineering, although this is not considered here. Changes in solar output would also alter forcing, although the estimated historical changes in solar forcing are much smaller than anthropogenic forcings to date (Forster et al., 2007).
2. For additional information see www.globalchange.umd.edu/models/MiniCAM/.
3. This is a standard methodological approach that has been employed by such studies as the IPCC *Special Report on Emissions Scenarios* (Nakicenovic and Swart, 2000), and the earlier IPCC IS92 scenarios (Leggett et al., 1992).
4. A variety of alternative scenarios have been developed including those with both higher and lower radiative forcing. See Nakicenovic and Swart (2000) or the more recent Van Vuuren et al. (2007).
5. The underlying technical assumptions that lead to this conclusion are documented in Clarke et al. (2007b).
6. Note that until the concentration reaches its steady-state level the economically efficient price rises at the rate of interest plus the average rate of ocean uptake (Edmonds et al., 2008). Once the concentration of CO_2 reaches its steady-state level, emissions rates, including both net terrestrial and industrial, are determined solely by rate of ocean uptake. Prices need no longer rise exponentially.

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