A simple model for determining levelized cost of electricity

INTRODUCTION

The electricity generating project takes place in two stages.

- **First stage, the development and construction**, during "M" time periods to develop, design, construct, commission, and start-up the power plant.
- **The second stage, operations**, lasts for "N" time periods, referred to as the operating life of the power plant.

A. The development & construction stage. A useful measure of development & construction expense is the "overnight capital cost", the sum total of direct expenditures C(m) during the development & construction phase "m", i.e., without including interest charges on funds borrowed to build the power plant. This quantity, denoted $I_{overnight}$, is just

$$I_{overnight}(0)=\sum_{m=1}^{M}C(m).$$

It is referred to as the overnight cost because it can be thought of as the amount of money that would be required to build the power plant if the construction could be done instantaneously, or "overnight", i.e., without incurring any interest during construction. Note that in this calculation – and in the discussion to follow – we will assume that there is no inflation.

The **capitalized construction cost, I**, at the beginning of operation takes into account the accumulated interest during construction.

It is assumed that construction is financed by a mixture of debt and equity, and that the ratio of debt to equity remains constant during the construction period.

It is further assumed that the required rate of return for both debt and equity is constant during this period. If the rate of return on debt is r_b, the rate of return on equity is r_e, and the ratio of debt to total capital is f, then the capitalized cost of the debt component of the investment at the start of plant operation:

$$L(0)=\sum_{m=1}^{M}fC_m(1+r_b)^{M-m}$$

and the capitalized cost of the equity component

$$E(0)=(1-f)\sum_{m=1}^{M}C_m(1+r_e)^{M-m}$$

B. Operation Phase. During the operation phase, the project will either make money or lose money. The outcome depends upon the balance of revenues and costs during this phase.

C. Revenue. The revenue, R(n), received by the owners of the generating plant in time period n is equal to the amount of electricity, Q(n), produced in that period times the price of the electricity, p(n), during that period:

$$R(n)\ (\$/yr) = Q(n)\ (kWe-hr/yr) \times p(n)\ (cents/kWe-hr) \times 10^{-2}\ (\$/cent)$$
$$Q(n)\ (kWe-hrs/yr) = 365\ (days/yr) \times 24\ (hrs/day) \times CF(n) \times K(MWe) \times 1000\ (kWe/MWe)$$

In these equations K is the rated capacity (in MWe) of the plant and CF(n) is the capacity factor of the plant in time period n. For simplicity, we take the capacity factor as constant and hence:

$$Q(n)\ (kWe\text{-}hrs/yr) = CF \times K(MWe) \times 8{,}760 \times 10^3$$

D. Costs. The revenue stream should cover the following:

1) fuel costs,
2) operations and maintenance costs,
3) taxes,
4) interest payments and principal repayments on the debt, and
5) return on equity.

1. **Fuel cost;** The fuel cost in year n is expressed as $C_{fuel}(n) = Q(n)\ c_{fuel}(n)$, where $c_{fuel}(n)$ is the fuel cost expressed in \$/kwe-hr in year n.
2. **O&M cost**; The O&M cost in year n is expressed as $C_{O\&M}(n) = Q(n)\ c_{O\&M}(n)$, where $c_{O\&M}(n)$ is the unit O&M cost expressed in \$/kWe-hr. In reality O&M has both a fixed and a variable part, but for simplicity we will lump them into a single category.
3. **Interest and principal payments on the debt**; We assume the debt has a term of N_D years and is serviced in equal annual installments, q. The annual debt service payment q includes both an interest component and a partial retirement of the outstanding principal. We assume that the loan payment is made at the end of the year. Let the amount of principal outstanding at the beginning of year n be L(n). Thus

$$\mathbf{q = r_b L(n) + L(n) - L(n+1).}$$

The proportions of interest and principal repayments in the annual loan payment vary over the life of the loan. Formulae for the interest, principal repayment, and outstanding loan amounts in each year are given in the Appendix.

4. **Taxes;** Usually income taxes are assessed against revenues after allowable deductions. Operating expenses (fuel and O&M costs) are in most countries deductible, as also interest payments on debt, INT(n), are. Furthermore, usually a 'depreciation allowance', D(n), can be deducted to reflect the partial 'using up' of capital assets during period n. If the tax rate is t, the taxes owed in year n, T(n), are then calculated at follows:

$$T(n) = t\left[R(n) - C_{fuel}(n) - C_{O\&M}(n) - D(n) - INT(n)\right].$$

   Note that payments to equity are not deductible for purposes of calculating taxes. The term in brackets on the right hand side of the equation is called the 'taxable income'.

5. **Depreciation**. In most of the countries, private firms are allowed to deduct a portion of the value of the original capitalized investment in each year of its life for purposes of computing taxable income. There are a number of different methods permitted by the IRS for computing the depreciation allowance – here the simplest method was adopted, which is "straight line" depreciation over the 'depreciation life' of the asset N_T. The depreciation life is set by the tax authorities, and in general is based on the length of time beyond which it is no longer economic to operate the asset – either because it has 'worn out' or because other, newer technologies or developments in the marketplace have made it obsolete. The depreciation life N_T is in general different than the economic life of the plant N_E because there may be business reasons other than asset lifetime that determine the length of the project. In this simple model, we will set the depreciation lifetime, N_T, equal to N_E. Thus:

$$D(n) = \frac{K}{N_E}.$$

6. **Return on equity;** The owner of the generating plant can adopt many different strategies for making money from this investment. One example is to insist on a payout in each time period at a fixed rate of return, r_e, during the economic life of the project, N_E. Because of the higher risk associated with equity, $r_e > r_b$. The owner will also require the original equity investment to be paid down (i.e., recovered) over the life of the project.

APPENDIX

Determining the amount of the uniform annual payment, q, that will pay off a loan bearing an interest rate "r" of term "N" periods

Assuming the outstanding value of the loan (the remaining principal) is L(n) at the beginning of period "n." A uniform payment "q" goes to paying the interest due on the loan and to repaying part of the outstanding principal:

$$q = r_b L(n) + L(n) - L(n+1)$$
$$\text{or} \quad L(n+1) = (1 + r_b)L(n) - q$$

The general solution to this difference equation is of the form:

$$L(n) = A + B(1 + r_b)^n$$

The constant A = q/r. If the initial value of the loan is L(0) then

$$L(n) = -\frac{q}{r_b} + \left[L(0) + \frac{q}{r_b}\right](1 + r_b)^n.$$

The value of the uniform payment, q, is determined from the condition that at the end of the loan period, N_D, $L(N_D) = 0$. Thus:

$$q = r_b L(0)\left\{\frac{(1 + r_b)^{N_D}}{(1 + r_b)^{N_D} - 1}\right\}.$$

The loan balance, L(n), in each time period is:

$$L(n) = L(0)\left\{\frac{(1 + r_b)^N - (1 + r_b)^n}{(1 + r_b)^N - 1}\right\}$$

The interest payment, I(n), is I(n) = r_b L(n), and the annual reduction of principal, P(n), is

$$P(n) = q - I(n).$$

Example
Gas Turbine Combined Cycle Power Plant
fired by Natural Gas

What is the lifetime levelized cost of electricity from a natural gas-fired, gas turbine combined cycle power plant (CCGT)? In the analysis based on our model, we assume the following parameters:

No inflation	$r_i = 0$
50/50 debt equity ratio	f = 0.5
Interest on debt, 5%	$r_b = 0.05$
Return on equity, 10%	$r_e = 0.10$
Economic life of project	N_E = 20 yrs
Depreciation lifetime	N_T = 20 years
Capacity factor	CF = 0.85
Heat Rate	H = 7200 BTU/kwhe
Tax rate	t = 0.38
Debt term	N_D = 20 years
Construction stage	M = 2 years
O&M cost	$c_{O\&M}$ = 0.75 cents/kWe-hr
Fuel cost	c_{fuel} = $4.50/MCF+variable

Construction stage for a 1000 MWe CCGT

	Outlay in year 1 (millions USD)	Outlay in year 2 (millions USD)	Overnight cost (USD/kW)	Capitalized cost at start of operation (USD/kW)
Total	300	300	600	
Debt (r_b=0.05)	150	150	300	307.5
Equity (r_e = 0.1)	150	150	300	315

Assuming 85% capacity factor, so the annual production of electricity from this CCGT Q(n), will be 7,446 10^6 kWh. The O&M cost will be 0.75 cents per kWh. The initial loan balance is L(0)=307.5 Mio USD.

The initial equity balance, E(0) =315 Mio USD. Using the formal in the Appendix, the annual loan payment, q=24.7 Mio USD. The annual depreciation allowance (based on the straight line method applied to the overnight cost as the basis) is 30 Mio USD/Year.

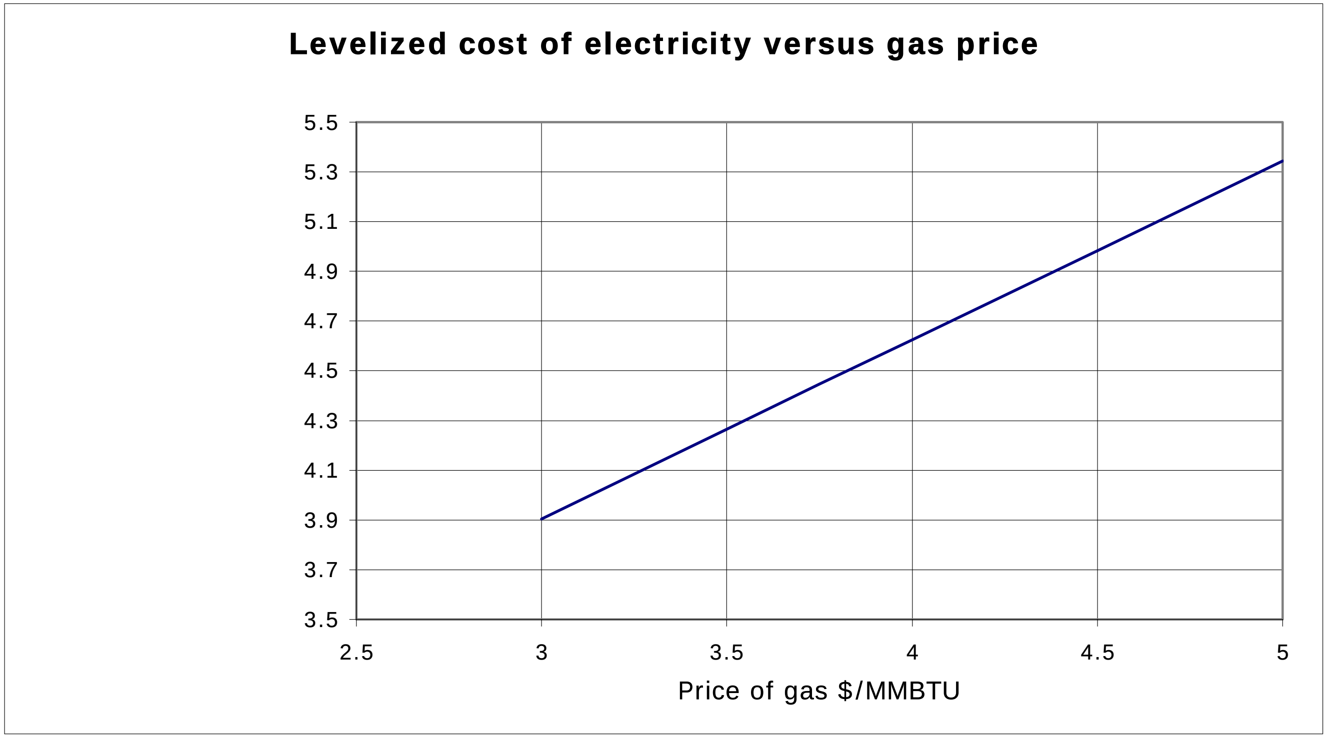
In the case of this CCGT, the price of NG will be an important determinant of the cost of electricity. For the assumed heat rate the fuel cost $c_{fuel}(n)$ = 53,611 10^3 p USD/Year, where p is the price of natural gas expressed in USD per MMBTU.

An excel spreadsheet is used to display the annual cash flows. The key step is to determine the constant price of electricity that provides sufficient cash flow to pay the operating costs, interest and principal repayments on the loan, taxes, and the return on equity, and conclude at the end of the 20-year economic life of the project with all the equity paid off.

We find the levelized cost of electricity to be 4.984 US¢/kWh.

Natural gas power cost model (zero inflation case)
1000MWe CCGT 85% capacity factor; heat rate = 7200 BTU/kwhe
f = 0.5, r_b=0.05, r_e=0.10

Time period, n	1	2	3	4	5	10	20
Price, p (cents/kwhr)	4.984	4.984	4.984	4.984	4.984	4.984	4.984
Revenue, R(n) (10^6$)	371.4	371.4	371.4	371.4	371.4	371.4	371.4
Price of gas ($/MMBTU)	4.5	4.5	4.5	4.5	4.5	4.5	4.5
Fuel cost, Cfuel(n) ($)	241.4	241.4	241.4	241.4	241.4	241.4	241.4
O&M cost, Co&m(n) ($)	55.9	55.9	55.9	55.9	55.9	55.9	55.9
Operating income, OI(n) = R(n)-Cfuel(n)-Co&m(n)	74.1	74.1	74.1	74.1	74.1	74.1	74.1
Loan balance at BOY, L(n) ($)	307.5	298.2	288.4	278.2	267.4	205.0	23.5
Loan payment,q ($)	24.7	24.7	24.7	24.7	24.7	24.7	24.7
Interest payment, I(n) ($)	15.4	14.9	14.4	13.9	13.4	10.2	1.2
Principal repayment, q-I(n) ($)	9.3	9.8	10.3	10.8	11.3	14.4	23.5
Depreciation allowance, D ($)	30.0	30.0	30.0	30.0	30.0	30.0	30.0
Taxable income, TI(n)=OI(n)-I(n)-D	28.7	29.2	29.6	30.2	30.7	33.8	42.9
Taxes, T(n)=0.38 TI(n)	10.9	11.1	11.3	11.5	11.7	12.9	16.3
Net income,NI(n)=OI(n)-q-T(n)	38.5	38.3	38.1	37.9	37.7	36.5	33.1
Outstanding equity at BOY,E(n)	315.0	308.0	300.5	292.4	283.7	229.1	30.4
Return on equity e(n)	31.5	30.8	30.1	29.2	28.4	22.9	3.0
Free funds available to reduce equity	7.0	7.5	8.1	8.7	9.4	13.6	30.1
price of gas $/MMBTU	3	3.5	4	4.5	5		
Cost of electricity cents per kWe-hr	3.904	4.264	4.624	4.984	5.344		


Levelized cost of electricity versus gas price
5.5
5.3
5.1
4.9
4.7
4.5
4.3
4.1
3.9
3.7
3.5
2.5
3
3.5
4
4.5
5
Price of gas $/MMBTU