Techno-economic Evaluation of Fossil Fuel Electric Power Plants

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Introduction

The function of a fossil fuel-fired power plant is to convert fuel, typically coal and natural gas, into electricity. A number of different factors affect the performance and cost of a power plant. For example, in a coal-fired power plant the choice of coal type, type of boiler, steam turbine, and pollution control technologies, and so on, directly or indirectly affect the performance and cost of the entire power plant. Thus, a systems-wide techno-economic evaluation of power plants is needed for making key decisions such as the technological choices to be made for building a new power plant, retrofitting an existing power plant with a new technology component, or for comparing different power plant options in the light of new market and regulatory factors. This article provides a broad overview of the factors affecting the performance and cost of a power plant, followed by illustrative case studies. The article also demonstrates the use of the Integrated Environmental Control Model (IECM), a power plant modeling software tool developed at Carnegie Mellon University [1].

Quantitative Metrics for Evaluation of Power Plants

A variety of quantitative metrics are needed for evaluating a power plant in general. These quantitative metrics usually relate to performance, emissions and ultimately, cost. A few of these are defined below.

Power Plant Performance

Typically, a power plant is designed to generate a desired quantity of net electrical output. All the other choices are centered on that. In a pulverized coal (PC) power plant, coal is combusted in a boiler which generates steam. Depending on the boiler design, the steam could be sub-critical, super-critical or ultra super-critical. The steam runs a steam turbine which generates electricity. Similarly, in a natural gas combined cycle (NGCC) power plant, product gases from natural gas combustion run a gas turbine to generate electricity. The hot exhaust gas from the gas turbine is used to generate steam which in turn runs a steam turbine, generating more electricity.

Plant Thermal Efficiency

The amount of fuel needed to generate the desired quantity of electricity is an indication of the performance of the power plant. Consequently, the most widely used performance metrics for a power plant are its thermal efficiency and plant heat rate. Thermal efficiency of a plant indicates how much output can be obtained from a given amount of input and conversely, heat rate indicates the amount of input needed to generate a unit of output. Output here means the electrical energy and input is the fuel energy. Thermal efficiency is typically expressed as percentage and heat rate is expressed as BTU/kWh or kJ/kWh.

Both of these parameters can be evaluated on either a “gross” power basis or a “net” power basis. The electricity generated by the turbine generator is called the “gross” power output. Some of this electricity is utilized within the power plant in order to meet some auxiliary loads (fans, blowers, pumps etc). Most modern power plants are also equipped with various pollution control technologies, in order to limit harmful emissions into the atmosphere. These emission control technologies also consume a part of the plant’s gross electrical output. The resulting power output is the “net” electricity which is sold to the grid. By definition, gross plant thermal efficiency is always higher than the net thermal efficiency. Conversely, the net plant heat rate is always higher than the gross plant heat rate.

Power Plant Emissions

In general, power plants need to meet different emissions standards, like the new source performance standard (NSPS) or its equivalent. Emissions control technologies include electrostatic precipitator (ESP) or fabric filter for particulate removal; wet or dry flue gas desulfurization (FGD) for SOx removal; selective catalytic reduction (SCR) for NOx control; and possibly carbon dioxide capture and storage (CCS) for CO_2 control.

Emissions can be quantified on an absolute basis (mass flow rate). However, emissions normalized over unit input or output energy is often used in comparative analysis (e.g., kg/BTU fuel input or kg/kWh output). Many regulations are specified in normalized units. For instance, the new source performance standards regulate SO_2 emissions from fossil-fired power plants to 0.258 mg/kJ of fuel input. On the other hand, the EPA's final rule on greenhouse gas emissions for coal-fired boilers limits the CO_2 emissions to 1,305 lb/MWh (0.653 kg/kWh) of net power [2].

While meeting the emissions standards, the plant with a higher net thermal efficiency (or lower net heat rate) is considered to have a better performance than a plant with lower net thermal efficiency (or higher heat rate).

Power Plant Costs

Costs associated with power plants are key parameters in decision-making. Some of the most commonly used metrics are the plant's capital cost ($), operational and maintenance (O&M) cost ($/year) and the cost of electricity ($/MWh). Capital cost mainly depends on the sizes of different equipment which are generally a function of the flow rates. O&M costs can be divided further into fixed O&M (FOM), variable O&M (VOM) and fuel cost (FC). Sometimes fuel costs are included within the VOM costs. The cost of electricity (COE) or levelized COE (LCOE) is the cost of generating a unit of electricity. LCOE depends on both capital and O&M costs as well as the financial structure of the project (e.g., interest rate, plant life, etc.) and its capacity factor. LCOE, expressed in the equation below, effectively embeds all the performance and cost parameters of the plant.

$$LCOE\left(\frac{\$}{MWh}\right)=\frac{TCR\ (\$)\times FCF\left(\frac{1}{year}\right)+FOM\left(\frac{\$}{year}\right)}{8766\left(\frac{hr}{year}\right)\times CF\times MW_{net}}+\frac{VOM\left(\frac{\$}{year}\right)}{8766\left(\frac{hr}{year}\right)\times MW_{net}}+FC\left(\frac{\$}{BTU}\right)\times\frac{HR\left(\frac{BTU}{kWh}\right)}{1000}$$

TCR is the total capital requirement of the plant which includes direct costs of equipment, indirect costs such as contingencies (which depend on factors such as the technological maturity of the process) and sometimes owner's costs. FCF is the fixed charge factor (also called capital charge factor) used to annualize capital costs over the lifetime of the power plant. FCF depends on the plant life and financial variables such as discount rate. CF is the capacity factor which indicates the effective fraction of time the power plant operates at full capacity in a year.

Thus it is clear that a variety of technological and financial parameters affect the LCOE.

Two additional cost metrics can be used to evaluate the cost effectiveness of a CO_2 capture technology. One is called cost of CO_2 captured and the other is the cost of CO_2 avoided. Cost of CO_2 captured denotes the cost of capturing a tonne of CO_2, compared to a reference plant without CO_2 capture, while still providing a unit of electricity. This does not include the cost of CO_2 transport and storage. This measure is used to compare the economic feasibility of a CO_2 capture system compared to a market price of CO_2 (for example, for enhanced oil recovery).

$$Cost\ of\ CO_2\ captured\left(\frac{\$}{tonne}\right)=\frac{LCOE_{CCS}\left(\frac{\$}{MWh}\right)-LCOE_{ref}\left(\frac{\$}{MWh}\right)}{\left(\frac{tCO_2}{MWh}\right)_{captured}}$$

On the other hand, cost of CO_2 avoided quantifies the cost of avoiding a tonne of CO_2 compared to a reference plant without CCS. This includes the cost of transport and storage, since CO_2 is avoided only when it is sequestered. This metric is used to assess the feasibility of CO_2 capture in general. For instance, this is the CO_2 tax ($/tonne of CO_2 emitted) beyond which CO_2 capture would become more economical for the reference plant.

$$Cost\ of\ CO_2\ avoided\left(\frac{\$}{tonne}\right)=\frac{LCOE_{CCS}\left(\frac{\$}{MWh}\right)-LCOE_{ref}\left(\frac{\$}{MWh}\right)}{\left(\frac{tCO_2}{MWh}\right)_{ref}-\left(\frac{tCO_2}{MWh}\right)_{CCS}}$$

It must be noted that the choice of reference plant is critical to the values of cost of CO_2 captured and avoided. More details about techno-economic evaluation of power plants are available in Rubin et al (2013) [3].

Ideally, a power plant should give the best performance at the lowest cost.

Illustrative Case Studies

To illustrate the effect of different technological and financial variables on the performance and cost of a power plant, a few case studies are presented here. PC and NGCC power plants without CO_2 capture are used as the base cases. To illustrate the effect of coal type, two types of coal are used – Appalachian medium sulfur coal and Wyoming Powder River Basin (PRB) coal. The former is a higher quality coal (bituminous) but with relatively high sulfur content while the latter is a lower quality coal (sub-bituminous) but with much lower sulfur content. The lower sulfur coal would require a smaller FGD unit, leading to possible cost savings. Sensitivity analyses are also conducted to understand the effect of key variables on the performance and cost of different plants. The effect of CO_2 capture on a PC power plant has also been illustrated. The Integrated Environmental Control Model (IECM), developed at Carnegie Mellon University, has been used for performing these case studies.

Integrated Environmental Control Model (IECM)

The Integrated Environmental Control Model (IECM), developed at Carnegie Mellon University, is a freely and publicly available power plant modeling computer tool which evaluates the performance and costs of several types of fossil fuel power plants, including pulverized coal (PC), coal-fired integrated gasification combined cycle (IGCC) and natural gas combined cycle (NGCC) power plants. Based on fundamental mass and energy balances, together with empirical data, the IECM calculates plant-level performance and material flows, including environmental emissions, for current and advanced power plant designs whose configuration and parameters are specified by the user. Each power plant configuration can be designed with a variety of emission control options, including CO_2 capture and storage. The IECM also provides the capability to quantify uncertainties in model input parameters and express results as probability distribution functions as well as deterministic values. Comparative analyses of different system designs also can be performed easily. The following sections provide some illustrative case studies of techno-economic evaluation of power plants using the latest version of IECM (v 9.0.2).

Case Study Results

All the plants in the case study are designed to generate 580 MW of net electrical output. A fixed charge factor or 0.113 and a base case capacity factor of 75% are assumed.

Table 1 compares the performance and cost characteristics for the PC and NGCC power plants considered here. Most of the performance and cost metrics described before are illustrated in the table. It can be seen from the table that the NGCC plant has a much better performance (net plant efficiency of 50%) compared to the PC plants (net plant efficiencies in the range of 36-39%). Coal plants emit more than twice the CO_2 compared to NGCC. Within the PC plants, the bituminous coal plant has a higher net thermal efficiency than that of the sub-bituminous coal plant. Because sub-bituminous coal is of lower quality, a much higher quantity is needed to produce the same amount of electricity. The higher flow rates also lead to higher capital costs, as shown in the table. In general NGCC plants cost much less to build. The table also shows the LCOE results for the three power plants. It can be seen that NGCC generates electricity at a much lower cost ($34/MWh) compared to the PC plants. Among the PC plants, the sub-bituminous coal plant has a lower LCOE ($52/MWh) compared to the bituminous coal plant ($60/MWh), even though the capital cost of the sub-bituminous coal plant is about 5% higher and the fuel flow rate is almost 70% higher compared to the bituminous coal plant. This difference can be directly attributed to the much lower price of sub-bituminous coal ($9.6/tonne, compared to $49.9/tonne of bituminous coal). The table also shows the contribution of capital cost element to the LCOE for the three plants. In coal plants, more than half the LCOE can be attributed to plant capital cost, the rest being the O&M costs. On the other hand, LCOE of NGCC plants is dominated by O&M costs. It may be noted that a significant fraction of O&M costs comes from the fuel costs.

Sensitivity Analysis

The performance and cost results presented so far are specific to the input assumptions made for different plants. Changing the input assumptions will affect the outputs as well. The IECM is used to perform sensitivity analyses to understand the variation in LCOE when key input parameters are changed. As we have seen earlier, fuel price is a key variable in determining the cost of electricity generation. Figure 1 shows the effect of varying fuel price on the LCOE for the three plant designs. It is clear that LCOE is very sensitive to variation in fuel price, with NGCC being more sensitive than PC plants. The economic viability of NGCC plants relative to coal plants thus depends on the price of natural gas. Historically, coal prices have been relatively more stable compared to natural gas prices. The graph shows that, for fixed coal prices, NGCC becomes more costly (in terms of LCOE) than sub-bituminous coal and bituminous coal plants if the natural gas prices were over about $180/mscm ($4.7/GJ) and $230/mscm ($6/GJ), respectively.

Another important variable affecting the LCOE is the plant's capacity factor, which is an indication of the amount of time a power plant operates in a year. Capacity factor depends on the maintenance schedule of the power plant as well as the electricity demand in that region. Base load plants generally have higher capacity factors compared to peaking plants. Figure 2 shows the effect of variation in the capacity factor on the plant's LCOE for the bituminous coal plant and NGCC plant. For the NGCC plant, two natural gas price scenarios are shown – low price ($91.8/mscm or $2.4/GJ) and high-price ($268/mscm or $7/GJ). It can be seen that the higher the plant's capacity factor, the lower is its LCOE. For the low natural gas price case, NGCC is always cheaper than the bituminous coal plant (in terms of LCOE). However, for the high natural gas price case, NGCC becomes costlier than the PC plant at capacity factors greater than about 55%. In general, PC plants have been used as base load plants (i.e., have higher capacity factor) and NGCC plants have been used as peak load plants. This shows that the relative economic feasibility of PC and NGCC plants depends simultaneously on multiple factors.

Inputs			
	PC-b	PC-sb	NGCC
Fuel	Coal		Natural gas
Quality	Bituminous	Sub-bituminous	-
Higher heating value (MJ/kg)	30.8	19.4	52.3
Sulfur content (wt%, as-received)	2.1	0.37	-
Fuel price	$49.9/tonne ($1.62/GJ)	$9.6/tonne ($0.50/GJ)	$91.8/mscm ($2.42/GJ)
Boiler/Turbine technology	Supercritical boiler		GE 7FB gas turbine
Results			
Gross power out (MW)	620	630	595
Fuel input	175 tonnes/hr (5,380 GJ/hr)	295 tonnes/hr (5,700 GJ/hr)	80 tonnes/hr (4,180 GJ/hr)
CO_2 emissions (kg/kWh)	0.82	0.90	0.36
Gross thermal efficiency (% HHV)	41.6	39.7	51.3
Gross plant heat rate (kJ/kWh)	8,660	9,060	7,010
Net thermal efficiency (% HHV)	38.9	36.7	50.0
Net plant heat rate (kJ/kWh)	9,260	9,820	7,200
Total capital cost ($/kW-net)	1,960	2,060	774
LCOE ($/MWh)	60.4	51.8	33.6
Capital cost contribution to LCOE	56%	68%	39%

Table 1. Performance and cost results of the case study power plants (PC-b – PC plant with bituminous coal; PC-sb – PC plant with sub-bituminous coal; NGCC – natural gas combined cycle power plant). All plants generate 580 MW of net electrical output. A capacity factor of 75% and a fixed charge factor of 0.113 are assumed.

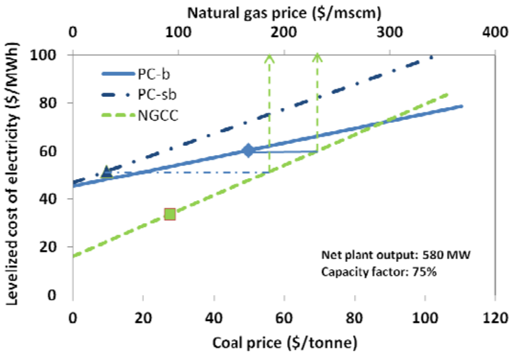

Figure 1. Sensitivity of LCOE of the three power plants to fuel price. Markers show the fuel prices assumed for base cases (results shown in Table 1).

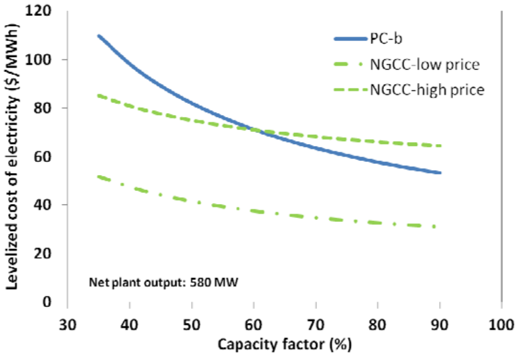

Figure 2. Sensitivity of LCOE to capacity factor.

Effect of CO_2 Capture

The IECM can be used to evaluate the effect of different CO_2 capture options on a power plant performance and cost. A bituminous coal PC plant, generating net electricity of 580 MW and equipped with an amine-based CO_2 capture system that captures 90% of CO_2 emissions, has a net thermal efficiency of 28% (heat rate of 12,840 kJ/kWh). Capital cost of the plant increases to $3,430/kW-net and LCOE increases to $104/MWh, about 70% higher than the plant without CO_2 capture. When the plant without CO_2 capture is used as the reference plant, the cost of CO_2 captured is $38/tonne and the cost of CO_2 avoided is $62/tonne. This means that the captured CO_2 should be sold (for example, for enhanced oil recovery) for at least $38/tonne or the CO_2 tax should be at least $62/tonne, for CCS to become economically viable for this plant. In this way, techno-economic models like the IECM can be used to make informed decisions and policies.

Conclusion

This article demonstrated that a systems-level techno-economic evaluation of power plants is very important for decision-making. The Integrated Environmental Control Model (IECM), developed at Carnegie Mellon University, was used for the case studies, analyzing the effect of various technical, operational and financial parameters on a plant's performance and cost. Three different power plants were considered for case studies – PC power plants using bituminous and sub-bituminous coals; and NGCC power plant. It was also shown that the relative economic feasibility of power plants depends simultaneously on multiple factors.

For more details about the IECM and exploring its analysis capabilities, the readers are encouraged to visit the model's website (www.iecm-online.com).

References

[1] Integrated Environmental Control Model (IECM), Carnegie Mellon University, www.iecm-online.com

[2] US Environmental Protection Agency, Clean Power Plan Final Rule, 2015. www.epa.gov

[3] Rubin E.S., et al, 2013. A proposed methodology for CO_2 capture and storage cost estimates. International Journal of Greenhouse Gas Control, 17, 488-503.