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: $PV_{\text{cost}}$
- Present value of revenue: $PV_{\text{rev}}$
- Net present value is the difference

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

- 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

\[
PV(P) = \frac{P}{(1 + i_R)^n}
\]

- 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 $i_R = (1 - i_{\text{Tax}})i_{\text{Tot}}$
The Effects of Inflation

- Assume you buy equipment $n$ years from now that costs $P_n$
- Its present value is
  \[ PV(P_n) = \frac{P_n}{(1 + i_R)^n} \]
- However, because of inflation the future cost of the equipment is higher than today’s price
  \[ P_n = (1 + i_I)^n P_i \]
The Bottom Line

- Include return on investment and inflation
- $P_i \times n$ 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 $P_e = 1 \text{ GWe}$
- 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: \( P_{\text{over}} = \$2500M \)
- No revenue during construction
- Money invested at \( i_R = 12\% \)
- Optimistic but simple
- Cost inflates by \( i_I = 3\% \) per year
## Construction Cost Table

<table>
<thead>
<tr>
<th>Year</th>
<th>Construction Dollars</th>
<th>Present Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>500 M</td>
<td>500 M</td>
</tr>
<tr>
<td>2001</td>
<td>515 M</td>
<td>460 M</td>
</tr>
<tr>
<td>2002</td>
<td>530 M</td>
<td>423 M</td>
</tr>
<tr>
<td>2003</td>
<td>546 M</td>
<td>389 M</td>
</tr>
<tr>
<td>2004</td>
<td>563 M</td>
<td>358 M</td>
</tr>
</tbody>
</table>
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 $K_F = \$2000 / \text{kg}$
- Plant capacity factor $f_c = 0.85$
- Thermal conversion efficiency $\eta = 0.33$
- Thermal energy per year

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

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

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

$$W_e = \eta W_{th} = 74.6 \times 10^8 \text{ kWhr}$$
The equivalent sales revenue in 2000 is

\[ P_R = \frac{(COE)(W_e)}{100} = \frac{(COE)f_cP_eT}{100} = ($74.6M) \times COE \]

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 $\text{NPV} = 0$

\[ PV_R = PV_{cons} + PV_{OM} + PV_F \]

- This gives an equation for the required $\text{COE}$

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

\[ = 3.61 + 1.27 + 0.56 = 5.4 \text{ cents/kWhr} \]
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 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: $f \sim 0.85 \rightarrow \beta = 0.23$
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 → accurate COE estimate
- Uncertain data → error bars on COE
- Risk $\propto$ size of error bars
- Quantify risk → calculate COE ± standard deviation
- Several ways to calculate $\sigma$, the standard deviation
  - 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 $\sigma$ for the overall COE including all uncertainties
- Plan:
  - Calculate $\sigma$ for a single uncertainty
  - Calculate $\sigma$ 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 $C = 1 \text{ cent/kWhr}$
- 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
  \[ \sigma = \frac{1}{\bar{C}} \left[ \int_0^\infty (C - \bar{C})^2 P(C) \, dC \right]^{1/2} \]

- A Gaussian distribution is a good model for \( P(C) \)
  \[ P(C) = \frac{1}{(2\pi)^{1/2} \sigma \bar{C}} \exp\left[ -\frac{(C - \bar{C})^2}{2(\sigma \bar{C})^2} \right] \]
**Multiple Uncertainties**

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

\[
\bar{C}_{Tot} = \sum_j \int C_j P_j(C_j) dC_j = \sum \bar{C}_j.
\]

- 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:

\[
\sigma_{Tot} = \frac{\sqrt{\sum_j (\bar{C}_j \sigma_j)^2}}{\sum_j \bar{C}_j}
\]
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
  - $C_{\text{cap}} = 3.61$, $\sigma_c = 0.1$
  - $C_{\text{O&M}} = 1.27$, $\sigma_{OM} = 0.15$
  - $C_{\text{fuel}} = 0.56$, $\sigma_f = 0.4$
The total standard deviation is then given by

\[ \sigma = \sqrt{(\sigma_C \overline{C}_{\text{cap}})^2 + (\sigma_{OM} \overline{C}_{O&M})^2 + (\sigma_f \overline{C}_{\text{fuel}})^2} \]

\[ \frac{\overline{C}_{\text{cap}} + \overline{C}_{O&M} + \overline{C}_{\text{fuel}}}{5.4} \]

\[ = \sqrt{0.130 + 0.0363 + 0.0502} = 0.086 \]

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