Amortized Cost of Electricity from Solar Power Stations with Thermal Storage vs. Pulverized Coal Facility with Amine-Scrubbing

The goal of this paper is to compare the amortized cost of electricity from two different types of solar thermal energy technologies with the cost of electricity from a coal-fired power plant utilizing newly developed carbon capture (amine-scrubbing) technology.

I. Coal Power Plants and Solar-Powered Energy

Coal, natural gas, and nuclear fuels are the dominant sources of electrical energy in the United States. Currently, the primary source of electricity in the United States is coal.¹ According to the Energy Information Analysis, 45.9% of electric power in the United States was generated from coal in January 2011. Coal has been widely used for energy generation since the Industrial Revolution of the 1800’s, after the invention of the coal-powered steam engine.² The infrastructure for generating electricity from coal has existed for much longer than the infrastructure for energy generation through nuclear fissions or natural gas combustion. Coal has been burned for electricity production since the 1880’s. By comparison, the first nuclear fission power plant was constructed in 1954.³ The current quantity of coal reserves is expected to last for 129 years at the current rate of production.⁴
combination of long-lasting supply and existing infrastructure make coal a viable source of continued electric power generation. However, coal prices have been rising in recent years and the cost of coal-generated electricity is subject to fluctuations in fuel cost. Additionally, total coal consumption is projected to increase with time as developing nations industrialize and use coal more extensively.

Conventional coal-fired plants release carbon dioxide, nitrogen oxides, and sulfur oxide during operation; the first is a greenhouse gas while the last two are air pollutants. Geoscientists have raised concerns about the effect of using conventional fossil fuel based energy sources on climate patterns due to the greenhouse effect created by excess carbon dioxide in the atmosphere. Thus, from a long-term standpoint, CO₂ emissions result in an uncounted cost on consumers (nitrogen oxide and sulfur oxide emissions are now regulated by the government). By contrast, solar thermal plants that use only sunlight as fuel and operate without fossil fuel based backups do not have the externality of emissions imposed upon energy consumers. This paper compares solar thermal energy to coal-based energy when the externality associated with carbon dioxide emissions is as similar as possible between the two types of energy technologies. The theoretical coal power plant that is analyzed in this paper uses amine scrubbing to capture carbon dioxide, with a carbon dioxide capture rate of 90%. Thus, the externality associated with CO₂ emissions is reduced significantly for this plant. Amine scrubbing is a post-combustion method of carbon dioxide capture which uses nitrogen compounds to remove carbon dioxide from the exhaust gas produced from burning coal. This
method of carbon capture reduces a coal-fired power plant’s electricity output by 30% to 40%, since some of the energy generated by the power plant is used to power amine scrubbers. In addition to lacking emissions during operation, energy generation technologies that are powered only by the sun have no fuel costs. The primary forms of solar electric power generation are photovoltaic technology and solar thermal technology. Photovoltaic technology relies on photons colliding with silicon or other conductive material to produce a flow of electrons. Solar thermal energy uses mirrors to concentrate heat energy from the sun to heat fluids; the heat from these fluids is used to generate steam to turn a turbine. Two types of solar thermal energy technology currently exist: power tower and parabolic trough technology. Power tower systems use a field of mirrors (known as a heliostat field) to concentrate sunlight onto a receiver atop a “power tower”, a device that collects radiation energy from sunlight. This radiation is used to heat water and produce steam, which drives a turbine. Parabolic trough power stations have a field of parabolic mirrors with piping passing through the trough of the mirror. This piping is filled with a heat transfer fluid; the parabolic mirrors concentrate sunlight on the pipes at their troughs. The concentrated sunlight heats the fluids, which flow to the main power block, where the heat is transferred to a steam generator through heat-exchangers.

i. Thermal Storage

Thermal storage systems have improved the efficiency of power tower and parabolic trough power stations by enabling the storage of solar thermal energy
periods of inconsistent sunlight. The primary thermal energy storage systems used by solar thermal power plants are the two-tank direct system, the two-tank indirect system, the single-tank thermocline, and the direct molten salt heat transfer method. All but the two-tank direct system involves the use of molten salts. The two-tank direct system involves transporting a heat-transfer fluid between two tanks at different temperatures. The fluid is heated by energy from sunlight and stored in the hot storage tank; later, this higher temperature fluid is used as a source of thermal energy to generate electricity and is transferred back to the cold storage tank as it loses heat. The two tank indirect approach involves the use of a heat transfer fluid as an intermediate form of storage and molten salt as the primary storage mechanism. A heat transfer fluid is heated by sunlight as before; however, heat is transferred from the hot fluid to cold molten salt through heat exchangers. After it is heated, the molten salt is stored in the hot storage tank. Later, stored
energy in the hot molten salt is transferred back to the heat transfer fluid through the heat exchangers; the heat transfer fluid heats water to power a turbine and the

http://www.tonopahsolar.com/the_technology.html cooled molten salt returns to the cold storage tank.

A single tank-thermocline operates similarly to the two-tank direct system. However, the hot and cold fluids are stored in a single tank with a separation zone known as a thermocline. A major advantage of a single-tank thermocline is the cost reduction resulting from using one tank instead of two. Another source of cost reduction in this system is the potential for using cheap filler material instead of molten salt as the storage medium. Direct molten salt heat transfer uses molten salts to transport heat from the solar field to the storage containers without an intermediate heat transfer fluid. This approach saves money by eliminating the need for heat exchangers and a separate heat transfer fluid. Molten salts are nitrate salts
that are non-toxic and are more environmentally friendly than other heat transfer fluids, which are typically made from synthetic oils. Furthermore, the salts can be heated to much higher temperatures (more than 500 °C) than synthetic oils. Both of the solar thermal power stations examined in this paper use molten salt thermal storage.

II. Calculating Amortized Cost of Electricity

Total costs of two separate solar thermal power projects that are in their early stages of development are considered representative of current costs of all plants using their type of power-generating technology. Cost data for the pulverized coal plant with amine scrubbing was obtained from the FAS (Federation of American Scientists). The two planned solar thermal projects examined in this paper are the Tonopah project in Nevada, a 110 MW solar thermal power tower plant with two-tank direct molten salt storage, and the Solana Generating Station in Arizona, a 280 MW solar thermal parabolic trough plant with a two-tank indirect storage system. All of the amortization calculations are performed over the lifetime of the power plants; the 110MW solar thermal plant has an expected lifetime of 25 years, the 280MW solar thermal plant has an expected lifetime of 30 years, and the coal plant has a lifetime of about 50 years. The monthly payment required of the owner of the power plant is determined by the formula for amortization through monthly payments:

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MP = \frac{LP(1 + \frac{r}{12})^n}{(1 + \frac{r}{12})^n - 1}
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(where MP is the monthly payment, LP is the amount of money to be amortized, r is the discount rate, and n is the number of months in the lifetime of the plant.)
(finance) rate, and n is the time in months. The discount rate is the rate of return (expressed as a fraction of the original cost of a project) required for the present value of revenues of the project to equal the present value of expenditures for the project (i.e. the net cash flow is zero) over a given period of time. The ‘present value’ refers to the value of future cash flows adjusted (discounted) to account for inflation over time. To equalize the comparison, we assume that all three projects have the same discount rate, equal to the finance rate given for the Tonopah project.

The Tonopah plant has a capital cost of $850,000,000, an annual operating budget of $5,000,000 that accounts for variable operation and maintenance costs, and a discount rate of 6%. Its annual output is 480,000,000 kWh (with a peak capacity of 110,000kW) and its expected lifetime is 25 years (300 months). Using the formula given above, the calculated monthly payment is $5,476,561. The annual payment is $5,476,561 * 12 = $65,718,732. When the annual operating budget is added to this cost, the total annual cost is: $65,718,732 + $5,000,000 = $70,718,732. Therefore, the annual cost per kilowatt-hour is: $70,718,732 / 480,000,000 kWh = $0.147/kWh.

Abengoa Solar has negotiated a 30-year power purchase agreement with Arizona Public Service to build the Solana Generating Station in Gila Bend, Arizona. Solana has a rated capacity of 280 MW and a capital cost of approximately $2 billion. Unlike the Tonopah power plant, Solana uses synthetic oils as heat transfer fluids in the solar field and molten salt for storage only. An estimate of Solana’s annual output can be calculated using solar resource data for the region in which the plant will be constructed. Solar resource is the amount of radiation energy from the
sun that collects on a square meter of area in a single day; this quantity is dependent on region. Within the United States, the southwestern states have the highest solar resource levels. The intensity of the sun is about 1000 W/m² at the equator. This figure can be used as an approximation of the Sun’s intensity in the southwestern U.S. (although the actual intensity of sunlight in Arizona is less than 1000 W/m² and varies by season). According to the National Renewable Energy Laboratory, the average solar resource (also known as insolation) averaged over a year at the location of the power plant is 6,800 Whrs/ m² day. This figure is divided by the intensity of sunlight to find the average hours of sunlight at Solana’s operating site. The average number of sun hours in Gila Bend is 6.8. To account for variation in solar intensity due to latitude and season, this number can be rounded down to 6 hours. Solana has a maximum thermal storage capacity of 6 hours. Therefore, the station is capable of operating for approximately 12 hours each day. Solana’s annual energy output can be calculated using the assumption that it operates at peak capacity. The annual output is 280 MW * 12 hours/day * 365 days/year = 1,226,400 MWh. Since the annual variable operating cost is not provided, we can assume it is 1% of the capital cost, or $20,000,000. Using the formula given above, the monthly payment required for amortizing the capital cost is $11,991,011. The total annual payment is twelve times the monthly payment plus the annual variable cost: $11,991,011 * 12 + $20,000,000 = $163,892,132. Dividing this cost by the station’s yearly output results in the annual cost of electricity: $163,892,132/1,226,400,000 kWh = $0.134/kWh.
A 600MW pulverized coal power facility with amine scrubbing technology and a capacity factor of 85% has an expected overnight capital cost of $4,025/kW (in 2008 dollars). This cost assumes the power plant can capture 90% of the carbon dioxide emitted. After accounting for inflation, the overnight capital cost of this power plant in 2010 dollars is $4,076/kW. Since amine scrubbing technology reduces the facility’s energy output by at least 30%, the capital and fixed operation costs required to build and maintain the power plant will need to be calculated for a facility with 1.3 times the rated capacity as a conventional 600 MW power station (assume the costs are the same as that of a 788 MW power station). Therefore, the capital cost is $3,211,888,000. The fixed operation and maintenance cost (O&M) cost is $43.44/kW and the variable O&M cost is $13.65/MWh (measured in 2006 dollars). After accounting for inflation, the fixed O&M cost in 2010 dollars is $46.99/kW (or $37,028,120) and the variable O&M cost is $14.76/MWh. The principal value to be amortized is the sum of the overnight capital cost and the fixed O&M cost. Using the amortization formula, the calculated monthly payment is $17,102,450. Using the plant’s capacity factor, the total annual output of the plant is: 600MW * 24 hrs * 365 * 0.85 = 4,467,600 MWh. The annual variable O&M cost is then $14.76/MWh * 4,467,600 MWh = $65,941,776. Fuel costs also account for a substantial part of the yearly variable cost. According to the Energy Information Analysis, the cost of coal in January 2011 was $2.34/MMBtu. The coal plant examined in this paper has a heat rate (a measure of a power plant’s fuel to energy output conversion efficiency) of 12,080 Btu/kWh. The product of the heat rate, the plant’s annual output, and the cost of coal per MMBtu yields a total fuel cost of
$165,856,326 per year. The total annual variable cost is the sum of the fuel cost and
the variable O&M cost: $231,798,102. The total annual payment is the sum of the
yearly variable cost and twelve times the amortized monthly payment:
$231,798,102 + 17,102,450*12 =$437,027,502. Therefore, the annual cost of
electricity per kilowatt-hour is $437,027,502 / 4,467,600,000 kWh = $0.0978/kWh.
This figure is comparable to the current average price of electricity in the United
States.18

Amortizing the cost of electricity produced from the three types of power
plants shows that coal-fired power stations with amine scrubbing carbon capture
produce electricity at a lower cost than both types of currently existing solar
thermal power technologies with molten salt thermal storage.

References: