Reflections—The Economics of Renewable Energy in the United States

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Introduction

Renewable energy has become the *energy du jour* in the United States. In his inaugural address, President Obama promised to "... harness the sun and the winds and the soil to fuel our cars and run our factories." The U.S. Department of Energy (DOE) asserts that 10 percent of U.S. electricity should come from renewables by 2012 and 25 percent by 2025.[1] These aims are supported by the Renewable Portfolio Standards (RPS) of 28 states, which require that between 15 and 20 percent of all electricity be from renewable sources by 2020–2030. For those with a historical bent, there is a real sense of déjà vu here: three centuries ago, we used nothing but renewables, with a fully sustainable energy system consisting of wind power (windmills), hydropower (water mills), and biofuels (wood stoves and animal power). Now we are trying to return to the past, with the addition of a few new sources such as solar and geothermal. But in the interim our population has increased by a factor of ten and our economic activity by several orders of magnitude.

One might think that the current goals for renewable energy are based on a detailed analysis of the prospects for a rollout of renewable energy, and that there is a comprehensive literature on the economics of renewable energy. Sadly, this is not the case: there is a literature containing some notable contributions, but nothing remotely in keeping with the emphasis on renewables in policy circles. So this article is both a reflection on the literature we have now and a call for a literature that we need to have. I begin with some background and a review of the economic factors that are relevant to understanding renewable energy. I then examine each of the renewable technologies, studying their economic characteristics and the role that they can be expected to play in the U.S. energy system over the next few decades.

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[1] http://www.whitehouse.gov/agenda/energy_and_environment.

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Background

The first discussion of renewables in the economics literature was in the post-1973 oil shock era, when we rediscovered and refined Hotelling's work on resource depletion. We invented the phrase "backstop technology," a technology that would eventually replace exhaustible resources with an energy source continuing forever. Partha Dasgupta and I used the idea in our work extending Hotelling's analysis (Dasgupta and Heal 1973), William Nordhaus worked with this idea in his book on the efficient allocation of energy resources (Nordhaus 1973), and so did many others. In fact, a quick search for "backstop technology" on Google Scholar produced 8,540 references. No one modeled the backstop explicitly, but clearly it was not a fossil fuel that we had in mind.

The need for renewables, in the sense of energy from non-exhaustible sources that have no environmental footprint, was also recognized and featured in the literature on "spaceship earth." But again there was little discussion of the details of these energy sources and their characteristics. For example, Boulding's work on *The Economics of the Coming Spaceship Earth* (1966) and D'Arge and Kogiku's paper on *Economic Growth and the Environment* (1973) both pointed to the need for inexhaustible low-impact energy sources, generally taken to be nuclear fusion, but did not grapple in any detail with the economics of such sources.

Renewables come in many different forms: they certainly include but may not be limited to hydro, solar (photovoltaic and thermal), wind, geothermal, tidal, biofuels, and waste-to-energy processes. Most renewables have certain economic characteristics in common—large fixed costs and low or no variable costs, and consequently average costs that are very dependent on output levels. Solar, wind, hydro, geothermal, tidal, and waste-to-energy—all require substantial up-front capital expenditures before any energy is generated, but have no fuel costs (all except waste-to-energy need no fuel, and waste is usually free). In contrast, fossil fuel power stations have significant fuel costs: a large coal-fired power station can use 10,000 tons of coal daily, costing between \$50 and \$100 per ton, so that fuel costs can be between half a million and a million dollars daily. Incidentally, burning one ton of coal will produce between 1.5 and 3.5 tons of CO_2, depending on the carbon content of the coal, implying that a big coal power station produces 15–30 or more thousand tons of CO_2 daily. This provides some insight into the sensitivity of coal's competitive position relative to the price of carbon: a price in the range of \$30 per ton of CO_2 could double the fuel costs of a coal power station. Nuclear is close to renewables in its cost structure: large capital costs and small ongoing fuel costs.

The fact that renewable energy sources are generally capital intensive and have no running costs has an interesting consequence. If we build a renewable power station today, we are providing free electricity to its users for the next 40 years, while if we build a coal-fired power station today, we meet the capital costs now but leave it to our successors to meet the large fuel costs and the external costs associated with the plant's pollution over its 40-year life. When we build a renewable power station, we are effectively prepaying for the next 40 years of electricity it produces. This has implications for what kind of financing might be appropriate—in particular, it makes long-term debt financing seem fair.

Issues and Concepts in the Economics of Renewables

There are two questions that policymakers need to have answered to make informed decisions about the future of renewable energy. First, is renewable energy more expensive than fossil energy? Second, can it be made available on a large enough scale to replace much of our fossil fuels use? Neither of these questions is easy to answer.

Comparing the Costs of Renewables and Fossil Fuels

One difficulty in assessing the cost of renewable energy is that the average cost, which depends on the scale, can vary greatly, and the marginal cost is very low. Presumably, we want to compare average costs, and for this we need a sense of scale. The usual cost measure is the levelized cost of electricity (lcoe), which is defined as the constant price at which electricity would have to be sold for the production facility to break even over its lifetime, assuming a reasonable level of capacity utilization. This is usually presented in terms of private costs, but from a policy perspective we need the lscoe, the levelized *social* cost of electricity, which includes external costs. We clearly have reasons to expect the external costs of renewables to be less than those of fossil fuels, particularly with respect to emissions of greenhouse gases, but data on this are rather thin.

Social Costs

What is the social cost of using a fossil fuel? Obviously, an important component of the external costs of fossil fuels is the social cost of the greenhouse gases emitted. Here we have a vast range of estimates. We can look at prices on the European Union's Emissions Trading Market, which have varied between $13 and $25 per ton of CO_2 over the last year and a half. But the EU system has many idiosyncrasies and it is not clear that this should be used as a definitive estimate of social cost. Analyses of the costs of climate change such as the Stern Review (Stern 2006) or William Nordhaus's reports based on his DICE model (Nordhaus 2009) provide explicit estimates of the social costs of CO_2 emissions, though there is little agreement here. Nordhaus's estimate of the social cost of CO_2 emissions is about $8 per ton, while Stern's estimate, at $85 per ton, is an order of magnitude greater. There are many reasons for the difference in these estimates, but one of the main ones is that Nordhaus discounts the future at 4 percent but Stern discounts it at 0.1 percent: over periods of a century or more, this is a massive difference (see Hope and Newberry 2007). As I have said elsewhere (Heal 2009), I see Stern as being closer to correct in this debate, and I thus take his estimate of the social cost of CO_2 as likely to be nearer to a true estimate. However, it is clear from this review of the estimates out there that we are not going to get an unambiguous value for the social cost of using fossil fuel.

Given this range of values for the social costs of CO_2 emissions, a recent study by Strand (2008), an IMF economist, is interesting. He calculates the prices of CO_2 implied by various policy measures to reduce emissions, and finds that the price is rarely less than several times the Stern value of the social cost. Subsidies to biofuels are some of the worst offenders.

The costs of greenhouse gases are not the only external costs of fossil fuel use: there are other emissions, such as SO_2, oxides of nitrogen, and fine particles, all of which are associated with environmental damage, poor health, and early death. Parry (2001) and Parry and Small (2005) have studied the social costs of these emissions. The U.S. EPA and the European Commission also report on their Web sites studies of the social costs of electricity production (European Commission [n.d.]). These studies find a wide range of social costs, from almost zero for renewable sources to as much as 15 Euro cents per kilowatt-hour (kWh) for lignite coal in Belgium.

Most studies produce numbers that are much smaller for the United States than for Europe. For example, Krupnick and Burtraw (1996) compare estimates of the external costs of electricity generation for the United States and Europe in various studies. Their review suggests that the health impacts of the introduction of new fossil fuel capacity for power generation in the United States are small, perhaps because of the high emissions standards enforced on new plants. Because there is a cap on total SO_2 emissions in the United States, it is reasonable to assume that any new fossil capacity has zero marginal impact on total SO_2 emissions. In this sense it is not surprising that the marginal external cost in the United States is low, and lower than in Europe.

The external costs associated with greenhouse gases are not affected by these arguments. As I noted above, a ton of coal produces between 1.5 and 3.5 tons of CO_2, at a social cost that could be almost $300 (using the Stern figure), between three and six times the (private) cost of the coal. If incorporated into the power station's cost base, this is sufficient to raise the lcoe from around 6 cents per kWh to as high as 11 cents per kWh. By comparison, the external health costs, at least in the United States, are less than 1 cent per kWh. So, for the remainder of this article, I will focus only on the external costs associated with climate change.

Private Costs

So the external costs of renewables are less than those of fossil fuels by as much as 5 cents/kWh. What about the private costs of renewables? Is investing in renewables an attractive proposition? This depends on four parameters—the costs of oil and other fossil fuels (they tend to move together), the cost of carbon emissions or equivalently the extent to which external costs are internalized, the cost of capital, and the incentives available to producers of green electricity (another dimension of the internalization of external costs). Investing in a long-lived renewable power station is making a bet on the future values of these parameters—indeed, investing in any power station is making such a bet. Oil prices are volatile: after a long period of trading down in real terms until the 1970s, they now appear to be trending up, though with a great variance. This volatility seems natural given that both supply and demand are remarkably inelastic with respect to price,[2] and demand is sensitive to income. Income fluctuations lead to demand changes and a new equilibrium requires a large movement in the price. High oil prices were one of the factors driving investment in renewables in 2007 and 2008, and the decline in oil prices in late 2008 and 2009 has been widely cited as a factor contributing to the rapid decline in investments in renewables. As Hoel (2009) notes, oil prices are exogenous, so a transfer of demand to renewables may reduce oil prices.

The role of carbon prices in investments in renewables is obvious: we have seen how a price on carbon emissions can transform the cost of electricity from coal and make renewables

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[2] See Sweeney (1984) and Graham and Glaister (2002).

competitive. The expectation of a price on carbon emissions seems to have contributed to a sharp drop in investment in coal-fired power plants in the United States in the last five years.

That the cost of capital matters to the economics of renewables is also clear, given that the costs of renewables are almost entirely capital costs, and that their capital costs per megawatt of capacity are often higher than those of fossil power. Likewise, the importance of fiscal incentives for investment in renewables should not surprise an audience of economists. In this context a striking fact is that Germany has the highest market penetration of solar power in the world, but fewer hours of sunlight than many other countries. However, Germany also offers remarkably generous feed-in tariffs for solar power,[3] resulting from a government decision to make Germany the leading producer of solar equipment.[4] In the United States, the on-again, off-again policies on investment tax credits have had a clear impact on investment in renewables.[5]

Currently two of the four parameters that determine the attractiveness of renewables in terms of private costs are unfavorable to renewables in the United States: the price of carbon is zero, and capital is scarce. Only the regulatory regime is clearly favorable, and that has been the case only since the passage of the stimulus bill, with more positive moves promised for the budget. Oil prices, having been low, are now on their way up again, a positive for the economics of renewables. The carbon price is not expected to be zero for long, though there is considerable uncertainty about how far Congress will move on pricing carbon. This uncertainty is a major risk factor for any potential investor in electric power. A big question is whether the positive features of the regulatory regime more than offset the uncertainties about the price of carbon and the recent low costs of fossil fuels. On this latter point, it seems reasonable to expect that once the current crisis is over and the world economy resumes something approximating its previous growth patterns, the price of oil and other fossil fuels will jump up again.

Although the regulatory regime in the United States is currently favorable to renewables, it is unnecessarily complex. In order to use production tax credits (PTCs), a wind energy producer must have federal tax liabilities. But most start-up companies in the renewable area don't, so this concession is of no value to them. Furthermore, only the owner of the facility can claim these tax credits. So what operators have typically done is to bring in an investor who can use tax credits and set up the production facility as a limited partnership, with both investor and managers as partners. This arrangement gives the investor access to the tax benefits and allows the manager to continue to have a controlling stake in the operation. The recent massive drop in the incomes of financial institutions has greatly depleted the pool of investors interested in tax credits: the bottom line here is that direct subsidies are far more valuable in a start-up context than tax credits.

The Potential for Renewables to Penetrate the Market

Many of the most visible renewables have characteristics that limit the extent to which they can penetrate the market for electric power. To state the obvious, solar produces power if

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[3] That is to say, utilities in Germany are forced to purchase solar electricity at highly favorable prices.

[4] As of September 2009, press reports suggest that it has been overtaken by China.

[5] For a more detailed analysis, see Barradale (2008).

the sun shines and wind produces if the wind blows. This imposes a cost on utilities that use renewable power: they need backup capacity for when the sun doesn't shine or the wind doesn't blow. To date, this intermittency of solar and wind power has not been a major disadvantage for renewables because it has been more than offset by the premium placed on green power via the RPS requirements of many states, most of which are not yet satisfied. For investors, intermittency is reflected in wind and solar plants' low "capacity factors," which are measures of the actual power output as a fraction of the amount that could be produced if the plant were to operate at its rated maximum capacity 24/7. This is generally in the region of 25–35 percent, a sharp contrast to capacity factors in excess of 90 percent for geothermal or coal plants. The intermittency and resulting low capacity factors for wind and solar limits the markets in which they can compete, and of course raises the lcoe.

Electricity markets, post-deregulation, are complex. Let's take New York State as an example, where there are three markets: installed capacity markets, spinning reserve markets, and spot or dispatch markets. Electricity suppliers in New York face a demand that shows strong daily and seasonal peaking, peaking seasonally in the summer as a result of air-conditioning cooling demand, and daily in later afternoon and early evening when both residential and commercial users are active. Base load is the level below which demand never falls. This is the sales level of which the grid can always be confident. This power is supplied through long-term contracts at relatively low prices, and comes largely from big coal, nuclear, and hydro plants. As demand rises above the base load levels in the morning, more plants are brought online, some coal, diesel, natural gas, and renewable. The grid managers don't know how much power will be needed on any given day, and so are willing to pay for capacity to be available to call on if it is needed, something arranged through the installed capacity market. Here the grid operator in effect buys a call option from the power producers.

In the spinning reserve market, the grid operator pays a power producer to start and run a power station, just in case its output is needed (power stations take time to start up and close down). The last aspect of the market is the "spot market," which in the case of New York is a day-ahead auction market. The system operator asks for bids for power at various times the following day, and power producers bid in response. Intermittent renewables sell in this day-ahead market only, as they cannot offer service as base load generators nor commit well ahead of a given date to have power available at that time. The spot or day-ahead markets generally have the highest prices, but are buying for only a limited number of hours each day.

In addition to the markets for electricity or for capacity, in states with an RPS there is generally a market in RECs, or renewable energy certificates. Compliance with the RPS is ensured through these RECs, which are tradable certificates proving that 1 kWh of electricity has been generated via a renewable generator. Where there is an RPS, electricity distributors are required at the end of a given year to own sufficient credits to show that a specified share of their total annual power productions is from renewable sources.

If renewables could store power produced when there was no demand for it, then they could overcome some of the disadvantages of intermittency and sell into more markets. Until such storage is possible, there will be a continuing need for coal or nuclear as a source of continuous base load power.

One way of thinking about intermittency is to say that there is a social cost associated with the use of an intermittent power source: this is the cost of constructing capacity to replace the power source when it is not operating, or alternatively the cost of leaving demand unsatisfied at such times. This is not an externality in the classical sense, but it emphasizes the fact that there is a system-wide cost linked to the use of intermittent power sources.

Economic Characteristics and Potential of the Major Renewable Energy Technologies

Having provided some background on the economic factors relevant to renewable energy in general, I turn now to a more detailed examination of the technical and economic characteristics, relative cost competitiveness, and potential role of each of the main renewable energy technologies.

Wind

Wind is currently the most widely used renewable energy source, and one of the closest to being competitive with coal. It faces two difficulties in competing—intermittency and location, in that many sites with strong and regular winds are hundreds if not thousands of miles from where electric power is needed. So the deployment of wind requires investment in grid capacity. The best wind power sites in the United States are mainly in the center of the country. It has been widely stated that wind energy harvested from the Great Plains (Texas, Kansas, North Dakota) and domestic offshore sites could generate enough electricity to power the entire United States, though I have not found a peer-reviewed source for this. However, I have found two sources that contradict this statement (MacKay 2009 p. 234; Elliot et al. 1991).[6]

Offshore winds are stronger (power generation goes up with the cube of wind speed) and more regular, and offshore power stations can be built much nearer to demand centers. This higher power output and the reduced transmission costs and larger capacity factors can to some degree offset the greater capital costs of offshore plants ($4000 per kilowatt for offshore versus around $2000 per kilowatt for onshore). For comparison, coal capital costs are in the range of $1700–1900 per kilowatt, with some recent constructions even costing $2500 per kW, up very substantially from just a few years ago.[7] Lack of environmental objections may also make it possible to build wind turbines with larger rotors offshore. Since power output is proportional to the area swept by the rotor blades, which of course goes up with the square of the diameter, bigger and faster is definitely much better for wind turbines.

Where does this discussion leave wind in terms of its ability to compete in spot and day-ahead markets? The lcoe for on-shore wind is in the range of 8–10 cents/kWh; coal, with no charge for carbon emissions, is currently less than 7 cents/kWh, but carbon pricing will quickly bring coal above the cost of wind.[8] Natural gas and diesel are more expensive than coal, and are also sensitive to carbon prices, though less so than coal because they

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[6] See also http://www.awea.org/faq/wwt_potential.html.

[7] https://origin-www.glgroup.com/News/An-Update-on-Costs-for-New-Coal-Power-Plants-9783.html. Note that this estimate does not include the cost of carbon capture and storage (CCS). CCS is described in detail below.

[8] These figures reflect incentives and subsidies as of the end of 2008.

produce less CO_2 per unit of energy. There is a lot of debate about the costs of nuclear, with the most optimistic estimates in the range of 8–10 cents per kWh. It is worth noting that nuclear is notorious for its massive cost overruns. So onshore wind could be competitive in a carbon-constrained environment—at least when the wind is blowing! However, this analysis omits the cost of transmitting wind-generated electricity to customers, which could require significant investments.[9]

Solar

Solar is another high-profile renewable, and again there is no question about the abundance of solar energy striking the earth, or more specifically, the United States. According to a recent article published in *Scientific American* (Zweibel, Mason, and Fthenakis 2007), “The energy in sunlight striking the earth for 40 minutes is equivalent to global energy consumption for a year. The U.S. is lucky to be endowed with a vast resource; at least 250,000 square miles of land in the Southwest alone are suitable for constructing solar power plants, and that land receives more than 4,500 quadrillion British thermal units (Btu) of solar radiation a year. Converting only 2.5 percent of that radiation into electricity would match the nation’s total energy consumption in 2006.”

Solar power comes in two varieties, photovoltaic (PV) and solar thermal (concentrated solar power or CSP). With solar PV, light falls on photoelectric panels and generates an electric current, while with CSP, sunlight is concentrated by mirrors and used to generate steam to drive a turbine that generates electricity. Solar PV is the more widely known technology, with rooftop solar panels becoming almost ubiquitous in some parts of the world. Yet CSP may actually be nearer to large-scale viability because solar PV is expensive: the lcoe is in the range of 25–30 cents/kWh, and capital costs are about \$7000 per kW.[10] CSP appears to be more competitive: some companies claim to offer power at 11 cents/kWh under the present financial regime, and assert that costs will fall further.

Both forms of solar suffer from the intermittency problem, which reduces their potential for replacing fossil fuels. An interesting paper from the National Renewable Energy Laboratory (Denholm and Margolis 2006) studied the problems posed by intermittency. Figures 1 and 2 show their estimates of the total demand for electricity, solar PV output, and residual demand for nonsolar power in Texas on two summer days (Figure 1) and two spring (March) days (Figure 2). Figure 1 shows that solar power is available during some of the peak demand period in the summer, which helps flatten the demand for nonsolar power.

For the two spring days (Figure 2), when there is no demand for air conditioning, the demand after solar power is used is actually less than the base load power capacity. This poses a problem: base load power stations are normally nuclear or large coal, and their output cannot be varied easily. Therefore, the utility would probably rather reject the solar power than reduce output from its base load stations, meaning that solar power could not be sold

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[9] For example, a recent study for Texas indicated that the costs of connecting wind farms in the panhandle to major cities would be in the range of \$1.8–2.07 million per mile. See http://www.ercot.com/news/press_releases/2008/nr04-02-08.

[10] However, with current federal and state subsidies, the lcoe in California can be as low as 11 cents/kWh. During 2009 the cost of solar modules has halved, indicating a drop in solar lcoes on new solar PV installations.

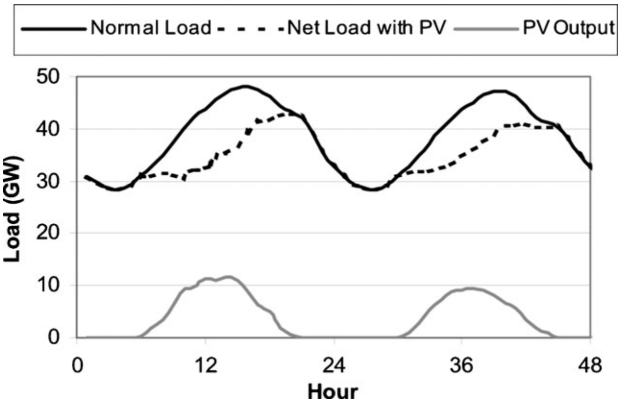

Figure 1 System load with and without a large (16 GW) PV system on two summer days.
Source: Denholm and Margolis (2006).

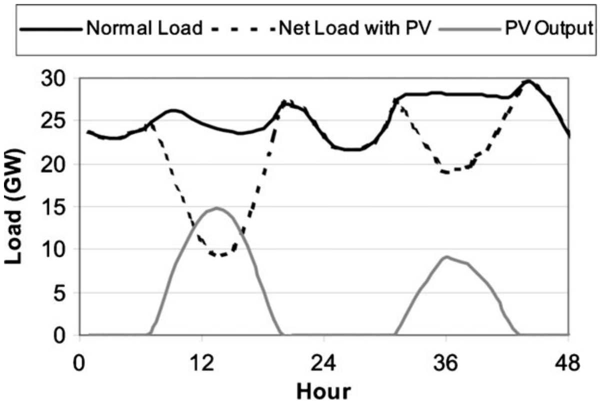

Figure 2 System load with and without a large (16 GW) PV system on two spring days.
Source: Denholm and Margolis (2006).

even if it were produced. Of course, as the marginal cost of the solar PV is zero it would be rational to store it in some way, for example by using it to hydrolyze water and then store the resulting hydrogen for use in fuel cells. The same is true for wind power. But to date this has not been done, which further reduces the economic attractiveness of intermittent power sources.

Solar thermal (or CSP) not only beats solar PV in cost terms, it also has the potential to store power, thus reducing the intermittency problem. CSP can be used to heat sodium chloride above its melting point, with the resulting heat being passed through heat exchangers to turbines. Liquid sodium chloride will keep most of its heat for up to seven hours, so that a CSP power station using this technology could provide power for at least seven hours after sunset, which would certainly cover the evening peak demand period. Implementing such a power storage program would raise the lcoe to about 15 cents/kWh, still above coal even with likely prices for carbon emissions, but close enough to have a real chance of becoming competitive soon. A solar thermal power plant that has been proposed near Sacramento, California, would have molten salt storage supplemented by 3,000 acres of adjacent land growing eucalyptus, which could be cut and burned to drive the turbine as an additional complement to the solar power. This would give the Sacramento plant even more capacity to operate when there is not bright sunlight. Moreover, growing and then burning wood is carbon neutral.

Although solar PV is not currently cost-competitive for grid connection, it is in many distributed applications. Where there is no grid, it is less expensive to install a series of small solar PV stations than to build one large coal station and a grid. And solar PV can be used at the level of the individual building, as demonstrated by California's drive to install solar panels on millions of rooftops. As part of this program, a company called SunEdison has pioneered deals with retail store chains (e.g., Staples, Whole Foods, and Walmart) through which it leases the roof space on stores, installs solar panels, and then sells the power to the store and its neighbors, and in some cases to the grid. Such deals do not primarily supply electric power to the grid, but they meet demand that would otherwise have fallen on the grid, and so effectively increase the capacity of the existing power stations.

Geothermal

Like solar, in principle, geothermal power sources have the capacity to meet all of the power needs of the United States. According to a recent study by the Massachusetts Institute of Technology (2006), just 2 percent of the geothermal heat located in the continental United States at depths between 3 km and 10 km is equivalent to more than 2,500 times the country's total annual energy use. Unlike wind and solar, geothermal does not suffer from an intermittency problem, though there is a problem of geographical distribution. Geothermal energy comes in a variety of forms: Dry Steam, Flash Steam, Binary, Enhanced Geothermal Systems (EGS), and Geoexchange. The key characteristics, common to all, are that they exploit the fact that the temperature of the earth increases as we move down toward its center, and that the temperature below the earth's surface is constant in the face of seasonal variations. Thus heat can be extracted from the earth by circulating water downward to warm it up. Somewhat paradoxically, this same fact can also be used to cool when needed. No fuel is needed, except a minor amount of electric power to pump water, so we again have a capital-intensive operation. Environmentally, geothermal gets high marks—no emissions of any sort, though there can be some disruption through the siting of the plant. The most familiar examples of geothermal energy are those that occur in seismically active countries such as Iceland, which derives most of its energy from geothermal sources, in fact from hot rocks very near the earth's surface. The Philippines derives about 20 percent of its energy from geothermal sources, and in the United States, California takes advantage of its seismic activity to derive 750 MW from geothermal sources.

Dry Steam, Flash Steam, and Binary geothermal systems require hot porous rocks in which water is naturally present and is superheated (raised above its boiling point but kept liquid by pressure). These systems exploit this naturally occurring steam to drive turbines, and are referred to as hydrothermal energy systems. Hot porous rocks containing water occur mainly in seismically active areas, and all commercially operating geothermal power plants use one of these three designs.[11] Although these three established technologies are restricted to seismically active areas, EGS is not. EGS is a way of extracting energy from hot underground

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[11] For details of these technologies, see http://www1.eere.energy.gov/geothermal/geothermal_basics.html.

rocks wherever they occur, independent of the availability of reservoirs of superheated water. The principle is to drill into hot dry rocks and then fracture them by pumping cold water at high pressure. The fractures form a reservoir in the rocks where water is heated, and hot water is extracted from this through another hole. Although simple in principle, this has proven challenging in practice, as it requires drilling through several miles of hard rocks.[12] In the meantime, hydrothermal energy is very competitive and profitable wherever it occurs, costing as little as 3.5 cents/kWh. Of course it can provide base load power, as it operates 24 × 7. Moreover, as mentioned above, it is environmentally benign and thus immune to CO_2 pricing.[13]

Geoexchange (or ground source heat exchange) refers to the use of heat pumps that capture shallow ground energy to heat and cool buildings. The top ten feet of the earth is at a nearly constant temperature of between 10 and 16°C (50–60°F). In winter, heat from the relatively warmer ground goes through the heat exchanger into the house. In summer, hot air from the house is pulled through the heat exchanger into the relatively cooler ground. Heat removed during the summer can be used as no-cost energy to heat water. Such systems are very inexpensive to operate, needing power only to pump liquids into the ground and back up. They are more expensive to install than conventional HVAC systems, but have a payback period of two to seven years. The payback period will almost certainly shorten if carbon emissions are priced. This technology is available and in use today, so in principle there is no reason why the great majority of new buildings in the United States should not be heated and cooled in a completely carbon-free way and with zero marginal cost.[14] It is striking how little awareness and appreciation there is of this technology.[15]

Energy from Water

There are three renewable technologies associated with water—hydropower and wave and tidal energy. Hydropower currently provides about 6 percent of U.S. electrical power, and of course generates no emissions of any sort. It was once considered environmentally benign, though today we are more aware of its consequences for riverine ecosystems. It is unlikely that more hydropower will be built in the United States. Indeed, the trend is in the opposite direction, with some dams being removed to protect endangered fish species. Wave power systems seek to use the kinetic energy in wave movements to generate electric power. While there is a great deal of research on this technology, there are as yet no commercial applications,

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[12] See http://apps1.eere.energy.gov/news/archive.cfm/pubDate=%7Bd%20%272006-07-06%27%7D?printfull for an illustration of some of the problems encountered in Australia.

[13] A recent MIT study (2006) suggests that, within two decades, EGS energy could be extracted for 5–10 cents/kWh in the United States, and that by 2050 a total of 100,000 megawatts of electricity could be derived from this source, about 10 percent of U.S. installed capacity. However, currently there are no EGS power plants operating commercially, and some commentators suggest that the extraction of heat would cool the rocks enough that over a decade or so they would become unusable and the drill holes would need to be moved to a new site. A report in the *New York Times* recently (June 24, 2009) suggested that EGS drilling has produced earthquakes around the sites where it is carried out.

[14] This is a technology that does not generate electric power, but rather reduces demand for electricity in heating and cooling.

[15] This is consistent with widespread findings that consumers are reluctant to pay for energy efficiency even when it offers a high rate of return: see Brown (2001), Hausman (1979), Jaffe et al. (1999), Levine et al. (1995), Muthulingam et al. (2009).

though several are currently being constructed, in northern California for PG&E and in Scotland. Indications are that the costs will be substantially above current market rates, though there is a chance that they will fall with experience. Tidal power also seeks to harness moving water, though in a more straightforward way: turbines, like small windmills, are placed in tidal flows and rotate as water passes over them, generating electricity. This technology is also in the experimental stage: there is a small tidal power plant operating in New York, in the East River between Roosevelt Island and Queens, and some small plants are operating in the United Kingdom. Costs are high, but again the expectation is that they will fall.

Making Dirty Energy Cleaner

Carbon capture and storage (CCS) is not a form of clean energy, but rather a way of making dirty energy cleaner. It offers a way of moving to "cleaner coal." There are several ways of preventing a coal-fired power station from emitting CO_2. One is to scrub the CO_2 out of the exhaust gases, using a technology that is very similar to the one for scrubbing SO_2. An alternative is to break the hydrocarbon molecules in coal into carbon, hydrogen, and oxygen before the coal is burned, remove the carbon, and burn the hydrogen. A final option is to remove all nitrogen from the air used to burn the coal, so that it is in effect burned in pure oxygen, giving an exhaust stream of pure CO_2. In this case the CO_2 does not have to be separated out and the entire exhaust stream is liquefied and stored.

All of these processes are based on well-understood and widely used chemical reactions and pose no technical difficulties. Likewise, liquefying and storing the CO_2 is straightforward. The only complication is finding somewhere to store it for a very long time without leaking. The preferred location is an exhausted oil or gas field, which held gas under pressure for many millions of years and can presumably hold CO_2 for a similar period. In many geological formations, the CO_2 will actually react with rocks to form solid carbonates, immobilizing it in perpetuity. Estimates by geologists suggest that decades or even centuries of CO_2 emissions could be safely stored underground, though not always near the power plants (IPCC 2006). In this case, the emissions would have to be transported through a pipeline, adding to the cost of CCS (IPCC 2006). Eventually, the capacity to store CO_2 underground will be exhausted, making it an exhaustible resource with a shadow price that should follow a Hotelling-type rule (see Narita 2009).

The biggest unknown about CCS is not its viability, which seems clear, but its cost. With no commercial-scale CCS plants in operation, we have only engineering estimates, which suggest a cost at present in the range of \$50–100 per ton of CO_2 (see IPCC 2005; IEA 2006). This cost is too high to be commercially attractive, as it would be more profitable to pay the likely price of carbon emission permits. However, it is likely that, with scale and experience, the cost of CCS will fall, to the range of \$30–60 per ton (IEA 2006; Stern 2006), and that the price of carbon will rise, so there is a reasonable chance of their paths crossing before too long. Moreover, retrofitting existing plants is more expensive than adding CCS to a new plant, with the added disadvantage that the older the plant, the smaller the number of years of output over which one can spread the extra cost.

Air capture is a variant on CCS: rather than extracting CO_2 from the exhaust gases of a power station, it is taken directly out of the atmosphere. If CO_2 can be extracted from the atmosphere at reasonable cost, it doesn't matter where this is done, as CO_2 mixes globally within a year of its emission. So it would be reasonable to extract it where it can be stored (i.e., on top of suitable geological formations), thus avoiding the costs of transporting the gas (see Lackner and Sachs 2005). Currently, only prototype air capture devices are in operation, removing CO_2 from the air at a cost of about $200 per ton. But there are hopes that technological improvements and large-scale manufacturing of the devices will bring costs down to the range of $50–100 per ton of CO_2.

Biofuels

Biofuels are not envisaged as a source of electric power but rather as replacements for gasoline, diesel fuel, and jet fuel. To date, American experience with biofuels has been unfortunate: corn-based ethanol has been seen more as an excuse for agricultural subsidies than as a power source (see Hahn and Cecot [forthcoming]). But in Brazil, ethanol from sugar, not corn, provides almost half of all gasoline consumed.[16] Sugar is a more efficient feedstock, and sugar-based ethanol is competitive with gasoline at oil prices of $50–60 per barrel and is environmentally safe, in the sense of having a zero carbon footprint over its life cycle and producing no other pollutants. Both India and China are developing bioethanol programs based on sugar. Land availability does not appear to be an issue: Brazil, for example, produces enough bioethanol to meet half its gasoline needs from only 1 percent of its arable land, using land in the southeast of the country, far from the Amazon, whose climate is unsuitable for sugar.

Biodiesel is produced from vegetable oils using a relatively simple process, and is a perfect substitute for conventional diesel as far as a diesel engine is concerned. Environmentally, it is preferable to conventional diesel as it is carbon neutral and produces fewer other emissions than conventional diesel. But growing the crops to produce vegetable oils as feedstock requires land, enough to be a constraint. For biodiesel to become a major component in vehicle fuels it will be necessary to develop new technologies, such as the algal farms now being tested. Certain species of algae remove CO_2 from the air and produce biomass from which diesel oil can be extracted, offering a chance of providing vehicle fuel that can be used in current diesel engines and is carbon neutral. Currently this process is far too expensive to be commercial, but it is attracting a lot of venture capital.

Investing in Renewables: The Scale and Cost

In an interesting study, MacKay (2009) asks whether the United Kingdom could meet all of its energy needs from renewable sources, strictly from the perspective of physical principles and not worrying at all about costs. His conclusion is negative: even covering much of the countryside and coastline with wind turbines, placing wave energy devices along many hundreds of miles of coast, covering most south-facing roofs with solar panels, and exploiting every hydro opportunity, there would not be sufficient power to meet current U.K. needs. He suggests three ways of filling the gap: either coal with CCS, nuclear, or the import of

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[16] Bioethanol can be burned in gasoline engines with no mechanical alteration if mixed with gasoline and forming less than 10 percent of the total mix. Otherwise the fuel injection system needs to be modified, though only in a minor way. Many new cars in Brazil have this modification and can run on any mix of gasoline and ethanol.

renewable energy from solar plants in the Sahara by long-distance direct-current high-tension lines.

The United States is better placed to use renewables. In principle, solar energy alone could meet its energy needs, in the sense of producing the number of kilowatt-hours over a year that is equal to present annual energy consumption. It would take an area of about 140,000 square miles covered with solar collectors to do this. To put this in perspective, the area of California is about 160,000 square miles. But this calculation does not address the intermittency problem. In his study of the United Kingdom, MacKay (2009) assumes that the intermittency problem is overcome by the large-scale application of pump storage technologies. However, it is not clear that there are sufficient pump storage sites in the United States to make this feasible, leading to the conclusion that to address the intermittency issue, renewables would have to be supplemented by fossil fuels or nuclear.

I began this "Reflections" with DOE's aim of obtaining 25 percent of U.S. electricity from renewables by 2025. What would this cost? I'll try to answer an easier question: supposing that electricity consumption stays constant from now to 2025 (actually it will grow, quite a lot, if we move to electric cars), what would it cost to replace 25 percent of U.S. generating capacity with renewables? Here's a rough estimate. Installed electric capacity is one million megawatts (or one thousand gigawatts, or one terawatt). Wind capacity costs about \$2000 per kilowatt to install, excluding the costs of connection to the grid. One terawatt is 10^9 kilowatts, so the investment required if we were to use wind to replace 25 percent of U.S. generating capacity is $10^9 \times 2 \times 10^3 \times 0.25/0.25$, where $10^9 \times 2 \times 10^3$ is the cost of replacing all capacity by wind. We multiply by 0.25 as we are replacing 25 percent, and divide by the capacity factor of wind, which I am assuming to be 25 percent. So the answer for wind is two trillion dollars, almost certainly an underestimate as we are leaving out the cost of grid connections and using the capital cost of onshore wind (both offshore wind and solar are more expensive). This is about 15 percent of current U.S. GDP, and over 15 years it is roughly 1 percent of current GDP annually. In addition to being an underestimate, this calculation does not address our dependence on foreign oil for transportation or furnaces. It would reduce fossil-generated electricity from about 70 percent to about 45 percent of the total.[17]

How much CO_2 would this save? The answer depends on what the wind power displaces. If it displaces coal, then the savings is about one billion tons of CO_2 annually,[18] or about one-seventh of total U.S. emissions (7.28 billion tons in 2007, according to the EIA [http://www.eia.doe.gov/oiaf/1605/ggrpt/index.html]). Unfortunately, wind is unlikely to displace only, or even largely, coal, because the intermittency issue means wind will not be used for base load power, which comes mainly from coal and nuclear. Rather the wind power will displace the load-following power stations that use oil and natural gas, plus some small coal stations. As oil and gas are cleaner than coal, the net savings would be less than if only coal were displaced.

[17] For data on the composition of electric power station fuels, see http://www.eia.doe.gov/cneaf/electricity/epm/epm_sum.html.

[18] Here is the calculation. In 2008, the United States used about 10^9 tons of coal in generating electricity (http://www.eia.doe.gov/cneaf/electricity/epm/tablees1a.html). This produced 50 percent of its electricity, so using wind for 25 percent of electric power and displacing coal would reduce coal use by 0.5×10^9 tons, and at 2 tons of CO_2 per ton of coal this saves 10^9 tons of CO_2. Note that 2 tons of CO_2/ton of coal is a conservative number.

Thus, until we have effective storage technologies, substantial reductions in base load coal emissions of CO_2 can only come from increased use of nuclear or the introduction of CCS.[19] Note that once we have made the upfront investment of around $2 trillion, the running costs of the renewable power plants would be close to zero, certainly far less than the fuel costs of the fossil fuel plants they would replace. Taking this into account, the lifetime costs per kWh of the renewable energy plants would not be greatly in excess of the costs of fossil fuel plants if these plants are charged for the emission of CO_2 at anything close to the upper range of estimates of its social costs.

The bottom line here is that renewable energy sources do have great potential to displace fossil fuels, but there are technical problems that have to be overcome before this potential can be fully realized. The biggest issue is storage or some other way of allowing renewables to play a role in the generation of base load electric power, which now comes mainly from coal and is the principal source of greenhouse gases and other pollutants in energy production. Without a steady, reliable, and predictable flow, renewables will be confined to the market for load-following power, where they will make a smaller contribution to both reducing greenhouse gases and meeting our energy needs.

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[19] For risks of nuclear power, see Heal and Kunreuther (2009).

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