NBER WORKING PAPER SERIES

THE ECONOMICS OF RENEWABLE ENERGY

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Working Paper 15081
http://www.nber.org/papers/w15081

NATIONAL BUREAU OF ECONOMIC RESEARCH
1050 Massachusetts Avenue
Cambridge, MA 02138
June 2009

I am grateful to Columbia Business School students in my course "Current Developments in Energy Markets" for discussions of the material in this paper. The views expressed herein are those of the author(s) and do not necessarily reflect the views of the National Bureau of Economic Research.

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JEL No. Q3,Q4,Q5

ABSTRACT

Greater use of renewable energy is seen as a key component of any move to combat climate change, and is being aggressively promoted as such by the new U.S. administration and by other governments. Yet there is little economic analysis of renewable energy. This paper surveys what is written and adds to it. The conclusion is that the main renewables face a major problem because of their intermittency (the wind doesn't always blow nor the sun always shine) and that this has not been adequately factored into discussions of their potential. Without new storage technologies that can overcome this intermittency, much of the decarbonization of the economy will have to come from nuclear, carbon capture and storage (CCS) and energy efficiency (geothermal and biofuels can make small contributions). Nuclear and CCS are not without their problems. New energy storage technologies could greatly increase the role of renewables, but none are currently in sight.

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Renewable energy is the *energy du jour*. 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." In keeping with this theme, he has allocated substantial subsidies to renewables while asserting that the United States will obtain a significant portion of its energy from renewables within one or two decades. According to the Department of Energy 10% of our electricity should come from renewables by 2012 and 25% by 2025,[2] aims supported by the Renewable Portfolio Standards of 28 states requiring between 15 and 20% of all electricity to be from renewables by 2020 to 2030. There is even talk of a Federal RPS, mandating similar goals at the national level. For those with an 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), hydro power (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. In the interim our population has increased by a factor of ten and economic activity by several orders of magnitude.

One might think that these heroic goals would be based on a detailed analysis of the prospects for a rollout of renewable energy, with a comprehensive literature on the economics of renewable energy. Sadly this is not the case: there is a literature, and there are some notable contributions, but nothing remotely in keeping with the emphasis on renewables in policy circles. So this paper is both a reflection on the literature we have and a call for a literature that we don't yet have.

The first discussion of renewables in economics was in the post-73 oil shock era, when we rediscovered Hotelling's work on resource depletion and refined it in various ways. 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

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

analysis (Dasgupta and Heal, 1973), William Nordhaus worked with this idea in his book on the efficient allocation of energy resources (Nordhaus 1973), in which he tried to work out the competitive price of oil, and so did many others – a quick search for "backstop technology" on Google Scholar produced 8,540 references. No one modeled the backstop explicitly, but it was clearly not a fossil fuel that we had in mind: it could have been nuclear fusion, or solar or wind energy. The only economic role it played was in setting an upper limit to the price of fossil energy, an endpoint for the price path of an exhaustible resource.

The need for renewables, in the sense of energy from non-exhaustible sources having 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. Kenneth Boulding's work on *The Economics of the Coming Spaceship Earth* (Boulding 1966) and Ralph D'Arge and Kiichiro Kogiku's paper on *Economic Growth and the Environment* (D'Arge and Kogiku 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.

The need to act on climate change, coupled with the realization that there are no silver bullets like nuclear fusion, has forced policy makers to grapple with the merits of alternative energy and consider the consequences of moving to carbon-free energy within a few decades. Of course, carbon-free is not the same as renewable: nuclear is carbon-free, but probably not what most people have in mind as renewable, and coal with carbon capture and storage (CCS) is also carbon-free at the output level, and again not what most environmental groups think of as renewable. It does seem uncontroversial that at least one of nuclear, coal with CCS and renewables has to be adopted on a very large scale for a sustainable future, and I will argue below that either nuclear or coal with CCS must be in the mix as well as many types of renewables, at least for the foreseeable future.

Renewables come in many different flavors: they certainly include but may not be limited to hydro, solar (photovoltaic and thermal), wind, geothermal, tidal, biofuels, and waste-to-energy processes. I will focus mainly on those that can be used to generate electricity, or to replace it. Most of them 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). Their only ongoing costs are maintenance and operation, plus some energy input in the case of waste-to-energy. 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 fifteen to thirty or more thousand tons of CO_2 daily. This gives some insight into the sensitivity of coal's competitive position to the price of carbon: a price in range of $30 per ton 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 implication. If we build a wind (or other renewable) power station today, we are providing free electricity to its users for the next forty years: if we build a coal-fired power station today, we are meeting the capital costs but leaving our successors over its forty year life to meet the large fuel costs and the external costs associated with its pollution. When we build a renewable power station we are effectively pre-paying for the next forty years of electricity from it. This has implications for what kind of financing might be appropriate – in particular it makes long-term debt financing seem fair.

There are two questions that policy-makers need answered: is renewable energy more expensive than fossil energy, and can it be made available on a large enough scale to replace much of our fossil fuels use? Neither is easy to answer.

You can see one difficulty in assessing the cost of renewable energy – the average cost depends on the scale, and 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 in this business is the levelized cost of electricity, lcoe. This 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 that it operates at full capacity. This is usually presented in terms of private costs, but from a policy perspective we need the lscoe, the levelized social cost of electricity, with external costs included. We clearly have reasons to think that the external costs of renewables are less than those of fossil fuels, particularly with respect to emissions of greenhouse gases, but data on this is rather thin.

What for example is the social cost of using a fossil fuel? In any comparison of the costs of renewable and fossil sources of electricity, this is a key fact. 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 Emission Trading Market, which have varied between $13 and $25 a ton of CO2 over the last year and a half. But the EU system has many idiosyncrasies and it is not clear that this should be a definitive estimate of a social cost. Ideally we want a forward-looking estimate, an estimate of the social cost of a ton of CO2 emitted today over the course of its residence in the atmosphere, which could be as long as the next century. 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 estimates of the social costs of CO2 emissions, though there is little agreement here. Nordhaus has an estimate of the social cost of CO2 emissions that is about $8 per ton: Stern's estimate is an order of magnitude greater at $85. There are many reasons for the difference but a main one is that Nordhaus uses a pure rate of time preference (utility discount rate) of 4% while Stern uses 0.1%: over periods of a century or more this is a massive difference. Stern also has a more comprehensive and up-to-date estimate of the costs of climate change, and allows for uncertainty and a wide range of possible outcomes along a business as usual scenario. But the bulk of the difference is in the discount rates (see Hope and Newberry 2007). As I have said elsewhere (Heal 2009), I see Stern as clearly closer to being correct in this debate, and take his estimate of the social cost of CO2 as likely to be nearer to a true estimate. But 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 CO2 emission, a recent study by Jon Strand (Strand 2008) of the IMF is interesting: it calculates the prices of CO2 implied by various policy measures to reduce emissions, finding that this 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: these include other gaseous emissions such as SO2 and various oxides of nitrogen and fine particles, all of which are associated with environmental damage, poor health and early death. The costs of these emissions have been studied by researchers at Resources for the Future in the context of the social costs of gasoline use, and Parry (2001) and Parry and Small (2005) are good sources. The US EPA and the European Commission also report on their web sites studies of the social costs of electricity production, with some numbers from the European study being reproduced in figure 1 below (European Commission n.d.).

External cost figures for electricity production in the EU for existing technologies[1] (in € cent per kWh*)									
Country	Coal & lignite	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
AT				1-3		2-3	0.1		
BE	4-15			1-2	0.5				
DE	3-6		5-8	1-2	0.2	3		0.6	0.05
DK	4-7			2-3		1			0.1
ES	5-8			1-2		3-5**			0.2
FI	2-4	2-5				1			
FR	7-10		8-11	2-4	0.3	1	1		
GR	5-8		3-5	1		0-0.8	1		0.25
IE	6-8	3-4							
IT			3-6	2-3			0.3		
NL	3-4			1-2	0.7	0.5			
NO				1-2		0.2	0.2		0-0.25
PT	4-7			1-2		1-2	0.03		
SE	2-4					0.3	0-0.7		
UK	4-7		3-5	1-2	0.25	1			0.15

* *sub-total of quantifiable externalities (such as global warming, public health, occupational health, material damage)*
** *biomass co-fired with lignites*

Figure 1

They show a very wide range, from almost zero for renewable sources to as much as 15 Euro Cents per KWH for lignite coal in Belgium. These figures appear to include up to Euro 16 per ton of CO2 emissions, a modest number. Most studies cited in the US result in numbers that are very much smaller indeed: for example Krupnik and Burtraw (1996) review several studies of the external costs of electricity generation, two for the US and one for Europe. Their comparison and evaluation is detailed and clear, but also lengthy and necessarily complex and not susceptible of easy summary. It does however suggest that the health impacts of the introduction of new fossil fuel capacity in power generation in the US are small, perhaps because of the high emissions standards enforced on new plants. Because there is a cap on total SO2 emissions, for example, it is reasonable to assume that any new fossil capacity has zero marginal impact on total SO2 emissions. In this sense it is reasonable that the marginal external cost in the US is low, and lower than in Europe.

The external costs associated with greenhouse gases are not, however, affected by these arguments. As I noted, a ton of coal produces from 1.5 to 3.5 tons of CO_2, with a social cost that could be almost $300 (using the Stern figure), between 3 and 6 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 kilowatt-hour as far as 11 c/kwh. By comparison, the external health costs, at least in the US, are under 1 cent per kwh, so from now on I will focus only on the external costs associated with climate change. (This is leaving out environmental costs associated with producing the fossil fuels, such as the costs of mountaintop removal as practiced in parts of the US: such costs are probably not negligible.) And the external climate costs of all of the renewables I mentioned earlier, together with nuclear, are effectively zero.

So the external costs of renewables are less than those of fossil fuels by as much as 5 c/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. As you must be aware, oil prices are volatile – figure 2 shows their movement since oil was traded commercially. After a long period of trading down in real terms till the 1970s, they now appear to be trending up, though with a great variance. The volatility seems natural given that both supply and demand are remarkably inelastic with respect to price,[3] 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

[3] See Sweeney 1984 and Graham and Glaister 2002.

prices were one of the factors driving investment in renewables in 2007 and 2008, and the drop in late 2008 and 2009 was widely cited as a factor contributing to the rapid drop in this investment. As Michael Hoel (2008) notes, oil prices are exogenous: a transfer of demand to renewables may reduce oil prices.

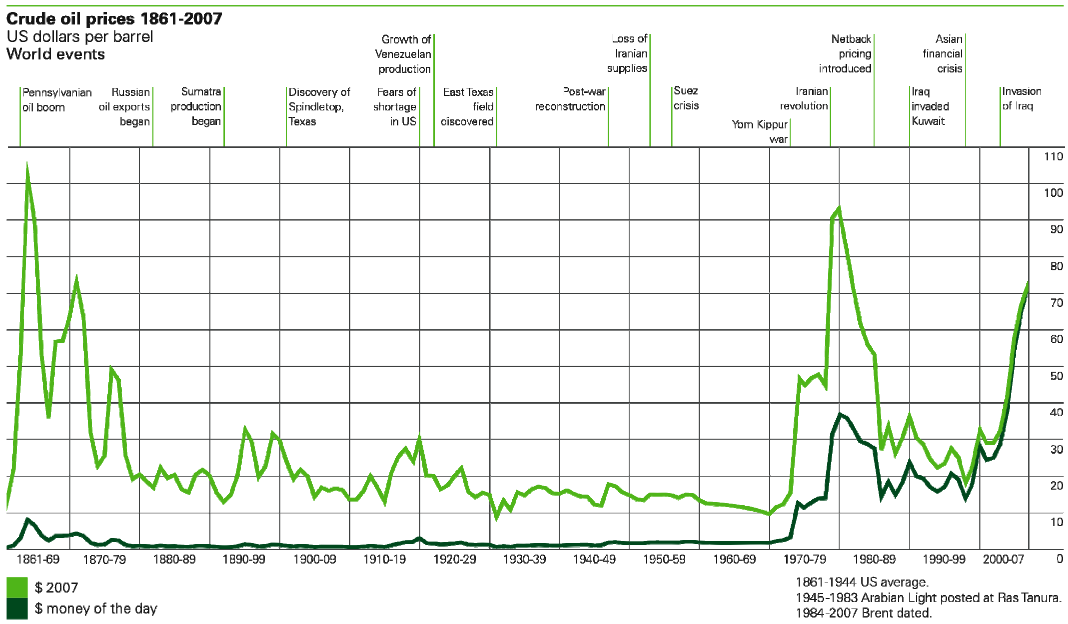

Figure 2[4]

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

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[4] From BP Statistical Review of World Energy at www.bp.com. After the period covered by this graph the price rose to $147 and then fell as low as $35 before stabilizing temporarily at about $50 and then rising again to near $70.

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: it also offers remarkably generous feed-in tariffs for solar power, resulting from a government decision to make Germany the leading power in solar equipment production. In the US the on-again off-again policies on investment tax credits had a clear impact on investment in renewables, as the data in figure 3 show. [5]

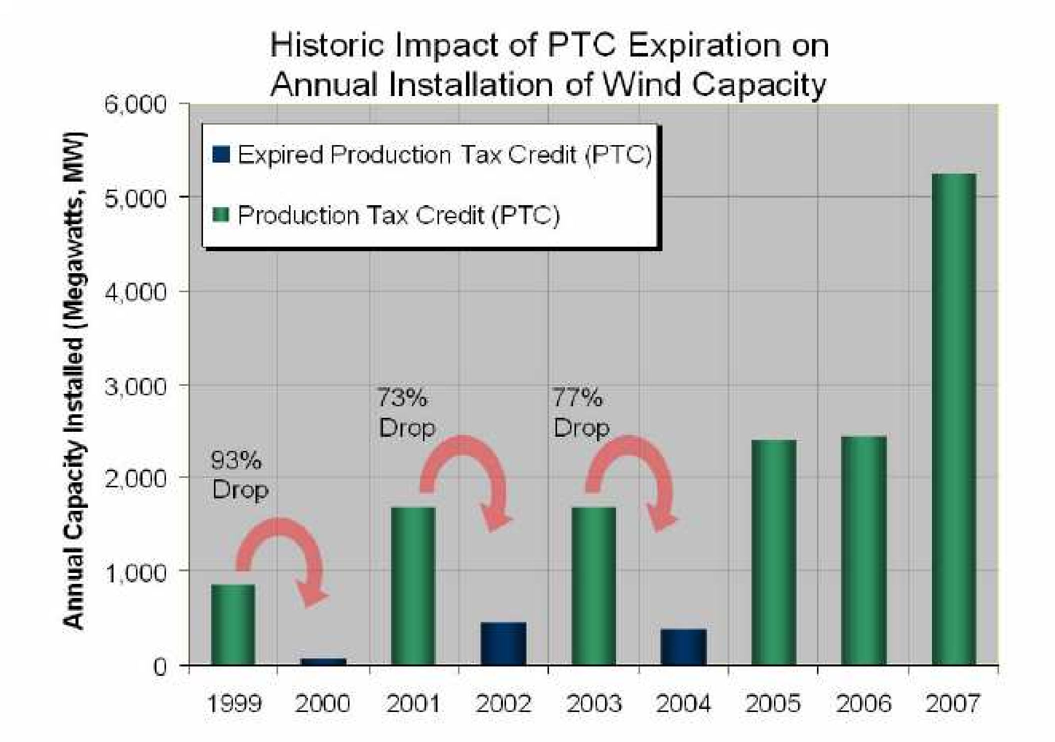

Figure 2

Currently three of these four factors are unfavorable to renewables in the US: the price of oil and other fossil fuels is low, the price of carbon is zero, and capital is scarce. Only the regulatory regime is favorable, and that only since the passage of

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

the stimulus bill, with more positive moves promised for the budget. The carbon price is not expected to be zero for long, though there is considerable uncertainly about how far congress will move on pricing carbon and this is a major risk factor for any potential investor in electric power. A big question is whether the positive aspects of the regulatory regime more than offset the uncertainties about the price of carbon and the 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: as noted, demand and supply are insensitive to prices and demand is responsive to income, so an upswing in demand due to rising incomes may need a big price movement to clear the market.

Although the regulatory regime in the US is currently favorable to renewables, it is complex, unnecessarily and unhelpfully so. To use the production tax credits (PTCs) generated, a wind energy producer has to have federal tax liabilities. 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, set up the production facility as a limited partnership with both investor and managers as partners, giving the investor access to the tax benefits and allowing the manager to continue to have a controlling stake in the operation. The massive drop in incomes of financial institutions recently 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.

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 the sun shines and wind produces if the wind blows. Neither is true all the time, and neither is fully predictable. 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 has not been a major disadvantage for renewables, having 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, this is reflected in the low “capacity factors” of wind and solar plants, 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 15 to 30%, a sharp contrast with capacity factors in excess of 90% for geothermal or coal plants. This intermittency and the resulting low capacity factors limits the markets in which wind and solar can compete, and of course raises the lcoe. Electricity markets post-deregulation are complex: in New York State, as an example, there are three markets, installed capacity markets, spinning reserve markets and spot or dispatch markets. Electricity suppliers face a demand that shows strong daily and seasonal peaking, in New York peaking seasonally in the summer as a result of air-conditioning 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, the sales level of which the grid can always be confident. This power is supplied on long-term contracts at relatively low prices, and comes largely from big coal, nuclear and hydro plants. As demand rises above base load levels in the morning, more plants are brought online, some coal, diesel, and renewable. The grid managers don’t know how much power will be needed on any given day, and so are wiling 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 of day 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 having power available then. The spot or day-ahead markets generally have the highest prices, which is good for renewables, but are buying for only a part of each day.

If renewables could store power produced when there is no demand for it, 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. Coal can in principle be close to carbon-free, so this does not necessarily contradict the goal of massive reductions in GHGs. In addition to these 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, which are tradable certificates proving that 1kWh 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 % of their total annual power productions is from renewable sources.

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 it 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.

Wind is the most widely-used renewable currently, and one of the closest to 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 US are mainly in the center of the country. It is 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 US, though I have not found a peer-reviewed source for this and do have sources for the opposite statement (MacKay

2009 p 234, Elliot et al. 1991)[6]. We will later see statements that solar and geothermal power could meet all the US's energy needs: renewable resources are clearly there, if we can harness them at reasonable costs.

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, so that more power output, reduced transmission costs and larger capacity factors can to some degree offset the greater capital costs - $4000 per kilowatt for offshore vs. around $2000 onshore. For comparison coal capital costs are in the range of $1700 to $1900 per kilowatt, some recent construction even costing $2500 per kw, without CCS, 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, and power output is proportional to the area swept by the rotor blades, which of course goes up with the square of the diameter. So bigger and faster is very much better with 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 region of 8-10 cents/kwh: coal with no charge for carbon emissions is less than 7, but carbon pricing will quickly bring this 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 (less $CO2$ 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 over-runs. So onshore wind could be competitive in a carbon-constrained environment – at least when the wind is blowing! Omitted from this analysis is the cost of transmitting wind-

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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

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

generated electricity from wind sites to customers, which could require significant investments: 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 to $2.07 million per mile.[9]

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 U.S. According to the Scientific American, "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."[10] Solar power comes in two varieties, photovoltaic (PV) and solar thermal or concentrated solar power (CSP). In solar PV light falls on photo-electric panels and generates an electric current, while in CSP sunlight is concentrated by mirrors and used to generate steam and drive a turbine that generates electricity. Solar PV is the more widely known, with solar panels on roofs becoming almost ubiquitous in some parts of the world, yet CSP may actually be nearer to large-scale viability. Solar PV is expensive: the lcoe is in the range 25-30 cents/kwh, and capital costs are about $7000 per kw, although with the current federal and state subsidies the lcoe can be as low as 11cents/kwh in California. Costs have been falling fast for decades and there is a general expectation that solar PV will match coal as a power source somewhere in the period 2015 to 2020, possibly earlier if a significant carbon price is introduced.

Solar thermal or CSP appears to be more competitive: some companies are claiming to offer power at 11 cents/kwh in the present financial regime, and

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[9] http://www.ercot.com/news/press_releases/2008/nr04-02-08

[10] Ken Zweibel, James Mason and Vasilis Fthenakis 2007

asserting 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 (NREL) studied the problems posed by intermittency, and figures 4 and 5 show their estimates of the total demand for electricity, solar PV output and residual demand for non-solar power on two summer days in Texas and two days in March.[11] In the former case, figure 4, solar power is available during some of the peak demand period and helps flatten the demand for non-solar power.

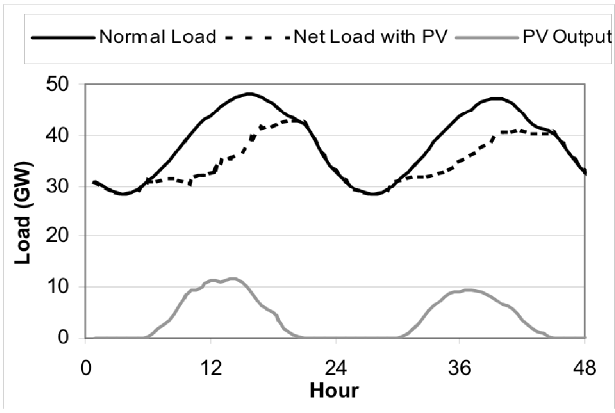

Figure 4: System Load with and without a large (16GW) PV system on two summer days

In the case of spring days, when there is no demand for air conditioning, the demand remaining net of solar power is less than baseload power capacity. This poses a problem: baseload power stations are normally nuclear or large coal, and their output cannot be varied easily. The utility would therefore probably rather reject the solar power rather than reduce output from baseload stations, meaning that solar power cannot be sold even if it is produced. Of course, as its marginal cost 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 of wind power. But to date this has not been done. It further reduces the economic attractiveness of intermittent power sources.

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[11] P. Denholm and R. Margolis, 2006.

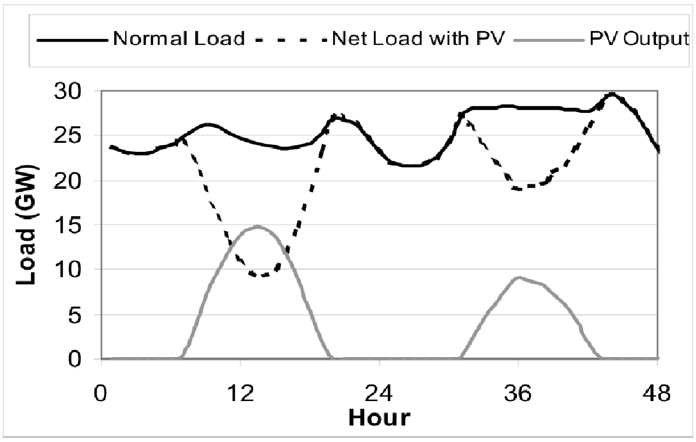

Figure 5: System Load with and without a large (16GW) PV system on two spring days

Solar thermal not only beats solar PV in cost terms, it also has potential for storing power to reduce the intermittency problem. The concentrated solar power can be used to heat sodium chloride above its melting point, with the heat from this being passed through heat exchangers to turbines. Liquid sodium chloride will keep most if 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 this would raise the lcoe to about 15 cents/kwh, 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 currently being proposed near Sacramento, California, would have molten salt storage supplemented by 3,000 acres of adjacent land growing eucalypts which could be cut and burned to drive the turbine as an additional complement to the solar power, giving the station even more capacity to operate outside of bright sunlight. (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. A company called SunEdison pioneered deals with retail store chains in 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 into the grid. Staples, Whole Foods and WalMart have deals with SunEdison. Such deals do not 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.

Like solar, geothermal power sources have in principle the capacity to meet all of the power needs of the U.S. According to a recent MIT study, just 2% of the geothermal heat located in the continental US at depths between 3km and 10km is the equivalent of over 2,500 times the country's total annual energy use.[12] 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 flavors, Dry Steam, Flash Steam, Binary, Enhanced Geothermal Systems (EGS) and Geoexchange. Key characteristics, common to all, are that they exploit the fact that the temperature of the earth increases as we move down, and that the temperature below the earth's surface is constant in the face of seasonal variations. Heat can be extracted from the earth by circulating water downwards to warm it up, and 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. And environmentally it gets high marks – no emissions of any sort, though there is 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% of its energy from geothermal sources, and in the US California takes advantage of its seismic activity to derive 750 MW from geothermal sources.

[12] Massachusetts Institute of Technology, 2006.

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): they exploit this naturally-occurring steam to drive turbines, and are referred to as hydrothermal energy systems. Hot porous rocks containing water occur largely in seismically active areas, and all commercially operating geothermal power plants use one of these three designs.[13] So these established technologies are restricted to seismically active areas, but EGS is not: this is a way of extracting energy from hot underground rocks wherever they occur, independently of the availability of reservoirs of superheated water. The principle is to drill into hot dry rocks and then by pumping cold water at high pressure to fracture them. 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 through hard rocks.[14] A recent MIT study suggests that within two decades EGS energy could be extracted for 5 – 10 cents/kwh in the US, and that by 2050 a total of 100,000 megawatts of electricity could be derived from this source, about 10% of the US's current installed capacity. However, this suggestion has to be qualified by the fact that 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.[15] In the meantime, hydrothermal energy is very competitive and profitable wherever it occurs, costing as little as 3.5 cents/kwh. And of course it can provide baseload power as it operates 24/7, and as mentioned is environmentally benign and so immune to CO2 pricing.

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

[14] 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.

[15] MacKay 2008, pers comm. Klaus Lackner

Geoexchange refers to the use of heat pumps to use 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 degrees C (50 and 60 degrees 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, which 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 buildings should not be heated and cooled in a completely carbon-free way and with a zero marginal cost.[16] It is striking how little this technology is appreciated.

There are three renewable technologies associated with water – hydro power and wave and tidal energy. Hydropower currently provides about 6% of US electrical power, and of course generates no emissions of any sort.[17] 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 US: 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, though several are currently being constructed, in northern California for PG&E and in Scotland. Indications are that the costs will be substantially

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

[17] For data on the composition of energy supply in OECD countries see Anderson 2006.

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. Again this is in its 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 operating in the UK. Costs are high but again the expectation is that they will fall.

Carbon capture and storage (CCS) is not a form of clean energy, but a way of making dirty energy cleaner. It's a way of moving to "cleaner coal." Clean coal, of course, is a controversial concept, ardently advocated by the coal industry and stigmatized as unreal by environmental groups.[18] The criticisms appear to be firstly that it is not yet an operational method, and secondly that even were it to be operational, clean coal would remain an oxymoron because of the environmental impact of coal production and transportation. There seems some merit in this point, but the focus here is on the economics of CCS as a possible route to carbon-free energy at competitive costs. It's potential as a competitor for renewable energy is so great that any discussion of renewables has to consider CCS too.

There are several ways of preventing a coal-fired power station from emitting CO2. One is to scrub it out of the exhaust gases, using a technology very similar to that for scrubbing SO2. Exhaust gases pass up a scrubber tower down which falls water with ammonium carbonate in solution. The CO2 reacts with the ammonium carbonate to form ammonium bicarbonate, and is removed from the exhaust gases. The bicarbonate is then heated, when it turns back to carbonate and releases the CO2, which is liquefied and stored in a safe place, generally underground.

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[18] For more details see IPCC 2006.

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. The exhaust gas is water vapor, and the carbon is burned in the oxygen to make CO2 where it is easily captured.

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 CO2. In this case the CO2 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 CO2 is straightforward. The only complication here is finding somewhere to store it where it will remain without leaking out for a very long time, the preferred location being an exhausted oil or gas field which held gas under pressure for many millions of years and can presumably hold CO2 for a similar period of time. In many geological formations the CO2 will actually react with rocks to form solid carbonates, immobilizing it in perpetuity. Estimates by geologists suggest that decades or even centuries of CO2 emissions could be safely stored underground, though not always near the power plants, in which case it would have to be transported through a pipeline, adding to the cost.[19] Eventually the capacity to store CO2 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 not its viability, which seems clear, but its cost, which is not. With no commercial scale CCS plants in operation, we have only engineering estimates. They suggest a cost in the range of $50–100 per ton of

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[19] IPCC 2006

CO2 at present,[20] which is too high to be commercially attractive: it would be more profitable to pay the likely price of carbon emission permits. However, the cost is likely to fall and the price of carbon to rise, so there is a reasonable chance of their paths crossing before too long, with costs expected to fall to the range $30-60 per ton. In such a situation, there is an understandable reluctance to construct a power plant with CCS, as this would lock in a technology that might be obsolete well within the life of the plant. Retrofitting existing plants is more expensive than adding CCS to a new plant, with the added disadvantage that the number of years of output over which one can spread the extra cost is smaller, the older the plant.

Air capture is a variant on CCS: rather than extracting CO2 from the exhaust gases of a power station, it is taken directly out of the atmosphere. If CO2 can be extracted from the atmosphere at reasonable cost, it doesn't matter where this is done, as CO2 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, avoiding the costs of transporting the gas (see Lackner and Sachs 2005 for a discussion). Currently only prototype air capture devices are in operation, removing CO2 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 to the range of $50-100 per ton CO2.

Biofuels are not envisaged as a source of electric power but 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 2008). But in Brazil ethanol from sugar, not corn, provides almost half of all gasoline

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[20] According to estimates from McKinseys, the IPCC and the IEA.

consumed.[21] 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 lifecyle 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 1% of its arable land, and uses land in the south east of the country, far from the Amazon, whose climate is unsuitable for sugar.

Biodiesel is produced from vegetable oils by a relatively simple process, and is a perfect substitute for conventional diesel as far as a diesel engine is concerned. Environmentally it is preferable, being carbon neutral and producing 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 CO2 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 a lot of venture capital money is going into this field.

So what is the answer to the earlier question – can renewables provide power on a large scale at a reasonable cost? Hydrothermal power is cheap, available now and environmentally harmless. It's profitable at current prices and should be used whenever possible, but sadly that's not very often, as it relies on unusual geological structures. Geoexchange can heat and cool buildings in an

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[21] Bioethanol can be burned in gasoline engines with no mechanical alteration if mixed with gasoline and forming less than 10% 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.

environmentally-friendly way and is also attractive at current prices: that it is used so little seems to reflect the type of market failure which is common in cases of investing in energy efficiency.[22] Enhanced geothermal systems might provide power on a large scale at competitive costs sometime before 2050, but are far from there currently. Wind is competitive, at least when there are strong and regular winds near to population centers, and will be more so with a price on CO2. Off-shore wind could be an attractive development, with higher and more regular winds close to population centers. Solar PV is expensive and not competitive currently, though there is a widespread expectation that it will be by 2020: meanwhile solar thermal is a better bargain, just about competitive (before a price on CO2) and offering some storage possibilities to reduce the intermittency handicap. Waste to energy can also be competitive where trash disposal fees are high, but is always going to be a niche market. So the bottom line is that only geothermal, wind and solar thermal can be provided at competitive costs currently, with the first being limited by geography and the second and third by their inherent intermittency. Solar PV, enhanced geothermal systems and off-shore wind may all come, but are not yet here, and engineering forecasts have a tradition of being optimistic.

Going beyond renewables to other forms of carbon-free energy, CCS and nuclear are contenders. Nuclear already provides 20% of US electric power, but since Three Miles Island and Chernobyl it has been a hard sell politically. (On the risks of nuclear power, see Heal and Kunreuther 2009.) It has also proven far more expensive than expected, and has been a loss-maker for utilities. Various new technologies are now available, but as none are operating commercially it is impossible to judge the optimistic cost claims made by their proponents. Certainly a price on carbon will tip some demand from coal to nuclear. The economics of

[22] This is a topic on which there is a substantial literature – see for example Brown (2001), Hausman (1979), Jaffe Newell and Stavins (1999) and Levine et al (1995).

CCS are enigmatic: with only one commercial plant in operation, and that on a very small scale, it is hard to judge the cost forecasts available. However it seems likely that within twenty years CCS will be competitive with the cost of emitting CO2. Air capture of CO2 is an intriguing possibility, as it could manage the emissions from non-point sources as well as those from concentrated sources. It could allow us to continue using fossil fuels, but to the extent that we continued with oil we would not solve the problems of high oil prices and energy security that are driving interest in non-fossil sources. Air capture at a cost in the range of $30 to $50 per ton would change the energy landscape fundamentally.

An interesting study by MacKay (2009) asks whether the United Kingdom could meet its total energy needs from renewable sources, looking 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 and covering most south-facing roofs with solar panels, and exploiting every hydro opportunity, there would not be sufficient power to meet current UK needs. He suggests three ways of filing the gap: either coal with CCS, or nuclear, or the import of renewable energy from solar plants in the Sahara desert by long distance direct current high tension lines. The US is better placed to use renewables: solar energy alone could in principle meet its energy needs, in the sense of producing a number of kilowatt hours over a year equal to present annual energy consumption. It would take an area of about 140,000 square miles covered with solar collectors to do this: for comparison, the area of California is about 160,000 square miles. But this statement does not address the intermittency problem. MacKay, in his study of the UK, assumes that this is overcome by large-scale application of pump storage technologies (using electricity to pump water uphill to an elevated reservoir from which it can be used to generate hydro power when the sun is not shining). It is not clear that there are sufficient pump storage sites in the US to make this feasible, leading to the conclusion that renewables would have to be supplemented by fossil fuels or nuclear to overcome the intermittency issue.

We began with the US DoE's aim of obtaining 25% of our electricity from renewables by 2025. What would this cost? I'll try to answer an easier question: suppose 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% of our generating capacity by renewables? Here's a rough calculation. Installed electric capacity is one million megawatts, or one thousand gigawatts, or a terawatt. Wind capacity costs about $2000 per kilowatt to install, leaving out costs of connection to the grid. One terawatt is 10^9 kilowatts, so the investment required if we are using wind is $10^9*2*10^3*0.25/0.25$ where 10^9*2*10^3 is the cost of replacing all capacity by wind, we multiply by 0.25 as we are replacing 25% and divide by the capacity factor of wind, which I am taking to be 25%. The answer 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% of current GDP, and over 15 years it is roughly 1% of current GDP annually. In addition to being an underestimate, it does not address our dependence on foreign oil for transportation or furnaces. It would reduce fossil-generated electricity from about 70% to about 45% of the total.[23] How much CO2 would this save? The answer depends on what the wind power displaces: if nuclear or hydro, then there is no saving of CO2, but if it displaces coal, then the saving is about one billion tons of CO2 annually,[24]

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

[24] Here is the calculation. In 2008 the US used about 10^9 tons of coal in generating electricity (http://www.eia.doe.gov/cneaf/electricity/epm/tablees1a.html). This produced 50% of its electricity (see figure X) so using wind for 25% of electric power and displacing coal would reduce coal use by $0.5*10^9$ tons, and at 2 tons CO2 per ton of coal this saves 10^9 tons of CO2. Note that 2 tons CO2/ton coal is a conservative number.

about one seventh of total US 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, as because of the intermittency issue wind will not be used for base load power, which comes mainly from coal and nuclear: it 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 are less than if only coal was to be displaced. Until we have effective storage technologies, substantial reductions in base-load coal emissions of CO2 can only come from increased use of nuclear or the introduction of CCS.

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