Toolbox 7: Economic Feasibility Assessment Methods

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Introduction

- We have a working definition of sustainability
- We need a consistent way to calculate energy costs
- This helps to make fair comparisons
- Good news: most energy costs are quantifiable
- Bad news: lots of uncertainties in the input data
  - Interest rates over the next 40 years
  - Cost of natural gas over the next 40 years
  - Will there be a carbon tax?
- Today's main focus is on economics
- Goal: Show how to calculate the cost of energy in cents/kWhr for any given option
- Discuss briefly the importance of energy gain

Basic Economic Concepts

- Use a simplified analysis
- Discuss return on investment and inflation
- Discuss net present value
- Discuss levelized cost

The Value of Money

- The value of money changes with time
- 40 years ago a car cost $2,500
- Today a similar car may cost $25,000
- A key question – How much is a dollar *n* years from now worth to you today?
- To answer this we need to take into account
  - Potential from investment income while waiting
  - Inflation while waiting

Present Value

- Should we invest in a power plant?
- What is total outflow of cash during the plant lifetime?
- What is the total revenue income during the plant lifetime
- Take into account inflation
- Take into account rate of return
- Convert these into today's dollars
- Calculate the "present value" of cash outflow
- Calculate the "present value" of revenue

Net Present Value

- Present value of cash outflow: PV_{cost}
- Present value of revenue: PV_{rev}
- Net present value is the difference

$$NPV = PV_{rev} - PV_{cost}$$

- For an investment to make sense

$$NPV > 0$$

Present Value of Cash Flow

- \$100 today is worth \$100 today – obvious
- How much is \$100 in 1 year worth to you today?
- Say you start off today with \$$P_i$
- Invest it at a yearly rate of i_R%=10%
- One year from now you have \$(1+ i_R)P_i=\$1.1P_i
- Set this equal to \$100
- Then

$$P_i = \frac{\$100}{1+i_R} = \frac{\$100}{1.1} = \$90.91$$

- This is the present value of \$100 a year from now

Generalize to *n* years

- \$P *n* years from now has a present value to you today of

$$PV(P) = \frac{P}{\left(1 + i_R\right)^n}$$

- This is true if you are spending \$P *n* years from now
- This is true for revenue \$P you receive *n* years from now
- Caution: Take taxes into account $i_R = (1 - i_{Tax}) i_{Tot}$

The Effects of Inflation

- Assume you buy equipment *n* years from now that costs $\$P_n$
- Its present value is

$$PV(P_n) = \frac{P_n}{\left(1 + i_R\right)^n}$$

- However, because of inflation the future cost of the equipment is higher than today's price
- If i_I is the inflation rate then

$$P_n = \left(1 + i_I\right)^n P_i$$

The Bottom Line

- Include return on investment and inflation
- $\$P_i$ *n* years from now has a present value to you today of

$$PV = \left(\frac{1 + i_I}{1 + i_R}\right)^n P_i$$

- Clearly for an investment to make sense

$$i_R > i_I$$

Costing a New Nuclear Power Plant

- Use NPV to cost a new nuclear power plant
- Goal: Determine the price of electricity that
  - Sets the NPV = 0
  - Gives investors a good return
- The answer will have the units *cents/kWhr*

Cost Components

- The cost is divided into 3 main parts

$$\text{Total} = \text{Capital} + \text{O\&M} + \text{Fuel}$$

- Capital: Calculated in terms of hypothetical "overnight cost"
- O&M: Operation and maintenance
- Fuel: Uranium delivered to your door
- "Busbar" costs: Costs at the plant
- No transmission and distribution costs

Key Input Parameters

- Plant produces P_e = 1 GWe
- Takes T_C = 5 years to build
- Operates for T_P = 40 years
- Inflation rate i_I = 3%
- Desired return on investment i_R = 12%

Capital Cost

- Start of project: Now = 2000 → year $n = 0$
- Overnight cost: P_{over} = \$2500M
- No revenue during construction
- Money invested at $i_R = 12\%$
- Optimistic but simple
- Cost inflates by $i_I = 3\%$ per year

Construction Cost Table

Year	Construction Dollars	Present Value
2000	500 M	500 M
2001	515 M	460 M
2002	530 M	423 M
2003	546 M	389 M
2004	563 M	358 M

Mathematical Formula

- Table results can be written as

$$PV_{CAP} = \frac{P_{over}}{T_C} \sum_{n=0}^{T_c - 1} \left(\frac{1 + i_I}{1 + i_R} \right)^n$$

- Sum the series

$$PV_{CAP} = \frac{P_{over}}{T_C} \left(\frac{1 - \alpha^{T_C}}{1 - \alpha} \right) = \$2129M$$

$$\alpha = \frac{1 + i_I}{1 + i_R} = 0.9196$$

Operations and Maintenance

- O&M covers many ongoing expenses
  - Salaries of workers
  - Insurance costs
  - Replacement of equipment
  - Repair of equipment
- Does not include fuel costs

Operating and Maintenance Costs

- O&M costs are calculated similar to capital cost
- One wrinkle: Costs do not occur until operation starts in 2005
- Nuclear plant data shows that O&M costs in 2000 are about

$$P_{OM} = \$95M\ /\ yr$$

- O&M work the same every year

Formula for O&M Costs

- During any given year the PV of the O&M costs are

$$PV_{OM}^{(n)} = P_{OM}\left(\frac{1+i_I}{1+i_R}\right)^n$$

- The PV of the total O&M costs are

$$PV_{OM} = \sum_{n=T_C}^{T_C+T_P-1} PV_{OM}^{(n)}$$

$$= P_{OM}\sum_{n=T_C}^{T_C+T_P-1}\left(\frac{1+i_I}{1+i_R}\right)^n$$

$$= P_{OM}\alpha^{T_C}\left(\frac{1-\alpha^{T_P}}{1-\alpha}\right) = \$750M$$

Fuel Costs

- Cost of reactor ready fuel in 2000 $K_F = \$2000\,/\,kg$
- Plant capacity factor $f_c = 0.85$
- Thermal conversion efficiency $\eta = 0.33$
- Thermal energy per year

$$W_{th} = \frac{f_c P_e T}{\eta} = \frac{(0.85)\left(10^6 kWe\right)(8760hr)}{(0.33)} = 2.26 \times 10^{10}\ kWhr$$

- Fuel burn rate $B = 1.08 \times 10^6\ kWhr\,/\,kg$
- Yearly mass consumption

$$M_F = \frac{W_{th}}{B} = 2.09 \times 10^4\ kg$$

Fuel Formula

- Yearly cost of fuel in 2000

$$P_F = K_F M_F = \$41.8M\,/\,yr$$

- PV of total fuel costs

$$PV_F = P_F \alpha^{T_C} \left(\frac{1-\alpha^{T_P}}{1-\alpha} \right) = \$330M$$

Revenue

- Revenue also starts when the plant begins operation
- Assume a return of $i_R = 12\%$
- Denote the cost of electricity in 2000 by *COE* measured in *cents/kWhr*
- Each year a 1GWe plant produces

$$W_e = \eta W_{th} = 74.6 \times 10^8 \ kWhr$$

Formula for Revenue

- The equivalent sales revenue in 2000 is

$$P_R = \frac{(COE)(W_e)}{100} = \frac{(COE)\, f_c P_e T}{100} = (\$74.6M) \times COE$$

- The PV of the total revenue

$$PV_R = P_R \alpha^{T_C} \left(\frac{1-\alpha^{T_P}}{1-\alpha} \right) = \$(74.6M)(COE)\,\alpha^{T_C} \left(\frac{1-\alpha^{T_P}}{1-\alpha} \right)$$

Balance the Costs

- Balance the costs by setting NPV = 0

$$PV_R = PV_{cons} + PV_{OM} + PV_F$$

- This gives an equation for the required *COE*

$$COE = \frac{100}{f_c P_e T}\left[\frac{P_{over}}{T_C}\frac{1}{\alpha^{T_C}}\left(\frac{1-\alpha^{T_C}}{1-\alpha^{T_P}}\right) + P_{OM} + P_F\right]$$

$$= \quad 3.61 + 1.27 + 0.56 = 5.4\ cents\,/\,kWhr$$

Potential Pitfalls and Errors

- Preceding analysis shows method
- Preceding analysis highly simplified
- Some other effects not accounted for
  - Fuel escalation due to scarcity
  - A carbon tax
  - Subsidies (e.g. wind receives *1.5 cents/kWhr*)

More

- More effects not accounted for
  - Tax implications – income tax, depreciation
  - Site issues – transmission and distribution costs
  - Cost uncertainties – interest, inflation rates
  - O&M uncertainties – mandated new equipment
  - Decommissioning costs
  - By-product credits – heat
  - Different f_c – base load or peak load?

Economy of Scale

- An important effect not included
- Can be quantified
- Basic idea – "bigger is better"
- Experience has shown that

$$\frac{C_{cap}}{P_e} = \frac{C_{ref}}{P_{ref}} \left(\frac{P_{ref}}{P_e} \right)^{\alpha}$$

- Typically $\alpha \approx 1/3$

Why?

- Consider a spherical tank
- Cost $\propto$ Material $\propto$ Surface area: $C \propto 4\pi R^2$
- Power $\propto$ Volume: $P \propto (4/3)\pi R^3$
- COE scaling: $C/P \propto 1/R \propto 1/P^{1/3}$
- Conclusion:

$$\frac{C_{cap}}{C_{ref}} = \left(\frac{P_e}{P_{ref}}\right)^{1-\alpha}$$

- This leads to plants with large output power

The Learning Curve

- Another effect not included
- The idea – build a large number of identical units
- Later units will be cheaper than initial units
- Why? Experience + improved construction
- Empirical evidence – cost of n^{th} unit

$$C_n = C_1 n^{-\beta}$$

$$\beta \approx -\frac{\ln f}{\ln 2}$$

- f = improvement factor / unit: $f \sim 0.85 \quad \rightarrow \quad \beta = 0.23$

An example – Size vs. Learning

- Build a lot of small solar cells (learning curve)?
- Or fewer larger solar cells (economy of scale)?
- Produce a total power P_e with N units
- Power per unit: $p_e = P_e/N$
- Cost of the first unit with respect to a known reference

$$C_1 = C_{ref} \left(\frac{p}{p_{ref}} \right)^{1-\alpha} = C_{ref} \left(\frac{N_{ref}}{N} \right)^{1-\alpha}$$

Example – cont.

- Cost of the n^{th} unit

$$C_n = C_1 n^{-\beta} = C_{ref}\left(\frac{N_{ref}}{N}\right)^{1-\alpha} n^{-\beta}$$

- Total capital cost: sum over separate units

$$C_{cap} = \sum_{n=1}^{N} C_n = C_{ref}\left(\frac{N_{ref}}{N}\right)^{1-\alpha}\sum_{n=1}^{N} n^{-\beta} \approx C_{ref}\left(\frac{N_{ref}}{N}\right)^{1-\alpha}\int_1^N n^{-\beta}dn$$
$$= \frac{C_{ref}N_{ref}^{1-\beta}}{1-\beta}N^{\alpha-\beta} \propto N^{\alpha-\beta}$$

- If $\alpha > \beta$ we want a few large units
- It's a close call – need a much more accurate calculation

Dealing With Uncertainty

- Accurate input data $\rightarrow$ accurate COE estimate
- Uncertain data $\rightarrow$ error bars on COE
- Risk $\propto$ size of error bars
- Quantify risk $\rightarrow$ calculate COE $\pm$ standard deviation
- Several ways to calculate σ, the standard deviatiation
  - Analytic method
  - Monte Carlo method
  - Fault tree method
- We focus on analytic method

The Basic Goal

- Assume uncertainties in multiple pieces of data
- Goal: Calculate σ for the overall COE including all uncertainties
- Plan:
  - Calculate σ for a single uncertainty
  - Calculate σ for multiple uncertainties

The Probability Distribution Function

- Assume we estimate the most likely cost for a given COE contribution.
- E.g. we expect the COE for fuel to cost *C = 1 cent/kWhr*
- Assume there is a bell shaped curve around this value
- The width of the curve measures the uncertainty
- This curve *P(C)* is the probability distribution function
- It is normalized so that its area is equal to unity

$$\int_0^\infty P(C)\,dC = 1$$

- The probability is 1 that the fuel will cost something

The Average Value

- The average value of the cost is just

$$\bar{C} = \int_0^\infty C P(C)\, dC$$

- The normalized standard deviation is defined by

$$\sigma = \frac{1}{\bar{C}} \left[\int_0^\infty \left(C - \bar{C}\right)^2 P(C)\, dC \right]^{1/2}$$

- A Gaussian distribution is a good model for *P(C)*

$$P(C) = \frac{1}{(2\pi)^{1/2} \sigma \bar{C}} \exp\left[-\frac{\left(C - \bar{C}\right)^2}{2\left(\sigma \bar{C}\right)^2} \right]$$

Multiple Uncertainties

- Assume we know $\overline{C}$ and σ for each uncertain cost.
- The values of $\overline{C}$ are what we used to determine COE.
- Specifically the total average cost is the sum of the separate costs:

$$\overline{C}_{Tot} = \sum_j \int C_j P_j(C_j) dC_j = \sum \overline{C}_j.$$

- The total standard deviation is the root of quadratic sum of the separate contributions (assuming independence of the C_j) again normalized to the mean:

$$\sigma_{Tot} = \frac{\sqrt{\sum_j (\overline{C}_j \sigma_j)^2}}{\sum_j \overline{C}_j}$$

An Example

- We need weighting - why?
- Low cost entities with a large standard deviation do not have much effect of the total deviation
- Consider the following example
  - $C_{cap} = 3.61$, $\sigma_c = 0.1$
  - $C_{O\&M} = 1.27$, $\sigma_{OM} = 0.15$
  - $C_{fuel} = 0.56$, $\sigma_f = 0.4$

Example Continued

- The total standard deviation is then given by

$$\sigma = \frac{\sqrt{(\sigma_c \overline{C}_{cap})^2 + (\sigma_{OM} \overline{C}_{O\&M})^2 + (\sigma_f \overline{C}_{fuel})^2}}{\overline{C}_{cap} + \overline{C}_{O\&M} + \overline{C}_{fuel}}$$

$$= \frac{\sqrt{0.130 + 0.0363 + 0.0502}}{5.4} = 0.086$$

- Large σ_f has a relatively small effect.
- Why is the total uncertainty less than the individual ones? (Regression to the mean)

22.081J / 2.650J / 10.291J / 1.818J / 2.65J / 10.391J / 11.371J / 22.811J / ESD.166J
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