Electricity, Emissions, and Pricing Carbon

10

10.1 The Electricity Sector

Worldwide, the two largest sources of greenhouse gas emissions are electricity generation and transportation. Electricity generation is the topic of this chapter while transportation is part of the next.

Coal, even today, makes up by far the largest fraction of fuel used to produce electricity. The United States and China are the Saudi Arabias of coal, and coal with all its emissions problems is the fastest expanding fuel for electricity production worldwide, though not in the United States because of its shale-gas revolution. Outside the United States, coal is the lowest in cost because of its abundance and ease of extraction, and because power plants can be built relatively quickly. Unless fracking spreads through the rest of the world leading to low-cost shale gas, without some sort of emissions charge or other limitation mechanism coal will remain the lowest-cost fuel for a long time to come. Finding a substitute for coal or a way to reduce emissions from coal is critical to the world effort to reduce greenhouse gas production.

In the United States, coal and natural gas are used to generate 70% of electricity, and, according to the EIA, in 2007 were responsible for producing nearly 40% of US greenhouse gas emissions. The percentages were not very different from those of other industrialized countries,
with the exception of France. France gets most of its electricity from greenhouse-gas-free nuclear power and has much lower emissions per unit GDP and very much lower emissions from the electricity sector. I will come back to this in the chapter on nuclear power.

There are only four ways to go about reducing the emissions from electricity generation:

- Emit less greenhouse gas by making electricity generation more efficient (less fuel for the same electrical output);
- Catch the greenhouse gases and store them away (carbon capture and storage or CCS);
- Use electricity more efficiently (less demand means less generation which gives lower emissions);
- Substitute lower- or zero-emission sources for what we use now (solar, wind, or nuclear power, for example).

I start with the efficiency of the existing electrical generating system which is not nearly as good as it could be, then look at what happens when gas displaces coal, go on to what the charge for carbon emissions might be if the costs to society that come from emissions were to be included in the price of electricity generated from fossil fuels, and end with catching and storing the greenhouse gases, something I am skeptical about, but which has such potential that it is worth a try. End-use efficiency and carbon-free or low-carbon sources are discussed in later chapters.

The reason for the inefficiency in generation and the larger-than-needed emissions that go with it is a combination of low fuel costs for fossil-fueled generation plants,
and ignorance of the consequences of greenhouse gas emissions until relatively recently. Most of the US electrical generating plants are old with an average age of 35 years. When they were built, fuel was cheap and global warming was a thing few scientists worried about, much less citizens or governments. As a result, the US electricity supply (and the world’s) has come to depend more and more on coal, which has been the lowest-cost generator of electricity and still is today outside the United States. Figure 10.1 from the EIA [19] shows the evolution of the US electricity supply from 1949 to 2007. Coal was king of electricity generation, and with its crown came a large increase in emissions. By 2007 it supplied 50% of the electricity while gas and nuclear supplied roughly 20% each, hydroelectric dams supplied 7%, and the renewables supplied the rest. The same report [18] also
showed the flow of energy into the generating system and the flow of electricity out. From it you can find that:

- Only 35% of the primary energy in the fuel gets transformed into electricity;
- Of that, some of the electricity is used inside the power plants, some is lost along the way in the distribution system, so only about 31% of the fuel energy reaches the consumers in the form of electricity;
- Gas is better than coal – 40% of the energy in gas is turned into electricity, but only 33% for coal.

The emissions in electrical generation depend on the fuel used in the power plant. I often get questions when talking about low- or zero-emission sources of power about what happens if I include the emissions in manufacturing the power plant as well as the emissions from its operation. The answer is in Figure 10.2 which shows the life-cycle emission per gigawatt-hour of electrical output.
for coal, gas, and several forms of carbon-free energy (not totally carbon-free but nearly so) [20, 21, 22]. Life-cycle emissions take the total emissions coming from everything except burning the fuel (making the steel and concrete used in the plant, mining and transporting the fuel, maintaining, repairing, and upgrading the plant, etc.), averaging them over the expected lifetime of the plant to get non-fuel emissions per hour and adding that to the direct emissions from operations. In this kind of analysis even wind power, which uses nothing but the natural wind to generate electricity, has some life-cycle emissions from manufacturing and maintaining the wind turbines. Replacing coal plants or gas plants with any of the carbon-free sources can make big reductions in greenhouse gas emissions even when every input is included. Even replacing coal plants with gas plants makes a big reduction in emissions.

It is also worth taking a look at the comparative risks of all the main sources of electricity. Table 10.1 summarizes estimates made by W. Krewitt and colleagues on the comparative risks of various energy systems [23].

Table 10.1 *Comparative risks of different energy sources expressed as years of life lost per billion kilowatt-hours, based on an end-to-end analysis for Germany*

<table>
<thead>
<tr>
<th>Source</th>
<th>Ref. [23]</th>
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<tbody>
<tr>
<td>Coal</td>
<td>138</td>
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<tr>
<td>Natural gas</td>
<td>42</td>
</tr>
<tr>
<td>Nuclear</td>
<td>25</td>
</tr>
<tr>
<td>Photovoltaic</td>
<td>58</td>
</tr>
<tr>
<td>Wind</td>
<td>3</td>
</tr>
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Source: Ref. [23]
Krewitt’s analysis is for Germany, is based on European Union regulations for emission controls, and uses German government numbers for health effects. His comparisons are for the same amount of electricity generation from each source, one terawatt-hour (one gigawatt of electricity for 1000 hours), and are supposed to be end-to-end; that is, to include mining, transportation, fuel fabrication, plant construction, operation, and the effect of emissions on public health. The fact that coal is the worst of the major fuels for electricity generation is no surprise. The biggest surprise for me was the large number for photovoltaic generation. Krewitt’s analysis is based on the use of polycrystalline photocells which use many toxic gases in fabrication. I would expect the thin-film cells coming into use now to be less hazardous, but there are not enough of those deployed to make a good estimate as yet. The analysis does not deal with uncertainties as well as I would like and the numbers give an impression of precision that I think is unwarranted. Nonetheless, of the major fuels, coal is clearly the worst, wind the best, and nuclear seems somewhat better than photovoltaic or gas.

The efficiency of electricity generation is important in discussing emissions. The aging fleets of US coal and gas-fired power plants run at average efficiencies of about 33% and 40% respectively, while the most modern coal plants run at 43% and gas plants at 60%. Though the United States prides itself on technology, it is a long way from the best in the world when it comes to efficiency of electricity generation [24]. Denmark is best with coal at 43% efficiency while Luxemburg and Turkey lead the way with gas at 55%. Honors for being the worst go to India for coal at 27% and Russia for gas at 33%.
If all of today’s coal and gas plants in the United States were converted to even 50% efficient natural-gas plants, emissions from electricity generation would drop by nearly 1500 million tonnes per year or nearly 25% of total emissions. Gas plants are not only more efficient than the best of coal plants, but emit less greenhouse gas for the same amount of energy used.\(^1\) In the United States a move away from coal is happening because of the dramatic drop in the price of natural gas that goes with the increase in supply from shale gas. At the end of 2013, coal-generated electricity had dropped to about 40% of the total while gas-generated had risen to about 30%. With the change goes a reduction of emission from the electricity sector of about 14%, a lower average cost of electricity, and a healthier public.

The reasons for continued reliance on coal for electricity generation are that there are a lot of plants already in existence, and, more importantly, coal is cheaper than gas as a fuel in most of the world. The United States is a special case that I will come to below. Even though a coal plant with all its pollution-control equipment costs more than a natural-gas plant to build, the difference in fuel costs make coal a source of lower-cost electricity (according to the EIA, in 2007, before the shale-gas revolution, gas cost more than three times coal for the same energy content).

\(^1\) A reminder; gas gets half of its energy output from turning its hydrogen into water with no greenhouse gas emissions whereas coal gets all its energy from turning carbon into CO\(_2\). Add to this the better efficiency of a gas plant compared with a coal plant, and conversion of an old coal plant to a modern gas plant reduces emissions threefold for the same electricity output.
Very few people under the age of 60 have ever seen a lump of coal. Until roughly 1950 many homes were heated with coal and those of us who are old enough remember what it looks like, and remember with little pleasure how to run a furnace. I can still remember the sound of coal hissing and rattling as it slid down a metal chute into the family basement, and the relief my father and I felt when he converted our heating system to an oil burner and we no longer had to shovel the stuff into the furnace and take out the ashes.

The old 33% efficient coal plants mainly use powdered coal as a fuel, a different form from what slid down into my basement. The lumps of coal are ground into something as fine as talcum powder and blown into the furnace with the correct amount of air to assure proper burning, generating the steam used to run the electric generators. A new coal power-plant technology called Ultra-Supercritical (USC) uses the same powdered-coal fuel but reaches a higher efficiency (about 43%) by running the steam system at higher temperature and pressure than the standard plants. The technology is new, and there are not many of these plants around. USC technology has a slightly older brother called Supercritical (SC) that has an efficiency of 38%, and there are more of these. The newest technology of 2007 is called Integrated Gasification Combined Cycle (IGCC). Here the coal is first turned into a gas which then runs a combined cycle generator like those used in the best of the gas-fired power plants. While the potential efficiency of the combined cycle part of the system is very good, the gasification process uses lots of energy and the overall efficiency is more like that of the SC plant. The reason
for interest in IGCC is that it is easier to capture the carbon dioxide if it is to be captured and stored away (see Section 10.2).

The shift toward gas for electricity generation, one of the four options to reduce emission mentioned at the beginning of this chapter, is happening in the United States because the balance of fuels used for generation of electricity has changed significantly since the end of the year 2008 when the first edition of this book was finished. As mentioned earlier, the contribution of coal has fallen to about 40% and is still falling, whereas that of natural gas has risen to 30% and is still rising. Nuclear energy stays at about 20%, and the renewables are about 10%. However, the renewables have two parts: old-fashioned renewables such as hydroelectric dams and burning biomass, and newer ones like wind and solar. There is much in the news about the large addition to capacity by wind and solar, but be careful here. Typical average output of land-based wind farms in the United States is only about 30% of capacity, while for solar it is only about 20% in the best places such as the Southwest. In 2011, the old-fashioned renewables contributed about 8%, while wind and solar added 2%. The reduction of CO₂ emissions in the United States is mainly due to the move away from coal toward natural gas.

The surge in natural gas use for the generation of electricity is mainly a US phenomenon because of a big addition to supply from the new technique of fracking. Unlike oil which is easy to move around the world, gas is hard and expensive to move so that the world price for gas does not reflect the highest-cost sources of supply. In the United States, gas costs about $4 per million BTU, in
Europe about $12, and in Asia about $15. Gas is moved by pipeline as a gas and by ship as liquefied natural gas (LNG). The only way to get low-cost US gas to the rest of the world is to chill it to a liquid, load it on special ships with refrigeration equipment to keep it cold, and turn it back into gas at an overseas port and ship it on by pipeline. I am told this process costs about $4 per million BTU.

Other regions do have the kind of shale that holds the gas, but do not have the drill rigs and technical knowhow to extract the gas, nor do they have the local pipelines to get it to market. Until they do, low-cost gas will remain a US privilege.

What is needed in regions without low-cost shale gas, to accelerate the move to more efficient generation, is what the economists recommend: a price on emissions as discussed in Chapter 7, which makes disposal of waste part of the cost of doing business. As long as the world’s atmosphere is regarded as a free dump for greenhouse gases, utilities will continue to build the plants that generate the lowest-cost electricity. If they had to pay for the emissions, the situation would change in a flash.

10.2 Pricing Carbon Emissions: Carbon Capture and Storage

If there were a way to arrive at an appropriate price for emissions, a price could be set and the incentives to produce power plants with low or no emissions would soar, making the move from a coal-dominated to a lower-emission electricity sector occur much faster. There are many ways to set such a price. One is to set it
such that your favorite carbon-free power source becomes less costly than the high-emission ones we use now. Another way is to see how much it would cost to eliminate the emission from our present coal-based system and include that as a fee paid to the government if you emit the greenhouse gas — no emissions means no fee to be paid. The technology being investigated to eliminate the emissions is called carbon capture and storage (CCS).

The basic idea of CCS is to capture the greenhouse gas emissions from our conventional power plants and put them away somehow so that they do not add to the atmospheric load of greenhouse gases. There is an IPCC Special Report on CCS published in 2005 that gives the details [25]. Its Summary for Policymakers is quite readable. Another good, but more technical, reference is a 2007 report from the Massachusetts Institute of Technology entitled “The Future of Coal.”2 Cost estimates from the IPCC report have large uncertainties since they have to consider conditions all over the world while the MIT report focuses on the United States. I will use the MIT numbers for costs.3

CCS is used today in limited applications. One example is a Norwegian natural gas field in the North Sea that has a large amount of CO$_2$ mixed in with the gas. The CO$_2$ is separated at the well site and re-injected underground into a local reservoir. They inject about 3000 tons of CO$_2$ per day and estimate that they can put away up to

2 http://web.mit.edu/coal.
3 Both the IPCC and MIT reports focus on disposing of the CO$_2$ as gas injected underground or under the sea. Another process in the research phase looks at the possibility of combining it with other elements into carbonate rock.
20 million tons. Another example is enhanced oil production from wells where injecting CO$_2$ increases the pressure in the oil reservoir, pushing out more oil to be recovered. In this case the CO$_2$ comes from other industrial processes and is typically sent by pipeline to the oil field where it is pumped underground. Both of these examples are much simpler than CCS at a power plant where a very hot gas stream has to be treated, but they do give an experience base, though a small one, on which to base part of the cost analysis. There is a scale-up issue. A 1-gigawatt coal-fired electrical plant produces in a few hours what the Norwegian gas field produces in a day, and there are many thousands of such coal-fired generating plants.

The problem for a power plant in the carbon capture part of CCS is the separation of the CO$_2$ from the much larger amount of nitrogen in the gas stream. Air used to burn coal is 80% nitrogen and only the 20% that is oxygen combines with the fuel to make CO$_2$. Two processes are being investigated: separation before or after combustion. In the first case, the oxygen is separated from the nitrogen in air, and only the oxygen goes into the combustion chamber and ideally only pure CO$_2$ comes out. It can be cooled, compressed, and pumped off in a pipeline to a storage site. In the second case the hot mixture of CO$_2$ and nitrogen is cooled and passed through a chemical process that absorbs the CO$_2$, and the nitrogen is sent back into the atmosphere. The CO$_2$ absorber is then reheated, the CO$_2$ comes out, is compressed, and sent on its way. In either case the carbon capture process uses lots of energy, and the MIT study estimates that the CC part of CCS lowers the overall
generating efficiency by nine percentage points; that is a reduction to 34% efficient from the 43% typical of a USC plant.

The MIT study estimates that the cost of electricity would increase by about 3 cents per kilowatt-hour (kWh) because of the carbon capture process. Although they did not estimate the cost of carrying it away and pumping underground, I would guess that would add another 1 to 2 cents per kWh, for a total CCS cost of 4 to 5 cents per kWh. Since one kilowatt-hour of electricity from coal produces about one kilogram of CO$_2$, at that rate CCS costs $40$ to $50$ per tonne of CO$_2$, or around $160$ per tonne of carbon. The European Union has a carbon emissions market that has functioned for several years. Prices have been quite volatile and as of January 2014 are around $6.50$ (€5) per tonne, well below my estimate of capture and sequestration costs.

Two ways to internalize the cost of emissions are being discussed that if done would dethrone coal as the low-cost power source and turn industry to other fuels that emit less or no CO$_2$. One proposal is to impose a simple fee on emissions. The other is called Cap and Trade and would limit the total emissions from all sectors. These are discussed later in the policy chapters.

10.3 Does What Goes into Storage Stay There?

My skepticism about CCS is less about the capture technology than about the ability of the storage systems to keep the CO$_2$ out of circulation for a long time. Two scenarios have been discussed. One puts the CO$_2$ in the
deep ocean, transporting it there either by pipeline or as a liquid in a ship. This one doesn’t work. The other puts it under the surface in depleted oil and gas reservoirs or in what are called deep saline aquifers. These contain mineral-laden waters deep underground that are not connected to fresh water supplies. This one might work.

The issue is, does the CO₂ stay where you put it? For the oceans we know the answer and it is no. Surface waters in the oceans are slowly carried to the deeps and deep waters are slowly transported to the surface. How fast the process runs depends on the depth. The IPCC Special Report estimates that if we deposit 100 years’ worth of CO₂ produced in this century at a depth of about 2500 feet in the ocean, about 50% would have come back out by the end of the next century. Deeper is better, and if it were put at a depth of 5000 feet only 25% would have come back out.

Storage underground on land raises two issues. The first is the same as for the oceans – does the CO₂ stay where you put it? The second is the capacity of the underground sites. The IPCC Special Report estimates that, worldwide, depleted oil and gas reservoirs can store between 675 and 900 billion tonnes of CO₂ while the deep saline aquifers can store between 1000 and 10,000 billion tonnes. The business-as-usual scenario would give about 4000 billion tonnes for the total emissions in this century, and that much is a tight fit for what we know of the potential storage sites. In addition, the sites are not uniformly distributed around the world. There seem to be lots of deep saline aquifers under the United States and few under China, the two largest emitters.
We know that the oil and gas reservoirs did not leak before they were exploited. If they had, the gas would be gone and the pressure in the oil reservoirs would also be much lower than it is found to be. However, the reservoirs have had many holes punched in them, and all those holes would have to be plugged; probably not a big problem, but a concern. We do not know about the long-term behavior of the saline aquifers. The leaks of concern in those are not like the catastrophe that occurred at Lake Nyos in the Cameroon in 1986 [26]. (Nyos, a lake with huge amounts of CO$_2$ dissolved in its cold bottom waters from volcanic activity, released the gas in a rush, creating an asphyxiating cloud that suffocated most living things within 10 kilometers.) Leaks from CO$_2$ reservoirs will be slow. However, given the litigious nature of many of the world’s countries (particularly the United States), liability for leaks will surely delay any large-scale implementation of a CCS program.

The CCS option needs to be tested. If it works, the world will be able to continue using coal for some time while newer carbon-free technologies mature, especially important for the developing nations. We know enough from small-scale applications to know that it works in principle, but we do not know if it works at the scale required for a power plant. The US DOE started such a project, but recently canceled it as costs went up and up and up. I always thought this project, called FutureGen, was misguided. It tried to do too much: produce electricity, produce hydrogen, and demonstrate CCS at an industrial scale. I would separate the parts. An industrial-scale demonstration of CC needs to be done for separation both before and after combustion to learn...
something about costs and efficiency of the capture process. How much energy does it take and what fraction of the CO$_2$ is captured in the real world? CCS does not have to be perfect to make a huge contribution to cutting greenhouse gas emissions. At 90% capture efficiency, coal would become a small contributor to climate change and the world would have much more time to develop the technologies that will be needed in the long term to get emissions fully under control.

Tests of the deep saline aquifers with carbon dioxide loading don’t need a new power plant to supply the gas. We can start with CO$_2$ from any source (a lot is needed) and begin to learn what happens as the system becomes more acidic with CO$_2$ loading. No one seems yet to be doing that.

In October of 2013 the US Environmental Protection Agency (EPA) proposed regulations limiting the CO$_2$ emissions of both coal- and gas-fueled electric power plants. There will be a comment period and then final regulations will be issued. At the time of writing I do not know what the final regulations will be, but do not think much of the proposal in any event. They are for new plants, and modern gas plants already meet them. Coal plants do not and the EPA says that CCS is a viable technology, citing experience with injection into oil fields for enhanced recovery of oil (EOR). Their example is irrelevant because the amount of CO$_2$ used in EOR is tiny compared with what is produced in electricity generation, and so the problem is fundamentally different. There is potential large-capacity underground storage capability in deep saline aquifers, but no one knows if these can contain CO$_2$ for centuries without leaking. If
I were on a technical panel recommending what to do, I would say that CCS is not ready today for large-scale use.

What the EPA should be doing first is aggressively enforcing their limits on mercury emission from power plants that were imposed in 2012. Those standards will be phased in over the next three or four years and should force the dirtiest of the old coal-fired power plans to shut down by requiring expensive new technology. The oldest of the coal-fired plants were exempted from the emission regulations for sulfur dioxide and nitrogen oxide, and so have no scrubbers. It is very expensive to install them, so those plants will all close. The newer plants already have scrubbers that can be tweaked to take care of mercury, but the worst of the emitters of both mercury and CO₂ will shut down.

Next, the administration should get serious about regulating emissions from existing plants. Tests of CCS at an appropriate scale need to be done, and if it works, it should be required at existing coal plants. This will further increase the cost of electricity from them so more of them will close down too.

Finally, the Administration, Congress, and the public should read the National Academy of Sciences 2010 study Hidden Cost of Energy [3] which estimates that environmental effects including public health effects from coal-fired power plants cost the nation about $62 billion per year. There is no excuse for the continued use of coal to generate electricity that costs too much and is a health hazard to everyone who lives anywhere near a coal-fired power plant.

The conclusion of this section in the first edition is still correct today: test CCS at the appropriate scale in deep
saline aquifers, and put a price on carbon at least equal to the cost of sequestering it. Money talks in all societies and we might do well to listen; more on this in Chapter 15.

10.4 Summary and Conclusion

Coal is the mainstay of world electricity production and is not going away soon. Indeed, coal use is growing. While the United States is not adding coal-based generation capacity, China and India are adding plants rapidly (over the next four years 160 in China and 46 in India), and even Europe is considering new ones.

We will have those emissions with us for a long time unless there is some powerful incentive to phase them out. The best incentive is to make other options more attractive than continued reliance on coal. That can be done in several ways, one of which requires that emissions be made to bear some sort of cost. Based on the analyses in the IPCC Special Report and the MIT report I concluded that CCS costs about $40 to $50 per ton of CO$_2$. We do not have to know if CCS works to add a fee to CO$_2$ emissions and let the emitters work out how to reduce their costs by increasing the efficiency of their power plants, developing CCS systems, or turning to other sources of electricity that would no longer need subsidies to be more economically attractive than coal.

In the spirit of no silver bullets, CCS is worth an industrial-scale experiment aimed at storage in the deep saline aquifers. They have the capacity to store a large amount of CO$_2$ and therefore CCS has the potential to solve part of our problem. The test should be a combined private–government funded program. FutureGen, begun...
several years ago but canceled in 2008 when costs greatly increased, was the wrong program because it tried to do too much too soon. If I was running the program I would have had an existing coal plant equipped with the best of the post-combustion CO$_2$ separations technology to test it out. I also would have supported a test of pre-combustion separation of oxygen from the nitrogen in the air. Finally I would have a program of CO$_2$ injection into the deep saline aquifers to see what happens to it.

Conversion of old coal plants to modern gas plants reduces emission to one-third of the original coal plant emissions for the same electric power generation. Part of the reduction comes from the fuel switch and part comes from the higher efficiency of the gas-fired power plants. This should be encouraged, but somehow it doesn’t seem to have the emotional attraction of renewable energy, though it is much less costly, and can be done on a very much larger scale than solar power.

More emission-free electricity can come from nuclear power plants or from the renewables. These are the subject of later chapters.