Technological Change for Stabilizing Atmospheric Greenhouse Gas Concentrations

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1. Introduction

Article 2 of the United Nations Framework Convention on Climate Change (UNFCCC, 1992) states that "the ultimate objective of this Convention" ... is the ..."stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."[1] However, UNFCCC does not indicate exactly what the "stabilization level" should be, or what the "dangerous anthropogenic interference" is, but does state that stabilization "level should be achieved within a time horizon sufficient to allow ecosystems to adapt naturally to climate change to ensure that food production is not threatened and to proceed in a sustainable manner." The Intergovernmental Panel on Climate Change (IPCC, Morita *et al.*, 2001) and many other studies have considered alternative GHG stabilization levels and their possible implications for climate change as an attempt to evaluate ways of fulfilling the three UNFCCC criteria and in particular the stabilization objective. The IPCC assessments are based on a very large and still growing literature about alternative GHG stabilization levels. Common to all stabilization scenarios is that the anthropogenic GHG emissions, notably those of CO_2, have to peak during this century and proceed to fall well below the current levels if the stabilization is to be achieved during the 22nd century. Noteworthy is that this finding is independent of the stabilization level itself and is a direct result of achieving stabilization in the distant future. As a rough approximation, this means that the net carbon emissions have to asymptotically decline to zero in order to achieve stabilization of CO_2 concentrations (see Figure 6 below). The exact nature of this (convex) emissions path is uncertain implying a relatively high degree of flexibility. In addition, other GHG such as methane, nitrous oxide and f-gases such as halocarbons increase the flexibility of future emissions paths and can potentially reduce the costs of mitigation efforts required to achieve stabilization. However, the ultimate goal of the UNFCCC can only be achieved if and when future net GHG emissions approach zero. This is an important, powerful and robust result considering the multitude of complexities associated with human interference in the climate system and deep scientific and political uncertainties wrought with climate change.

In this paper we first show how large are the future ranges of energy requirements and resulting GHG emissions. Than we outline the future emissions paths that lead to stabilization of atmospheric GHG concentrations and possible emissions mitigation strategies for achieving these. They include energy efficiency improvements, decarbonization of energy through a shift toward less carbon-intensive and carbon-free energy sources and carriers, carbon capture and storage and finally reduction of other non-CO_2 GHG (multigas) emissions.

2. GHG Emissions and Energy

In contrast to the ultimate objective of the UNFCCC, global anthropogenic GHG emissions continue to increase in the world from year to year leading to further increases in atmospheric concentrations. For example, CO_2 concentrations have increased continuously from some 280 parts per million volume of air (ppmv) characteristic of the pre-industrial period to some 370 ppmv today. The ice core analyses indicate that the concentrations varied between some 180 and 280 ppmv for close to a million years with oscillations in the range of hundreds of thousands of years between the glacial and interglacial periods. CO_2 concentrations continue to increase today. Most of this historical and current increase in GHG emissions is related to energy extraction, conversion, transport and end use and the largest part due to CO_2 emissions. Thus, the key to achieving atmospheric GHG stabilization is the future evolution of global energy. It is useful to first assess the historical dynamics of the global energy system before looking into the possible future developments and emissions mitigation potentials.

The global energy has evolved during the two centuries years from a reliance on traditional energy sources to coal, then on oil and more recently on increasing shares of natural gas. Figure 1 shows the historical substitution of traditional energy forms first by coal and later by oil and gas. This development has resulted in a substantial decarbonization of the global energy system. As Figure 2 shows, the ratio of carbon emissions per unit of primary energy consumed globally has fallen by about 0.3 percent per year since 1860. The ratio decreased because high-carbon fuels, such as wood and coal, have been continuously replaced by those with lower carbon content, such as gas, and also in recent decades, albeit to a much lesser extent, by nuclear and renewable energy, which contain no carbon (see Marchetti and Nakicenovic, 1979; Nakicenovic, 1986; Nakicenovic *et al.*, 1996).

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[1] The UNFCCC has been ratified by most countries in the world and as such has entered into force.

Given the abundant hydrocarbon occurrences (Nakicenovic *et al.*, 1998; Rogner *et al.*, 2000), the global dependence on fossil fuels can continue for a long time. At the same time, the vast renewable potentials and resources of fissile materials (uranium and thorium) could in principle provide for much more vigorous decarbonization in the world. The historical decarbonization rates are too low to offset the expected future demand increases. The decarbonization rate of some 0.3 percent per year (since the 1860s) is to be compared with a simultaneous historical primary energy growth of some two percent per year, resulting in an increase of CO_2 emissions at about 1.7 percent per years. This means that while the carbon intensity of energy continues to decline in relative terms, the absolute emissions continue to increase at the global level outpacing the decarbonization rates. It is undisputed that increases in energy services, the main cause of growing emissions worldwide, are essential for further development in the world. This is a central challenge facing the humanity in the 21st century: how to provision affordable access to energy services without irreversibly changing the climate.

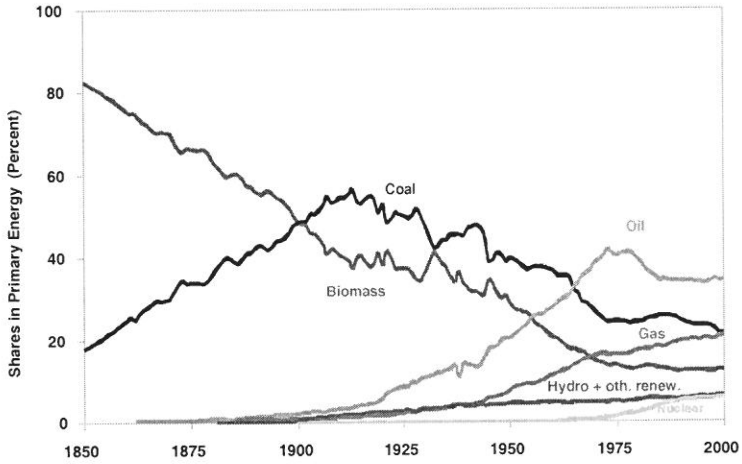

Figure 1: Substitution of primary energy sources in the world, in percent. Source: Updated from Nakicenovic *et al.*, 1998.

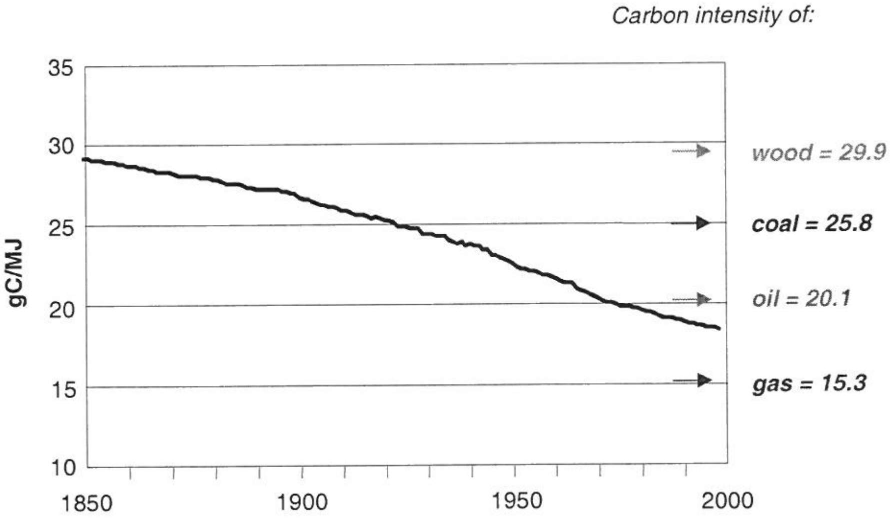

Figure 2: Decarbonization of global primary energy in grams of elemental carbon (gC) per megajoule of energy (MJ). Source: Updated from Nakicenovic *et al.*, 1998.

3. Global Energy Requirements

There are a number of energy challenges for the 21st century. As mentioned, the first challenge is that about one third of the global population, or some two billion people, do not have access to affordable and clean energy services and need to be "connected" to reliable and affordable sources of energy. These are often the same people who do not have access to clean water or sanitation and are, in general, deprived from adequate access to many other essential amenities. Because of the dangers of climate change, it follows that the access to energy services cannot be provided exclusively by now predominant ways of converting hydrocarbon sources into electricity and fuels. The developing parts of the world cannot rely on following the same energy and materials intensive development path that the now industrialized countries took. The second challenge is how developing countries can leapfrog some traditional development phases and directly adopts the newest practices and technologies. This is exceptionally difficult to achieve in the view that technology adoption and diffusion is historically a long process, especially in the case of energy-related infrastructures. Historically, it has taken between 20 years to half a century and more for new technologies to substitute the old ones. In other words, time itself is a limited resource. A further challenge is finding the means to finance the energy investments that are required for achieving these transformations in a world where ODA (official development aid) and FDI (foreign direct investment) are already falling short of the development needs. Total global investments in energy systems to achieve such a transition toward adequate provisioning of energy services is estimated at some $300 to 500 billion per year during the next 20 years (WEA, Goldemberg *et al.*, 2000). This corresponds to some ten percent of total global investment indicating again the magnitude of such a challenge. Finally, perhaps the biggest challenge from today's perspective is how to combat the adverse impacts of energy systems across all scales, from local indoor air pollution all the way to climate change. However, to achieve a sustainability transition, all of the above challenges need to be faced and resolved.

Thus, a prerequisite for achieving further economic development in the world are adequate levels of energy services. Figure 3 compares future energy requirements across a wide range of scenarios developed by the Intergovernmental Panel on Climate Change (IPCC) in its Special Report on Emissions Scenarios (SRES, Nakicenovic *et al.*, 2000) with the historical development. Since the beginning of the industrial revolution, global primary energy has grown at about two percent per year since the beginning of the industrial revolution. The IPCC scenarios indicate a seven-fold increase in primary energy requirements at the high end of the scale and at least almost a two-fold increase at the low end. What is interesting to note is that the scenarios in the lower range represent sustainable futures with a transition to very efficient energy use and high degrees of conservation that result in a radical departure from the current development paths. Generally, these are also the scenarios in which energy sources with low carbon intensity play an important role leading to vigorous reduction of future GHG emissions.

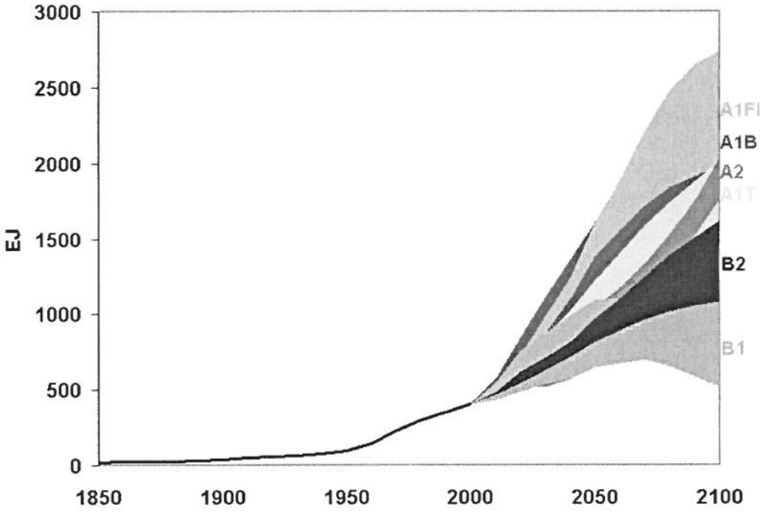

Figure 3: Global primary energy requirements since 1850 and in the IPCC SRES scenarios to 2100 in EJ per year. Source: Based on IPCC SRES (Nakicenovic *et al.*, 2000).

Figure 4 illustrates alternative energy systems structures across the range of scenarios. Relative shares of different energy sources, in percent, show the historical evolution of the global energy supply since the 1850s (Figure 4a). The first transition of the energy system started with the introduction of coal that replaced traditional sources such as fuel wood and working animals. This transition lasted about 70 years until the 1920s. During that time, the share of coal increased from 20 percent in 1850 to more than 60 percent by 1920. This development phase was characterized by the introduction of the age of steam, steal and railways. The next transition lasted another 70 years and is characterized by the replacement of coal by oil and natural gas. It can further be characterized by the rapid expansion of internal combustion, electricity, petrochemicals and the automobile. By the 1990s, more than 80 percent of global energy was supplied by hydrocarbon sources, that is, coal, oil and natural gas. Zero carbon sources such as hydropower and nuclear play only a limited role today, while traditional renewables supply the rest of the energy needs, especially in the developing countries.

Looking into the future, different possibilities unfold across the scenarios. Some of the scenarios as studied by IPCC, shown in this view graph, foresee a return to coal (Figure 4d). This is especially important for those regions of the world that have ample coal resources, e.g., India and China. Other scenarios put more emphasis on stronger reliance on oil and gas (Figure 4c), while yet other scenarios foresee a transition toward zero carbon sources with a much stronger role being played by nuclear, solar, modern biomass and other renewable energy sources (Figure 4b). The scenario shown in Figure 4b, in fact, would lead to a dominance of non-carbon energy sources by the end of the 21st century.

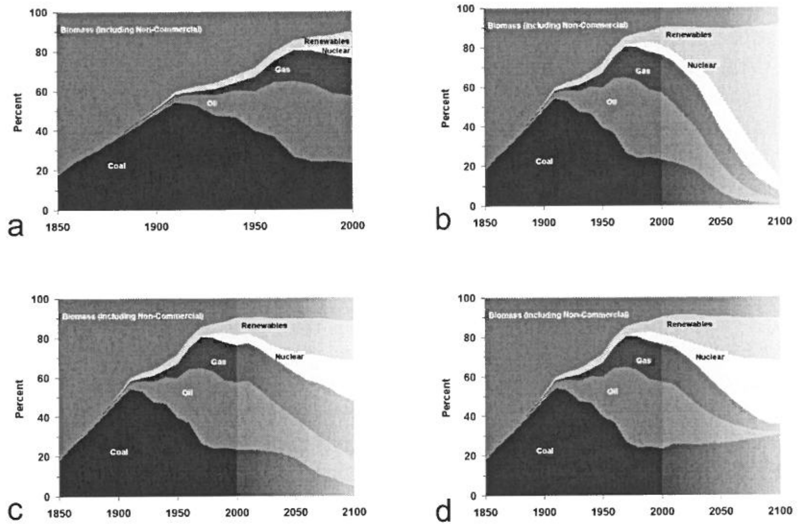

Figure 4: Historical evolution of energy systems structures, as shares of different primary energy sources (a) and future developments in IPCC SRES MESSAGE A1T (b), A1B (c) and A1FI (d) scenarios. Source: Based on IPCC SRES (Nakicenovic *et al.*, 2000).

4. Global Climate Change

The alternative developments of the energy systems structures in the future across the scenarios imply developing a whole host of new energy technologies, and have different implications, for example, for climate change. Figure 5 is from the IPCC Third Assessment Report (Cubasch *et al.*, 2001). It shows the changes in the mean global surface temperature for the last 1,000 years and contrasts this with future climate change across SRES scenarios.

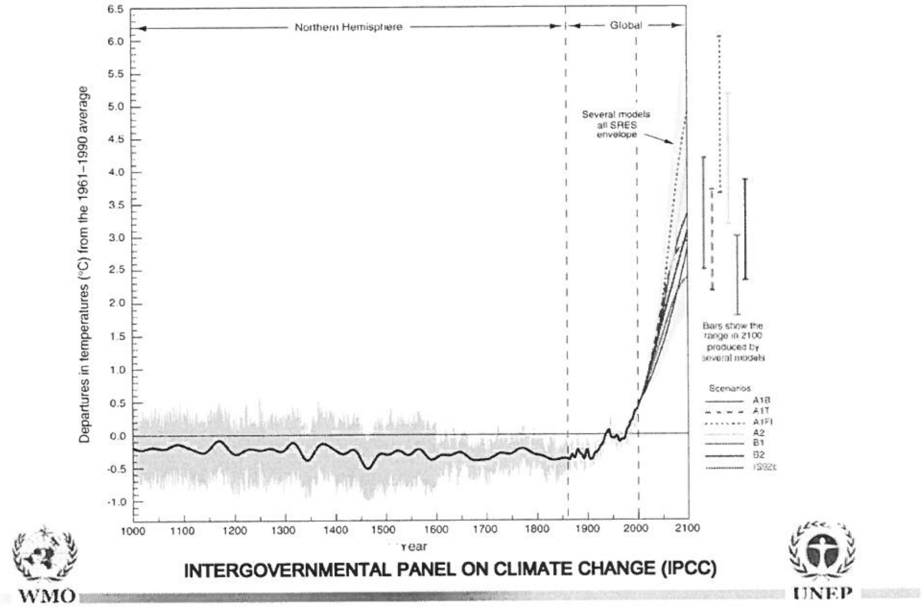

Figure 5: Global mean surface temperature reconstructed for the northern hemisphere for the last 1,000 years, for the globe since 1860 to present and for IPCC SRES scenarios to 2100. Source: Cubasch *et al.*, 2001.

Clearly, this historical record is highly uncertain as illustrated by the wide error bands (shown in gray). The temperature varied, but what is important is that a trend cannot be discerned. A noticeable increase starts after the 1850s with the beginning of industrialization the resulting fossil energy use and the continuous increase of anthropogenic GHG emissions. Compared to this historical development a large funnel of future possibilities opens for the next 100 years, from a minimal increase of 1.4 degrees Celsius to a high of 5.8 degrees. Zooming in on these future possibilities shows possible future temperature increase range based on the IPCC SRES scenarios shown in Figures 3 and 4.

IPCC used different climate change models to assess the full range of future emissions (Cubasch *et al.*, 2001). Half of the uncertainty between low and high ranges of temperature change is due to the fact that we do not know today how sensitive climate will be to the future emissions, the other half is due to the fact that we do not know which emissions path humanity will embark on in the future. However, while we do not know exactly how to influence climate sensitivity itself, we can in principle decide on the emissions paths as they depend on our present and future actions, which technologies will be deployed, choice of future lifestyles, and so on. Here, we focus on the technological measures and policies that would be required to achieve stabilization of future GHG concentrations in the atmosphere in accordance with the Article 2 of the UNFCCC.

Figure 6 shows alternative future emissions paths during the next 100 years that lead toward achieving atmospheric stabilization in the 22nd century (Wigley, Richels and Edmonds, 1996). One generic finding that emerges out of the required reductions is that emissions can increase somewhat for a while but must peak during the next decades and decline well below current levels, say down to a quarter or at most a third of current levels. In the very long run, beyond this time horizon of this century, net emissions must slowly cease and approach zero. In other words, achieving total decarbonization of the global energy system is a must, if the concentrations are to be stabilized. This is independent of the stabilization level chosen, be it high or low! For higher stabilization levels there is a bit more time before the peak should be reached: 2065 to 2090 for 1000 ppmv (parts per million volume) on one end of the scale, but as soon as 2005 to 2015 to achieve stabilization at 450 ppmv. Even for 550 ppmv, emissions must peak between 2020 and 2030.

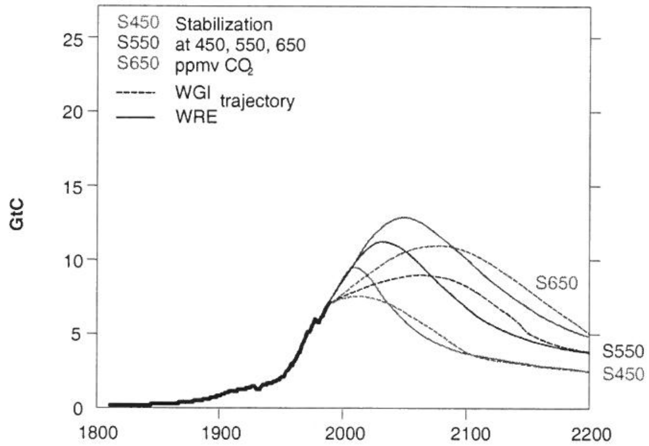

Figure 6: Global carbon dioxide emissions in billion tons of carbon (GtC) per year since 1800 to present and for alternative paths for stabilizing atmospheric concentrations at 450, 550 and 650 ppmv (parts per million volume) for IPCC WGI and WRE stabilization trajectories. Source: Based on Nakicenovic *et al.*, 1998 and Wigley, Richels and Edmonds, 1996.

5. Emissions Scenarios and Decarbonization

Various mitigation measures and policies need to be invoked in the scenarios to achieve these stabilization levels. Figure 7 shows the carbon dioxide emissions across the IPCC scenarios against the background of the historical increase since 1850. Carbon dioxide emissions grew on average at 1.7 percent per year. Current energy-related carbon dioxide emissions are in excess of 6 GtC (billion tons of elemental carbon or more than 22 billion tons of carbon dioxide). They increase more than seven-fold in the highest IPCC emissions scenarios, that is, those scenarios that envisage the return to coal with high overall energy demand, and decline in the lowest scenarios to less than half the current levels (Nakicenovic *et al.*, 2000). These are the scenarios that describe a more sustainable future with relatively low energy demand and a transition toward less intensive and zero-carbon energy technologies.

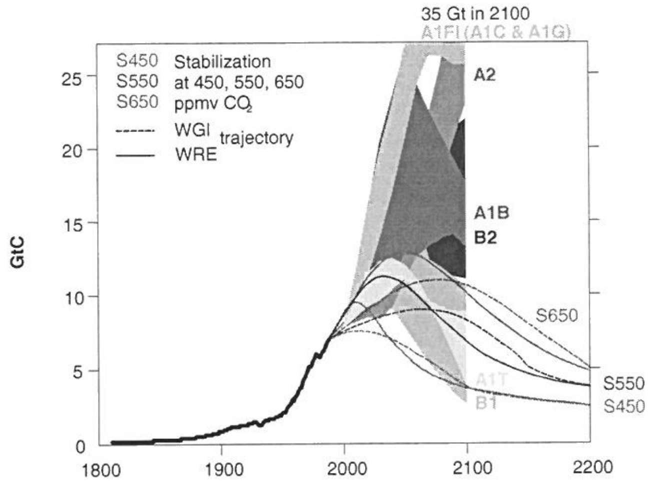

Figure 7: Global carbon dioxide emissions in billion tons of carbon (GtC) per year since 1800 to present, for alternative future paths for stabilization paths (IPCC WGI and WRE) and for IPCC SRES scenarios to 2100. Source: Based on Nakicenovic *et al.*, 1998, Wigley, Richels and Edmonds, 1996 and Nakicenovic *et al.*, 2000.

IPCC developed a set of stabilization scenarios that were quantified on the basis of the SRES scenarios (Morita *et al.*, 2001). They illustrate how large mitigation measures and policies might be needed to achieve concentration stabilization according to the UNFCCC in more than a century from now. These so-called Post-SRES scenarios cover a very wide range of emission trajectories, but their collective range is clearly below the SRES range. They jointly illustrate the range of the "gap" between emissions in the (reference SRES) scenarios and the stabilization paths. All scenarios show an progressive increase in CO_2 reduction requirements over time. Energy reduction shows a much wider range than CO_2 reduction, because in many scenarios a decoupling between energy use and carbon emissions takes place as a result of a shift in primary energy sources.

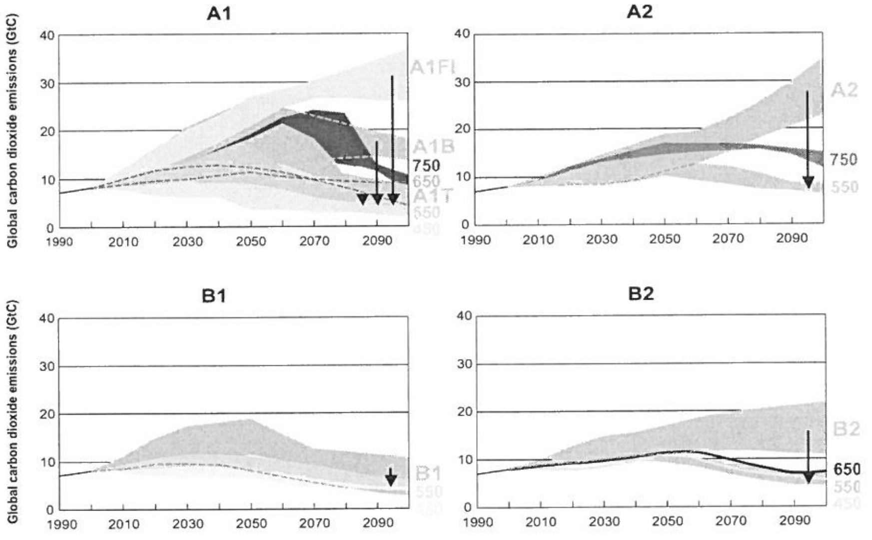

Figure 8: Carbon dioxide gap between SRES baseline scenarios and Post-SRES stabilization cases for 750, 650, 550 and 450 ppmv, shown as differences in carbon dioxide emissions between the baselines and stabilization scenarios. The ranges in future emissions both in baselines and stabilization scenarios are due to different quantifications of the four storylines by nine integrated-assessment models that developed the scenarios. Source: IPCC Third Assessment Report (Morita *et al.*, 2001).

In general, the lower the stabilization target and the higher the level of baseline emissions, the larger the CO_2 divergence from the baseline that is needed, and the earlier that it must occur. The A1FI, A1B, and A2 worlds require a wider range and more strongly implemented technology and/or policy measures than A1T, B1, and B2. The 450 ppmv stabilization case requires very rapid emission reduction over the next 20 to 30 years.

Figure 8 shows the gaps opening between SRES and Post-SRES scenarios for achieving stabilization levels of 750, 650, 550 and 450 ppmv compared with current concentrations of 370 ppmv. B2 scenario family portrays emissions reductions gap that falls in-between other scenarios. It represents a "median" future and illustrates what kind of mitigation effort would be required on balance to achieve GHG stabilization.

In case of A1FI (fossil-intensive A1 scenario group) the gap attains enormous magnitude toward 2100. In contrast, A1T and B1 scenarios indicate a relatively small gap as many of the carbon mitigation measures are already an integral part of the baseline developments. In other words, the total emissions reduction effort required is significantly smaller as well because of the much lower baseline emissions in the first case. In more carbon intensive future they need to be invoked in addition to those that are included in the baseline if the gap is to be closed. This generally increases the overall energy-system costs significantly, in some case up to 50 percent.

The wide range of future energy needs for provisioning adequate access to energy services shown in Figure 3 indicates that different development paths are possible. This is further amplified by alternative energy systems structures in Figure 4. Scenarios with a high degree of decarbonization achieve this either through a shift toward less carbon intensive hydrocarbons such as natural gas (shown in Figure 4c) and thorough a transition away from the dependence on hydrocarbon energy sources toward zero-carbon sources such as renewables and nuclear energy (shown in 4d). Figure 8 indicated that even the most environmentally oriented set of future scenarios as depicted by B1 scenario family needs "moderate" additional emissions mitigation measures to achieve more stringent stabilization levels of 550 and 450ppmv. All other scenarios require much more vigorous decarbonization strategies. Some of the more fossil-intensive future such as the A1FI are exceedingly challenging given how truly gigantic emissions reductions would have to be to achieve even some of the less ambitious stabilization levels in the ranges of 650ppmv and more.

So far we have discussed energy efficiency improvements, a shift toward less fossil-intensive hydrocarbon sources and carriers (such as energy gases) and a transition toward carbon-free sources of energy (renewables and nuclear) as main technological strategies for achieving GHG stabilization. An additional alternative decarbonization strategy involves carbon capture from hydrocarbon sources and carriers and geological storage. Decarbonization can occur before combustion such as steam reforming of natural gas (synthesis gas resulting from coal gasification) with a subsequent carbon capture. Other possibilities include carbon scrubbing from flue gases of power plants. All of these different decarbonization strategies necessitate long-term storage of separated CO2. Financially most attractive is the use of CO_2 for enhanced oil and gas recovery. CO_2 can also be stored in depleted gas and oil fields. Storage capacities are rather limited and might suffice for storing future emissions for a few decades. A much larger storage capacity is estimated for underground (saline) aquifers that could absorb virtually all expected emissions during the 21st century. Finally, deep oceans contain a vast carbon pool, about 50 times larger than that of the atmosphere. However, there are numerous ecological and other concerns associated with ocean storage. In contrast, the first three options are being exploited today and look quite promising.

6. Emissions Mitigation Technologies

No single technological measure will be sufficient for the timely development, adoption and diffusion of mitigation options to stabilize atmospheric GHGs. There is no "silver bullet" among the mitigation technologies. Instead, a portfolio based on technological change, economic incentives, and institutional frameworks should be adopted. However, a combined use of a broad array of known technological options has a long-term potential which, in combination with associated socio-economic and institutional changes, is sufficient to achieve stabilization of atmospheric CO_2 concentrations in the range of 450-550 ppmv or below.

Assumed mitigation options differ among scenarios and are strongly dependent on the particular energy model used to implement mitigation measures and policies. This is reflected in the wide range of stabilization paths shown in Figure 8. The first class of measures and policies directed at reducing emissions are related to demand reductions and energy savings. This is true across all scenarios, whether they have high or low emissions. The next class of measures includes changes in the structure of the future energy system compared to the baseline, and involves using new technologies to reduce carbon intensity. Primarily, this involves shifting away from coal to fossil energy sources with less carbon such as natural gas and a shift away from fossils in general toward zero-carbon options such as renewables and nuclear. The last class of mitigation measures is technologies for so-called carbon capture and storage. This involves removing carbon from fuels either before combustion or scrubbing the carbon dioxide from the combustion gases. In either case, this necessitates collecting carbon and storing it over geological periods of time, that is, hundreds if not thousands of years. Some other common features of mitigation scenarios include afforestration and reforestation, but they all require energy supply-side technologies. Possible robust options include using natural gas and combined-cycle technology to bridge the transition to more advanced fossil fuel and zero-carbon technologies, such as hydrogen fuel cells. Solar energy as well as either nuclear energy or carbon removal and storage would become increasingly important for a higher emission world or lower stabilization target.

Mitigation efforts vary for different SRES baselines and for different Post-SRES stabilization levels. This indicates that the emission path we choose to embark on will make an enormous difference. For obvious reasons shown here, the mitigation task is more humble and more likely to take place if the reference emissions are lower, if there is a transition toward "leaner" patterns of energy use and toward decarbonization of the energy system for other reasons than climate change. This not only makes the resulting climate change much less threatening, but also makes the task of reducing emissions to a given stabilization level easier to reach and much less costly. This is even more important when one considers the long time required to make structural changes in the energy system. Considering that the two pervious transitions (from traditional energy to coal and to oil and gas, see Figure 1) took on the order of 70 years each; and assuming that the next one lasts as long, it appears that the lower levels of stabilizing atmospheric GHG levels might be rendered impossible with or without carbon sequestration.

7. Multigas Stabilization

Achieving stabilization of atmospheric GHG will require a combination of many different mitigation measures and options. Mitigation CO_2 emissions itself requires deployment of many different options ranging from energy efficiency improvements to carbon capture. In addition, reforestation and afforestration are important migration measures as well because they enhance CO_2 sinks. Here, we consider the role other GHG (non-CO_2) gases might play in stabilization scenarios. While CO_2 is mostly emitted from the energy sector, methane (CH_4) and nitrous oxide (N_2O) emissions are largely associated with activities in the industrial, agriculture and waste sectors. In the future, emissions from these sources are expected to grow, with the largest increases expected in developing countries (Rao and Riahi, 2004). The drivers for these emissions are diverse. While population and economic growth are the main ones, changes in industrial processes, agricultural practices and waste management also play an important role. A number of effective and cheap mitigation options for different sources have been identified but their actual costs still remain uncertain. Some of them adversely affect food production and may involve substantive changes in traditional agricultural practices, thus making them difficult to implement, especially in developing countries.

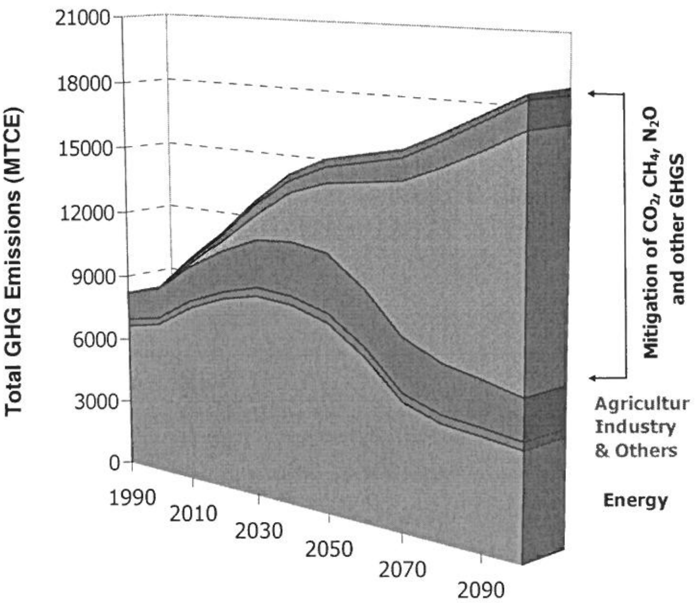

Figure 9. The figure shows the various sources of GHG emissions based on the IPCC SRES B2 scenarios compared to the emissions of the same scenario that includes technological measures required to achieve GHG stabilization (carbon dioxide, methane, nitrous oxide and f-gases) at approximately 550 ppmv of carbon dioxide equivalent (or about 4.5 w/m^2 radiative forcing increase compared to the preindustrial levels of some 280 ppmv of carbon dioxide equivalent). Source: Riahi and Rao, 2004.

Figure 9 shows the contribution of a wider range of mitigation measures and policies in a "multigas" stabilization case for IPCC SRES B2 scenario (Rao and Riahi, 2004). As mentioned, this is a "median" future development path with a rather balanced energy system. Thus, its multigas stabilization trajectory represents a "median" mitigation effort across a wide range of possible options. As such it is representative of the magnitude of the stabilization challenge during the 21st century. The multigas mitigation scenario in Figure 9 corresponds roughly to the 550 ppmv (carbon equivalent) stabilization level (or to the stabilization of global radiative forcing at 4.5 W/m^2 by 2100 as compared to pre-industrial times). This roughly corresponds to a global temperature change of 2.5 degrees measured at median climate sensitivity. Energy-related measures comprise the largest mitigation potential (shown as the dotted wedge). Industry (including solid waste) represents the top non-energy sector for potential mitigation. Agriculture is a larger source of GHG emissions but mitigation potential is limited.

An important result is that non-CO_2 mitigation plays a particularly important role in the short and medium term, bridging a cost-effective transition to a less GHG intensive long-term economy. In a multigas scenario, the bulk of reductions in the long term still come from CO_2, due to the comparatively limited mitigation potential for the non-CO_2 gases. Thus, reduction of emissions is unavoidable in the long run to achieve stabilization in the 22nd century. However, the multigas mitigation options offer addition diversity of the mitigation portfolio especially in ths short to medium term. Some of the more promising technologies in the short term include recovery of CH_4 from landfills and reduction of N_2O from nitric acid production while carbon capture and sequestration, nuclear energy and BECS contribute significantly in the longer term (Rao and Riahi, 2004).

Another important result is that the multigas stabilization scenario is seen to be significantly cheaper than the CO_2-only scenairos. The relative price difference between the CO_2-only and the multigas scenario is more pronounced in the short and medium term. Thus, this might be a significant benefit for sort-term mitigation strategies such as those required under the Kyoto Protocol and periods immediately thereafter. The evolution of long-term prices in our analysis is largely driven by the assumptions on technological change and the adoption of advanced technologies in the system. While the exact path of this change is somewhat uncertain, we find that such technological change is vital to foster the deployment of more advanced technologies (such as BECS), thus enabling cost-effective climate change mitigation in the long term.

8. Technological Change and Diffusion

New technologies play an important role across all scenarios in the literature and even more so in cases where emissions mitigation is required to achieve GHG stabilization. To provide for the growing need for energy services in the stabilization scenarios, new technologies diffuse in an ever more efficient, less polluting and, also essential, a less costlier manner. Technological change plays an important role in this process along with other important developments such as new institutional arrangements, adequate investments in energy, capacity building and education, or free trade to mention just a few enabling developments. For example, traditional oil and gas power plants are rendered obsolete and decommissioned by the 2020s and 2030s across all emissions scenarios (including SRES baselines and Post-SRES stabilization cases). Traditional coal power plants remain in service only a few more decades at the longest. Natural gas combined cycle (NGCC) power plants are an important source of electricity throughout the century and are already today the cheapest and most efficient plants wherever gas is available. In the mitigation scenarios, coal and gas power plants with carbon removal and disposal are introduced as well, in some of them as early as the 2020s. Fuel cells are another important technology in most of the scenarios and their widespread diffusion is expected to occur during the 2030s. Initially, they would be fueled mostly by natural gas but later, as hydrogen production increases, they would provide a carbon and pollution free source of mobile and stationary electricity. Hydrogen production starts as early as 2020 in some of the scenarios. Finally, in the future, coal conversion to electricity would rely on advanced coal technologies in all scenarios, at the latest by the 2050s. Integrated gasification combined cycle (IGCC) is one such technology that also has the advantage of being suitable for carbon sequestration.

Thus, numerous new and advanced energy technologies will have to be developed and deployed during the next 100 years. This means that large R&D efforts would be required. What is perhaps more important is that extensive experimentation with those new technologies will also be required, starting with investments in demonstration projects and early deployment. This involves creating niche markets and sometimes requires subsidies because these two phases of technology development are often associated with high costs and frequently inferior performance of new technologies compared with the old ones. However, dedicated development often, but not always, brings improvements. In economics this is called technological learning or learning by doing. In engineering and business one often refers to so called cost buy-downs along a learning curve. It is only after the costs have been reduced and performance improved that the actual widespread diffusion can take place and new ones replace old technologies. There is a rich literature and practical experience on enormous improvements and cost reductions that could be achieved with accumulated experience and deployment of new technologies eventually resulting in superior performance and lower costs than older competitors. Gas turbines are such an example. It should be mentioned that these stages in the innovation chain are not intended to be linear or sequential, it is an interactive process. R&D is always required and niche markets for experimentation are needed for advancing even the mature technologies.

Figure 10 shows an impressive example of technological learning from a developing country – ethanol production from sugar cane in Brazil. When the program started in the aftermath of the oil crisis, methanol was about three times more expensive than crude oil at about US$150 per barrel of oil equivalent (bbl) even though oil was at an historically high price. Over the last 20 years, the costs of alcohol have decreased enormously, at some 30 percent per doubling of accumulated output. This is typical of cost buy-downs for many energy technologies, from photovoltaics, to wind mills and gas turbines. Today, ethanol prices appear to be competitive with gasoline in Brazil. In February 2003, the alcohol price was about 1.50 Rials per liter compared with gasoline at about 2.25 Rials per liter. It should be mentioned that gasoline also includes some alcohol and that there is a hefty gasoline tax. This means that the two fuels are roughly competitive. Nevertheless, the future is highly uncertain, it is by no means clear whether alcohol will remain to be competitive. The reason for showing the impressive learning curve in Figure 8 is that the improvements did not occur for free – the accumulated difference between the oil and alcohol prices, the red and the blue curves, shows that Brazil invested at least an estimated US$2 billion to achieve this competitiveness. To achieve the competitiveness of the other advanced technologies that play important roles in IPCC scenarios will also require large investments world wide, however their costs would still be relatively low compared to the alternatives of not developing competitive new technologies.

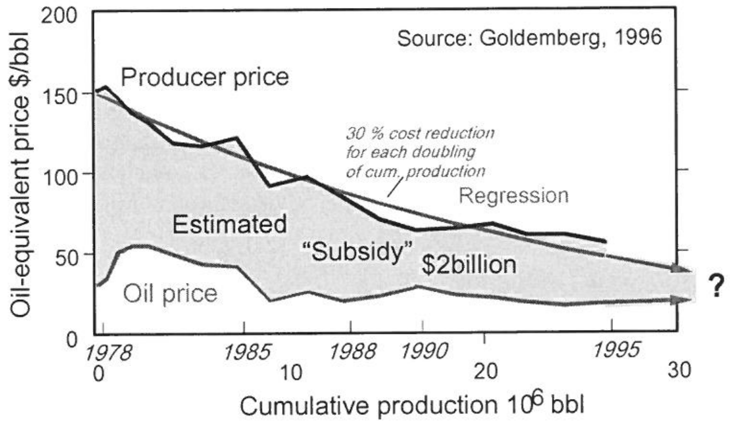

Figure 10: Learning curve for ethanol production from sugar cane expressed in US dollars per barrel of oil (bbl) equivalent as a function of cumulative production since 1978 indicating a 30 percent price reduction per doubling of cumulative production; crude oil price is also shown on the same scale; the cumulative difference between the two curves corresponds to about US$2 billion investment to bring ethanol prices to competitive levels with crude oil. Source: Grübler, 1998.

It is however important to be aware of the deep uncertainties surrounding future scenarios. This is not only the case with future climate change scenarios, but also with any attempt provide a future perspective because of our inherent inability to predict future. In the context of technological change, it should be noted that we do not have any *a priori* means of distinguishing success from failure. Many technologies will need to be developed but only a few will be successful. However, the converse is certainly true, we will need to invest in new technologies if some of them are to become competitive and lead to lower future emissions as well as better and more affordable energy services for human progress and prosperity. Thus, it is timely to promote the early deployment and market introduction of new energy infrastructures and technologies in order to achieve "cost-buy downs" and technology improvements through experience and learning, recognizing that only a few options are likely to be successful. This is, however, necessary for achieving the widespread diffusion and transfer of new technologies.

In conclusion, it should be noted that typical diffusion time constraints for achieving a fundamental transition in the global energy system lasts a very long time, from at least 20 to between 50 and 70 years. Such a transition might involve, say, replacing some 80 percent of energy capital stock. At the same time, it is clear that the premature replacement of energy technologies is too costly. Thus, there is very little time left to waste for initiating extensive early introduction and experimentation with new technologies. As was shown, this is a prerequisite for achieving cost buy-downs through experience and preparing for timely capital replacement.

It is essential, therefore, to put new policies in place and formulate new public-private partnerships, together with science and engineering communities and other stakeholders, directed at providing more sustainable energy services. Here, the developed countries should take a leading role with their generally higher capacity and means for developing and introducing more affordable and environmentally benign energy systems.

Another important finding across scenarios is that a vigorous improvement of energy efficiencies and conservation throughout energy system and end use is also essential for lowering future GHG emissions. Thus, it is also essential to achieve both substantially higher rates of energy decarbonization and energy efficiency improvement rates. High rates of energy decarbonization and efficiency improvement are essential but not the only measures for achieving GHG stabilization. Other sectors such as agriculture and forestry must be included in these considerations as well both sources and potential sinks of GHG emissions. It is also important to include other GHG gases (such as methane, nitrous oxide and f-gases such as halocarbons) in these considerations in addition to CO_2, which is the main cause of global warming. Generally speaking, decarbonization is a good proxy for reductions of other GHG emissions due to many ancillary benefits and close links across drives of different GHG emissions. Together, the main three driving forces, conservation, efficiency and decarbonization, are the required for reaching a peak of global GHG emissions during this century and a drastic decline thereafter.

9. Conclusion

The role of technology is unique in helping achieve the enormous challenge of stabilizing GHG concentrations. Technology is one of the main driving forces of increasing GHG emissions. But it is also an important part of the possible solution both in mitigating global warming through reductions of GHG emissions and in helping adapt to its impacts. Technology was very important in catalyzing the historical drive of doing more with less – from increasing efficiency of factor inputs to reducing some of the adverse impacts of human activities – and it at the same time important driving force of ever-higher (per capita) consumption levels. In a way, this is the paradox of technology of being both a part of the problem and a part of the solution.

The main energy-related technology measures for reducing GHG emissions are efficiency improvements, decarbonization of fossil energy, carbon capture and storage (over hundreds if not thousands of years), a shift toward less carbon-intensive and zero-carbon energy sources, and reduction of other GHG gases in energy and other sectors. The challenge is most of these new and innovative technologies are more costlier compared to the more emissions-intensive alternatives. Equally important is that they are deployed today in very limited niche markets and often only because of the subsidies and other support mechanisms. Therefore, the more widespread introduction and market deployment of these new and advanced technologies will take a long time. For example, the historical replacement of older by new energy systems and sources is a slow process; it took on the order of more than 20 to 50 years to replace 80 percent of energy capital stock in the past. Extrapolating similar diffusion dynamics of new and advanced, carbon-saving technologies, implies that it will be very difficult to achieve the emissions peak in time to achieve the atmospheric GHG stabilization. There is no single "silver bullet" and all mitigation options and measures will have to be deployed (see the mitigation effort required to achieve stabilization in IPCC SRES B2 scenario in Figure 9).

However, multigas stabilization strategies might significantly reduce the mitigation costs in the short to medium term and thus enhance emissions reductions through Kyoto commitment period and beyond. In the long run, CO_2 reduction is a must and becomes ever more important. This is where early and dedicated investment in mitigation measures and options, especially in the energy sector are essential in order to "by-down" the total costs of reducing future emissions and achieving GHG concentrations stabilization.

Thus, it is necessary to introduce new and advanced energy technologies as soon as possible in order to achieve cost reductions and other technology improvements through learning and increasing returns to scale. Generally, cost reductions and improvements will be required to assure timely replacement of fossil intensive systems by those with lower or zero emissions. At the same time, technology improvements through learning and increasing returns to scale are uncertain. Investments in new and advanced technology will only achieve improvements and cost reductions in some cases. However, the corollary is also true, without such uncertain investments there surely will be no improvements. Thus, experimentation and accumulation of experience are indispensable to achieve technological change and the replacement of old by new systems. This calls for a global process and timely local and international action. This also means that early emissions reductions, even if only humble, are necessary for buy-downs along learning curves for some of the more successful technologies. Thus, the nature of technological change requires innovations to be adopted as early as possible in order to lead to lower costs and wider diffusion in the following decades. The longer we wait to introduce these advanced technologies, the higher the required emissions reduction will be. At the same time, we may miss the opportunity window for achieving substantial buy-downs. This is a direct consequence of technological path-dependency to be contrasted with higher degrees of freedom associated with emissions paths from the climate change perspective.

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