Efficiency and Cost

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Metrics to compare conventional power plants & renewables

I) Thermal Efficiency ($\sim$ output/input)

> usually expressed as heat rate

- Heat rate:
  > thermal input (Btu or kJ) required to deliver 1kWh of electrical output
  [units: kJ/kWh or Btu/kWh]
  > Lower heat rate $\rightarrow$ better
  > heat rate $\propto \frac{1}{\eta}$ ← thermal efficiency
  > Average coal plant: $\eta = 33\%$, combined cycle: 45-50%
  > theoretical limit of Carnot Cycle: 65%

$$1\,\text{kWh} = 1\,\frac{\text{kJ}}{\text{s}} \cdot \frac{3600\,\text{s}}{\text{hr}} \cdot \text{hr} = 3600\,\text{kJ}$$

▸ If $\eta = 1$, heat rate = 3600 kJ/kWh

> In general, heat rate = $\dfrac{3600\ \text{kJ/kWh}}{\eta}\left[\dfrac{\text{kJ}}{\text{kWh}}\right]$

Since 1Btu/kWh = 1.055 kJ/kWh,

$$\text{heat rate} = \frac{3412\ \text{Btu/kWh}}{\eta}\left[\frac{\text{Btu}}{\text{kWh}}\right]$$

▪ Eg. Plant has heat rate = 10340 Btu/kWh

Burn coal with carbon content = 24.5 kg C/GJ

a) Efficiency of plant?

$$\eta = \frac{3412\ \text{Btu/kWh}}{10340\ \text{Btu/kWh}} = 0.33 = 33\%$$

b) Carbon emission rate?

$$\frac{24.5\ \text{kgC}}{10^9\ \text{J}} \cdot \frac{10340\ \text{Btu}}{\text{kWh}} \cdot \frac{1055\ \text{J}}{\text{Btu}} = 0.2673\ \text{kgC/kWh}$$

c) CO_2 emission rate?

Recall molecular weight of $CO_2 = 12 + 2(16) = 44\ g/mol$

$$\frac{0.2673\ kg\ C}{kWh} \cdot \frac{44g\ CO_2}{12\ g\ C} = 0.98\ kg\ CO_2/kWh$$

d) Suppose CO_2 is taxed at $\$10/ton = \$10/1000kg$. What is the additional cost of electricity?

$$\frac{0.98\ kg\ CO_2}{kWh} \cdot \frac{1000¢}{1000\ kg} = 0.98¢/kWh$$

II) Cost

> Borrow from lenders and investors to raise capital at the beginning of project with investment horizon of n years. A loan that converts capital costs into a series of equal annual payments that eventually pay off loan w/ interest (or return on investment)

> Also incurring costs annually

- **Fixed Costs:**
  - money that must be spent even if plant is never turned on.
    e.g. Capital Costs, property tax, insurance, fixed O&M
- **Variable Costs:**
  - additional cost of actually running the plant
    e.g. fuel, variable O&M
- **Levelized Cost of Energy (LCOE)**

$$LCOE\ [\$/kWh] = \frac{(\text{Annual fixed} + \text{Annual Variable})\ [\$/yr]}{\text{Annual energy output}\ [kWh/yr]}$$

(i) Annual Energy Output

> Plant rated power (P_R) → Power delivered at full capacity

> Capacity factor (CF) → $\dfrac{\text{Actual energy delivered}}{\text{energy that would have been delivered if plant had run continuously at } P_R} = \dfrac{\text{average power}}{\text{rated power}}$

or:

> equivalent number of hours per year of plant operation at rated power

$$\text{Annual energy}\left[\frac{kWh}{yr}\right] = P_R[kW] \cdot \frac{24\,hr}{day} \cdot \frac{365\,days}{1\,yr} \cdot CF$$

$$= 8760 \cdot P_R \cdot CF$$

(ii) Annual Fixed Cost [$/yr] = P_R [kW] · capital cost [$/kW] · FCR [%/yr]

> Fixed charge rate (FCR) → a constant payback rate that accounts for interest on loans and acceptable returns for investors

> Components include:

> Capital recovery factor (largest)

present value function

$$CRF(i,n) = (PVF(i,n))^{-1}$$

> property tax

> fixed O & M

(iii) Annual Variable Cost [$/yr]

> (fuel + O&M) [$/kWh] + Annual energy [kWh/yr]

can modify PVF to account for fuel cost escalation rate

$PVF(i',n)$

- Levelized cost estimation

① Find PV of all variables

$$PV = A_0 \cdot PVF(i',n)$$

... Present value of all future annual costs

② Find equivalent annual costs (like for fixed costs)

$$\text{Annualized variable cost} = \underbrace{A_0 \cdot PVF(i',n) \cdot CRF(i,n)}_{\text{Call the levelizing factor (LF)}}$$

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$\rightarrow$ Annual fuel cost [\$/yr] = Energy [kWh/yr] $\cdot$ Heat rate [Btu/kWh] $\cdot$ Current fuel cost [\$/Btu] $\cdot$ LF

P_R [kW] $\cdot$ 8760 [hr/yr] $\cdot$ CF

$\rightarrow$ Annual variable cost [\$/yr] = fuel cost [\$/yr] = fuel cost [\$/yr] + O&M [\$/kWh] $\cdot$ Energy [kWh/yr]

Combine (i), (ii), (iii) to compute LCOE