Chapter 15. Limiting US and Chinese emissions: the Beijing agreement

Introduction. In a landmark agreement reached in Beijing on November 11, 2014, US President Obama and his Chinese counterpart President Xi Jinping announced plans to limit future emissions of greenhouse gases from their two countries. President Obama's commitment was for the US to emit 26% to 28% less carbon in 2025 than it did in 2005, a target more ambitious than one he had announced earlier (in 2009) that would have called for a decrease of 17% by 2020. The prior target would have required a reduction in emissions at an annual average rate of 1.2% between 2005 and 2020. The more recent agreement dictates a faster pace, at least in the later years, 2.3 - 2.8 % per year between 2020 and 2025. The longer-term goal for US climate policy, announced at the Climate Change Summit in Copenhagen in 2009, is to reduce emissions by 83% by 2050 relative to 2005.

President Xi's commitment in Beijing was that China's emissions would peak by 2030, if not earlier, and that non-fossil sources would account for as much as 20% of China's total primary energy consumption by 2030. As indicated in the fact sheet released by the White House describing the agreement (http://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c, read November 12, 2014), Xi's pledge would require "China to deploy an additional 800-1,000 GW of nuclear, wind, solar and other zero emission generation capacity by 2030 – more than all of the coal-fired plants that exist in China today and close to total current electricity generating capacity in the United States".

The key question is whether the US and China can live up to the ambitious goals set by their presidents. The more serious challenge may be for the US, where the President Obama's ability to influence policy is conditioned to a large extent by rulings by the Supreme Court declaring that climate-impacting emissions can be regulated under authority granted by the Clean

Air Act. Obama, however, is scheduled to leave office in January 2017. The Congress that took over in January of 2015, with republican majorities in both House and Senate, is unlikely to share his view as to the importance of the climate issue. They may seek to overturn the executive actions he has taken and might take in the future to limit emissions. They are unlikely, however, to meet with success since the President can veto any contrary legislation that might come to his desk and Congress is unlikely have the votes to override his veto. The question is what happens when Obama leaves office, when a new administration and a new Congress come into office with potentially different views as to the importance of the climate issue. Can the Obama commitment survive under these circumstances? President Xi is in the early days (late 2014) of an initial 5-year presidential term in China, renewable potentially for a second five years. He heads a government with significantly greater executive authority than its more fragmented counterpart in Washington. The odds suggest that China may be more likely than the US to live up to the landmark climate agreement struck in Beijing in November of 2014.

The chapter focuses on what the Beijing agreement implies in the near and intermediate terms for energy policies in both the US and China, concluding with a summary of key points.

The Beijing agreement: the challenge for the US. As indicated earlier (Chapter 3), the transportation and power sectors accounted for 72% of total US CO_2 emissions in 2013, 34% and 38% respectively. Historical data on emissions from these sectors are displayed in Figure 15.1, which includes also the target that would have to be met in 2025 assuming that the decrease in emissions from the combination of these sectors should mirror the decrease envisaged for greenhouse gases as a whole. The breakdown in terms of emissions from the individual fossil sources - coal, oil and natural gas - is presented in Figure 15.2. Emissions of CO_2 from oil and coal both peaked in 2005, at annual levels of 2,623 million tons and 2,182 million tons respectively, dropping to 2,240 million tons and 1,722 million tons respectively by 2013. Emissions from natural gas increased from 1,183 million tons in 2005 to 1,399 million tons in 2013. Reductions in the use of oil, employed largely in the transportation sector, and coal, deployed primarily in the power sector, accounted for the bulk of the 10.5% reduction in emissions between 2005 and 2013.

A combination of factors was responsible for the decrease in oil use, notably a drop in the number of miles driven and a fleet of more efficient cars and trucks. The decrease in the use of coal resulted primarily from replacement of coal by natural gas as the fuel of choice in the power sector responding to unusually low prices for natural gas occasioned in recent years by the rapid increase in production from shale (demand for electricity was relatively constant over this period).

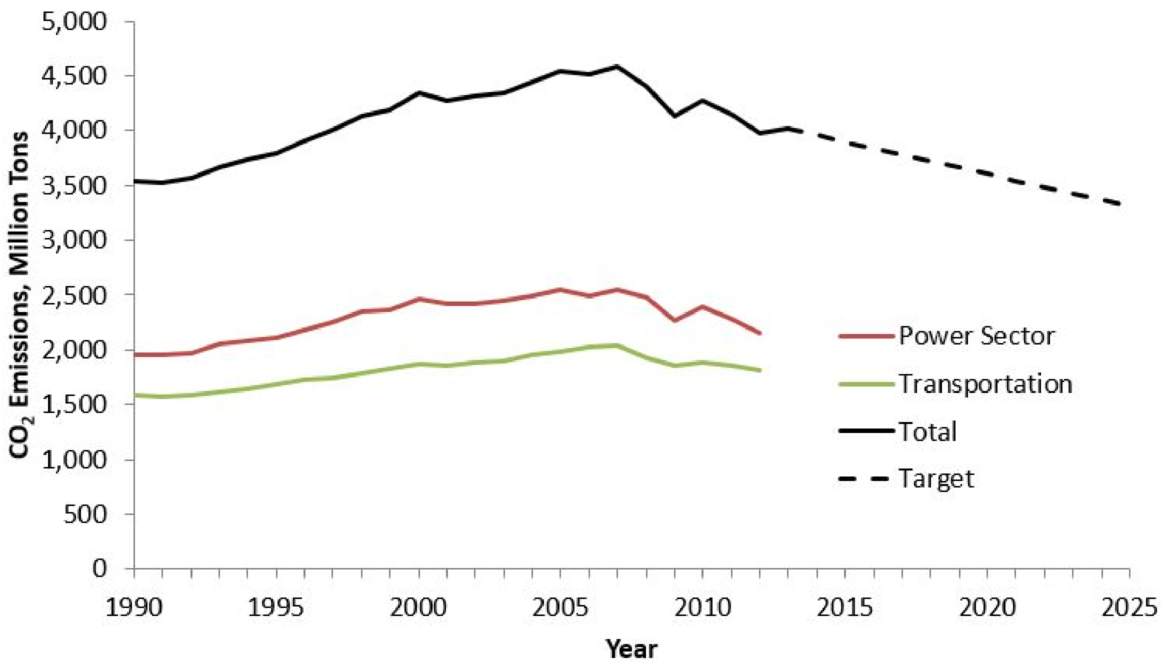

Figure 15.1. Historical data on emissions from both the power and transportation sectors with the dashed line indicating the trend required to meet the target set for emissions in 2025 assuming

that the decrease in emissions from these sectors should mirror the decrease envisaged for the overall fossil carbon economy. (Source: US EIA)

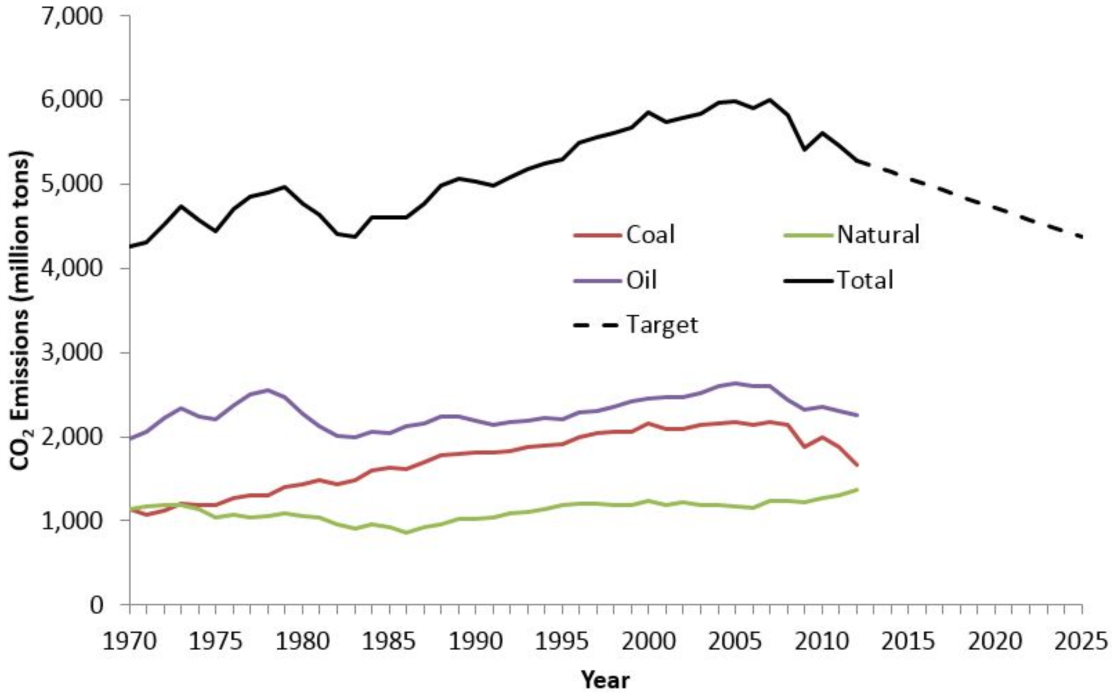

Figure 15.2. US emissions from individual fossil sources - coal, oil and natural gas - over the period 1970 to 2012. The dashed line indicates the trend required to meet the target set for 2025.

The trend in miles driven by light duty vehicles (LDV's) is displayed for the past 33 years in Figure 15.3. The figure includes also a record of the changes in oil prices that prevailed over this period. There is a clear association between the number of miles driven and the price of oil. National average prices for gasoline in the US rose first above the psychologically significant level of $2 a gallon in 2004, roughly coincident with the peak in miles driven. Gasoline prices rose above $3 a gallon in early 2008 shortly before the onset of the economic recession, settling back temporarily in the immediate aftermath before climbing again above $3, reaching a level of $3.50 in 2011.

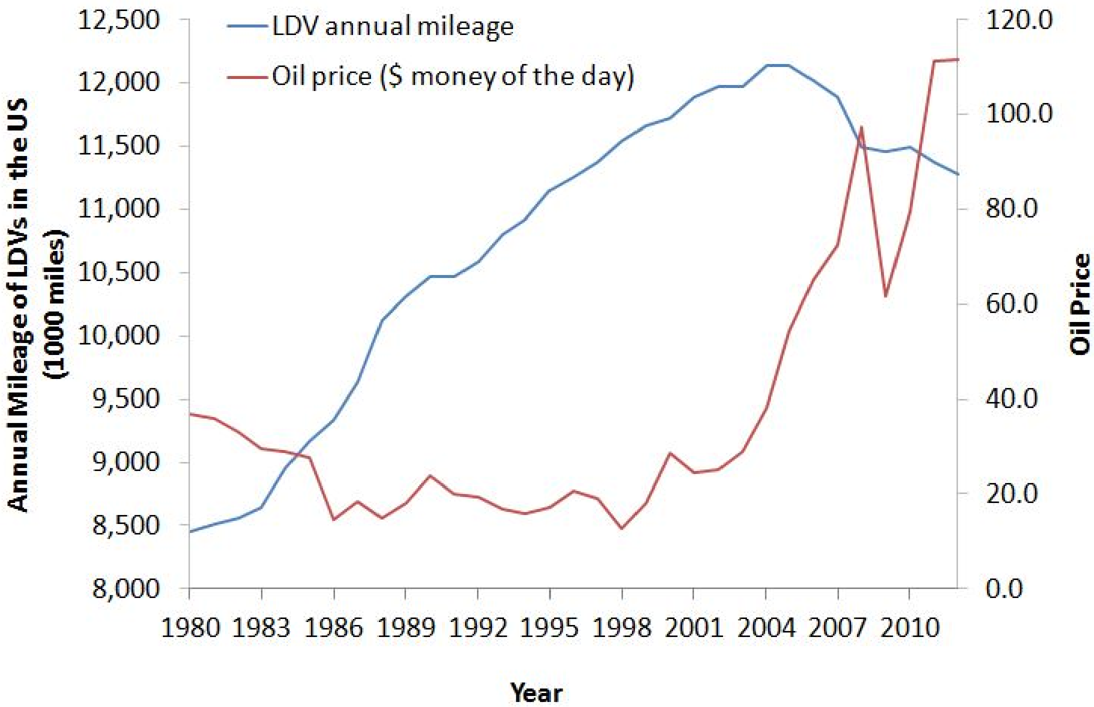

Figure 15.3. Trend in miles driven by US light duty vehicles (LDV's) over the past 33 years (1980 to 2012) compared with the record of changes in oil prices ($US per barrel). (Source: Transportation Energy Data Book 2014; BP Statistics 2014).

Mileage driven is of course not the only factor determining emissions from the transportation sector. Important also is energy efficiency, how far the average vehicle can be driven on a given amount of fuel. Corporate Average Fuel Economy (CAFE) standards, legislated by the US Congress in 1975 in response to the first oil shock, are designed to encourage automobile and truck manufacturers to increase the fuel efficiency of the vehicles they bring to market. The trend in CAFE standards over the past several decades and prospectively forward to 2025 is illustrated in Figure 15.4.

The initial legislation resulted in a significant improvement in the average fuel efficiency of passenger vehicles, rising from 18 miles per gallon (mpg) in 1978, to 27.5 mpg in 1985. Requirements remained relatively flat until December 19, 2007 when President Bush signed into law the Energy Independence and Security Act (EISA, discussed earlier in Chapter 14 in the context of the targets the legislation set for renewable fuels), which defined a goal of 35 mpg for the national fleet average efficiency in 2020. EISA identified different requirements for different vehicles depending on size - stringent for small vehicles, more relaxed, yet challenging, for larger vehicles. President Obama, on July 29, 2011, announced an agreement with 13 of the largest auto manufacturing companies to increase the average fuel economy to 54.5 mpg by 2025. The assumption in this agreement was that small cars such as the Honda Fit would realize an efficiency of 60 mpg offsetting higher consumption, 46 mpg, by larger cars such as the Mercedes Benz S-Class. Small trucks such as the Chevy S10 would be rated at 50 mpg with larger trucks such as the Ford F-150 required to achieve 30 mpg (http://en.wikipedia.org/wiki/Corporate_Average_Fuel_Economy, read December 26, 2014). The President further instructed the Environmental Protection Agency (EPA) and the Department of Transportation (DOT) to propose, by March 2015, new rules that would apply for the first time to medium and heavy trucks, requirements that would come into effect for vehicles entering the market in model year 2018.

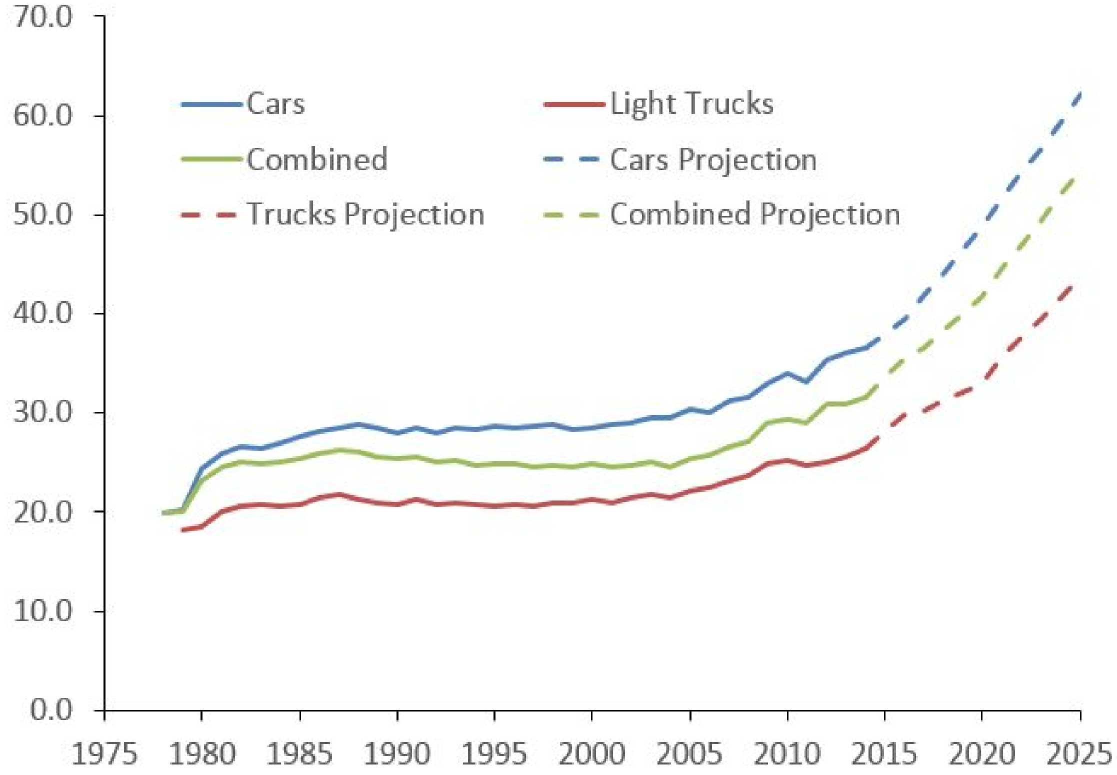

Figure 15.4. Trend in CAFE standards (miles per gallon gasoline equivalent) over the past several decades and prospectively forward to 2025 (http://www.epa.gov/fueleconomy/fetrends/1975-2013/420r13011.pdf, read December 2014).

EPA has taken steps to limit emissions from the power sector, announcing, on September 20, 2013, standards that would apply to emissions of CO_2 from future generating facilities (http://www2.epa.gov/sites/production/files/2013-09/documents/20130920factsheet.pdf, read December 31, 2014). As proposed, these regulations would distinguish between emissions from coal and natural gas fired systems. Fossil fuel- fired utility boilers and integrated gasification combined cycle (IGCC) plants, primarily coal fired, would be restricted to emissions of 1,100 pounds CO_2 /MWh gross over a 12-month operating period or 1,000 pounds CO_2 /MWh gross over an 84-month operating period. Natural gas fired systems would be limited to emissions of 1,000 pounds CO_2 /MWh for larger units (greater than 850 million BTU/hr), 1100 pounds CO_2 /MWh for smaller units (less than 850 million BTU/hr). The regulations would place a particular burden on coal-fired systems. Emissions from coal-fired plants currently average about 2,100 pounds CO_2 /MWh as compared to 1,220 pounds CO_2 /MWh for gas-fired systems (http://www.eia.gov/tools/faqs/faq.cfm?id=74&t=11, read December 31, 2014).

For new coal-fired plants to meet the proposed standards, they would have to be equipped to capture CO_2 from their exhaust. This would result inevitably in a significant increase in the price for electricity generated by these systems, an increase that could be justified only if the CO_2 captured in this process could be marketed to compensate for the extra expense. While economically profitable applications for this CO_2 could be contemplated potentially for the future (possible initiatives that could accomplish this objective are discussed in the following chapter), it is clear, at least in the short-term, that the requirement to capture and dispose of exhaust gas CO_2 will place new coal-fired facilities at an important disadvantage. Under current conditions, with low prices for natural gas and anticipated high expenses for the treatment of emissions from coal-fired plants, the future for new coal-fired systems would appear to be limited.

EPA is also exploring options to limit emissions from existing power plants. The approach in this case involves negotiations with individual states to identify cost-effective means to accomplish this objective. Options under consideration include: (1) reducing the carbon intensity of individual power plants by improving the efficiency with which they convert heat to electricity; (2) reducing emissions from the most polluting plants, compensating by promoting increased utilization of plants defined by lower carbon emissions; (3) increasing investment in low and zero carbon emitting sources; and (4) employing demand-side incentives to reduce overall demand for electricity. Following extensive consultations with individual states and stakeholders, taking account of prevailing conditions and circumstances, EPA has defined targets that individual states are expected to meet by 2030, including interim goals to be realized beginning in 2020. On a national basis, the measures proposed are intended to result in a decrease of approximately 30% in emissions of CO_2 from the power sector by 2030 relative to 2005. As envisaged, the major share of US electricity would continue to be provided by fossil sources, with coal and natural gas individually accounting for more than 30% of total national power production (https://www.federalregister.gov/articles/2014/06/18/2014-13726/carbon-pollution-emission-guidelines-for-existing-stationary-sources-electric-utility-generating -units, read January 1, 2015). Assuming that EPA's authority to regulate emissions is not constrained by future legislation, the target for the decrease in emissions of CO_2 from the power sector by 2030 would appear to be realistic and consistent with the decrease in overall greenhouse gas emissions of 26% to 28% identified for 2025 in the Beijing agreement. To meet the overall objective, however, will require a comparable reduction in emissions from the transportation sector.

The precipitous drop in oil prices that began in November 2014 and the related decrease in the national average price of gasoline – from \$3.76 a gallon on July 4, 2014, to \$2.30 a gallon on December 31, 2014 - will make it difficult to realize this objective for the transportation sector. When gasoline prices are low, people tend to drive more, consuming more fuel, emitting more CO_2 (Figure 15.3). Offsetting, cars and trucks are expected to become more efficient in the future in response to the anticipated rise in CAFE standards (Figure 15.4). It will take time however to see the full effect of these mandates: the turnover of the car/truck fleet in the US is relatively sluggish with new vehicles accounting for only about 10% of cars and trucks on the road in any given year. Further, based at least on past experience, there will be a tendency for people to buy larger cars and trucks should fuel prices continue to be depressed. With exceptionally low prices for motor fuels, could this not provide an opportunity to increase taxes on gasoline and diesel fuels, both as a means to influence behavior and as a relatively painless opportunity to raise revenue? The tax could be imposed in a revenue neutral mode with income used to reduce taxes in other areas of the economy or simply to pay down the deficit.

As indicated in Chapter 2, prices for motor fuels are exceptionally low in the US, less than half what they are in Europe, and significantly lower than in Japan and in other major Asian countries. The base price for motor fuels should be comparable for all countries, reflecting the international price of oil. Differences across countries respond therefore primarily to variations in taxes. The federal tax on a gallon of gasoline has been fixed at 18.4 cents a gallon in the US since 1993. Had it kept pace with inflation, it should have risen in the interim to at least 30 cents a gallon. Gasoline and diesel taxes in the US are used primarily to fund repairs and for maintenance on roads and bridges and for investments in related transportation infrastructure. The Federal Highway Trust Fund, which administers these activities, is currently effectively bankrupt, facing a deficit of as much as $160 billion over the next ten years in the absence of new sources of revenue.

Republican Senator Corker and Democrat Senator Murphy introduced a bill in the US Senate in June 2014 that would have raised the gasoline tax by 12 cents a gallon over a two-year period, indexing future taxes to prevailing rates of inflation. Even this modest proposal failed to gain traction, a victim of the pervasive antipathy of the US political establishment to increases in taxes for any reason, however compelling the justification.

We commented earlier (again in Chapter 2) on New York Times correspondent Tom Friedman's proposal that when gasoline prices were rising to nearly $4 a gallon, it was time to consider a $1 per gallon tax on gasoline to be phased in, rising by 5 cents a month, to meet this objective. His suggestion was that the revenue raised in this manner could be used to pay down the deficit. An appropriately designed gasoline tax could play an additionally important role in encouraging more conservative use of gasoline even under conditions when prices are falling. The tax could be structured to ensure a relatively constant retail price for gasoline. This could be accomplished by allowing the tax to increase as prices dropped, to decrease if they moved in the opposite direction. To be effective in the current context (to reduce or at least maintain a relatively constant level of emissions from the transportation sector in the face of falling prices), this arrangement should have been in place by early 2014. And, it should have been implemented so that the tax should have risen to a level of about $1 a gallon by the end of 2014. To introduce the tax option to adjust consumer behavior now, to encourage a return of retail gasoline prices to levels that prevailed in early 2014, would be difficult. Rather than the consumer experiencing effectively constant prices at the pump as would have been the case had the tax been introduced earlier, it would be necessary in the present instance to use the tax to drive prices higher. Given the current political climate in the US, prospects for introduction of such a tax are bleak. The question then is whether it might be possible to compensate for a slower rate of decline, or even an increase, in emissions from the transportation sector by requiring a more aggressive reduction from the power sector. And could this reduction be implemented cost effectively with minimal impact on the overall economy?

Coal accounted for emission of 1,664 million tons of CO_2 in the US in 2012 with an additional 1,364 million tons from natural gas and 2,255 million tons from oil. The power sector was responsible for 2,157 million tons of total emissions with an additional 1,819 million tons from transportation. To meet the target for total emissions set by the Beijing announcement will require that composite emissions in 2025 should be lower than in 2012 by 630 million tons. Coal accounted for 1514 TWh of electricity production in 2012 with an additional 1225 TWh from natural gas. The bulk of the contribution from gas (1104 TWh) was from natural gas combined cycle systems (NGCC), supplemented by a minor contribution from gas turbines deployed under peaking conditions (121 TWh). Capacity factors for coal and NGCC systems averaged 55.7% and 41.9% respectively in 2012. If the bulk of the reduction in emissions required by 2025 is to come from the power sector, it will be necessary to markedly reduce the contribution from coal.

As a conservative assumption, assume that demand for electricity in 2025 will be similar to what it was in 2012. A reduction in overall emissions of CO_2 by 630 million tons could be realized by effectively eliminating the contribution from coal, substituting a combination of enhanced production from natural gas, complemented by production from zero carbon sources such as nuclear, wind and solar. If the deficit were to be made up solely by increased use of the existing stock of NGCC plants, these plants would have to operate at an unrealistic CF level of 90%. The deficit could be accommodated by adding 126 GW of new capacity to the existing NGCC stock, assuming that the integrated NGCC system could operate at a CF level of 70%, a challenging, though potentially achievable, objective. Investments in zero carbon emitting systems, such as wind, would reduce the demand for new gas plants. The need for new gas systems could be completely eliminated by adding 103 GW of wind capacity assuming that the installed systems could operate at a CF of 30%. Wind capacity installed in the US amounted to

61.1 GW as of the end of 2013. Adding a little more than 6 GW per year over the next 10 years would appear to represent a readily achievable target. Production from solar sources, investments in which hit a record level of $150 billion in 2014, increasing by 25% with respect to 2013, could make an important additional contribution to the production of zero carbon emitting electric power.

Exceptionally low prices for natural gas, close to $3 per MMBTU at the end of 2014, are likely to encourage substitution of gas for coal in the US power sector. This could extend the trend responsible largely for the decrease in emissions over the past decade. To meet the longer-term objective of the Obama administration, to reduce emissions by 83% by 2050 relative to 2005, it would be preferable in the short term to invest in zero carbon emitting sources rather than expand the commitment to natural gas, despite the evident price advantages that this could entail at least for the short-term. The operational life of a typical gas-fired power plant extends to at least 40 years. Contemporary investments in such systems would have implications not only for emissions immediately but for the indefinite future.

The Beijing agreement: the challenge for China. As indicated at the outset, the commitment of President Xi with respect to China's future emissions was notably less specific than President Obama's pledge for the US. Emissions from China were projected to peak by 2030 if not sooner. The announcement did not identify a specific value for the magnitude of the emissions at that time. Zero carbon sources were proposed to account for 20% of total primary energy consumption. Left unstated were the magnitude and composition of the fossil fuel components that would account for the remaining 80%.

China has important reasons other than concerns about climate change to cut back on the use of fossil fuels and related emissions. Sulfur and nitrogen oxides produced as byproducts of the combustion of coal and, to a lesser extent, oil and natural gas have a significant negative impact on air quality. Chemical transformations of these species in the atmosphere, responding additionally to the presence of ammonia emitted from agricultural sources, lead to production of small particles (aerosols), characteristically 2.5 micro meters (μm) or less in size, referred to collectively as particulate matter 2.5 or $PM_{2.5}$. The presence of these particles in the atmosphere contributes to the formation of haze affecting visibility, the deterioration of which has been so extreme on occasions recently that it has been difficult to discern the identity of objects separated from the viewer by as little as a few tens of meters. More serious than the implications for visibility is the impact the haze, or smog as it is identified more appropriately, can have for humans exposed to breathing its constituent chemicals. This can lead to serious respiratory problems and, for vulnerable individuals, could even be life threatening. Paradoxically, as noted earlier in Chapter 4, the presence of these particles in the atmosphere has a positive impact on the climate system in that they can offset to some extent the warming induced by the increasing concentrations of CO_2 and other greenhouse gases. This should not under any circumstances be interpreted as justification to postpone action to reduce the conditions responsible for production of this toxic mix of local and regional pollution.

Public consciousness as to the gravity of the air pollution problem in China was sparked initially by a number of major episodes and by release through social media of data taken from a $PM_{2.5}$ instrument installed on the roof of the US embassy in Beijing. The data suggested that the concentrations of $PM_{2.5}$ were significantly higher than levels reported by official Chinese government sources. The public response was immediate and critical prompting the central government to announce an initiative to address the issue, the Air Pollution Prevention and Control Action Plan (APPCAP). In response, the number of cities in China in which $PM_{2.5}$ would be measured was more than doubled with results reported in real time on government websites. The credibility of the central government is seriously invested in the need to mitigate this high profile problem. In the public consciousness, it clearly ranks higher than the threat of climate change.

Policy initiatives to improve the efficiency of the energy economy are not new in China. The 11th Five Year Plan, developed in 2006, expressed the goal to reduce the energy intensity of the economy – the energy required to produce a given unit of gross domestic product (GDP) - by 20% by 2010 relative to 2006. The government announced a further goal in late 2009, to reduce the carbon intensity of the economy – the quantity of CO_2 emitted per unit of GDP – by 40% to 45% below 2005 levels by 2020. The 12th Five Year Plan, released in 2011, had dual prescriptions, to reduce the energy intensity by 16% and the carbon intensity by 17% over the interval covered by the Plan. It indicated further that non-fossil sources should account for 11.4% of total primary energy by 2015.

The objective announced by President Xi in his meeting with President Obama in Beijing in November 2014, that non-fossil sources should account for 20% of total primary energy consumption by 2030, may be considered simply a logical temporal extension of the commitments identified earlier under the 11th and 12th Five Year Plans. Plans for the more immediate near term, out to 2020, were formulated and announced more recently. They call for a cap on coal consumption at 4.2 billion tons, natural gas to account for 10% of total primary energy supply, nuclear power capacity to rise to 58 GW, an additional 30 GW of nuclear capacity to be under construction, hydro capacity to increase to 350 GW, investments in wind systems to reach 200 GW, solar PV to increase to 100 GW, and non-fossil sources to account for 15% of total primary energy consumption, all of this by 2020. Assuming that these ambitious near-term objectives can be realized, prospects for meeting the longer-term 2030 objectives announced by President Xi in the Beijing meeting with President Obama would appear to be excellent. This conclusion is consistent with results from a comprehensive analysis of potential future prospects for the Chinese energy economy by scientists at the Lawrence Berkeley National Laboratory of the US Department of Energy (Zhou et al., 2011). Their study, which extended out to 2050, explored a variety of potential paths for China's energy and carbon futures including detailed analyses of the influence of the important demographic, economic and social changes anticipated to develop in China over this expanded time horizon.

The Berkeley study recognizes that China's economy is currently in transition from the status classified as developing to developed. Demand for energy is particularly high during this phase. A premium is placed on investments in energy-intensive industries such as iron, steel and cement, products from which are needed to supply the materials required for construction of the roads, bridges, buildings, railroads, ports and airports critical for success during this phase of development. Accompanying this rapid industrial development is an equally significant change in the structure of Chinese society, reflected specifically in a mass relocation of people from the countryside to the cities. This results in additional demands for energy, for heating and cooling of new urban residences, for refrigerators and new labor saving devices, and for transportation. Compounding the importance of these changes is the fact that the Chinese population is aging, with the total population likely to peak at some point over the next few decades. Historical data and projections for the future changes in populations of rural and urban residents are displayed in Figure 15.5.

Zhou et al (2011) considered two models for China's energy future, a baseline Continued Improvement Scenario identified as CIS and an alternative Accelerated Improvement Scenario identified as AIS. Assumptions with respect to the growth of GDP are similar for both models: 7.7% per year from 2010 to 2020, 5.9% per year from 2020 to 2030 and 3.4% per year from 2030 to 2050. The targets announced by the Chinese government for 2020 for the combined capacities of hydro, wind and solar, 650 GW, are in fact significantly higher than the capacities envisaged for these sources in either of the Berkeley models for 2050: 535 GW for CIS, 608 GW for AIS.

Projections of the Berkeley models for total primary energy by fuel and by sector are summarized in Figure 15.6 and 15.7. The fraction of primary energy supplied by coal is reduced from 73% in the base year (2005) to 50% in the AIS scenario for 2030, to 30% in 2050. Notably, a significant fraction of total energy continues in all scenarios to be allocated to industry, more than 50%, with the combination of commitments to the residential, commercial and transportation sectors in the AIS model accounting for 41% of total energy use in 2030, rising to 48% in 2050.

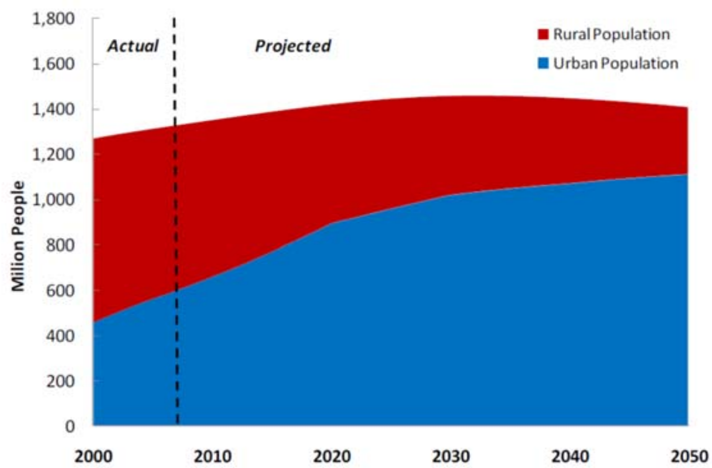

Figure 15.5 Historical data and projections for the future for populations of rural and urban residents (Zhou et al, 2011).

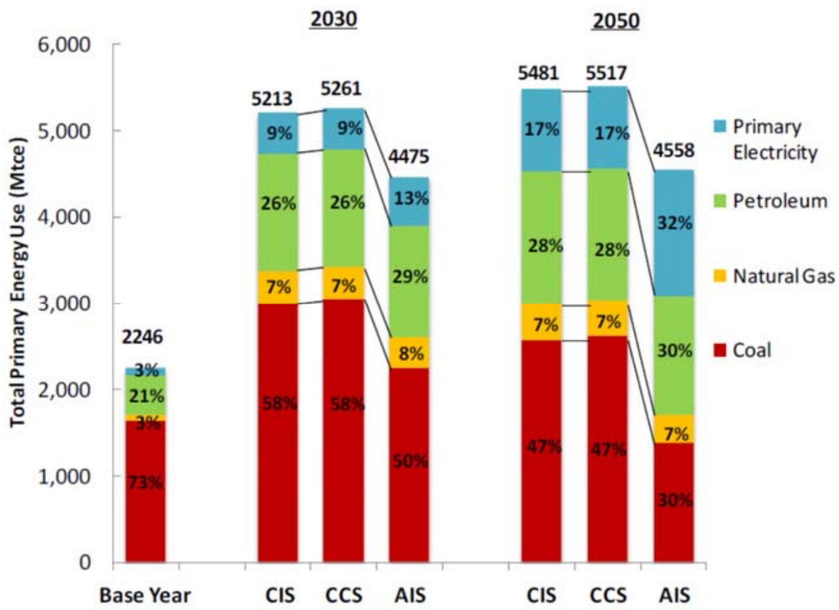

Figure 15.6 Projection of total primary energy use by fuel for China. CCS refers to an option that exploits carbon capture and sequestration as a strategy to reduce emissions of carbon dioxide but at a cost of more coal consumed to deliver a supply of useful energy (Zhou et al, 2011).

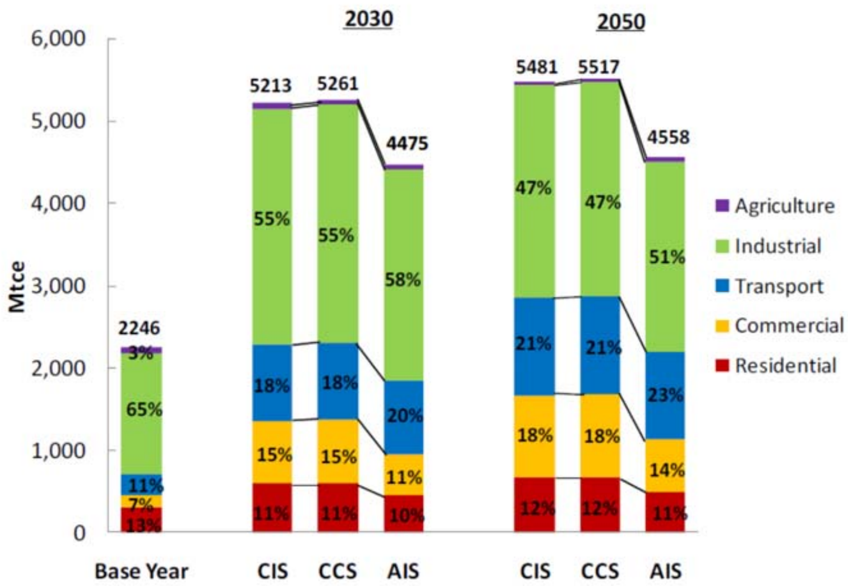

Figure 15.7 Projection of total primary energy use by sector in China (Zhou et al, 2011).

Projected emissions of CO_2 are displayed in Figure 15.8. Emissions for both the CIS and AIS models peak around 2030. In this context, the projections are consistent with President Xi's Beijing commitment. Notably, though, even in the context of the more aggressive AIS model, emissions from China are forecast to be more than 50% higher in 2030 than they were in 2005, approximately twice the level projected for the US in 2025. Offsetting the disparity in absolute emissions from the two countries is that the fact that per capita emissions from China are currently lower than those from the US by about a factor of 2.7 and that this difference is likely to persist.

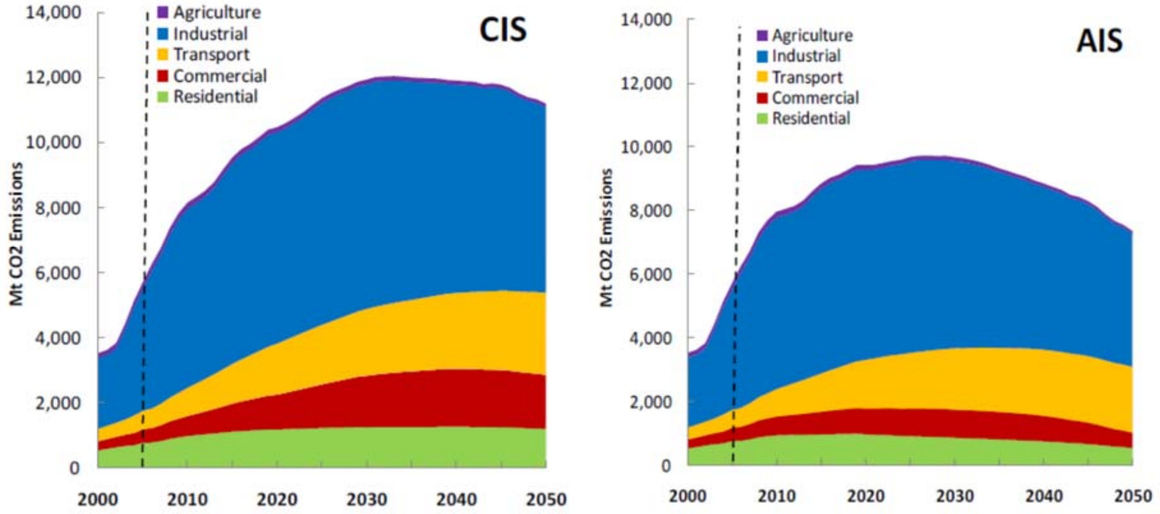

Figure 15.8 Carbon Emissions Outlook for CIS and AIS Scenarios in China (Zhou et al, 2011)

Key points:

(1) The agreement between the US and China announced by Presidents Obama and Xi in Beijing in November 2014 calls for a reduction in US emissions of CO_2 by 26% to 28% by 2025 relative to 2005.

(2) Based on extrapolation of the trend in emissions observed between 2005 and 2013, this target would appear to be reasonable and readily attainable. The decrease in emissions from the power sector over this period resulted in large measure from an increase in production of power from natural gas at the expense of coal, prompted by low prices for the former. The decrease in emissions from the transportation sector was prompted by a combination of factors: more efficient vehicles responding to more demanding Corporate Average Fuel Economy (CAFE) standards and reductions in mileage driven responding to high prices for motor fuels. In extrapolating past

trends to the future it will be important to account for the impact of the precipitous drop in the price of oil that developed over the second half of 2014.

(3) The average retail price of gasoline in the US decreased from $3.76 a gallon on July 4, 2014 to $2.30 a gallon on December 31, 2014. Should the lower prices persist, driving habits in the US are likely to change, with motorists favoring larger, less fuel-efficient, vehicles and using these vehicles to drive more. Emissions of CO_2 from the transportation sector are likely to rise accordingly.

(4) The response of motorists to lower prices for fuel could be tempered by a tax on motor fuels. To be effective though this tax would need to have the potential to rise to a level of as much as a dollar a gallon. Income from the tax could be used to offset other sources of government revenue and the tax could be administered in a revenue neutral mode. Prospects for introduction of such a tax under current political conditions n the US are not promising. Despite continuing improvements in CAFE standards, the decrease in emissions from the transportation sector recorded in the US over the past decade is unlikely to persist.

(5) Meeting the overall target for emission reductions announced for the US by President Obama in Beijing will require in this case a larger contribution from the power sector. This could be accommodated by further substitution of coal-fired generation by systems fueled by natural gas and/or zero carbon emitting alternatives such as wind and solar. To meet the required reduction in overall emissions exclusively from the power sector it will be necessary to effectively eliminate the contribution from coal. The preferred option for the long term would be to replace the coal source with zero carbon emitting alternatives rather than new

natural gas fired facilities. Investments in new gas fired systems would have implications for emissions over the indefinite future making it difficult to cost effectively meet the longer-term objective announced by President Obama, to reduce US emissions by 83% by 2050 relative to 2005.

(6) President Xi's commitment in Beijing was that Chinese emissions should peak by 2030 if not sooner and that zero carbon sources should account for as much as 20% of China's primary energy consumption by that date. The expectation is that both of these objectives can be met, noting in particular the major investments contemplated by China immediately, by 2020, in nuclear, hydro, wind and solar facilities.

(7) China surpassed the US as the world's largest emitter of CO_2 in 2007. With continuing growth since then, it is probable that when emissions peak as promised in 2030, the level of emissions from China will exceed those from the US by at least 50%, 9 billion tons CO_2 a year from China as compared to a little more than 4 billion tons CO_2 a year from the US. Per capita emissions from China however will be less that those from the US by as much as a factor of 2.7.

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Chapter 16. Vision for a low carbon energy future

Introduction. This chapter discusses steps that could be taken to realize the long-term goal of reducing if not eliminating climate-altering emissions associated with the consumption of coal, oil and natural gas. I choose to focus on initiatives that could be adopted over the next several decades to advance this objective in the US. The key elements of the vision proposed for the US should be applicable however also to China and to other large emitting countries. As indicated at the outset, the overall focus in this volume has been on the US and China, the world's largest emitters of greenhouse gases, recognizing at the same time differences in states of development and national priorities of the two countries. The vision I outline here for a low carbon US energy future should apply also to other countries. The time scale for implementation may differ however from country to country depending on details of local conditions and priorities - economic, social and environmental.

The data presented in Chapter 3 (Figures 3.1 and 3.2) provide a useful starting point - essential background - for discussion of potential future scenarios (U.S. EIA 2015). They define how energy is used in the current US economy and the services responsible for the related emissions, with key data summarized in Table 16.1. Generation of electricity was responsible for emission of 2,050 million tons of CO_2 in 2013, 1,580 million tons from combustion of coal, and 442 million tons from natural gas, with a minor contribution, 34.7 million tons, from oil. The residential, commercial and industrial sectors accounted respectively for 38%, 36% and 26% of emissions associated with economy-wide consumption of electricity. The power sector was responsible for 38% of total national emissions. Transportation contributed an additional 1,826 million tons, 34% of the national total. The bulk of the emissions from transportation, 98%, was associated with consumption of petroleum products, gasoline, diesel and jet fuel, with the balance from natural gas. Natural gas deployed in residential and commercial settings – as a source among others of energy for space heating and hot water – was responsible for emissions of 268 million tons and 178 million tons respectively with a further 93 million tons from consumption of oil used to provide heat and hot water for buildings in winter: 60 million tons from residences, 33 million tons from commercial establishments. Emissions associated with industrial combustion of natural gas, oil and coal accounted for 460 million tons, 369 million tons and 140 million tons of emissions respectively. In summary, generation of electricity was responsible for 38% of US emissions in 2013, transportation for 34%, with direct consumption of fossil fuels (oil, natural gas and coal) in the residential, commercial and industrial sectors contributing additionally 6%, 4% and 18% respectively.

Table 16.1 Breakdowns of energy consumption and associated CO_2 emissions for the US in 2013: (a) residential sector, (b) commercial sector, (c) industrial sector and (d) transportation sector.

1. Residential Sector

	Energy Consumption (Quads)	CO_2 Emissions (million tons)
Electricity	4.75	785.3
Coal	0	0
Gas	5.05	268

Oil	0.893	59.9
Biomass	0.42	0

2. Commercial Sector

	Energy Consumption (Quads)	CO_2Emissions (million tons)
Electricity	4.57	755.5
Coal	0.0454	4.28
Gas	3.36	178
Oil	0.477	33.4
Biomass	0.112	0

3. Industrial Sector

	Energy Consumption (Quads)	CO_2 Emissions (million tons)
Electricity	3.26	538.9
Coal	1.50	140
Gas	9.08	460
Oil	8.58	369
Biomass	2.25	0

4. Transportation Sector

	Energy Consumption (Quads)	CO_2 Emissions (million tons)
Electricity	0.0257	4.2
Coal	0	0
Gas	0.795	42.2
Oil	24.9	1780
Biomass	1.24	0

As indicated in the previous chapter, the long-term commitment of the US is to reduce net emissions of greenhouse gases by 83% by 2050 relative to 2005. The challenge is to meet this objective while maintaining the energy services and quality of life enjoyed by the current US population of 325 million, while planning for a population projected to exceed 400 million by 2050. If we are to limit the impact of increasing concentrations of greenhouse gases on future climate, we will need to markedly reduce emissions associated with the use of fossil fuels in the generation of electricity and in fueling our cars, trucks, trains, ships and planes. And we will need to explore options for the substitution of non-fossil alternatives for natural gas and oil in the residential and commercial sectors.

We paint a picture here for a future in which energy services are delivered to an increasing extent in the form of electricity. Electricity can substitute for natural gas and oil in heating buildings, in cooking, in providing hot water, and in a variety of other applications. It can complement gasoline and diesel fuels in propelling our cars and light trucks. And it can substitute for fossil fuels in supplying the energy needed to produce the steam deployed in a variety of industrial applications. Conservation can play an important role in minimizing the overall future demand for electricity. Despite this, if we are to meet the projected expanded market, it is clear that production of electricity will have to increase, perhaps by as much as 50%. The key, though, is that the electricity must be generated with minimal emission of CO_2.

Should we persist in requiring a continuing important contribution of power from coal and natural gas, we will need to invest in equipment to capture the associated emissions of CO_2 prior to their release to the atmosphere and to either bury them in a secure depository or find a productive use for them. As noted earlier, there is an inevitable energy penalty associated with capturing, concentrating and purifying the CO_2 included in the exhaust gases of fossil fuel fired power plants. What that means is that it would be necessary to burn more coal and natural gas to produce a given quantity of electricity. The better option, we shall argue, is to transition to a power system less reliant on fossil sources for its energy input.

Nuclear power can provide an important source of baseload (constant, on all the time) electricity. Prospects for investment in new nuclear power facilities in the US, at least over the immediate future, are not promising, as discussed in Chapter 9. The challenge will be to maintain as much of the present operational nuclear capacity as possible by extending the life of existing plants. The contribution of power from geothermal sources could be enhanced and could develop in the future as a significant contribution to both baseload and peaking demand. Whether this potential can be realized will depend, as discussed in Chapter 13, on investment in a significant program of research and development and a successful outcome from that activity – proof that geothermal power can provide an important source of future electricity at reasonable cost. Prospects for a consequential expansion in the contribution of power from hydro in the US are limited (Chapter 12). The burden for a major source of future fossil carbon free power is likely to fall thus by default on a significantly enhanced supply from wind and solar. The problem is that these sources are intrinsically variable – the wind doesn't blow all the time nor does the sun always shine. Much of the discussion that follows is devoted to strategies to allow maximum advantage to be extracted from these sources.

We discuss sequentially the need to build out the transmission system, opportunities to make greater use of electricity in domestic and commercial settings combining this with a heightened emphasis on conservation, increased use of electricity in the transportation sector, and opportunities to use biomass to produce carbon-neutral, possibly even carbon-negative, products that could substitute for the fossil fuel based sources that currently dominate the transportation energy sector (1). We continue, addressing actions that could be considered should we fail to take the steps recommended here to prompt the transformation of the energy system required to minimize the disruption of the climate system envisaged in Chapter 4. Potential responses include: initiatives to intervene actively to alter the climate to minimize the potential impact of human-induced change (what is referred to as geo-engineering); and steps to remove CO_2 from the atmosphere, to effectively cancel the input from fossil fuels. The chapter concludes with a summary of key points.

Planning for a 21st century electricity transmission system. As indicated in earlier chapters, the US is richly endowed in potential sources of renewable energy – wind, solar, hydro and geothermal. The cost for generation of electricity from wind is already competitive with the cost for generation using alternatives, with the possible exception of natural gas, which continues to benefit from unprecedentedly low prices for the underlying commodity. Costs for production of power from distributed photovoltaic (PV) sources (installed on domestic and commercial roof tops) are declining and investments in utility scale concentrated solar power (CSP) facilities are increasing. The challenge in capitalizing on the potential for wind and solar is that the most productive sources are physically removed from locations where demand is greatest, notably metropolitan regions in the east and west. Wind conditions are most favorable in the middle of the country, solar sources in the southwest. Priority number 1 should be to extend the existing transmission network, to better connect favorable source regions with centers of high demand.

For much of the past century, production and distribution of electricity in the US was controlled by a large number of small vertically integrated utilities, often single plants established to serve local markets. Through time, utilities elected to link their distribution networks, at least locally, to ensure a more reliable source of power for their customers. If generation facilities owned by one company had a problem and had to shut down, other interconnected facilities could pick up the slack. Through time, what developed in the US were three effectively isolated distribution networks, the Eastern Interconnection, the Western Interconnection, and the Electricity Reliability Council of Texas (ERCOT) with links also to Canada as illustrated in Figure 16.1.

The Federal Energy Regulatory Commission (FERC) has regulatory authority over interstate sales of electricity and the operation of regional markets. The North American Reliability Corporation (NERC), formed in the wake of a major blackout that struck the US northeast in 1965, operating through eight regional entities as indicated in Figure 16.1, is charged under FERC with ensuring the orderly function of the overall national system. Notably, six of the eight reliability entities are located in the Eastern Interconnection region with the Western Interconnection and ERCOT regions operating with centralized authority as integrated units. Jurisdictions for a number of these entities (WECC, MRO, and NPCC) extend into Canada. The figure indicates also locations for the limited number of ac-dc-ac connections that currently link the Eastern Interconnection, the Western Interconnection and ERCOT.

The Energy Policy Act of 1992 mandated open access to the transmission system. Subsequently, a variety of additional organizations, referred to as Independent System Operators (ISO's) or Regional Transmission Organizations (RTO's), were created to oversee grid operations and ensure equal access to transmission services for power producers in their regions. Where wholesale markets exist and where there is a significant presence of independent power producers, responsibility for transmission planning rests largely with the RTO's or ISO's. In regions where vertically integrated utilities continue to play a major role in the overall power system, notably in the West and in Texas, the organizational structure is more complex. The distribution of RTO's and ISO's across the US is indicated in Figure 16.2. Five of these organizations are located in the Eastern Interconnection Region (the Southwest Power Pool, the Midwest ISO, the Pennsylvania New Jersey Maryland Interconnection, the New York ISO and ISO New England), one in the west (the California ISO) and one in Texas (ERCOT). The Midwest ISO extends into Canada. As indicated, there are three additional Canadian based entities (the Alberta System Operator, the Ontario Electricity System Operator and the New Brunswick System Operator).

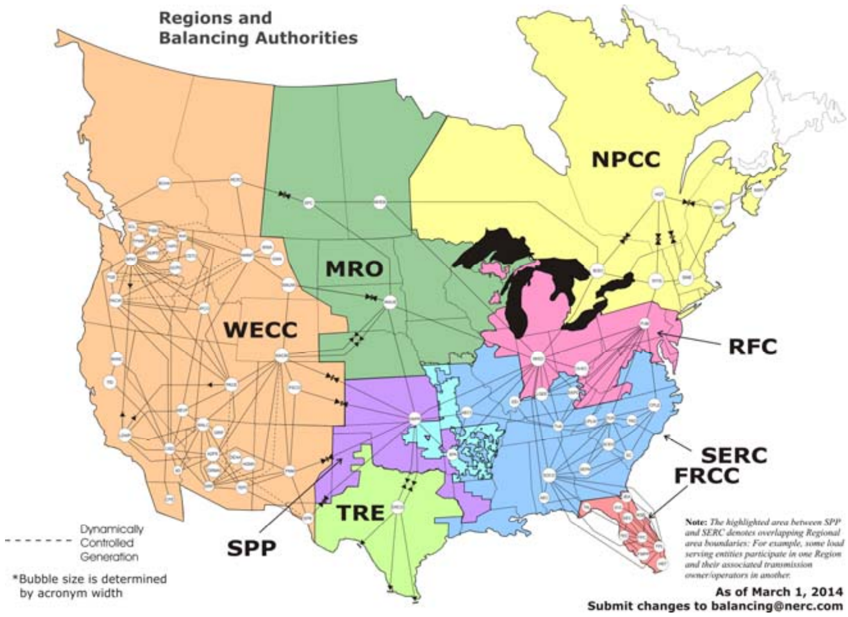

Figure 16.1 Regions and balancing authorities under the North American Reliability Corporation (NERC) (Source: http://www.nerc.com/comm/OC/RS%20Agendas%20Highlights%20and%20Minutes%20DL/BA_Bubble_Map_20140305.jpg, read February 1, 2015)

Notes:

Eastern Interconnection:	FRCC: Florida Reliability Coordinating Council
	MRO: Midwest Reliability Organization
	NPCC: Northeast Power Coordinating Council
	RFC: Reliability First Corporation (PJM)
	SERC: Southeastern Electric Reliability Council
	SPP: Southwest Power Pool
Western Interconnection:	WECC: Western Electricity Coordinating Council
Texas Interconnection:	TRE: Texas Regional Entity or ERCOT (Electric Reliability Council of Texas)

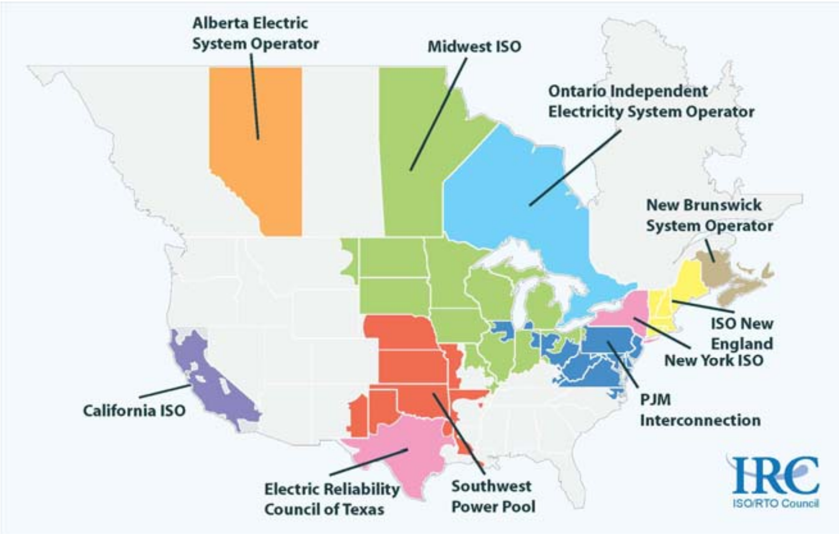

Figure 16.2 ISO and RTO regions for the US and Canada (Source: http://www.opuc.texas.gov/images/iso_rto_map.jpg, read February 1, 2015).

To take full advantage of the country's abundant wind and solar resources will require development of a more integrated national electric grid. The present system is fragmented, reflecting the piecemeal manner in which it evolved. It will be important to invest in ac-dc-ac connections to allow power to flow freely between the three autonomous grids – the Eastern Interconnection, the Western Interconnection and ERCOT. Conversion from ac to dc and then back to ac is necessary to ensure that the power transferred through these links can be matched precisely to the frequency, phase and voltage of the system to which it is connected (Masters 2004). Mai et al (2012) estimate that 200 million MW-miles of new transmission will be needed to support a future electrical system in which up to 90% of electricity would be supplied from renewable sources, primarily wind and solar. Much of this investment would be concentrated in the middle and southwestern regions of the country as indicated in Figure 16.3 (for 80% renewables in this case). Approximately 60 GW of the new capacity would be devoted to ac-dc-ac lines to provide for an essentially seamless connection between the present largely isolated asynchronous zones in the East, West and Texas. Building out the system could cost as much as $300 billion, an impressive number but not exorbitant given that the investment could be spread over an extended period. Providing context, a 16-year history of investments in the present transmission system is presented in Figure 16.4.

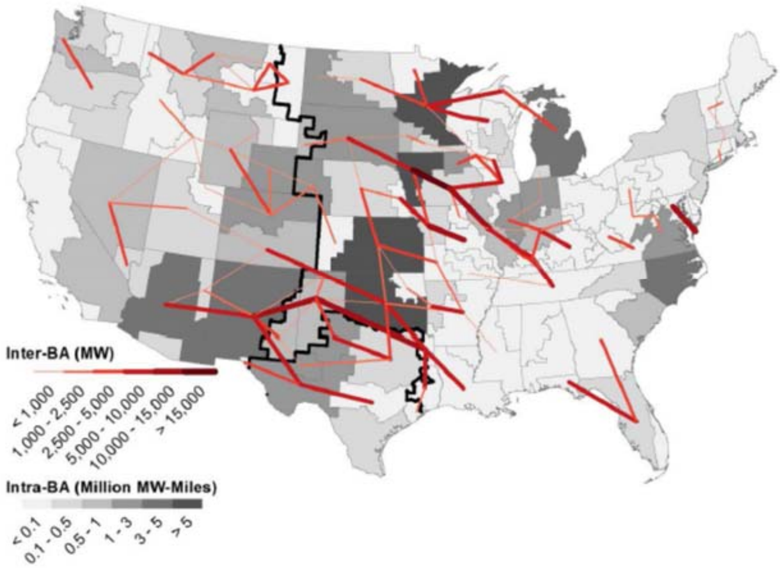

Figure 16.3 New transmission capacity additions required to accommodate the 80% renewable scenario considered by Mai et al (2012). The red lines indicate additions of capacity extending across individual balancing areas with higher capacities represented by deeper shades of red. Additions within balancing areas, expressed in units of capacity miles are indicated by the dark shading, the deeper the shading the higher the magnitude of the relevant capacity miles.

Authority for siting and permitting new transmission systems in the US rests at present with the states. Planning for and implementation of the expanded transmission network as envisaged in Figure 16.3 will require an unprecedented commitment in terms of multi-state coordination and cooperation. Not surprisingly, state regulatory agencies tend to emphasize interests of their immediate constituents. Under the circumstances, we may expect that it will be difficult, at least in some instances, for these bodies to respond affirmatively to advantages that could be realized regionally or nationally through a more comprehensive sharing of authority and interests. In the final analysis, FERC has authority to override local objections to specific multi-state transmission proposals should the US Department of Energy declare them to be in the national interest. As yet, though, there is no precedent for exercise of this authority.

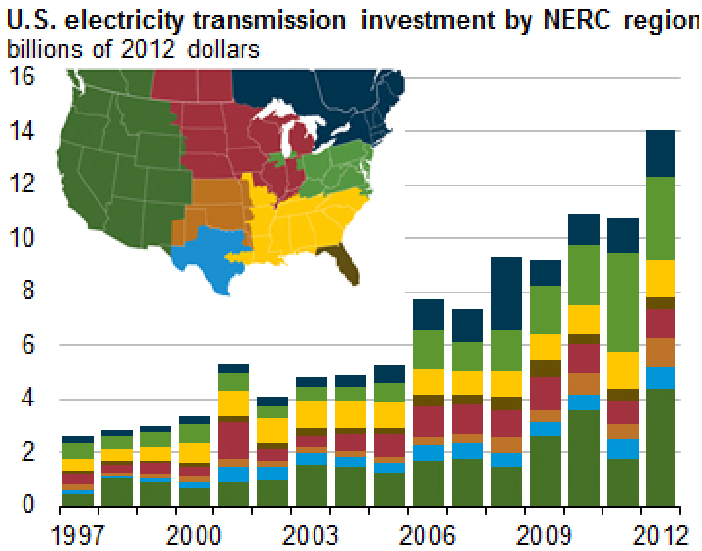

Figure 16.4. Annual investments in US transmission systems. Colors differentiate investments in the different NERC regions as indicated (http://www.eia.gov/todayinenergy/detail.cfm?id=17811#, read February 9, 2015).

As discussed in Chapter 10, electricity produced from a specific wind turbine or wind farm can vary on time scales as brief as minutes or even shorter in response to fluctuations in wind speeds associated with variations in local small-scale turbulence. Huang et al (2014) showed that this high frequency variability could be eliminated effectively by coupling outputs from as few as 5 to 10 wind farms distributed uniformly (equally separated) over a 10-state region in the central US. More than 95% of the residual variability would be expressed in this case on time scales longer than a day allowing grid operators to anticipate at least a day in advance the potential supply of electricity from wind and to plan accordingly. Output of solar generated power from a specific PV installation may be expected to vary similarly on high frequency time scales in response to localized changes in cloud cover, more slowly on multiday time scales associated with the passage of meteorological systems, the spatial dimensions of which can extend to hundreds if not thousands of kilometers. As with the contribution from wind, combining outputs from solar sources distributed over an extended region may be expected to reduce the variability of the integrated composite source, contributing to a more reliable, more predictable, power supply.

There is a further advantage that could be realized from a nationally integrated transmission system. Demand for electricity follows a typical diurnal pattern, high in the morning when people awake to begin their daily routine with a secondary peak when they return home in the evening. The pattern in the west is delayed with respect to the east by as much as three hours reflecting differences in local time. With a nationally integrated power system, inefficiencies associated with the inevitable diurnal peaks and lulls in demand could be reduced. On a national basis, demand for electricity in the US peaks in summer reflecting requirements for air conditioning. Wind and solar sources of electricity are complementary in the sense that the contribution from the former peaks in winter and at night while the latter is at a maximum during the day and in summer. A nationally integrated electricity system incorporating inputs from both wind and solar could be effective in taking advantage of this synergy. There will be times though when even the combined contributions of power from wind and sun may fall short of meeting demand. There will be a need in this case for backup generation to pick up the slack.

Backup generation in the present electrical system is provided mainly by natural gas fired systems capable of ramping up or down rapidly in response to changes in demand. Natural gas combined cycle (NGCC) systems are efficient and can respond on a time scale of hours. Gas turbines (GT) are less efficient but have the advantage that they can ramp up almost immediately. Assuming a major future commitment to the production of electricity from wind and sun, the demand for back up generation may be expected to increase significantly adding up to as much as a third of total generating capacity. The shortfall is likely to be greatest in summer when demand is highest and when the supply from wind is at a minimum (Mai et al., 2012). Emissions could be reduced by capturing CO_2 from the exhausts of these gas-fired plants, specifically from NGCC installations that are likely to see greater use given their higher efficiency. As discussed below, opportunities to store electricity when available in excess and to manage demand could reduce, though probably not totally eliminate, requirements for back up generation.

Energy use in the domestic and commercial sectors. A summary of energy consumption in the US residential sector, broken down by end use, is presented in Table 16.2. Space heating accounted for 39% of the energy consumed in the sector in 2012, followed by consumption for the supply of hot water (17%), space cooling (8%), lighting (6%), refrigeration (4%), cooking (3%), TV (3%) and computers (1%). The Table includes also a break down in the applications of energy supplied in the forms of electricity, natural gas, fuel oil, and propane. Electricity accounted for 45% of the total, followed by natural gas (41%), fuel oil (5%) and propane (5%), with the balance supplied primarily by wood products. Natural gas was responsible for 61%, 67%, and 62% of the total energy consumed in space heating, water heating and cooking respectively. Fuel oil and propane were used primarily for space and water heating.

Table 16.2 Energy use in the US residential sector in 2012 (Quads)

Function	Total	Electricity	Natural Gas	Fuel Oil	Propane
Space heating	4.07	0.29	2.5	0.44	0.37
Water heating	1.79	0.45	1.2	0.05	0.07
Cooling	0.88	0.85	-	-	-
Lighting	0.64	0.64	-	-	-
Refrigerator	0.38	0.38	-	-	-
Cooking	0.34	0.11	0.21	-	0.03
TV	0.33	0.33	-	-	-
Computers	0.12	0.12	-	-	-
Total	10.42	4.69	4.26	0.51	0.51

(Source: US EIA, Annual Energy Outlook 2014, http://www.eia.gov/forecasts/aeo/, read February 15, 2015)

Table 16.3 presents a summary of energy consumed in the commercial sector. The commercial sector classification encompasses a variety of different functions and buildings, including among others private and public offices, hotels, retail establishments, schools, and hospitals. Space heating, lighting, water heating, space cooling and ventilation accounted for 54% of the total energy used in this sector, 50% of which was supplied by natural gas, 45% by electricity. A diversity of functions is covered under the classification of "other", including applications in hospitals and for a variety of diverse laboratory facilities. Electricity and natural gas accounted respectively for 45% and 41% of the total energy consumed in the commercial sector.

Table 16.3 Energy use in the US commercial sector in 2012 (Quads)

Function	Total	Electricity	Natural Gas	Fuel Oil
Space heating	1.82	0.15	1.54	0.13
Lighting	0.94	0.94	-	-
Water heating	0.60	0.09	0.48	0.03
Space cooling	0.60	0.55	0.04	-
Ventilation	0.52	0.52	-	-
Refrigerator	0.38	0.38	-	-
Office equipment	0.33	0.33	-	-
Other	2.88	1.53	0.90	0.23
Total	8.29	4.52	2.96	0.42

(Source: US EIA, Annual Energy Outlook 2014, http://www.eia.gov/forecasts/aeo/, read February 15, 2015)

Initiatives at the national level have been notably successful in the US over the past several decades in improving the energy efficiency of a wide range of commonly used electric appliances, including refrigerators, air conditioners, television sets, washing machines, computers and lighting. Devices that meet a specified minimum standard for efficiency are given an Energy Star rating under programs administered by the Department of Energy and the Environmental Protection Administration. When you purchase a piece of equipment, assuming that it meets minimum standards defined by these agencies, you can readily learn from the attached labeling precisely how much energy the device will consume. The program has been markedly successful in reducing electricity consumption in both the home and workplace.

In a related development, the Energy Independence and Security Act (EISA) that went into effect in December 2007 mandated that energy inefficient light bulbs should be phased out over time, to be replaced by much more efficient alternatives. To give off light, the tungsten filament of the old standard incandescent bulb must be raised to a temperature of at least 2,500 C. Even at this elevated temperature, only 2% of the energy consumed by the light bulb is converted to photons in the visible portion of the spectrum – the light we need to see. The bulk of the energy is emitted at longer wavelengths in the infrared in the form of heat. The bulbs and lamps now on the market are notably more efficient in channeling the energy they consume into useful light. Compact fluorescent lamps (CFL's) are 3-5 times more efficient than the old incandescent lamps and light emitting diode bulbs (LED's) are even better. These devices cost more, but they last longer (a function of their lower emitting temperature) and the investment pays off over a relatively brief period of time in terms of lower bills for electricity.

Opportunities to conserve energy use for space heating and hot water. The cost for heating and cooling and for the supply of hot water accounts for a major fraction of the expense associated with the operation of both residential and commercial establishments. Investments in insulation and improved design of building shells (windows, doors, basements, walls, attics and roofs) could provide a double dividend: reduced operational expenses and at the same time a decrease in emissions of CO_2. California has led the way in the US in demonstrating and responding to the opportunities for savings in energy use that could be realized in the residential and commercial sectors without compromise to delivery of essential services. Statewide energy standards for buildings were instituted first in California in 1975, updated every 2 to 3 years thereafter. Consumption of natural gas per capita in the residential sector in California decreased by close to 50% between 1975 and 2005, almost twice the reduction realized over the same period in other states (Harper et al., 2011). Most of the energy savings initiatives adopted in California were implemented in the form of increasingly stringent building codes and applied primarily to new construction projects. It is more difficult to promote savings for existing structures. The decision to save or not in this case rests ultimately with property owners. How they elect to respond is likely to be guided more by considerations of personal financial advantage rather than by idealistic concerns otherwise for the health of the global environment.

A few years ago, we engaged a company to carry out an energy audit on our house in Cambridge. The audit was subsidized by the local gas/electric utility. The company that undertook this task was very professional. They sealed the doors and windows and measured the time for the air to turnover inside the house. They took infrared pictures of the interior walls and wrote a very nice report documenting their work and conclusions. In brief, they found that our house was reasonably tight but could benefit from additional insulation. I followed up, seeking to find out precisely where I should invest in this insulation, what it would cost, and how long it would take to recover the investment (the payoff). Regrettably, they were unable to provide this information, stating straightforwardly that they lacked the competence to do so. More disconcerting, they told me that they were unaware of any companies or organizations that could provide this level of end-to-end advice. If we are to encourage economically motivated decisions by owners of buildings, whether residential or commercial, to invest private capital to enhance the energy efficiency of their properties, with the attendant benefits in terms of reduced emissions of CO_2, there is clearly a need for such a service. I have a vision for how it might work.

Imagine an organization that could furnish an energy audit of a building using infrared imaging, with instrumentation mounted for example on a drone. These data could provide a quantitative record of precisely how much energy was leaking out of specific portions of buildings (BTU's per unit of time) and they could cover the entire neighborhood in one fell swoop. Armed with this information, the integrated energy company could supply the building owners with quantitative data on precisely how much energy was being lost from their properties and from where, what it was costing, how much capital would be required to plug the leaks, and what this would imply in terms of projected returns on investment. This could constitute, in my opinion, a win-win strategy for a broad constituency: a new business opportunity for investors; good paying jobs for technicians who could be trained and employed to contribute productively to this important new function; savings for property owners; and, of particular relevance in the current context, an opportunity to highlight cost-effective investments that could result in significant reductions in emissions of climate altering CO_2.

Heat pumps as an alternative source of space heat and hot water. Meeting the overall goal for a reduction in national emissions of greenhouse gases by 83% by 2050 relative to 2005 will require contributions from the residential and commercial sectors over and above what can be realized solely by conservation. It will be important to replace a fraction of the current fossil fuel based supply of electricity with a non-fossil alternative: as discussed earlier, wind and sun can offer plausible options. It will be necessary to cut back in addition on the use of natural gas and fuel oil as the primary energy sources deployed to heat buildings and for the supply hot water. Heat pumps fueled by low fossil fuel based electricity could provide a constructive alternative.

These systems operate by drawing energy from the external environment, either from the ambient air outside or from the ground, and deliver it to the interior of buildings in the form of heat.

Heat pumps are available in a variety of different operational modes. A particular device could function as follows. Heat would be transferred from the outside to the inside of a building through a circulating fluid. Absorption of heat by the fluid on the outside of the building could result in a change of phase of the fluid, a transition from liquid to gas. The temperature of the circulating gas could be raised subsequently by compression, with the energy for compression supplied by an electrically fueled pump. The hot gas would pass then through a series of coils, a heat exchanger, allowing heat to be transferred to the building interior either by blowing air across the coils or by pumping water across the heat exchanger. The fluid cooled in this process could condense back to the liquid state and continue its circulatory path returning to the external exchange unit where it would once again absorb heat from the exterior and the sequence would repeat. Traversing this cycle, the fluid would gain energy initially by transfer from the external medium (air or ground), benefit from an additional input from the compressor, delivering a fraction of the combined contributions to the interior of the building through the heat exchanger.

The efficiency of a heat pump is defined by the ratio of the electrical energy consumed in its operation to the energy content of the heat it delivers eventually to the building it services. This is referred to as the coefficient of performance or COP. The COP for a thermodynamically ideal system (a fundamental limiting theoretical construct) is determined by the ratio of the temperature at which the system absorbs heat from the outside to the temperature at which it delivers heat to the interior. The higher the external temperature and the lower the temperature at which the heat is delivered, the greater the potential value for the associated COP. Values of COP's for heat pumps currently on the market for space heating range from as low as 2 at an outdoor temperature of 0 ^{0}F, increasing to about 3 for a temperature of 32 ^{0}F, rising to values greater than 4 for temperatures higher than about 45 ^{0}F. If the electricity used to operate the heat pumps is produced from natural gas and if there is an option to heat the building using either a natural gas fired furnace or an electrically enabled heat pump, the breakeven point from an energy perspective is reached at a COP value of about 3 (as discussed in Chapter 2, 68% of the energy consumed in producing electricity in the US is rejected to the environment in the form of waste heat). The breakeven price from a cost perspective depends obviously on the difference between the prices for electricity and natural gas, which can vary significantly not only across the country but also in time.

The energy-adjusted cost for delivery of electricity to our home in Cambridge in December 2014 was 4.8 times higher than the cost for supply of natural gas. Massachusetts is unusual, however, in that the costs for electricity and natural gas are both artificially high, reflecting transportation bottlenecks in the delivery of natural gas (lack of adequate pipeline connections from supply points) and the fact that natural gas accounts for a dominant fraction of the state's production of electricity. In contrast, the residential price for electricity in Washington State in November 2014 (the state with the country's cheapest electricity) was only 2.4 times higher than the energy-adjusted price for natural gas. In terms solely of anticipated day-to-day expense, it would make sense to heat your home in Washington using an electrically powered heat pump rather than natural gas. On purely economic grounds, it would be more difficult to arrive at a similar conclusion in Massachusetts. In both states, though, switching from natural gas fired boilers to heat pumps would result in reduced demand for energy (average winter temperatures in both states are high enough to accommodate COP values generally greater than 3) and a similar conclusion should hold for a large portion of the country. Assuming that the electricity to fuel the heat pumps was derived primarily from non-fossil sources, switching from natural gas and oil-based sources to electrically driven heat pumps would be expected to lead to significant savings in terms of emissions of CO_2.

Reducing emissions from the transportation sector: opportunities for electric cars. The transportation sector is responsible for approximately one third of US national emissions of CO_2 (Chapter 3). Emissions from this sector are associated with the use of gasoline to drive cars and light trucks, diesel oil to fuel some cars but mainly heavier trucks, ships and trains, and jet fuel to supply requirements for domestic and military aircraft. The challenge in reducing emissions from the sector is to identify non-fossil substitutes for the fossil-based sources that currently dominate inputs of energy to this sector.

From both energy efficiency and economic perspectives, there is an advantage to using electricity rather than gasoline to drive cars and light trucks. Approximately 80% of the energy content of the gasoline consumed in a motor vehicle is wasted, converted to heat: only 20% is deployed to turn the wheels. In contrast, storing electricity in a battery and using this energy subsequently to drive the vehicle is much more efficient: losses in this instance amount to as little as 10%. Assume that 100 units of energy are used to produce 30 units of energy in the form of electricity and that 90% of this (27 units) is employed to drive a car or truck. Compare this with driving the vehicle using 100 units of energy in the form of gasoline. Only 20% of the gasoline energy (20 units) is usefully deployed in this case. So, driving using electricity is 25% more efficient from an energy perspective than using gasoline. From the point of view of cost, the electricity option is even more attractive.

The energy content of a gallon of gasoline is equivalent to 33.7 kWh of which 6.7 kWh (20%) is assumed to be available to propel an internal combustion (IC) powered vehicle. The electrical energy required to deliver the driving performance equivalent to what could be supplied with a gallon of gasoline fueling an IC car or truck would amount in this case to 7.4 kWh (assuming 90% efficiency). Given a retail price of 19.8 cents per kWh for electricity in Cambridge in December 2014, it would cost $1.46 to supply the driving capacity of an electrically powered vehicle competitive with what could be achieved by consuming a gallon of gasoline in a conventional IC vehicle, a significant savings even in the context of current low prices for gasoline. The comparison would be even more impressive if applied to the market in Washington State. As indicated earlier, electricity prices there are much lower, about 9 cents per kWh (Figure 2.1): the electrical option could provide the performance equivalence of a gallon of gasoline in this case for as little as 67 cents.

As for the relative advantages of electrically fueled transportation in terms of related emissions of CO_2, it depends on the nature of the source for the electricity. If the electricity were produced from coal, the balance would be negative: it would be preferable to use gasoline. If the electricity were produced from natural gas, there would be a significant savings in terms of emissions (production of CO_2 per unit energy delivered from natural gas is approximately half that from coal). If the electricity were produced from either wind or sun, the associated emissions would be negligible.

The market for electrically powered or electrically assisted vehicles has developed rapidly in the US over the past few years. As of early 2015, the consumer had a choice of some 25 different models sold by some 15 different manufacturers (http://www.plugincars.com/cars, read March 1, 2015). The choice includes models that operate exclusively with electricity supplied from the grid and models that use a combination of grid supplied electricity supplemented by on-board gasoline engines deployed either to provide back-up electric power or to drive the vehicles directly. The range for the electric only mode depends on the capacity of the installed battery pack and varies from about 60 miles to as much as 265 miles. Batteries are both weighty and expensive and prices for vehicles in this category vary accordingly. The most popular all-electric model is the Nissan Leaf priced at $29,000 with a range of 84 miles. Plug-in hybrids such as the Toyota Prius or the Honda Accord are equipped with batteries capable of drawing power from the grid and delivering between 10 and 13 of all-electric miles before switching to the standard gasoline/electric hybrid drive train. Vehicles classified as extended range have all-electric potentials that vary from as little as 20 to more than 80 miles, with options to travel much further using their gasoline back-up capabilities. The 22 kWh battery on the BMW i3, for example, provides for an all-electric range of between 80 and 100 miles, which can be extended to about 190 miles using the car's on-board gasoline-powered generator. The lower cost Chevy Volt has an even greater extended range capability, up to 300 miles, but with a much lower all electric potential of about 38 miles.

The top of the market for the electric only option is the Tesla Model S with a range of between 208 and 265 miles depending on the choice of battery capacity, 60 kWh or 85 kWh. The base cost for the Tesla S runs from $64,000 to $81,000 with the lower value associated with the smaller battery option. The Model S is powered by thousands of individual lithium ion cells similar to the cells used in a variety of consumer products including, most likely, your laptop. The battery pack is located under the floor of the car in a temperature-controlled compartment designed to ensure that the system should be secure (fire proof) even in the event of a serious collision.

As of November 2014, Tesla had installed 268 fast charging stations around the world, with 132 in North America, capable of providing the 85 kWh Model S with an additional 150 miles of range in as little as 20 minutes. The objective of the innovative CEO of the company, Elon Musk, is that the electricity for all of these stations should be supplied eventually from the sun, from panels installed on the roofs of the structures that shelter the charging stations or located otherwise nearby. He has engaged for this purpose Solar City, the company that installed the solar panels on the roof of our house on Cape Cod (Chapter 11). Speaking to the diversity of his expertise and overlapping interests, Musk, in addition to his role as CEO at Tesla, was a co-founder and currently serves as Chairman of Solar City.

Electric cars account for but a small fraction of the close to 250 million cars and light trucks on the road today in the US. Imagine what would happen if electrically propelled vehicles could account for a much larger fraction of the total vehicle population in the future, half or even more. Consuming electricity at an average rate of about 0.3 kWh per mile (the current standard), driving 10,000 miles annually, 100 million vehicles would consume annually about 3×10^{11} kWh, adding up to close to 10% of the total current national US demand for electricity. In the process we could save 20 billion gallons of gasoline annually (assuming that gasoline driven cars should have achieved by that time an average fuel efficiency of 50 miles per gallon) and avoid emissions of up to 176 million tons of CO_2 (assuming that the electricity for these cars and light trucks should be derived primarily from non-fossil sources). A further benefit from a large-scale transition to electrically propelled cars and light trucks is that the batteries of these vehicles could provide an important means for distributed storage of electricity.

Consumption of electricity in the US peaks during the evening on hot days in summer with load demands ranging as high as 770 GW. Peak demand in winter is less, about 620 GW. Demand during nighttime hours when people are normally asleep drops to about 400 GW in summer, to as low as 300 GW in winter. If the fleet of electric cars envisaged here were to draw power from the grid charging their batteries over a 5-hour period at night, the additional demand for electricity would amount to about 160 GW. If the connection between the vehicles and the grid could operate in both directions, a fraction of the electric car fleet not in operation during the day could be available to supply power to the grid under conditions where demand might otherwise outstrip supply. If 30% of the fleet could meet this criterion, the related supply could amount to as much as 50 GW. The difference between day and night demands for electricity would be lowered accordingly. Fewer generating facilities would be required to meet the extra daytime demand would be reduced, resulting in an increase in the efficiency of the overall electric power system. As indicated earlier, wholesale prices for electricity are typically low at night when demand is at a minimum, highest in morning and in the evening. The electric car owner could take advantage of this price differential, buying power at night when prices were low, selling during the day when prices were high. The utilities would benefit also, exploiting the flexibility afforded by the ability to store or draw power from the batteries of an expanded fleet of electric cars, easing thus the challenge faced in adjusting to the intrinsic variability of an enhanced supply of power from sun and wind.

Reducing emissions from the transportation sector: options for heavy vehicles, trains and planes. Gasoline driven cars and light trucks accounted for 60% of CO_2 emissions from the US transportation sector in 2012, with an additional 31% from diesel powered vehicles - heavy trucks (23%), ships (5%) and trains (3%) – with a further 9% from jet fuel used in aviation. As discussed in Chapter 8, a number of the major railroads in the US have plans to turn to natural gas in the form of LNG as a substitute for diesel to drive their trains, a development that should result in a reduction (as much as 25%) in associated emissions of CO_2. A large-scale transition from diesel to natural gas in the long-distance trucking industry is unlikely: it would require a major investment in infrastructure to accommodate demands for this alternate energy source (a supply of compressed natural gas to be available at a significant fraction of the large number of service stations that currently cater to these trucks). As discussed in Chapter 14, the source of diesel from biological sources (biodiesel) increased by 35% in 2013 relative to 2012. The increase was attributed in large measure to the introduction of a $1.00 per gallon rebate on taxes available to companies electing to blend biodiesel with conventional diesel. Despite the increase, the supply of biodiesel in the US in 2013 amounted to less than 1.3 billion gallons, as compared with overall demand for diesel in the heavy truck sector of close to 40 billion gallons. The source of biodiesel, as currently defined and configured, is unlikely to increase significantly in the future. Despite the tax subsidy, the US was obliged, for the first time in 2013, to turn to imports to meet requirements for the product mandated under the Renewable Fuel Standard (RFS). A better option for the future may development of a synthetic alternative produced from plant material taking advantage of what is known as the Fisher-Tropsch (FT) process, a procedure introduced almost 90 years ago in Germany by Franz Fisher and Hans Tropsch. This could provide an attractive biomass-based alternative also for jet fuel.

Reducing emissions from the transportation sector: opportunities for low, or even negative, carbon emitting FT-derived fuels from biomass. The FT process begins with a mixture of carbon monoxide and molecular hydrogen (CO and H_2) constituting what is referred to as synthesis gas or syngas. Syngas can be produced from a variety of feedstocks - from coal, natural gas, or biomass. It has been employed for many years in coal-rich South Africa, and earlier in similarly coal-rich Germany, to transform coal to a variety of liquid fuels including gasoline, diesel and jet fuel. Coal is composed of almost pure carbon. To produce the H_2 needed as input to the FT process, the CO produced from the coal is required to react with water in what is referred to as the water shift reaction. The product of this reaction, in addition to H_2, is CO_2. The quantity of CO_2 produced as an intermediate in this sequence is almost twice what is emitted to the atmosphere in conjunction with the eventual combustion of the liquid product. Assuming that the intermediate CO_2 is also emitted to the atmosphere, use of coal as a source of liquid fuel is decidedly negative in terms of its implications for net emissions of CO_2.

The FT process results in a concentrated source of CO_2. This allows for a relatively inexpensive option to capture and sequester this carbon and to bury it in a long-lived geological reservoir, effectively ensuring its permanent removal from the atmosphere. Incremental costs for capture and sequestration of CO_2 formed in the FT process are estimated to be as low as $10 to $20 a ton (Kreutz et al., 2008; Tarka et al., 2009; Schrag, 2009), as compared to costs for capturing and disposing of CO_2 developed from traditional coal and natural gas fired power plants projected at levels of $100 a ton of CO_2 or even higher (IPCC, 2005). If the CO_2 produced from FT processing of coal were captured and sequestered, emissions of CO_2 associated with combustion of the resulting liquid products would not differ significantly from emissions associated with the use of conventional liquid fossil fuel sources: 52% of the carbon contained in the coal could be captured and effectively permanently removed from the atmosphere (Kreutz et al., 2008). A more attractive option might be to employ biomass rather than coal as feedstock.

If the FT process were used to produce liquids from biomass alone, both the carbon consumed in the FT manufacturing process and the carbon emitted when the liquid product was eventually combusted would have been derived from the contemporary atmosphere. With carbon capture and sequestration, this sequence could result in a net sink for atmospheric CO_2. The downside is that the energy content of a given mass of plant material is less than the energy content of an equivalent mass of coal resulting in a reduced potential to produce marketable fuels per mass unit of input. A more realistic option, suggested by Kreutz et al (2008), favored also by Schrag (2009), would be to use coal but to incorporate some fraction of biomass into the initial feedstock, while capturing and sequestering the intermediate CO_2 product.

Kreutz et al (2008) explored a variety of possible choices for feedstock and operational procedures that could be deployed to produce liquids using FT. Of particular relevance in the present context is the model identified as CBTL-RC-CCS, short hand for conversion of coal and biomass to liquids through FT (CBTL), with recycling of unconverted syngas (RC), combined with carbon capture and sequestration (CCS). For this scenario, they postulated an input consisting of 2,441 tons of dry coal per day with 3,044 tons of dry biomass. In terms of carbon content, coal accounted for 54% of the input with 46% from biomass. Processing resulted in production of 10,000 barrels of liquid equivalent per day. The entire sequence was carbon neutral in the sense that the carbon emitted to the atmosphere when the fuel products were combusted was projected to be the same as the carbon introduced in the first place with the biomass incorporated in the feedstock. Up to 54% of the carbon supplied as input was assumed to be captured and sequestered. From an energy perspective, 44% of the energy contained in the input materials was converted to energy in the liquid products, with a further 5% deployed to generate 75 MW of carbon-free electricity available for export to the grid - an overall efficiency for end-to-end energy processing of 49%. According to the Kreutz et al (2008) analysis, the breakeven point for carbon neutrality is attained when the dry biomass content of the input material reaches a level of about 56%. With higher concentrations of biomass, the integrated sequence, from processing to fuel consumption, results in a net withdrawal of carbon from the atmosphere. The ultimate potential for biomass-fueled FT, both as a source of low carbon transportation fuels (gasoline, diesel and jet fuel) and as a potential sink for atmospheric CO_2, will depend on access to adequate supplies of biomass.

The advantage of the FT process applied to biomass is that, in contrast to the specific hydrocarbon inputs required for production of ethanol (corn, sugar cane, cellulose) and conventional biodiesel (soybeans, rapeseed, animal fats, recycled cooking grease etc.), the FT process can take advantage of any available source of chemically reduced carbon. Possibilities include agricultural and municipal waste, residues from paper production, and purposely grown crops. Switchgrass offers a particularly attractive possibility. It can be grown on marginal land. It is perennial and self-seeding. Requirements for fertilizer are modest. And an acre planted to a selected hybrid form of switchgrass could produce as much as 4 tons of harvestable dry matter per year with additional carbon stored in the soil (Mitchell et al., 2013). Idled cropland in the US amounts currently to about 40 million acres. Assuming that all of this land could be planted with switchgrass, this could provide for a sustainable annual source of as much as 160 million tons of dry biomass, sufficient, in combination with coal, to accommodate the biomass requirements for up to 155 individual plants with the 10,000 barrel per day FT carbon-neutral facilities described above. Liquid fuel output from these 155 plants could supply up to 18% of current (2012) US consumption of gasoline, 50 % of diesel and 150% of jet fuel. Additional supplies of biomass could be derived from fast growing trees such as poplars and willows and could be complemented by organic-rich wastes supplied from a variety of potential industrial, agricultural and municipal sources.

There is no doubt that biomass added to coal, processed using FT with capture and sequestration of product CO_2, could provide for a low carbon emitting alternative to conventional sources of gasoline, diesel, and jet fuel. At higher levels of biomass input, this could contribute to a net sink for atmospheric CO_2. As a further benefit, combining coal and biomass to produce low carbon emitting liquids could support a continuing market for coal, prospects for which would be limited otherwise in a fossil constrained future world. Similar benefits in terms of production of low carbon emitting fuels could be realized by using natural gas rather than coal as the biomass additive (Liu et al., 2010). A key question concerns cost. A comprehensive economic analysis should consider the expense for acquisition of necessary feedstocks (coal, natural gas and biomass), capital and operational costs for relevant processing facilities, and offsets available from marketing of the resulting liquid products. At current (March 2015) depressed domestic prices for natural gas (less than $3/MMBTU), costs for natural gas and coal are comparable on an energy basis in the US suggesting that natural gas could represent an economically viable alternative to coal as input for FT processing. Given the advantages of natural gas as a comparatively clean fuel relative to coal, however, this trend is unlikely to persist. In projecting future prices for production of liquids from FT processing of either coal or natural gas with biomass, it will be important to recognize that forecasts of this nature are intrinsically uncertain. In particular, they may fail to account for technological advances that could result in a lower cost for supply of biomass materials to a future generation of more productive FT facilities.

Summary comments on the vision for a low carbon energy future. The prospects for a low carbon future outlined here depend on the premise that energy services will be delivered in the future to a greater extent than today through electricity. It is essential that this electricity be supplied by fossil carbon-free sources. To this end, we emphasized the potential for wind and solar. There are twin challenges that must be addressed if these sources are to live up to their potential. First, the electrical transmission system must be upgraded to allow power from favorable source locations to be transferred efficiently to regions of high demand. Second, we need to adjust to the intrinsic variability of these sources. Both objectives can be advanced by investments in an integrated national power distribution system.

Transitioning to a system in which electric companies have the ability to respond not simply to demand but also to influence this demand can play an important ancillary role in easing the challenge posed by the variability of the power source. Advances in utility scale battery technology could be further influential. Important benefits could be derived also, as discussed, from a two-way connection between electric utilities and the batteries of a large future fleet of electrically propelled vehicles.

The guiding hand of government will be essential if we are to meet the stated US objective for emissions in 2050. Five years ago when I published my earlier book on energy (McElroy, 2010), I could argue that we needed to invest in a new energy system motivated not simply by the threat of human induced climate change but also to advance the interests of national energy security. The landscape is now totally different. The shale revolution has provided the US with abundant sources of both oil and natural gas. Prices have plummeted. The least efficient coal fired power plants are being mothballed and replaced by more efficient natural gas fired plants with significantly lower operational costs. It is more difficult under these circumstances to encourage the investments needed to support the transition to the low carbon future required to address the climate issue. There are advantages though to do so, and not just in terms of minimizing damage to the climate system. The levelized costs for power generated using either wind or solar are determined almost exclusively by the initial costs of capital: the fuels are free and operational expenses are minimal. What that means is that once the initial investment is made, the cost of power is totally predictable for at least 20 years in the future. There is no comparable guarantee for power generated using fossil fuel based alternatives.

Fossil fuels have profited from subsidies in the past and indeed continue to do so. To address the climate issue, it will be important that low carbon emitting alternatives should be similarly supported. Production tax credits and feed-in tariffs offer supportive options to meet this objective. It is imperative though that they should be implemented with a measure of predictability and continuity and that they not be subjected to the turn-on/turn-off pattern that has defined experience over much of the recent past.

Additional perspectives. Williams et al (2014) discussed a number of options that could be implemented to meet President Obama's commitment for an 83% reduction in US greenhouse gas emissions by 2050 relative to 2005. Their study was conducted as part of an international initiative, the Deep Decarbonization Pathways Project (DDPP), involving teams from 15 countries responsible for 70% of total current global emissions. The goal for the DDPP is to identify strategies by which individual countries could reduce their emissions of greenhouse gases to levels consistent with limiting the future rise in global average surface temperature to 2 ^{0}C or less. To this end, Williams et al (2014) considered four options for the US: a renewables-rich option, a nuclear-rich option, an option envisaging a major investment in carbon capture and sequestration (CCS), and a fourth incorporating a mix of the other three. The renewables-rich scenario comes closest to the vision outlined here. The stated challenge for 2050 refers to the totality of greenhouse gas emissions and not simply to CO_2 from the energy sector as emphasized in this study. Williams et al (2014) interpreted the composite 2050 commitment to imply that the contribution from fossil fuel related emissions should be limited by this date to a level not to exceed 750 Mt CO_2 per year. In their study, they modeled explicitly paths they thought could be followed to meet this objective. Between 2015 and 2050, they concluded that the stock in electric lighting could turn over as many as four times. Space heating systems might be replaced twice. Industrial boilers or electric power plants in contrast are likely to remain in place for most of this 35-year interval, turning over at most once, except under exceptional circumstances.

Consistent with the vision elaborated here, Williams et al (2014), in their renewables-rich scenario, assumed that electricity should play a much greater role in the future US energy system that it does today. They envisaged an increase in generating capacity from the present (2014) level of 1,070 GW to more than 3,600 GW by 2050 with the bulk of this increase taking place post 2030 as existing coal-fired plants are retired. The 2050 renewables-rich electrical system they contemplated would be dominated by contributions from wind and sun, accounting for 62.4% and 15.5% of the total respectively. The system would be oversized to ensure that the power available would be sufficient to meet demand most of the time. When available in excess, power could be deployed to produce hydrogen, using electrolysis (the process in which water molecules are split with electricity yielding a 2:1 mix of H_2 and O_2). The H_2 formed in this fashion could be fed directly into the natural gas distribution system, they suggested, or it could be used to produce synthetic natural gas, methane (CH_4), by reacting with CO_2 - four molecules of H_2 combining with one molecule of CO_2 to produce one molecule of CH_4 and two molecules of H_2O (2). The assumption was that this CO_2 should be derived from a biomass source and that the resulting synthetic natural gas product would be fossil carbon free – decarbonized, to use the language favored by Williams et al (2014). The overall sequence is referred to as power to gas (PtG). This decarbonized natural gas would be deployed where possible as a substitute for conventional fossil based natural gas. In particular, it could be used to complement diesel as the fuel of choice for propulsion of heavy trucks.

Williams et al (2014) concluded that the goal of reducing overall US greenhouse gas emissions by 83% by 2050 relative to 2005 could be met at relatively modest incremental cost. Their median estimate was for an increase in net energy system costs by 2050 of 0.8% of GDP with a 50% probability that the incremental expense should lie between -0.2% and +1.8%. They went on to note that “technology improvements and market transformation over the next decade could significantly reduce expected costs in subsequent years”. Success in meeting the objectives addressed by Williams et al (2014) and the more aspirational vision enunciated here will depend to a large extent on the posture adopted by government over the immediate future. If the challenge of human induced climate change is taken seriously, we can chart the course to a sustainable energy future. Should we choose to ignore it, we should be prepared to live with the consequences.

Can the climate system be managed to minimize future damage? Two possibilities have been suggested to address the issue posed by this question. The first involves altering the albedo (reflectivity) of the planet, cutting back on absorption of sunlight to offset the decreased capacity of the earth to cool in the face of enhanced insulation resulting from the increased concentration of heat absorbing greenhouse gases. The second proposes to remove CO_2 from the atmosphere, to bury it in a suitable long-lived depository effectively cancelling the impact of earlier additions.

The suggestion that it might be possible to cool the earth through active intervention is not new. The Russian climatologist Mikael Budyko proposed forty years ago that this could be accomplished by adding sulfur to the atmosphere (Budyko, 1974) complementing the impact that occurs naturally in conjunction with large volcanic eruptions. The eruption of Mount Pinatubo in the Philippines in 1991 introduced an estimated 14-26 million tons of SO_2 into the stratosphere with concentrations peaking near 25 km (Read et al., 1993). Over a period of a few months, this gaseous SO_2 was converted to sulfuric acid, forming small-sized reflective aerosols (suspended particles). This triggered transient negative radiative forcing estimated at as much as -3 W m $^{-2}$, comparable to the positive forcing associated with the enhanced concentration of greenhouse gases (IPCC. 2007). Radiative forcing, as discussed in Chapter 4, provides a measure of the rate at which the planet is absorbing net energy from the sun over and above what is being returned to space. Air in the stratosphere turns over on a time scale of a few years in response to exchange with the underlying troposphere. The impact of a volcano on the energy budget of the atmosphere is projected thus to be relatively short-lived. The observational data indicate that the temperature of the lower atmosphere decreased by about 0.4 ^{0}C in the first year following the eruption of Mount Pinatubo. Five years later, it had essentially recovered to the level that prevailed prior to the eruption (Soden et al., 2002).

Given the concerns over potentially disruptive warming triggered by the increasing concentration of greenhouse gases, it is not surprising that attention has turned more recently to the possibility that this warming could be offset through purposeful additions of sulfur to the stratosphere. The option has been identified variously as solar radiation management (Royal Society, 2009), albedo modification (NAS, 2015), or simply climate engineering (Keith, 2013). The NAS study concluded that: "albedo modification at scales sufficient to alter climate should not be deployed at this time". Keith (2013), on the other hand, expressed the view "that it makes sense to move with deliberate haste towards deployment of geoengineering". He contemplated an initial program in which 25,000 tons of sulfuric acid would be added to the stratosphere annually ramping up over a decade or so to approximately 10 times this amount. He argued that in its mature phase this program could be implemented by a small number of high-flying Gulfstream business jets at an annual cost of about $750 million.

I agree with the conclusion reached in the NAS study: a commitment to large-scale albedo modifications without prior deliberate assessment would be unwise. The concern is that the remedy could turn out to be worse than the disease.

The increase in the concentration of greenhouse gases is responsible for a net gain of energy by the Earth: the planet is currently absorbing more energy from the sun that it is emitting back to space. Adding reflective material to the atmosphere would trigger assuredly an immediate decrease in the rate at which the planet is absorbing energy from the sun. The imbalance between energy in and energy out would be reduced accordingly. The problem is that this would be accomplished not by cutting back on the source of the original imbalance but rather by introducing an entirely different disturbance. To the extent that the planet is absorbing less visible light from the sun, we might expect changes to develop not just in global average temperature but also in the hydrological cycle and in the metabolism of the global biosphere. The good news is that a disturbance introduced by adding reflective material to the stratosphere would be short-lived. There would be an opportunity to access the impact in real time and to decide whether to continue with the intervention or suspend it.

There could be an ancillary benefit to global cooling from an albedo altering intervention. The attendant decrease in atmospheric temperature would be associated most likely with a decrease in the concentration of atmospheric water vapor. As discussed in Chapter 4, the increase in the concentration of water vapor resulting from the increase in the concentration of greenhouse gases has been implicated in the extremes of weather observed in recent years – more floods, more droughts, and more energetic storms. Actions intended to mitigate the damage from weather disturbances of this nature by purposeful manipulation of the planetary albedo could be contemplated, I would suggest, but only after careful deliberation and solely if justified and supported by an extensive, focused, research program.

Rather than seeking to offset the effect of one major human induced global disturbance by introducing another, the better choice, I contend, would be proceed with the second option noted at the beginning of this section: to remove the offending gases directly from the atmosphere, specifically the most important culprit, CO_2, and to bury it in a secure geological depository.

Options for capturing CO_2 from the atmosphere. A number of approaches have been proposed to capture CO_2 from the atmosphere. It could be removed through reaction with a solvent such as sodium hydroxide (NaOH), converted in this case to sodium carbonate (Na_2CO_3). The chemistry of the resulting solution could be modified subsequently, by addition of quick lime (CaO) for example, leading to production of a stream of concentrated CO_2 available after further treatment for transfer to a designated depository, a conveniently located deep saline aquiver for example (IPCC, 2005).

The sodium hydroxide option was proposed by Keith et al. (2005), Bacciocchi et al. (2006) and Zeman (2007). Lackner (2009) opted for an alternative approach involving a commercially available plastic with the property that when dry it would be unusually effective in absorbing CO_2. The CO_2 captured in this process could be released subsequently by immersing the plastic in a bath of liquid water: CO_2 molecules absorbed by the plastic would be displaced by molecules of H_2O derived from the liquid.

There is an inevitable, thermodynamically defined, minimum energy that must be expended to concentrate CO_2 from the dilute form in which it is present in the atmosphere to the much higher pressures required for processing and eventual transfer to a designated depository. Capturing the compound from the atmosphere where it is present at a partial pressure of $4x10^{-4}$ atm and converting it to a concentrated stream at a pressure of 1 atm (3) requires a minimum expenditure of energy of 0.42 MMBTU per ton of CO_2. Concentrating it further to a pressure of 100 atm, as might be appropriate for transfer to a geological depository, would require an additional outlay of 0.25 MMBTU for a total of 0.67 MMBTU per ton of CO_2. The energy requirements for practical systems are likely to be significantly higher than these theoretically defined minima.

The transformations involved in capturing and concentrating CO_2 using the plastic option recommended by Lackner are intrinsically simpler than the more complex rearrangements implicit in the NaOH procedure. The energy cost should be lower accordingly, by at least a factor of 4 according to House et al. (2011). Lackner suggests that his procedure could be implemented to remove and sequester CO_2 from the atmosphere for as little as \$100 per ton of CO_2 (Lackner et al., 2012). In contrast, drawing on experience with existing large-scale gas removal systems, House et al (2011) concluded that the cost for realistic capture/sequestration systems could range as high as \$1,000 per ton of CO_2. Broecker (2015), acknowledging the wide disparity between these estimates, recommends that a "major effort should be initiated to narrow the wide range of estimates currently in play".

To put the cost numbers in context, a cost of \$100 for capturing and sequestering a ton of CO_2 from the atmosphere would be equivalent to adding 88 cents to the price of a gallon of gasoline or alternatively increasing costs for coal and natural gas by factors of 5 and 1.3 respectively, from \$50 to \$256 per ton in the case of coal, \$4 to \$5.3 per MMBTU for natural gas. Should costs range much higher than the value suggested by Lackner et al (2012), closer to the higher limit quoted by House et al (2011) or even the intermediate value (\$600 per ton of CO_2) recommended by APS (2011), prospects for capture of CO_2 from the atmosphere by direct chemical intervention using commercially available energy would appear to be limited. Tapping energy from the sun captured by green plants through photosynthesis could provide a more promising alternative.

There are a number of approaches that could be employed to engage the biosphere in an energy-assisted application to remove carbon from the atmosphere. Biomass could be combusted to produce electricity with capture and sequestration of the resulting CO_2 (Keith et al., 2005: House et al., 2011). CO_2 could be captured and sequestered in conjunction with the production of ethanol or it could be employed to produce H_2 (Keith et al., 2005). Costs associated with any and all of these options are uncertain, with estimates for the electricity option ranging from \$150 to \$400 per ton of CO_2 sequestered (House et al., 2011). To these opportunities we would add the possibility of applying the FT process, as discussed above, to a mix of biomass and coal (or natural gas) to produce high value liquid fuels. Combining this process with capture and sequestration of the incidentally produced CO_2, assuming a fractional abundance of more than 56% for the dry mass content of the biomass component of the input material relative to coal, could contribute to a net withdrawal of CO_2 from the atmosphere (Kreutz et al., 2008). Accounting for both the energy content of the product liquid fuels and the electricity generated as a by-product, it was concluded that up to 50% of the energy contained in the input materials (the biomass and coal in this particular instance) could be converted to energy-useful products (liquid fuels and electricity), in contrast to the much lower efficiency, closer to 20%, that would be realized if the biomass was simply combusted to produce electricity. The efficiency would be even less in this case if combined with capture and sequestration of the associated CO_2 emissions.

I offered a vision in this chapter for a future in which emissions of CO_2 associated with combustion of fossil fuels could be markedly reduced, effectively eliminated, on a time scale of decades. If this objective is to be addressed successfully, government must play an important role in guiding the necessary transition. The challenge is daunting given the current low price for fossil fuels in the US - coal, oil and natural gas. A tax on carbon, or alternatively a carbon-trading regime, could balance the scales, allowing renewable energy to compete with fossil alternatives. Incentives in the form of tax credits or feed-in tariffs for investment in renewable options could be similarly effective. As discussed by Williams et al (2014), the cost to effect the transition to a low fossil carbon emitting future need not be prohibitive. Indeed, there could be savings that could be realized should creativity be engaged and allowed to flourish. Public support, conviction that the threat of climate change is real and that it must be confronted, will be critical if we are to chart a successful course to the climate friendly, low carbon emitting, future proposed in this chapter.

Key points:

(1) Generation of electricity was responsible for 38% of US emissions of CO_2 in 2013 with an additional 34% derived from transportation, the balance from a combination of industrial (18%), residential (6%) and commercial (4%) sources.

(2) The goal enunciated by President Obama, to reduce US emissions of greenhouse gases by 83% by 2050 relative to 2005, will require energy services to be provided in the future to a greater extent than today in the form of electricity produced primarily from wind and sun with potential for an additional contribution from heat emanating from the earth's interior.

(3) Nuclear energy could make an important contribution to the objective of a low CO_2 emitting future. Current public antipathy and cost considerations suggest that the potential for this source of power is limited however for the US at least over the near term. Prospects are more encouraging for China.

(4) Electricity supplied by non-fossil sources could provide an environmentally and economically attractive substitute for gasoline and diesel oil as the energy source of choice for cars and light trucks.

(5) Batteries incorporated in an expanded fleet of electrically powered vehicles could provide an important opportunity for distributed storage of electricity. Batteries of these vehicles could be charged at night when demand for electricity is low. Assuming a 2-way connection between batteries and utilities, a fraction of the batteries could be available to transfer electricity to the grid under conditions where supply from conventional sources

may inadequate to keep up with demand. Access to this distributed storage could mitigate to some extent problems resulting from the variability of power supplied from sun and wind.

(6) The challenge in accommodating an expanded source of variable power from wind and sun could be eased by investments in the national electrical distribution system. Improving the links between the three effectively isolated autonomous grids that define the current system could allow for more efficient transfer of power from wind-rich regions in the mid west and sun-rich regions in the southwest to high demand centers in the west and east.

(7) Electricity fueled heat pumps could offer an alternative, or at least a supplement, for energy supplied currently in the form of natural gas and oil to heat water and to supply heat to commercial and residential buildings. Assuming that this electricity is produced from non-fossil sources, it could provide an additional opportunity to reduce prospective emissions of CO_2.

(8) Demand for energy to heat buildings could be reduced by purposeful investments in insulation for existing structures combined with building codes to motivate energy more efficient designs for the future.

(9) The Fisher-Tropsch process could provide an opportunity for efficient conversion of biomass, in combination with either coal or natural gas, to liquid fuels including synthetic forms of gasoline, diesel and jet fuel. Assuming a minimum threshold for incorporation of biomass in the relevant feedstock, capture and sequestration of CO_2 evolved as a byproduct of this process could result in a net sink for atmospheric CO_2.

(10) Costs to realize the goal for a low fossil carbon emitting future outlined here need not be prohibitive and could be accompanied by a variety of significant ancillary benefits in terms

of employment, infrastructure renewal, energy security, and international leadership. Successfully addressing the goal will require a commitment from government, supported by an educational program targeted to develop a broad based consensus as to its importance.

Notes

(1) The carbon negative concept assumes that CO_2 emitted in conjunction with use of these biomass derived products should be captured and deposited in a long-lived reservoir, effectively permanently separated from the atmosphere.

(2) Melaina et al (2013) concluded that hydrogen, H_2, could be added safely to the gas distribution system with concentrations ranging potentially as high as 15% by volume. They cautioned though that levels judged safe and acceptable should be assessed on a case-by-case basis.

(3) Pressures are quoted here in units of atmospheres, abbreviated as atm. A pressure of 1 atm is equivalent to the pressure of the atmosphere at sea level.

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