Online Appendix for

"The Private and Public Economics of Renewable Electricity Generation"

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Calculation of subsidies for fossil fuels

The paper states that "Adeyeye et. al. (2009) estimate that total subsidies for fossil fuels from 2002-2008 were $72 billion in the United States, of which about $21 billion plausibly went to domestically produced coal and natural gas that went into electricity production." Based on the descriptions on page 7-16 of Adeyeye et. al. (2009), this includes all of the categories that are primarily subsidizing coal: Credit for Production of Nonconventional Fuels ($14.1b), Black Lung Disability Trust Fund ($1.0b), Characterizing Coal Royalty Payments as Capital Gains ($1.0b), Exclusion of Benefit Payments to Disabled Miners ($0.4b), Other-Fuel Exploration & Development Expensing ($0.3b), Other-Fuel Excess of Percentage over Cost Depletion ($0.3b), Special Rules for Mining Reclamation Reserves ($0.2b), Natural Gas Distribution Lines Treated as Fifteen-Year Modified Accelerated Cost Recovery System (MACRS) Property ($0.1b), Expensing Advanced Mine Safety Equipment ($0.03b). In addition, for a number of oil and natural gas items, I've prorated for the value of natural gas used in electricity generation as a share of all oil and gas production in the U.S., which average about 16% over this period. This percentage is applied to Oil and Gas Exploration & Development Expensing ($7.1b), Oil and Gas Excess Percentage over Cost Depletion ($5.4b), Exception from Passive Loss Limitations for Oil and Gas ($0.2b). I also include in this category Reduced Government Take from Federal Oil and Gas Leasing ($7.0b), which is charging below-market rates for leases. These are arguably subsidies, but they are actually unlikely to be passed through to prices for natural gas. I do not include the Foreign Tax Credits, which could be subsidies, but are extremely unlikely to affect domestic prices for natural gas or coal.

Calculation of Levelized Cost for Residential Solar Photovoltaic Power

This is an extended version of the published section on levelized cost of residential solar PV, including citations for assumptions and discussion of some issues in more detail.

In this section, I apply the analytic approach described above to update the calculations of levelized cost of residential solar power from Borenstein (2008a), taking into account recent changes in the cost of solar photovoltaic systems.

According to Barbose et al (2011), residential-scale solar systems (less than 10 kilowatt capacity) in 2010 varied in average price from $6.3/watt in New Hampshire to $8.4/watt in Utah, with California – by far the largest state for residential solar – at $7.30. Taking California's number as the benchmark, Table 2 presents the implied levelized cost of power for a 5 kilowatt system located in Sacramento, California, under alternative real discount rates. The underlying assumptions, noted in the table, are intended to be median estimates, if anything tilted somewhat towards a lower cost of solar power.

The real interest rate of 3 percent implies a levelized cost of $0.315 per kilowatt-hour. I follow Borenstein (2008a) in adjusting for the timing of production, increasing the value of residential solar by 20 percent, which is slightly higher than the estimated gains of 15%-17% in a typical grid operation (with generation reserves) for Southwest facing panels in Sacramento, but lower than the 40%-50% premium in an "ideal" economic grid with no generation reserves and prices clearing the market hour by hour. I adjust for the location of production, increasing value by just 1 percent as found in Borenstein (2008a), because residential solar panels are not disproportionately located in congested areas. These effects are incorporated by adjusting the levelized cost down to $0.260 per kilowatt-hour ($= \frac{0.315}{1.2 \cdot 1.01}$). An additional downward adjustment of $0.02 per kilowatt-hour accounts for long-run savings in transmission investment, as discussed in Borenstein (2008b, p. 10), which brings the net cost to $0.240.[1] This compares to levelized costs for combined-cycle gas-fired generation that are now generally below $0.08 per kilowatt-hour given recent price forecasts for natural gas that account for supply increases from new production techniques.

Adjusting next for environmental externalities raises the issues discussed earlier about the cost of those externalities. If one assumes that new residential solar generation substitutes for new combined-cycle gas turbines, then the local pollutant reduction is valued at

[1] Even the figure $0.02 per kilowatt-hour is above the *average* transmission cost per kilowatt-hour in most U.S. utilities including California.

Table 2: Levelized Cost of Residential Solar Photovoltaic Power

Real Interest Rate	1%	3%	5%	7%	9%
Real Levelized Cost	\$0.249	\$0.315	\$0.389	\$0.468	\$0.551

Assumptions: Five kilowatt system costs \$36,500 installed (California estimate for 2010 from Barbaose et al (2011, p. 21)). Panels last for 30 years with no shading or soiling and no maintenance costs, producing on average 0.77 kilowatts over all hours in first year (based on Sharp corporation calculator for SSW facing panels in Sacramento, California (http://sharpusa.cleanpowerestimator.com/default.aspx). Output of panels declines by 0.5% per year due to degradation (Barbose et al (2011, p. 47)). Inverter replaced after 10 (at \$2552) and 20 (at \$2171) years, based on current cost of \$3000 (Barbose et al (2011, p. 16)) declining by 2% annually in real terms (Borenstein (2008a) and cites therein).

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about \$0.0015 per kilowatt-hour according to Muller, Mendelsohn and Nordhaus (2011). That leaves a cost gap between residential solar and combined-cycle gas turbine generation of at least \$0.158. The gas plant emits slightly less than 0.0005 tons of carbon dioxide per kilowatt-hour of electricity, so residential solar would be cost competitive on a social cost basis only if the cost of carbon dioxide emissions were greater than \$316 per ton. Nearly all social cost and price forecasts for carbon dioxide are well below \$100 per ton (Greenstone, Kopits and Wolverton, 2011), which leaves residential solar still at least \$0.108 per kilowatt-hour more expensive.

This analysis is for the cost of installation in 2010. Barbose et al (2011) report preliminary data suggesting that costs for systems below 10 kilowatts fell \$0.5 per kilowatt in the first half of 2011, but they don't report details for California. Nonetheless, this highlights the fact that such cost analyses are in constant flux as technology improves and as supply/demand factors change. It's also important to note that I have used the retail cost of installation (before subsidies) to represent the social cost of photovoltaics. Depending on the degree of capacity utilization, exercise of market power and the supply/demand balance in the equipment and installation markets, retail price may be above or below long-run marginal cost of production and distribution of a given technology.

This analysis does not account for distribution cost savings from distributed generation or for spillovers from learning-by-doing, for which analyses offer much less guidance. On the other side, it also doesn't incorporate reduced output due to shading or soiling of the panels, or installation at a less-than-ideal angle due to the building orientation, as discussed in Borenstein (2008b). Nor does it account for the cost of extra generation reserves to backup intermittent generation. In addition, it does not incorporate the expected returns to waiting and the option value of waiting: if cost declines are expected to occur for exogenous reasons, then installing solar in the future could have a higher social net present value that installing today. In addition, to the extent there is uncertainty about the rate of cost declines – in solar and in alternatives to solar – then waiting retains the option to pursue a different technology for a given project if it turns out to be less expensive. Nonetheless, this analysis does give a good notion of the gap that those omitted factors would have to fill on net in order for residential solar photovoltaics to cost-effectively substitute for gas-fired generation.

Medium-scale and large-scale solar photovoltaics installations and large-scale solar thermal generation are more cost competitive. Contracts for these larger systems are not public, but reports in the industry press suggest the unsubsidized levelized cost from these installations is probably between \$0.15 and \$0.20 per kilowatt-hour in 2011, before any of the market or externality adjustments, and likely using more than a 3% real cost of capital. These systems enjoy the same production timing benefit as residential solar, but less (or none) of the reduction in line losses and transmission savings. These systems would require a much lower cost of carbon dioxide to be competitive with gas-fired generation, though still probably \$100 per ton or greater.

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