Challenges for Environmental Science and Engineering

Michael B. McElroy

School of Engineering and Applied Sciences and Department of Earth and Planetary Sciences, Harvard University, Cambridge, Massachusetts, USA

To whom correspondence should be addressed. Email: mbm@seas.harvard.edu

Abstract
Perspectives on the challenge posed by potential future climate change are presented including a discussion of prospects for carbon capture followed either by sequestration or reuse including opportunities for alternatives to the use of oil in the transportation sector. The potential for wind energy as an alternative to fossil fuel energy as a source of electricity are outlined including the related opportunities for cost effective curtailment of future growth in emissions of CO₂.

Keywords: climate change, carbon capture, wind, ethanol, CO₂

1. Introduction

This paper is intended to provide an introduction to some of the critical challenges we face as a human society today, the threat of deteriorating environmental quality, scarcity of life essential resources, and perhaps most perplexing of all the challenge of adapting to an uncertain but surely different future global climate. As the late Roger Revelle famously remarked more than fifty years ago, we are conducting a great global geological experiment with uncertain foreknowledge as to the consequences. The concentration of carbon dioxide in the atmosphere is greater now that it has been at any time over the past several million years. If we continue our present course it will be higher a few decades from now than it was 65 million years ago when dinosaurs last roamed the Earth. Global climate is changing. Earth is absorbing increasingly more energy from the sun than it is returning to space. The globe is getting warmer. Weather patterns are shifting. The Arctic Ocean is rapidly losing its ice cover. Even the stability of the great ice sheets covering Greenland and Antarctica is threatened. And all of this is taking place at a time when the ability of peoples to adjust to deteriorating local conditions by moving elsewhere is restricted by increasingly impenetrable international borders, at a time when world population is greater than it has ever been, destined to increase by several additional billions over the next few decades. There is growing conviction that we need to radically alter the structure of our global energy economy. Carbon based fossil fuels have served us well for more than a century but we are forced now to confront the consequences. We need to change course: to switch from an unsustainable fossil fuel based energy economy to one based on more sustainable resources.
We begin in Section 2 with an account of the factors implicated in driving contemporary climate change, introducing the concept of radiative forcing. There is little doubt, as we shall see, that the Earth is presently absorbing more energy from the sun than it is returning to space in the form of long wave infrared radiation. Increases in the concentration of the so-called long-lived greenhouse gases (LLGHG’s), notably CO$_2$, CH$_4$, N$_2$O and various manmade halogenated compounds, are responsible for a reduction in emission of infrared radiation to space, for positive forcing of the climate system. Release of black sooty particulate matter, black carbon, is adding to this positive forcing, as are increasing concentrations of ozone in the lower atmosphere. Emissions of sulfur and nitrogen oxides are responsible for formation of bright colored particles in the atmosphere that act to reflect sunlight back to space serving to partially offset the positive forcing from the LLGHG’s, black carbon and lower atmospheric ozone. In addition, these particles, which are hydroscopic, are expected to enhance cloud formation resulting in additional negative forcing. But there are good reasons, despite their relatively positive implications for climate change (their role in offsetting the warming due to the LLGHG’s and lower atmospheric ozone), to reduce emission of nitrogen and sulfur oxides. They are major contributors to the problem of acid rain. And when inhaled by humans, they are responsible for a variety of serious pulmonary problems. Eliminating nitrogen and sulfur emissions, as we shall see, will act to make the climate change issue even more serious and more immediate.

The most important of the LLGHG’s in terms of their impact on climate is CO$_2$. Combustion of the fossil fuels – coal, oil and natural gas – is primarily responsible for the contemporary increase in the concentration of CO$_2$ with an additional contribution from the manufacture of cement and from deforestation, the latter primarily in tropical countries, notably in Brazil, Indonesia and Malaysia. Worldwide fossil fuel related emissions of CO$_2$ increased by 19.4% between 1984 and 1994 and by a further 24.6% between 1994 and 2004. Global emissions amounted to 7.9 billion tons of carbon in 2004 (multiply by 3.67 to convert to tons of CO$_2$) apportioned as follows: oil, 35.6%; coal, 35.9%; natural gas, 18.1%; cement, 3.8%. The US was responsible for 21% of 2004 global emissions of CO$_2$: 43.9% from oil, 35.7% from coal, with 19.5% from natural gas. China with 17.3% of the global total ranked number two in 2004 but has now surpassed the US. Coal accounted for 98.7% of Chinese emissions in 1950 with minimal contributions from either oil or gas. Oil is now responsible for 17% of emissions from China with the contribution from coal dropping to 71.9% despite rapid growth in consumption of both fuels in the interim. Manufacture of cement accounted for 9.7% to Chinese emissions in 2004 reflecting the rapid recent pace of development of that country’s infrastructure (China accounted for 44% of total global production of cement in 2004).

The concentration of atmospheric CO$_2$ increased by 4.1% between 1984 and 1994 (from 344.4 ppm to 358.63 ppm) and by an additional 5.3% (from 358.63 ppm to 377.55 ppm) between 1994 and 2004 (ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt, read December 11, 2007). It has risen more recently (by the end of 2007) to more than 382 ppm. Given any reasonable projection of future energy use, the concentration of atmospheric CO$_2$ is expected to climb to levels in excess of 500 ppm by mid-century. Approximately half of the CO$_2$ added to the atmosphere as a result of the combined influences of fossil fuel burning, cement
manufacture and changes in land use remains in the atmosphere with the balance absorbed by the ocean.

The most important use of coal, especially in developed countries, is associated with the generation of electricity. Oil is employed mainly in the transportation sector, as a source for the gasoline, diesel and jet fuel used to propel our cars, trucks, ships, trains and aircraft. Natural gas, the cleanest of the fossil fuels in terms of emissions of CO₂ per unit energy consumed, is used to generate electricity, for heating and cooking and as feedstock for a variety of important chemical industries, most notably in the case of China for the manufacture of nitrogen fertilizer. To the extent that coal is consumed largely in stationary facilities (power plants for example), it is possible in principle to contemplate capturing the related CO₂ product prior to emission to the atmosphere and to sequester it in some convenient geological reservoir. Prospects for CO₂ capture and sequestration are discussed in Section 3. Capturing CO₂ from mobile sources poses a more difficult problem. If sources from the transportation sector are to be reduced or eliminated, it will be necessary to switch to an alternate source of energy, a source other than oil. Possibilities for such switching are discussed in Section 4.

Industrial development in the 20th century was fueled for the most part by exploitation of the fossil fuels. Problems were recognized often retroactively rather than prospectively. When oxides of nitrogen emitted by automobiles were identified belatedly as an important contributor to the problem of photochemical smog in cities such as Los Angeles, the response was to search for a technological fix, leading in this case to the development and deployment of catalytic converters that would limit emissions of the offending chemicals from the tail pipes of the cars. When acid rain was identified as a problem contributing to fish kills and to the die back of forests in Scandinavia and in New England, the solution was to install equipment in the smoke stacks of power plants to limit emissions of sulfur and nitrogen oxides. A similar response was adopted to counter the problem posed by emission of particulates. It may be time now to address the prevailing problems at source rather than continue to rely on retroactive fixes, to look for environmentally more friendly alternatives to the fossil fuel energy sources, which, though they may have served us well in the past, appear now to be increasingly problematic. Possible replacements for fossil fuels include energy harvested from renewable sources such as wind, water (hydro), the atom (nuclear), the sun (both as a source of heat and electricity), and the interior heat of the Earth (geothermal). Section 5 explores the potential for one of these sources, namely wind.

2. Radiative Forcing

The concept of radiative forcing induced by a change in the concentration of a specific LLGHG involves an estimate of the resulting net change in energy absorbed by the Earth (energy absorbed from the sun minus energy radiated to space in the infrared). By convention, this change is referenced to the tropopause, the uppermost boundary of the lower atmosphere (the troposphere) where changes in climate are expressed most directly. In calculating the change in radiative flux (energy in minus energy out) at the tropopause, it is assumed that the temperature of the atmosphere above the tropopause, the region known
as the stratosphere, responds radiatively to the assumed change in composition (that is to say the temperature of the stratosphere is adjusted so that the energy absorbed by the stratosphere is precisely equal to the energy emitted). In computing the radiative forcing associated with any particular change in composition, the temperature at the surface and of the atmosphere between the surface and the tropopause is held fixed. So defined, radiative forcing is intended to provide an indication of the potential for a given change in composition to alter climate. When forcing is positive, the energy absorbed by the Earth from the sun exceeds the rate at which energy is emitted to space. When forcing is negative, the energy balance is altered in the opposite sense: the energy emitted to space exceeds the energy absorbed from the sun. In the former case, the planet may be expected to warm up to restore energy equilibrium. In the latter case, it would be expected to cool.

The radiative forcing in 2005 attributed to the increase in the concentration of LLGHG’s since 1750 is estimated at 2.63 W m\(^{-2}\) (IPCC 2007). Of this, 1.66 W m\(^{-2}\) is associated with the post-industrial increase in the concentration of CO\(_2\) (from 278 ppm to 379 ppm); 0.48 W m\(^{-2}\) to CH\(_4\) (increase from 715 ppb to 1,774 ppb); 0.16 W m\(^{-2}\) to N\(_2\)O (increase from 270 ppb to 319 ppb); with the balance due to SF\(_6\) and a variety of anthropogenically associated halocarbons (including a number of chlorine and bromine containing halocarbons implicated not only in radiative forcing of the climate system but responsible also for reduction of the abundance of ozone in the stratosphere). In position number one in terms of its contribution to the change in radiative forcing since 1750 is CO\(_2\): CH\(_4\) ranks number two; position number three is occupied, however, not by N\(_2\)O but by CF\(_2\)Cl\(_2\) (CFC-12). Emissions of CF\(_2\)Cl\(_2\) are regulated under the Montreal Protocol, the agreement reached by the international community in September 1987 in Montreal, Canada, to phase out emissions of a number of gases, including CFC-12, that were implicated in depletion of stratospheric O\(_3\). The lifetime in the atmosphere of CF\(_2\)Cl\(_2\) is exceptionally long, 108 years (McElroy 2002). As a consequence, even though emissions have been curtailed, the concentration CF\(_2\)Cl\(_2\) remains high and will decrease only slowly (with an e-folding time constant of 108 years equal to the lifetime) in the decades ahead. Given the steady increase in the concentration of N\(_2\)O, though, we may expect N\(_2\)O to assume the position of number three in the radiative forcing hierarchy in the not too distant future (most likely within a decade or so).

Trends in radiative forcing associated with variations in the concentrations of CO\(_2\), CH\(_4\) and N\(_2\)O over the past 20,000 years are illustrated in Figures 1 a–c. Temporal rates of change of radiative forcing associated with changes in the concentrations of these gases are presented in Figure 2d. Notable here is the unprecedented rapidity of the change in radiative forcing since 1750. The change in radiative forcing introduced by the increase in the concentrations of CO\(_2\), CH\(_4\) and N\(_2\)O since the end of the last ice age up to the beginning of the modern industrial era (taken as 1750 AD) amounts to about 2.6 W m\(^{-2}\), approximately equal to the change that has developed subsequently.

As noted earlier, not all of the changes in radiative forcing over the modern industrial era have been positive. Positive forcing driven by the increase in the concentrations of LLGHG’s and additional positive forcing induced by an increase in the abundance of O\(_3\) in the troposphere (O\(_3\) is also a greenhouse gas) have been offset to some
extent by negative forcing caused by an increase in the abundance of aerosols in the atmosphere (particulate matter suspended in the air). The increase in the abundance of tropospheric O3 is attributed to a combination of fossil fuel related emissions of nitrogen oxides and enhanced emissions of hydrocarbons from a variety of industrial sources. A variety of sources contribute to the increased burden of atmospheric aerosols. Combustion of sulfur rich fossil fuels is responsible for important emissions of SO2, which is oxidized in the atmosphere to form H2SO4 (sulfuric acid). The combination of H2SO4 and NH3 (ammonia) results in production of highly reflective (high albedo) particulate matter composed of ammonium sulfate. Oxidation of nitrogen oxides provides a source of HNO3 (nitric acid), which in combination with NH3 can contribute an additional source of reflective aerosols (ammonium nitrate in this case). Soot, black carbon, is responsible for another source of particulate matter. Radiative forcing is positive in this case reflecting the low albedo of this black material.

As indicated earlier, aerosols can have both a direct and an indirect effect on radiative forcing. The direct effect relates to the immediate impact of the aerosols on the transmission of visible solar radiation. Addition of a significant quantity of reflective aerosol (ammonium sulfate or ammonium nitrate for example) increases the overall albedo of the Earth: a greater fraction of the incident sunlight is reflected back to space contributing thus to negative radiative forcing. The indirect effect of aerosols relates to their impact on the properties of clouds. Aerosols such as ammonium sulfate or ammonium nitrate are hygroscopic (they readily absorb water) and can serve consequently as important sites or nuclei for condensation of water. Distribution of a given amount of condensable water over a larger number of condensation nuclei would imply that the resulting cloud would be composed of a larger number of cloud particles of smaller average size than would be the case with a smaller number of condensation centers. The reflectivity of the cloud with the larger number of smaller size scattering particles would be greater than the reflectivity of the cloud with the smaller number of scattering centers: increasing the number of aerosols that can serve as condensation nuclei may be expected thus to contribute to negative radiative forcing (a larger fraction of the incident sunlight would be reflected back to space). It could impact also the probability that the condensation process should result in precipitation as discussed for example by Qiu (2009).

A summary of the various contributions to radiative forcing as recommended by IPCC (2007) is presented in Figure 3, defined for the present environment relative to conditions in 1750. The combination of LLGHG’s and O3, according to this analysis, is responsible for net radiative forcing of +2.9±0.3 W m^-2. Larger uncertainty is associated with the composite impact of aerosols, estimated according to the analyses summarized by IPCC (2007) to lie in the range -2.2 to -0.5 W m^-2 with a median value of – 1.3 W m^-2. The IPCC recommendation for the composite effect of all radiative forcing for the period 1750 to 2005 is +1.6 W m^-2 with a 90% confidence range of between +0.6 and +2.4 W m^-2. Were we to eliminate emissions of sulfur and nitrogen oxides, and as noted earlier there are good reasons to do so, contemporary radiative forcing would jump to about +2.9 W m^-2.

Radiative forcing at a globally averaged level of 1.6 W m^-2 would imply an imbalance between energy absorbed from the sun and energy radiated to space equivalent
to about 24,500 Quad (1 Quad is equal to $10^{15}$ BTU), some 57 times total global consumption of commercial energy. It is not surprising under these circumstances that our planet is warming up. A record of the change in ocean heat content as observed since 1955 is presented in Figure 4 (IPCC Fig 5.1). The data displayed here refer to the upper 700 m of the global ocean. They are presented in terms of departures with respect to the 1961 to 1990 average. The increase in ocean heat content indicated here is consistent with a conclusion that as much as 80% of the extra heat added to the earth system due to the past imbalance between energy absorbed and energy emitted to space is stored in the ocean, an indication of the important lag between current radiative forcing and its ultimate impact on climate.

3. Prospects for Carbon Capture and Sequestration

The most promising approach to capturing CO$_2$ from a fossil fuel burning factory or power plant involves use of a solvent capable of selective absorption of CO$_2$. A solution composed of liquid water and mono-ethanolamine (MEA, C$_2$H$_7$NO), approximately 26% by weight mono-ethanolamine, offers one such possibility.

The key elements of a capture system consist of a column in which CO$_2$ is extracted from flue gases and incorporated in the solvent. This column is referred to as the absorber. Solvent is admitted to the absorber at its upper end and is allowed to flow under gravity to the bottom from whence it can be transferred (pumped) to the top of a second column, referred to as the stripper. The purpose of the stripper is to reverse the reaction that took place in the absorber, releasing a concentrated stream of close to pure CO$_2$. Lean solvent is reconstituted in the process. Exiting the bottom of the stripper, the reconstituted solvent, replenished with fresh supplies to replace solvent depleted in its passage through the absorber and stripper, is transferred back to the absorber where it is available once again to take up CO$_2$. All of these steps require significant inputs of energy. Energy is expended in removing sulfur and nitrogen oxides, particulates and other impurities from the initial flue gas stream, in cooling the resulting gas mix prior to transfer to the absorber, in powering the blower involved in this transfer, in heating the enriched solvent in the stripper to liberate CO$_2$ and H$_2$O, in removing this water, in pressurizing the resulting CO$_2$, and in running the pumps employed to transfer solvent between the absorber and stripper. Penalties in terms of an extra expenditure of energy average typically about 25%. That is to say, it is necessary to consume 25% more fuel to produce a given quantity of electricity.

The capture equipment is expensive and requires significant space for its installation. It is unlikely to be deployed with existing plants. Prospects for incorporating capture equipment in new plants will depend inevitably on the existence of government policies in the future restricting carbon emissions, the significance of economic penalties imposed to curtail such emissions, and the existence of cost competitive low carbon emitting energy alternatives. And there is also the challenge of finding a suitable reservoir to store the captured CO$_2$, the expense and the energy required to deliver it to this reservoir, and the costs to monitor its stability in the reservoir to guard against unexpected and potentially hazardous release. Potential storage reservoirs include depleted coal, oil and gas fields, subsurface salt deposits, the deep ocean and ocean sediments (IPCC 2005; McElroy 2009). It is this author’s opinion that the future of carbon capture and sequestration is most
likely limited, that economically more competitive strategies exist to reduce emissions of carbon to the atmosphere. A different conclusion could be reached if productive uses could be found for the captured carbon. Injection of CO$_2$ into depleted oil fields is currently employed to enhance recovery of oil. Similarly, injection into abandoned coalmines could promote mobilization of CH$_4$ bound to the residual coal - CH$_4$ that would not otherwise be available. A further possibility is noted below, the prospect that the CO$_2$ captured from smoke stacks could be combined with H$_2$ to form a product such as methanol that could provide a substitute for gasoline or diesel fuels in the transportation sector. Carbon capture followed by either productive use or by sequestration has the advantage though that it would allow for continued use of comparatively available and relatively inexpensive fuels such as coal. For this reason alone, it is likely to continue to draw attention and to find support.

4. Prospects for Reducing Demand for Oil in the Transportation Sector

As noted earlier, oil, deployed mainly in the transportation sector, accounts for approximately 44% of US emissions of CO$_2$. The source of CO$_2$ from oil use in China is much less than in the US but growing rapidly as China increases the scale of its automobile and truck fleets. It is worth noting in this context that for the first time in 2008 more automobiles were produced in China that were produced in the US. Both countries are critically dependent on imported sources of oil posing an important threat not only to their economic but also to their national securities should, for any reason, supplies of oil be withdrawn, even if only temporarily. The US experienced this threat not once but twice in the 1970’s, first in conjunction with the Yom Kippur war, later in the aftermath of the hostage crisis in Iran.

At least three options are available to reduce the demand for oil in the transportation sector: to switch to a liquid fuel such as ethanol or methanol that is not produced from oil; to substitute natural gas for current uses of gasoline or diesel; or third to switch from a propulsion system based on the 100-year old technology of the chemically fueled internal combustion engine to one driven directly by electricity. In the latter case, the electricity could either be produced on board, for example using a hydrogen fuel cell, or it could be supplied from batteries charged using power drawn from the conventional electrical grid.

Some 3.4 billion gallons of ethanol were produced from corn in the United States in 2004, sold as a blend with gasoline accounting for about 2% of total gasoline sales in that year by volume, or 1.3% of sales by energy content. By 2005, production had risen to 3.9 billion gallons accounting for 2.8% of sales by volume or 1.9% by energy content., reaching a level of 4.8 billion gallons per year by mid 2006,with plant under construction expected to add an additional 2.2 billion gallons of capacity over the subsequent several years. Federal policy in the United States during the Bush administration set a goal for up to 7.5 billion gallons of so-called renewable fuel to be used as an additive to gasoline by 2012(Farrell, Plevin et al. 2006). President Bush, in his State of the Union address on January 31 2006, expressed an objective “to replace more than 75% of our oil imports from the Middle East by 2025”.
Brazil is currently the world’s largest producer of ethanol (the US is number 2), produced in this case using sugar cane rather than corn. Some 4 billion gallons were produced in 2004 in Brazil as compared to 3.4 billion gallons in the US. The bulk of this production was consumed domestically, more than 80% in 2004. Domestic demand is growing rapidly in Brazil driven in part by the high price of oil, in part by the growing number of flex-fuel vehicles in that country (vehicles that can run on an arbitrary mixture of ethanol and either diesel or gasoline). Not surprisingly, prices have risen accordingly, by a record 14% in the month of March 2006 alone.

Production of ethanol from either corn or sugar cane poses a dilemma: whether the feedstock should be devoted to food or fuel. With increasing use of corn and sugar cane for fuel, a rise in related food prices would seem inevitable. There is a further problem associated the use of corn in particular as a feedstock for production of ethanol: significant quantities of fossil energy are consumed in the course of its production such that the savings in greenhouse gas emissions are minimal or even negative (McElroy 2009). For this and other reasons, not least the cost for its production, experts now view the future of corn derived ethanol as limited at best. Prospects for ethanol derived from sugar cane are more encouraging. It is unlikely however that either source can contribute significantly as a substitute for the future demand for oil in the global transportation system.

A more promising option involves the possibility that ethanol could be produced using cellulose, the ubiquitous component of indigestible grass and wood. Optimists foresee a future where currently idle land could be devoted to cultivation of fast growing grasses (prairie grasses for example) and trees (poplars and willows are mentioned) that could be harvested to produce cellulose to feed a new generation of ethanol factories capable of supplanting as much as 50% of current gasoline use in the US with important savings in terms of emission of greenhouse gases – a great, new, domestically based energy industry. This would require, however, a major commitment of land, perhaps as much as a 75% of the land currently devoted to crops in the US. The technology for cost effective production of ethanol from cellulose is presently unproven. It is difficult therefore to predict the ultimate prospects for ethanol derived from this source as a viable substitute for oil although the prospect certainly merits attention at least as a topic for serious research.

Methanol offers an interesting alternative to ethanol as a transportation fuel. More than 32 million tons of methanol were produced globally in 2004 employed largely as an intermediate for production of a variety of chemicals, notably formaldehyde (close to 40% of the total). The energy density of methanol is approximately half that of gasoline, roughly 25% less than ethanol, but with a higher octane rating allowing a methanol fueled engine to run with higher efficiency than an engine driven either by gasoline or ethanol (for an extensive discussion of the merits of a methanol fueled transportation economy see Olah et al., 2006). Methanol is produced today largely by processing of synfuel (a combination of CO, CO2 and H2) derived from steam reforming of methane, coal or potentially biomass (an endothermic reaction with water vapor over a suitable catalyst at high temperature). The net reaction for production of methanol, which is marginally exothermic, may be written as
If the hydrogen involved in (1) were produced by electrolysis and if the electricity used to supply it were generated using a non-carbon source of energy such as wind or nuclear and if the CO$_2$ consumed in (1) were produced by combustion of a biomass source, reaction (1) could provide a mechanism for production of a transportation fuel that would not add any additional CO$_2$ to the atmosphere. Alternatively, if the CO$_2$ in (1) were obtained by capture either from a fossil fuel derived source or by separation associated with the processing of natural gas, an objective being currently pursued by Exxon Mobil, reaction (1) could represent an interesting opportunity for reuse of carbon prior to its eventual release to the atmosphere, contributing thus to a net reduction in the build-up of CO$_2$ in the atmosphere.

For countries with extensive domestic supplies of natural gas (the US falls into this category, China does not), natural gas offers an attractive alternative to the use of oil-based fuels in the transportation sector (gasoline and diesel for example). It would be impractical however to use gas at the relatively low pressures at which it is supplied through the conventional distribution system (pressures just slightly larger than the pressure of the atmosphere). For gas to serve as a practical alternative to oil based fuels in the transportation sector, its pressure would have to be increased by at least a factor of 100, converting it to a form referred to as compressed natural gas or CNG. Energy would need to be expended to accomplish this upgrade and costs would be expected to rise accordingly although in the US, given current prices for natural gas and gasoline, CNG could still be cost competitive. Natural gas is unlikely to find application as a fuel for personal automobiles in the US where cars are generally expected to have a range between refueling of up to 300 miles. To accommodate this objective, cars would require large, sturdier, and consequently heavier, storage tanks and the overhead is unlikely to be acceptable in this case. There is no doubt though that there should be a useful market for the use of natural gas in heavier vehicles such as trucks and buses and potentially also for taxis where the bulk of the driving is likely to involve relatively short trips (natural gas is already extensively employed for this purpose in Hong Kong). Substitution of natural gas for oil in the transportation sector can not only contribute to a decrease in demand for oil, it can contribute also to an important reduction in emissions of CO$_2$ (a significant fraction of the energy released by combustion of CH$_4$, the primary component of natural gas, is contributed by oxidation of the constituent hydrogen to water). Given the scarcity of domestic supplies, natural gas is unlikely to play an important role as a substitute for oil-based fuels in the transportation sector in China. A more probable outcome, should the government chose to curtail its dependence on imports of oil, would appear to be an accelerated switch to the use of methanol. If this methanol is produced from coal, as seems likely for China, the inevitable and unfortunate consequence would be an increase in emissions of CO$_2$. Transitioning to increased reliance on electrical propulsion offers a more attractive and environmentally more constructive alternative.

Use of electricity for propulsion is intrinsically more efficient from an energy point of view than the traditional propulsion system based on the internal combustion engine. Less than 20% of the energy in gasoline or diesel is applied to turn the wheels of a vehicle: the balance is released as waste heat. In contrast, if an electrical motor is deployed to turn
the wheels of the vehicle, the efficiency can be as high as 90% or even greater (waste heat is negligible in this case). The electricity used for propulsion could be produced either on board the automobile, as is the case for example with the current fleet of hybrid vehicles, or it could be supplied from the commercial electrical grid and stored subsequently in on board batteries. Even if in the latter case the electricity were produced by combustion of coal, the electrical option might be expected to result in an important net reduction in emissions of CO₂, by as much as 20% adopting typical values for the efficiency of a coal fired power plant (about 35%) and allowing for the fact that the emission of CO₂ from combustion of gasoline is approximately 25% less on an energy basis than that associated with combustion of coal. Savings in CO₂ emissions would be of course much larger if the electricity were produced from a carbon-free source such as wind, solar, nuclear or geothermal.

With current battery technology, all-electric cars are limited in range to a driving distance of 50 miles or less. To increase the range would impose a serious penalty in terms of vehicle weight and the volume of space required to accommodate the necessary battery capacity. A better option would combine a storage battery providing limited all-electric range with an ability to extend the vehicle range using power that could be provided using an on board electric generator fueled by a conventional chemical energy source (gasoline, diesel, ethanol, methanol or potentially natural gas). Cars with this property are referred to as plug in hybrids. The Chevy Volt, scheduled to reach the US market in 2010 is projected under typical US city driving conditions to achieve a fuel economy equivalent to more than 200 miles per gallon of gasoline. The future of electric cars, especially cars of the plug in hybrid variety, is promising. The internal combustion engine has dominated the car market for more than a hundred years: it’s time for a new, environmentally friendly, competitive, alternative.

4. Prospects for Wind Generated Electricity

We have been engaged for the past several years with our group at Harvard University in an assessment of the potential for wind to replace fossil fuels as a major source of electricity. The analysis is based on an assimilation of global wind fields provided by the Goddard Earth Observing System Data Assimilation System (GEOS-5 DAS) as described by Rienecker et al (2007)). This database provides a record of global winds every 6 hours from the surface to an altitude of about 78 km with a horizontal resolution of approximately 67 km x50 km. We computed quantities of electricity that could be generated using turbines with rated capacities varying from 1.5 MW to 3.6 MW and explored the potential for both on-shore and off-shore deployment of these turbines. Deployment on-shore was restricted to non-forested, ice-free, non-urban areas. Deployment off-shore was limited to water depths less than 200 m in regions located no further than 93 km from the nearest shore line.

Preliminary reports of results from these studies have been reported by Lu et al (2009) and by McElroy et al (2009). The first of these papers examined the potential for wind-generated electricity on a global scale. The second explored more specifically the potential for China considering not only the extent of the physical resource but also the opportunity for its cost-effective exploitation based on the existing government-approved
bidding process for new wind farms. The key consideration in this case involves the price at which the resulting electricity can be delivered profitably to the grid. In this sense, the analysis for China was constrained not only by the physical limitations imposed by the existing wind resource but also by considerations of the relevant economics. The China study was conducted in collaboration with our colleague Professor Wang Yuxuan at Tsinghua University.

Table 1 presents a summary of estimates for the wind resources of the ten countries identified as the largest global emitters of anthropogenic CO2 in 2005 (China has since, in 2006, supplanted the US as the number one global emitter). The results summarized here for potential wind-generated electricity are restricted to values for production of electricity from wind farms located in regions where the electricity they generate can amount to at least 20% of the rated capacity of the turbines, installations with capacity factors greater than 20% (the fraction of the electricity produced by a turbine expressed as a ratio with respect to the electricity it would generate should it operate to the maximum of its rated capacity is referred to as the capacity factor, denoted as CF). The Table includes values for annual emissions of CO2 from these countries together with data for their current electricity consumption. It is instructive to note that on-shore generation of electricity could comfortably account for present demand for electricity in all of the countries included in Table 1 with the exception of Japan. If offshore potential were taken into account, wind resources could accommodate more than three times Japan’s current demand.

The Chinese government made a major contribution to the development of renewable energy with passage of the Renewable Energy Law in 2005. This has provided an important boost to the development of wind-generated electricity in the country. Projects larger than 50 MW are authorized under a bidding process administered by the National Development and Reform Commission (NDRC). Concessions are granted typically for a 25-year period at sites selected by the NRDC. Provincial grid companies are required to purchase the power generated by these wind projects. The price at which this power is supplied during an initial period, typically about 10 years, is determined as a result of the bidding process. Thereafter the price is expected to adjust to the prevailing price for electricity in the region served by the grid. Projects are approved commonly on the basis of a financial plan with 20% equity and 80% debt, the latter financed typically at an interest rate of about 6.2% per year. Investors are permitted a return of about 10% per year on their investment. The critical component of the bidding process involves therefore the price for electricity the investors expect to realize over the initial period. The more efficient the wind farm - the higher the capacity factor - the lower the price at which the investment can be profitable.

McElroy et al (2009) evaluated the electricity that could be produced using state-of-the-art 1.5 MW turbines assuming further that the capacity of the grid to absorb the electricity produced by these turbines should not impose any limitations. The assumption in this case was that the infrastructure serving the wind farms, and the turbines themselves, should be comparable to the best available on the international market. Their conclusion was that at a bidding price of 0.516 RMB (7.6 US cents) per kilowatt-hour, wind could accommodate the total demand for electricity projected to be needed by China in 2030 (approximately twice current consumption). To meet the increased demand for electricity
expected by 2030 using coal would require construction of approximately 800 GW of new coal fired power plants resulting in emission of an additional 3.5 billion tons of CO$_2$. McElroy et al (2009) concluded that an investment of approximately 6.0 trillion RMB (900 million US dollars) in wind turbines (640 GW) could result in a reduction in Chinese emissions of CO$_2$ by as much as 30% relative to what would be the case in the absence of such investment (i.e. assuming that the extra electricity was generated primarily using coal). The investment required is large but appears feasible given the current size of the Chinese economy (annual GDP of about 26 trillion RMB) and the need in any event to invest in new plant. It should be emphasized that the numbers quoted here refer to the total capital cost for the turbines, which would inevitably be spread over a number of years. Continuing operational costs for wind installations are relatively modest and in contrast to the case of coal-fired power plants the fuel for the wind farm is supplied form the atmosphere free of charge!

China now ranks number 4 in the world in terms of installed wind capacity, trailing only Spain, Germany and the US (the US now ranks number 1). Given the rapid recent growth in the Chinese wind industry encouraged by the Renewable Energy Law, China is likely soon to surpass Spain and Germany. The future for wind energy in China would appear to be promising given the government’s commitment and with it the prospect to curtail the nation’s expected future emission of greenhouse gases.

4. Concluding Remarks

Environmental science and engineering faces new challenges, and new opportunities. Traditionally, the discipline was focused on the objective to understand, to assess, and to develop strategies to mediate the adverse impacts of local and regional air pollution, and the consequences of deteriorating air, soil and water quality. The threat of potential future global climate change poses a new challenge. We need to better understand the nature of this change, the implications it may have for both human and natural systems, and the options available to minimize potential future adverse impacts. The good news is that solutions are available and we have attempted here to focus on some of the possibilities. There is no place for pessimism but much work remains to be done.

Acknowledgements. Much of the material presented here was the subject of a talk presented at the 20th Tsinghua University Forum on challenges for a future low-carbon global economy with ancillary benefits for air quality and public health. I would like to express my gratitude to Professors Hao Jiming, Qian Yi, Yu Gang and Wang Yuxuan for the opportunity to address this distinguished forum and to acknowledge my appreciation for the long-standing collaboration on environmental research between Harvard University and Tsinghua University, for the successes it has achieved and for the enduring friendships it has fostered. I wish to acknowledge also my thanks for the important contributions to our renewable energy work both by Lu Xi at Harvard and by Wang Yuxuan at Tsinghua. This work was supported by National Science Foundation Grant ATM-0635548.


Figures and Tables:

Figure 1 Changes in concentrations of the greenhouse gases CO$_2$ (red), CH$_4$ (blue), and N$_2$O (green) derived from measurements of air trapped in ice cores drilled in Antarctica. Variations of the relative abundance of deuterium in the ice ($\delta$D; black) provide a proxy for local temperature. The benthic 18O data provide a proxy for changes in the volume of land-based ice. From IPCC (2007).
Figure 2  Figure 13.2 Concentrations and contribution to radiative forcing over the past 20,000 years (20 kyears) for (a) CO2, (b) CH4, and (c) N2O. Contributions from the combination of all three gases to the rate of change of radiative forcing over the past 20 kyears is displayed in panel (d). Data reflect analyses of gas extracted from ice and firn samples from both Greenland and Antarctica complemented for the most recent period by direct measurements of the atmosphere. The range of variability observed over the past 650 kyears, excepting the recent post-industrial period, is indicated by the grey vertical bars in panels (a–c). From IPCC (2007).
Figure 3 Summary of the principal components of the radiative forcing of climate change. From IPCC (2007)
Figure 4 Time series of global annual ocean heat content (10^22 J) for the 0 to 700 m layer. The black and red curves denote the deviation from the 1961 to 1990 average and the shorter green curve denotes the deviation from the average of the black curve for the period 1993 to 2003. From IPCC (2007).
Table 1. Annual wind energy potential, CO₂ emissions, and current electricity consumption for the top 10 CO₂ emitting countries

<table>
<thead>
<tr>
<th>Country</th>
<th>CO₂ emission (million tonnes CO₂)</th>
<th>Elec. Consumption (TWh)</th>
<th>Potential Wind Energy (TWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>U.S.</td>
<td>5956.98</td>
<td>3815.9</td>
<td>74000</td>
</tr>
<tr>
<td>China</td>
<td>5607.09</td>
<td>2398.5</td>
<td>39000</td>
</tr>
<tr>
<td>Russia</td>
<td>1696.00</td>
<td>779.6</td>
<td>120000</td>
</tr>
<tr>
<td>Japan</td>
<td>1230.36</td>
<td>974.1</td>
<td>570</td>
</tr>
<tr>
<td>India</td>
<td>1165.72</td>
<td>488.8</td>
<td>2900</td>
</tr>
<tr>
<td>Germany</td>
<td>844.17</td>
<td>545.7</td>
<td>3200</td>
</tr>
<tr>
<td>Canada</td>
<td>631.26</td>
<td>540.5</td>
<td>78000</td>
</tr>
<tr>
<td>U.K.</td>
<td>577.17</td>
<td>348.6</td>
<td>4400</td>
</tr>
<tr>
<td>S. Korea</td>
<td>499.63</td>
<td>352.2</td>
<td>130</td>
</tr>
<tr>
<td>Italy</td>
<td>466.64</td>
<td>307.5</td>
<td>250</td>
</tr>
</tbody>
</table>

Note: CO₂ emission and electricity consumption for 2005, data source from EIA (http://tonto.eia.doe.gov/country/index.cfm).