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SUSTAINABLE ENERGY

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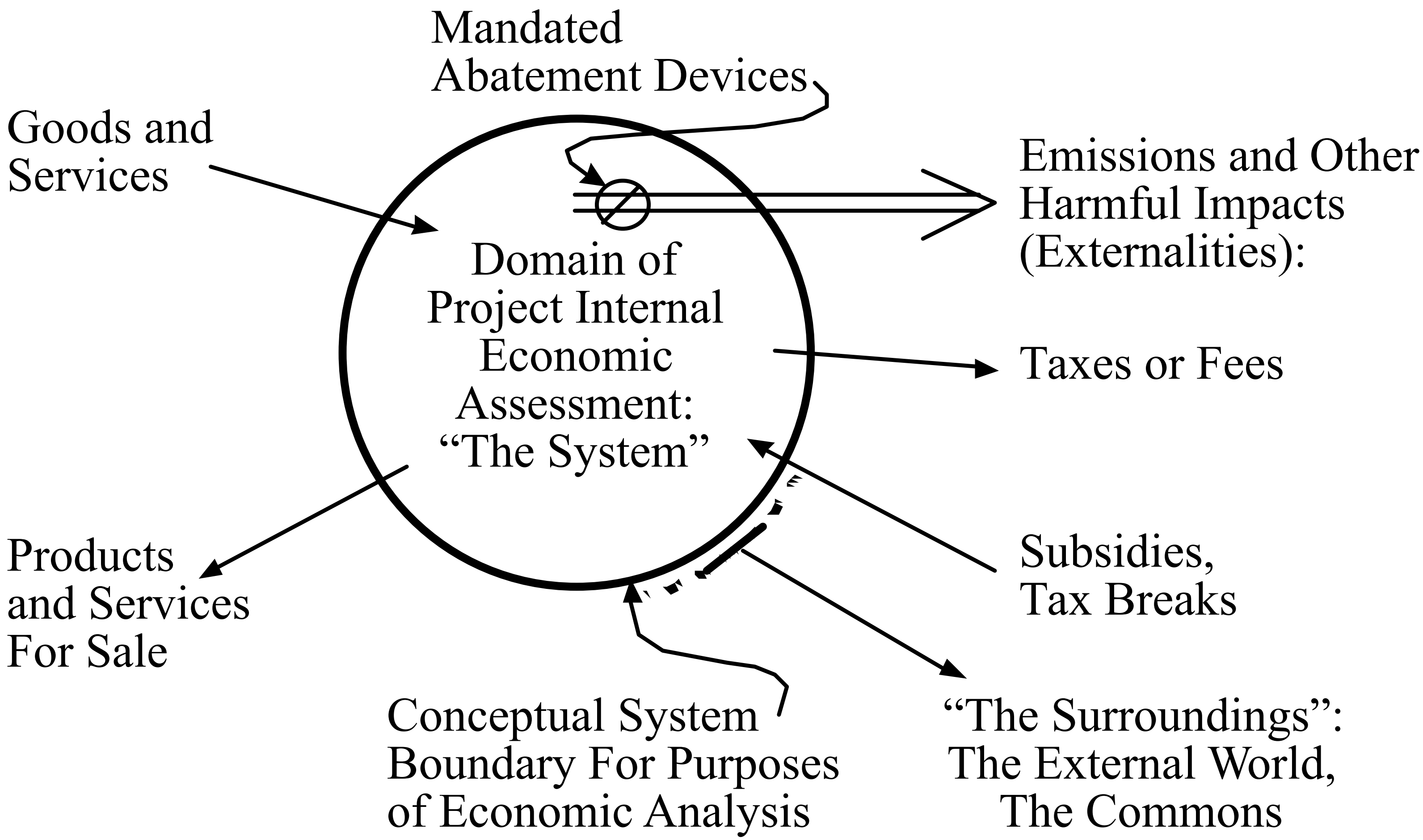
ECONOMIC FEASIBILITY AND ASSESSMENT METHODS

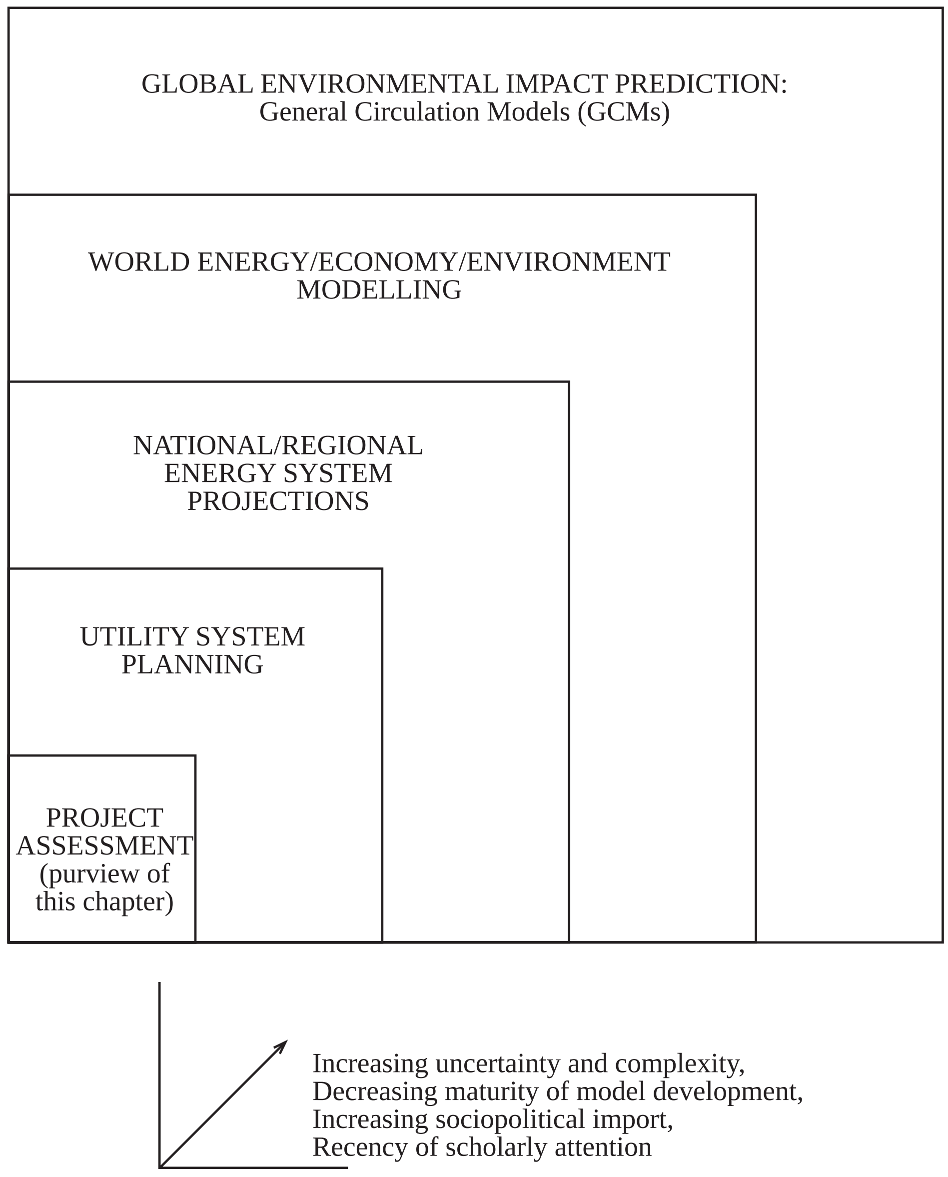
PROJECT LEVEL ECONOMIC ANALYSES LECTURE OUTLINE

- Introduction – Levels of Analysis
- Time Value of Money and Discounting
- Inflation
- Economies of Scale and Learning (serial production)
- Treatments of Uncertainty
- Externalities

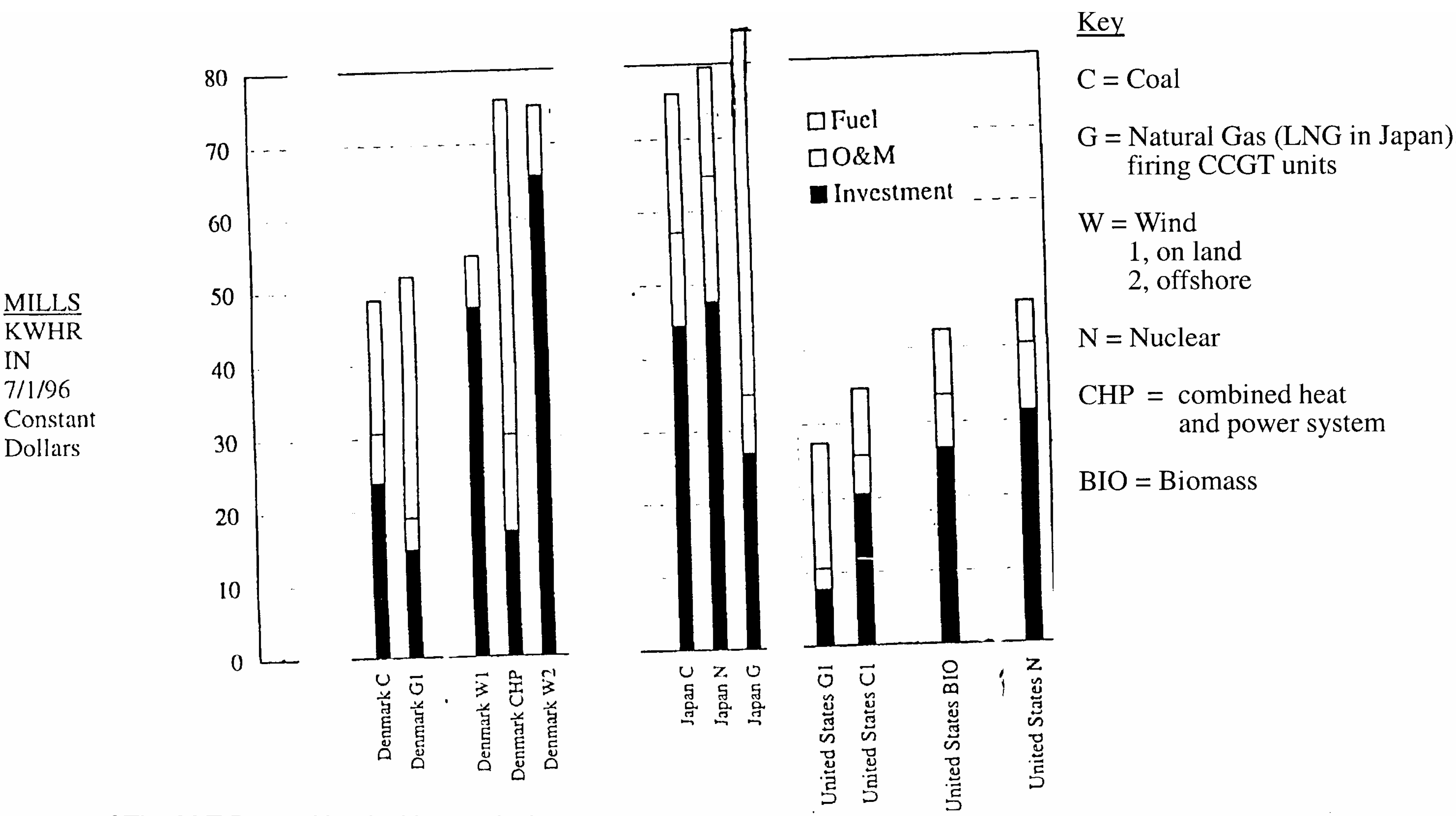
SCHEMATIC OF OUR POINT OF VIEW FOR ECONOMIC ANALYSES



HIERARCHY OF ENERGY MODELS



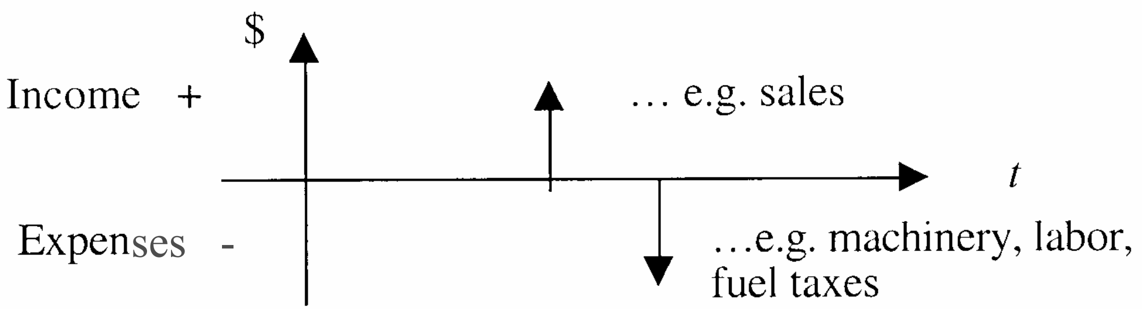
LEVELIZED ELECTRICITY GENERATION (BUSBAR) COST PROJECTIONS (at 10%/yr Real Discount Rate)



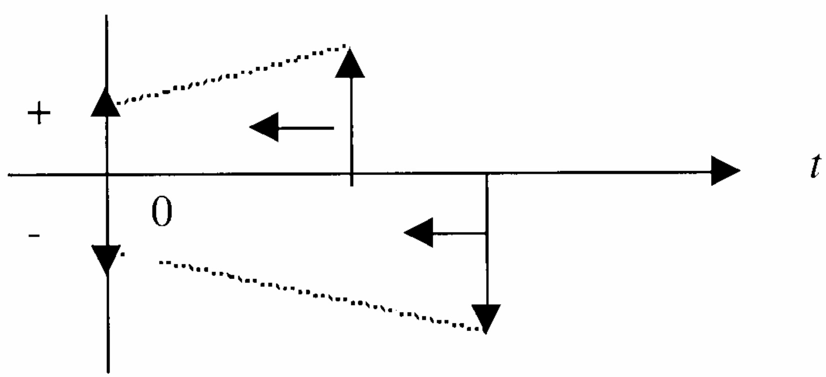
Source: Figure 5.3 in Tester, et al. *Sustainable Energy: Choosing Among Options*. Cambridge, MA: MIT Press, 2005.

HOW TO CALCULATE LIFETIME LEVELIZED COST AND/OR RATE OF RETURN

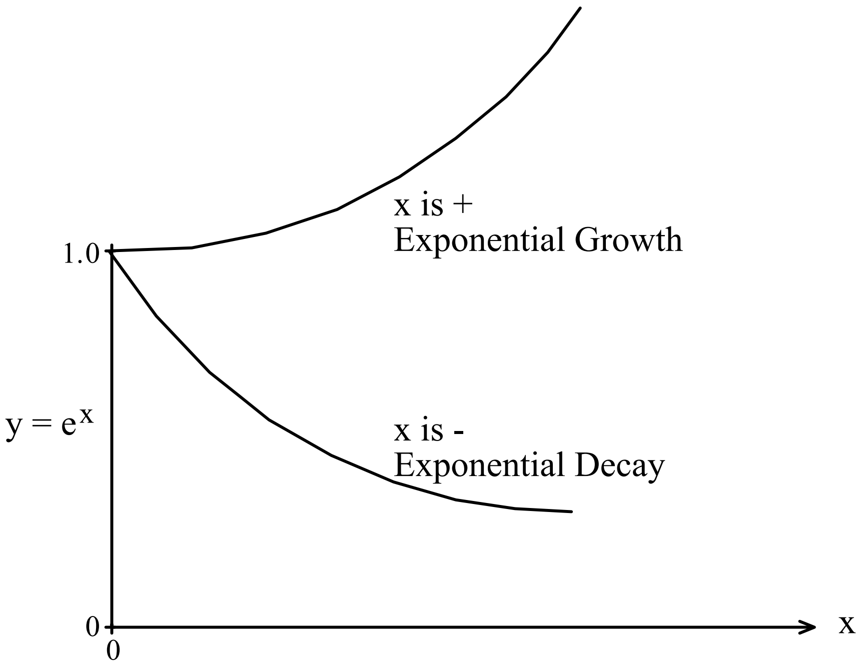
(1) Draw a cash flow diagram showing all cost vectors as a function of time.

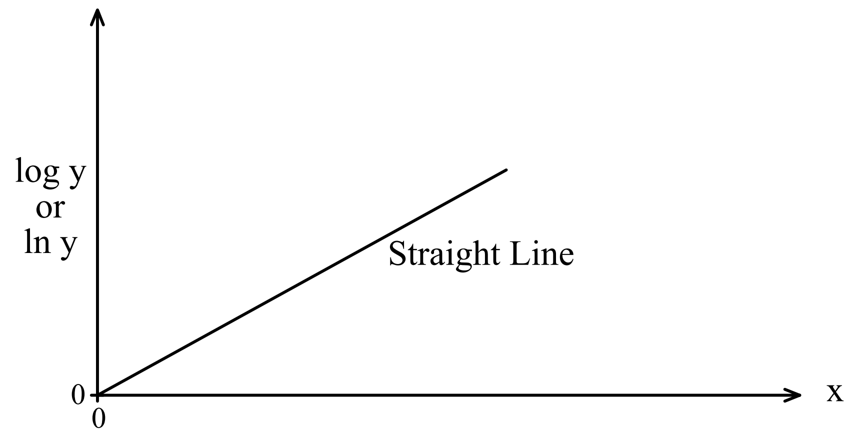


(2) Bring all cash flows back to time zero using $P = F\,e^{-it}$ and (separately) sum revenues and expenses.



ILLUSTRATIVE BEHAVIOR OF THE EXPONENTIAL FUNCTION





The exponential function applies to processes where the % increase in *y* is a fixed fraction of the % increase in *x*.

Pragmatically:

Just push the e^x button on your scientific calculator

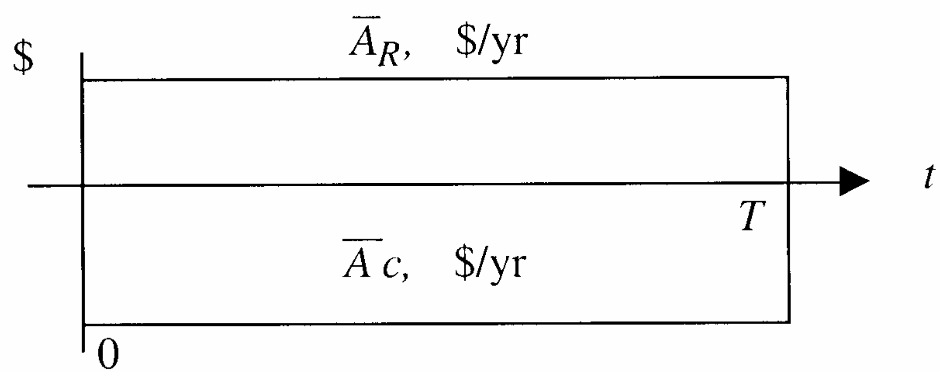
or

Use the exp(x) function in most computer languages.

HOW TO CALCULATE LIFETIME LEVELIZED COST AND/OR RATE OF RETURN, Continued

(3) Using $\overline{A} = \left[\frac{i}{1 - e^{-iT}} \right] P_T$, redistribute all j cash flows, $\sum_j P_j$, uniformly over the appropriate time horizon, T, with

$$\overline{A} = \frac{i \sum_j P_j}{\left(1 - e^{-iT}\right)}$$



(4) Equate levelized revenues and costs to calculate either

- cost of product at a specified rate of return

or

- rate of return for a projected viable price for the product

PRESENT WORTH OF A UNIFORM DISCRETE SERIES OF CASH FLOWS

The familiar geometric series encountered in algebra texts has a first term A at the beginning of the first interval and successive terms weighted by the ratio R to the power $(n-1)$.

It has the sum

$$S = A + AR + \ldots AR^{n-1} = A\left[\frac{1-R^n}{1-R}\right]$$

In engineering economics we are often interested in the present worth of a series of uniform discrete cash flows starting at the end of the first interval.

Hence

$$P = S - A$$

$$N = n - 1$$

$$R = \begin{cases} e^{-i} & \text{for continuous compounding} \\ (1+x)^{-1} & \text{for periodic compounding at the end of interval} \end{cases}$$

PRESENT WORTH OF A UNIFORM DISCRETE SERIES OF CASH FLOWS, Continued

Therefore

$$P = A\left[\frac{e^{Ni}-1}{\left(e^{i}-1\right)e^{Ni}}\right]; \quad P = A\left[\frac{(1+x)^{N}-1}{x(1+x)^{N}}\right],$$

which also satisfies the equivalence $i = \ln(1 + x)$.

Note that the continuous compounding result is for discrete cash flows; for continuous cash flows: of $\overline{A}$ \$/yr starting at time zero one has the substitutions

$$A = \frac{\overline{A}}{i}\left(e^{i}-1\right)$$

$$A = \overline{A}\left[\frac{x}{\ln(1+x)}\right]$$

Details on derivations and applications of the above expressions are found in most engineering economics textbooks.

LIFETIME-LEVELIZED BUSBAR COST OF ELECTRICAL ENERGY*

e_b cents per kilowatt hour (0.1 times mills per kilowatt hour) is the sum of:

CAPITAL-RELATED COSTS:

$$\frac{100\,\phi}{8766 \cdot L}\left(\frac{I}{K}\right)_{-c}\left[1+\frac{x+y}{2}\right]^{c}$$

PLUS OPERATING AND MAINTENANCE COSTS:

$$+\frac{100}{8766 \cdot L}\left(\frac{O}{K}\right)_{o}\left[1+\frac{yT}{2}\right]$$

PLUS FUEL COSTS:

$$+\begin{cases} \text{Nuclear} & \left[\dfrac{100}{24}\,\dfrac{F_o}{\eta\,B}\right]\left[1+\dfrac{yT}{2}\right] \\ \text{or} & \\ \text{Fossil} & \left[\dfrac{0.34\,f_o}{\eta}\right]\left[1+\dfrac{yT}{2}\right] \end{cases}$$

*Note that these costs represent only the cost of generating the electricity, i.e., excluding transmission and distribution. These costs are lifetime-average (i.e., "levelized") costs for a new plant starting operations today.

LIFETIME-LEVELIZED BUSBAR COST OF ELECTRICAL ENERGY, Continued

where

		Typical LWR Value
L	= plant capacity factor: actual energy output ÷ energy if always at 100% rated power	0.80
ϕ	= annual fixed charge rate (i.e., effective "mortgage" rate) = $x/(1-\tau)$ where x is the discount rate, and τ is the tax fraction (0.4)	0.15/yr
x	= $(1-\tau)b \cdot r_b + (1-b)r_s$, in which b is the fraction of capital raised selling bonds (debt fraction), and r_b is the annualized rate of return on bonds, while r_s is the return on stock (equity)	0.09/yr
$\left(\frac{I}{K}\right)_{-c}$	= oversight specific capital cost of plant, as of the start of construction, dollars per kilowatt: cost if it could be constructed instantaneously c years before startup in dollars without inflation or escalation	1400$/KWe
y	= annual rate of monetary inflation (or price escalation, if different)	0.04/yr
c	= time required to construct plant, years	5 yrs
T	= prescribed useful life of plant, years	30 yrs
$\left(\frac{O}{K}\right)_{o}$	= specific operating and maintenance cost as of start of operation, dollars per kilowatt per year	95$/KWe yr

LIFETIME-LEVELIZED BUSBAR COST OF ELECTRICAL ENERGY, Continued

η =	plant thermodynamic efficiency, net kilowatts electricity produced per kilowatt of thermal energy consumed	0.33
F_o =	net unit cost of nuclear fuel, first steady-state reload batch, dollars per kilogram of uranium; including financing and waste disposal charges, as of start of plant operation	2000$/kg
B =	burnup of discharged nuclear fuel, megawatt days per metric ton	45,000
f_o =	fossil fuel costs, at start of operation, cents per million British thermal units = (approximately) dollars per barrel times 16 for residual oil; dollars per ton times 4 for steam coal; cents per thousand standard cubic feet for natural gas; zero for solar or fusion energy	

Thus for a light water reactor (LWR) nuclear power plant, using the representative values cited above:

		Cap	+	O&M	+	Fuel		
e_b	=	4.1	+	2.2	+	0.9	=	7.2 cents/kWhre

$$\int_{o}^{T} \overline{A}\, e^{-it}\, dt = P_T \qquad \text{Eq. (1)}$$

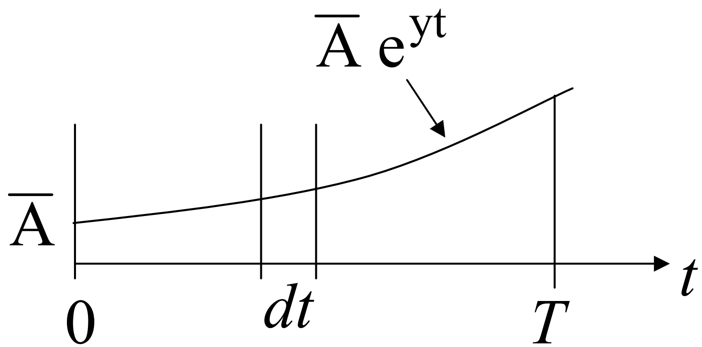
Thus

$$\overline{A} = \left[\frac{i}{1 - e^{-iT}}\right] P_T \qquad \text{Eq. (2)}$$

In the limit of large T

$$\overline{A} \Rightarrow iP_T \qquad \text{Eq. (3)}$$

Consider a uniform annual rate of expenditure, \$/yr, but escalated at y/yr over a period T, discounted at x/yr.



Levelizing to find the equivalent annual rate $\overline{A}_L$

$$\int_o^T \overline{A}_L\, e^{-xt}\, dt = \int_o^T \overline{A}\, e^{yt}\, e^{-xt}\, dt \qquad \text{Eq. (4)}$$

Then

$$\frac{\overline{A}_L}{\overline{A}} = \frac{\int_o^T e^{-(x-y)t} dt}{\int_o^T e^{-xt} dt} = \left(\frac{x}{x-y}\right) \frac{1 - e^{-(x-y)T}}{1 - e^{-xT}} \qquad \text{Eq. (5)}$$

Expand the exponentials as Taylor series and retain terms through second order, which yields to first order:

$$\frac{\overline{A}_L}{\overline{A}} = \frac{1 - \frac{(x-y)}{2} T + \ldots}{1 - \frac{x}{2} T + \ldots} \approx 1 + \frac{y}{2} T + \ldots \qquad \text{Eq. (6)}$$

which is the multiplier used on today's O&M and fuel costs used to calculate the Lifetime-Levelized Busbar Cost of Electrical Energy (slides 10 through 12).

$$F = e^{xT} \int_{o}^{T} \overline{A}\, e^{yt}\, e^{-xt}\, dt \qquad \text{Eq. (7)}$$

Integration yields

$$F = (\overline{A}\, T)\, e^{xT} \left[\frac{1 - e^{yT}\, e^{-xT}}{(x-y)T} \right] \qquad \text{Eq. (8)}$$

and series expansion gives to first order

$$F = (\overline{A}\, T) \left[1 - \frac{(x-y)}{2} T \right] [1 + x\, T]$$

or

$$F = (\overline{A}\, T) \left[1 + \frac{x+y}{2} T \right] \approx (\overline{A}\, T) \left[1 + \frac{x+y}{2} \right]^{T} \qquad \text{Eq. (9)}$$

which is the desired relation.

For the examples in slides 10 through 12, we can compare the "exact" exponential relations (Eqs. 5 and 8) to their linearized versions (Eqs. 6 and 9):

(1) Let $T = 30$ yrs, $y = 0.04$/yr, and $x = 0.09$/yr

Then exact 1.50

Whereas $\left(1 + \frac{yT}{2}\right) = 1.6$; 6.7% high.

(2) Let $T = c = 5$ yrs, $y = 0.04$/yr, and $x = 0.09$/yr

The exact = 1.39

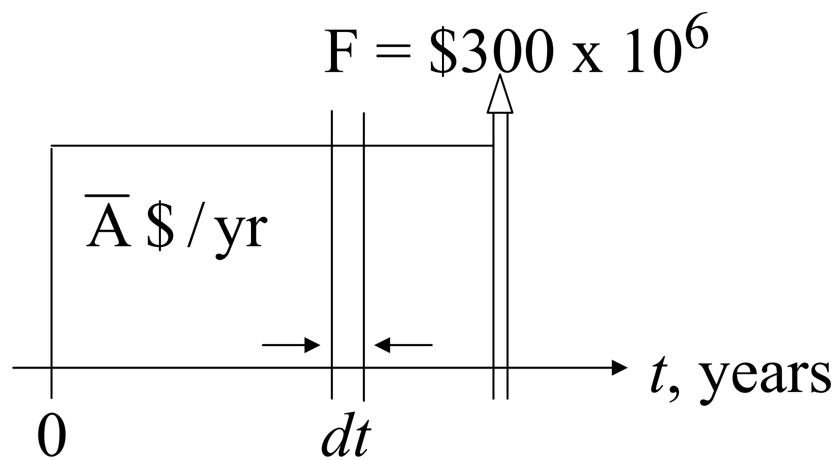
Whereas $\left[1 + \frac{x + y}{2}\right]^{c} = 1.37$; 1.4% low.

SAMPLE PROBLEM

Question: In some jurisdictions, owners must contribute to a separate interest earning account—a so-called sinking fund— to provide a future amount sufficient to decommission a nuclear power plant at the end of its useful life. Working in constant dollars, calculate the uniform rate of contributions in dollars per year at a real interest rate of 5% per year, which will total 300 million in today's dollars 30 years from now.

Specimen Solution

We have the cash flow time diagram:



Question: Suppose instead that the utility were required to deposit a sufficient amount as a single up-front payment.

Answer: We merely need to compute the present worth of 300 M$ @ 5% yr for 30 years.

$$P = 300 \bullet e^{-0.05(30)}$$
$$= \underline{66.94 \text{ million dollars}} \text{ (in today's, i.e. constant, dollars)}$$

Following the algorithm recommended in slides 5 and 7, we equate present worths (in millions of dollars):

$$\int_0^{30} \overline{A}\, e^{-0.05t}\, dt = 300\, e^{-0.05(30)}$$

carrying out the integration gives:

$$\frac{\overline{A}}{0.05}\left(1 - e^{-0.05(30)}\right) = 300 e^{-1.5}$$

or

$$\overline{A} = \frac{(300)(0.05)}{\left(e^{1.5} - 1\right)} = \underline{\text{4.31 million dollars per year}}$$

which is only a few percent of the annual carrying charge rate on a plant costing on the order of two billion dollars.

Question: What would the actual fund accrue in t = 30 year dollars if the rate of inflation anticipated is 3% per year.

Answer: The market interest rate would then be 5 + 3 = 8% yr and the future worth:

$$
\begin{aligned}
F &= 66.94\, e^{0.08(30)} \\
&= \underline{738 \text{ million dollars}}
\end{aligned}
$$

A simple example will help illuminate this issue. Consider a generating facility having an initial capital cost I_0 \$ and a lifetime of T years over which O&M costs, initially at the rate A_0 \$/yr, escalate exponentially with time at the rate of monetary inflation, y per yr, i.e.,:

$$\overline{A}(t) = A_o e^{yt} \qquad \text{Eq. (10)}$$

Discount rates are:

Constant dollars $x = x_0$ per year

Current dollars $x = x_0 + y$ per year

Furthermore, we neglect the effect of taxes and hence take x as the cost of borrowed money for our capital investment.

Then the lifetime levelized O&M cost is:

$$\overline{A}_L \int_o^T e^{-xt}\, dt = A_o \int_o^T e^{yt}\, e^{-xt}\, dt \qquad \text{Eq. (11)}$$

From which:

$$\frac{\overline{A}_L}{A_o} = \left(\frac{x}{x-y}\right)\left(\frac{1-e^{-(x-y)T}}{1-e^{-xT}}\right) \qquad \text{Eq. (12)}$$

Which, recall, is the same as Eq. 5; it has the asymptotic limits, which we upon occasion have employed in other instances:

For very long *T* (*xT*>>1)

$$\left(\frac{\overline{A}_L}{A_o}\right)_\infty \Rightarrow \frac{x}{x-y} \qquad \text{Eq. (13)}$$

For short-to-intermediate time horizons, series expansion gives to the first order (see Eq. 6):

$$\left(\frac{A_L}{A_o}\right)_T \Rightarrow \left\lfloor 1+\frac{yT}{2}+\ldots \right\rfloor \qquad \text{Eq. (14)}$$

For a capital expenditure at time zero having zero salvage value, the annual carrying charge rate (capital recovery factor) is given by:

$$\phi = \frac{x}{1 - e^{-xT}} \text{ per year} \qquad \text{Eq. (15)}$$

SIMPLE PAYBACK

Although much denigrated by the sophisticated analyst, the "simple payback" approach is quite common because of its readily understandable nature. One merely has:

$$T_{PB}\text{, payback time,years} = \frac{\text{initial additional capital cost,}}{\text{incremental annual savings/yr}} \qquad \text{Eq. (16)}$$

Thus spending an extra dollar now to save twenty cents per year thereafter corresponds to a five-year payback.

Note that neither discount rate nor rates of future cost escalation are involved. So long as simple and similar cash flow patterns apply to all alternatives, and the time horizon is short, the simple payback method is not terribly misleading. It has the considerable merit of being immediately comprehensible to the general populace.

There is no hard and fast criterion of acceptability, but payback times of three or four years or less appear to be the order needed to inspire favorable action by the proverbial "man in the street". For the simple case of a capital increment at time zero followed by uniform annual savings ad infinitum, one has the rate of return:

$$i = \frac{100}{T_{PB}} \text{ \%/yr, or 20\%/yr in our example above} \qquad \text{Eq. (17)}$$

TREATMENTS OF UNCERTAINTY

Four approaches are common:

(1) Poll the experts and report their consensus plus and minus absolute (or relative percentage) spread on values for estimates of the subject genre.

(2) Carry out a Monte Carlo analysis. Repeat the calculation many times using randomly selected input variables from probability distributions characterizing their likely uncertainty, and compute the results for the output parameter. From this compute the standard deviation.

(3) Use a decision tree approach—which amounts to a crude Monte Carlo calculation in which variable probabilities are confined to only a few outcomes.

(4) Propagate and aggregate uncertainties analytically for the governing equations under simplifying approximations such as random independence of variables which are characterized by a normal (Gaussian) probability density function.

A brief sketch of the latter three approaches follows, beginning with the analytic. Clearly we can not do justice to any of these topics here, but again a minimum useful level of understanding is the goal.

ANALYTIC UNCERTAINTY PROPAGATION

For independent variables distributed according to the familiar normal or Gaussian probability density function (the familiar bell-shaped curve) the uncertainty is readily and completely characterized as a standard deviation σ, from the mean, $\bar{e}$. A randomly selected large set of data will fall within plus or minus one sigma of the mean 68% of the time, and within $\pm 2\sigma$, 95% of the time. Furthermore, the cumulative variance σ^2 in a dependent parameter e can be estimated from that for several uncorrelated independent variables x_i as follows:

$$\sigma_e^2 = \sum_i \left(\frac{\partial e}{\partial x_i} \right)^2 \sigma_{x_i}^2 \qquad \text{Eq. (18)}$$

A simple example may help.

As presented in slides 10 through 12, the busbar cost of electricity is made up of three components, representing capital, operating and fuel costs:

$$e = e_I + e_{O\,\&\,M} + e_F \qquad \text{Eq. (19)}$$

where for fossil fuels

$$e_f = \frac{0.34f}{\eta} \qquad \text{Eq. (20)}$$

where *f* is, for example, the cents per 1000 SCF paid for natural gas. We recognize that fuel cost is the principal uncertainty in estimation of the busbar cost of electricity from (for example) a combined cycle gas turbine (CCGT) unit.

Applying Eq. 18 in a conveniently normalized form one has:

$$\left(\frac{\sigma e}{e}\right)^2 = \left(\frac{e_f}{e}\right)^2 \left(\frac{\sigma_f}{f}\right)^2 \qquad \text{Eq. (21)}$$

THE MONTE CARLO METHOD

Refer to slides 33 through 36. Given a normalized probability density function (PDF), $P(z)$, one can integrate from $-\infty$ to z to obtain the cumulative distribution function CDF, $P \leq z$, which gives the probability of a variable being z or less; or if one prefers, integrate z to $+\infty$ to obtain its complement CCDF, $P \geq z$. Then in Step 2, choose a random number between 0 and 1 and use the CDF(z) to select a value for z; repeat this for all independent variables to create an input data set. In Step 3 use this set in the governing analytic relation to compute a value of the dependent parameter (for example, busbar cost of electricity). Repeat Steps 2 and 3 a large number of times (e.g., 1000).

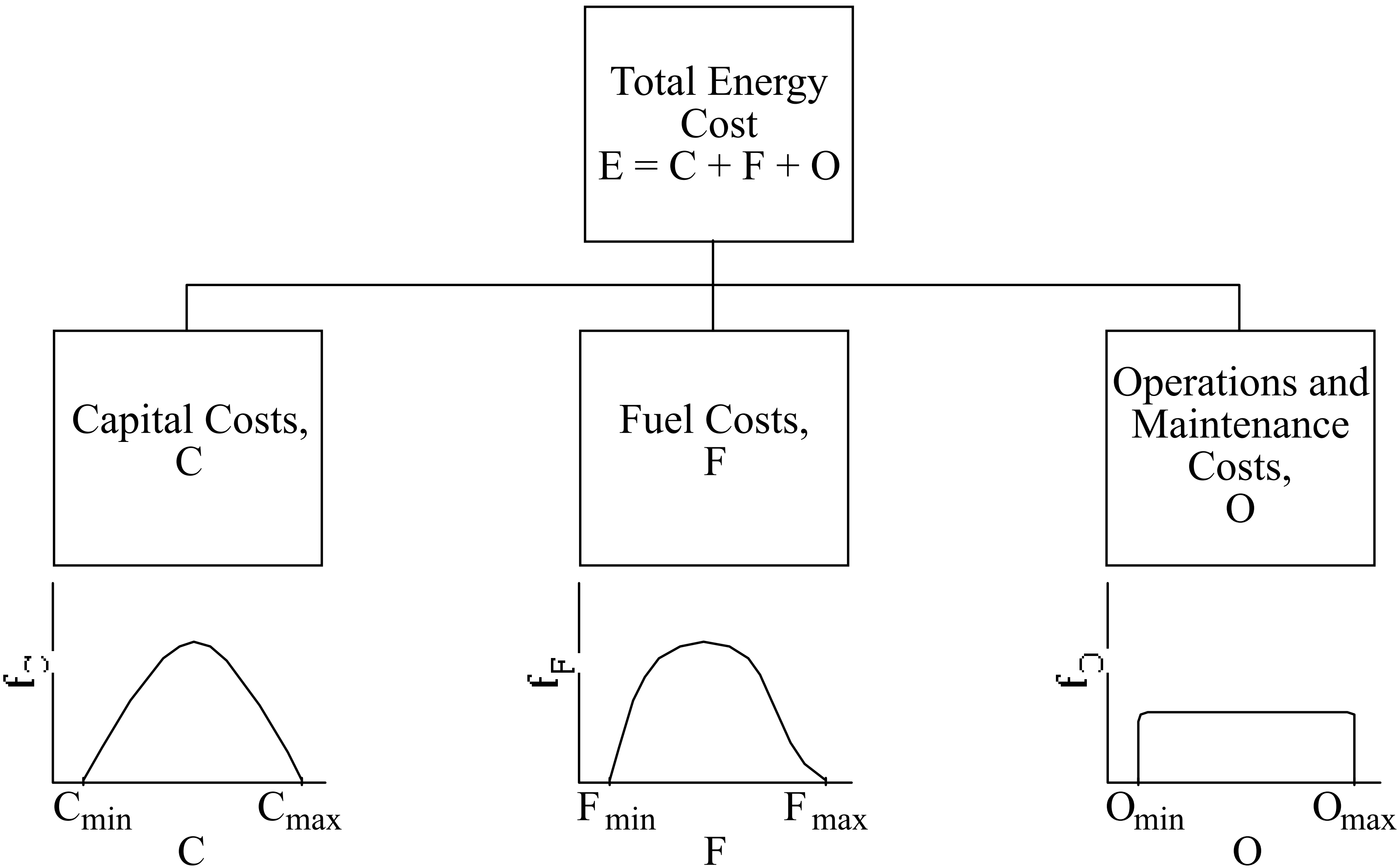
Then the expected value $\bar{e}$ and its σ can be calculated from the accumulated output set as follows

$$\bar{e} = \frac{\sum_{j=1}^{N} e_j}{N} \qquad \text{Eq. (22)}$$

and for large *N*

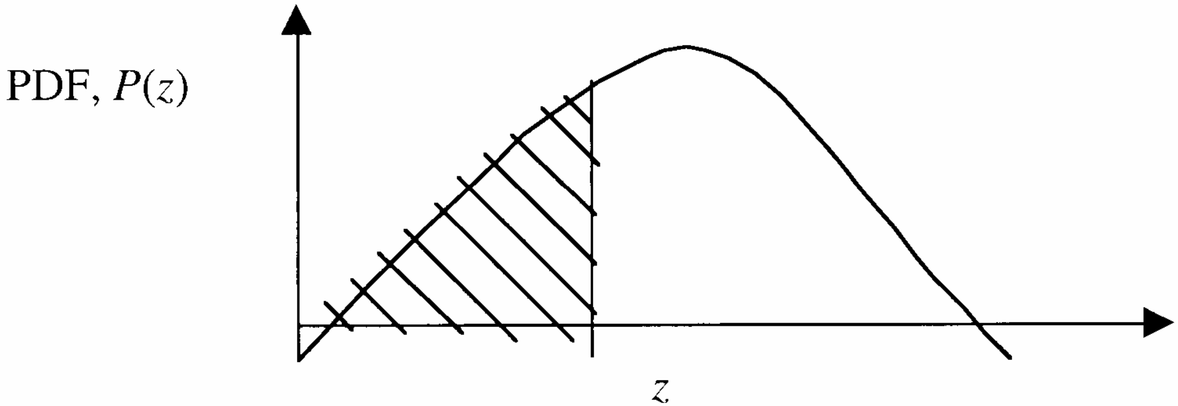
$$\sigma^2 = \frac{\sum_{j=1}^{N} (e_j - \bar{e})^2}{N(N-1)} \qquad \text{Eq. (23)}$$

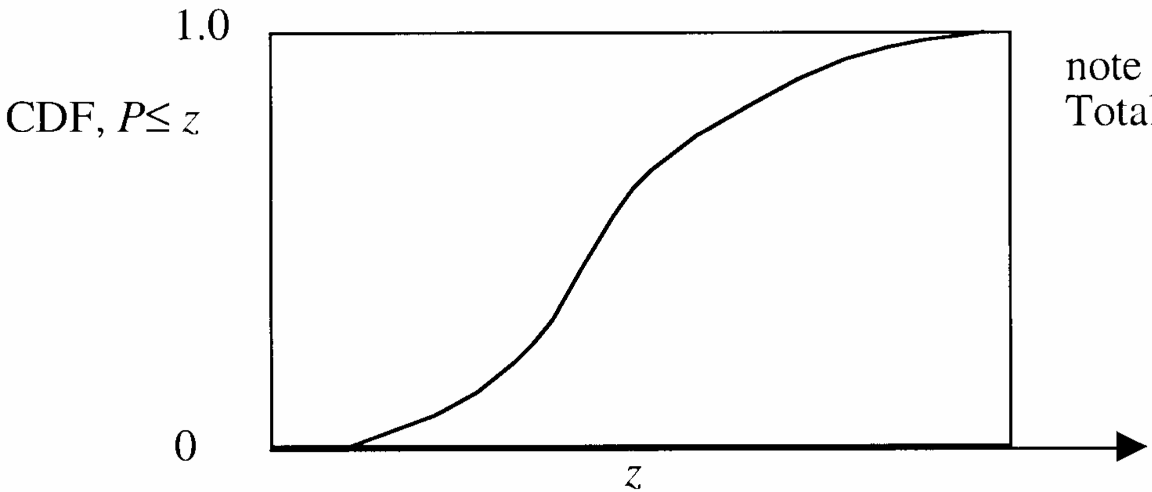
EXAMPLE OF COST FACTORS THAT CAN BE COMBINED USING THE MONTE CARLO METHOD



OUTLINE OF MONTE CARLO APPROACH

Step 1   Concoct a Probability Density Function (PDF) and integrate under it to develop a Cumulation Distribution Function (CDF)

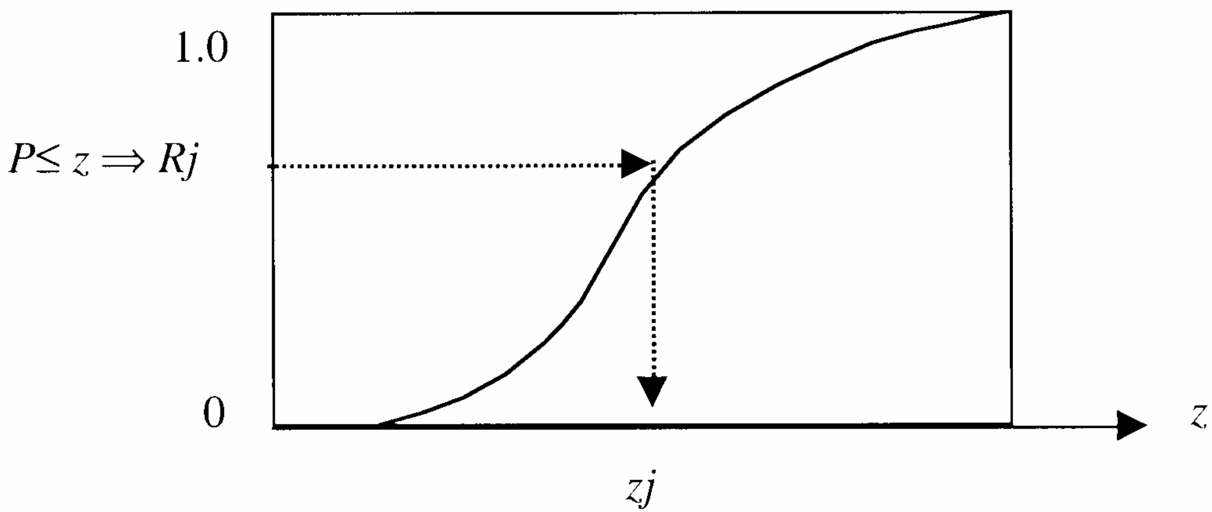




note normalization:
Total area = 1.0

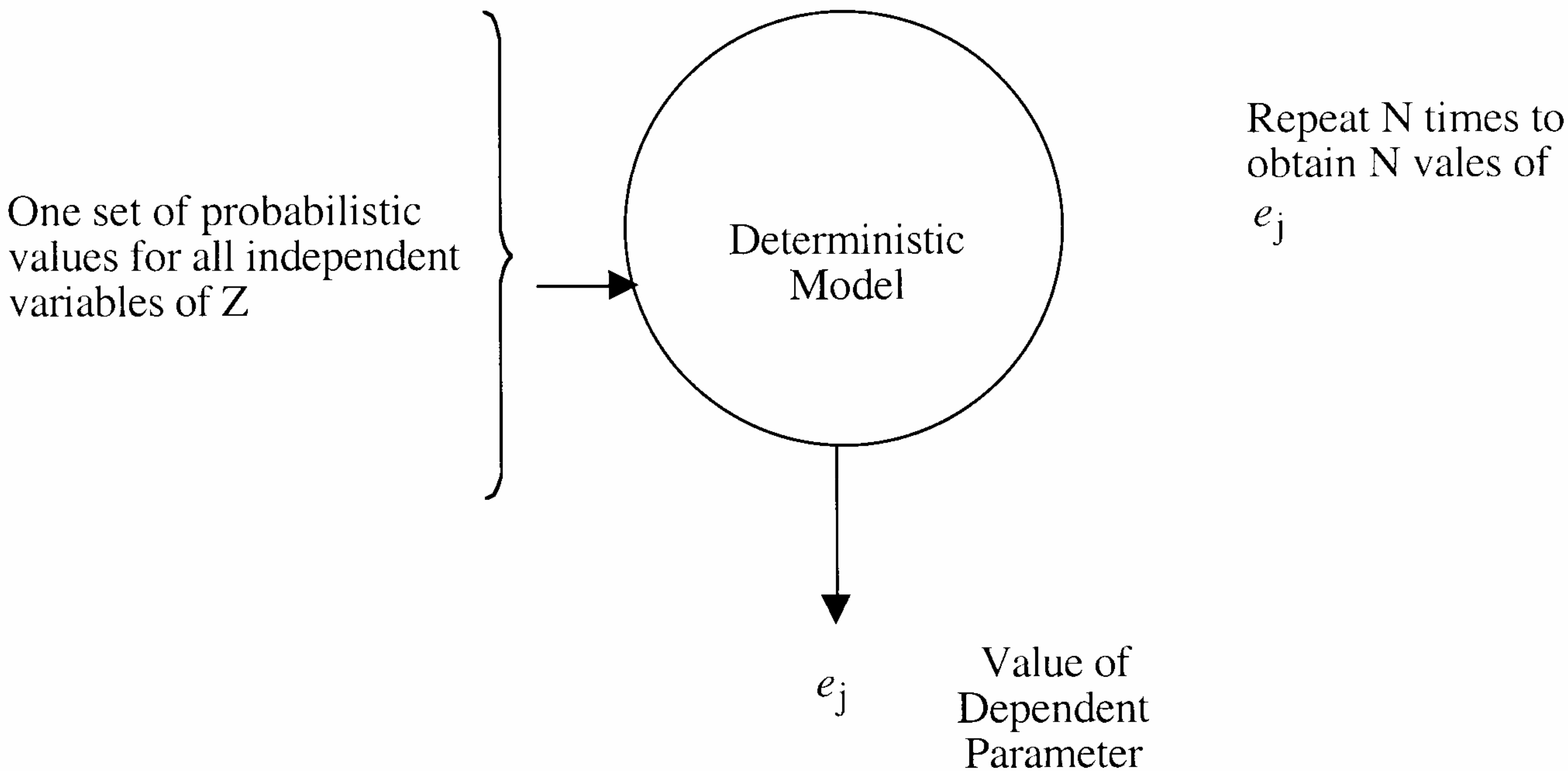
OUTLINE OF MONTE CARLO APPROACH, Continued

Step 2 Use the CDF to select a random entry for z by generating a random number to use as $P \leq z$.



OUTLINE OF MONTE CARLO APPROACH, Continued

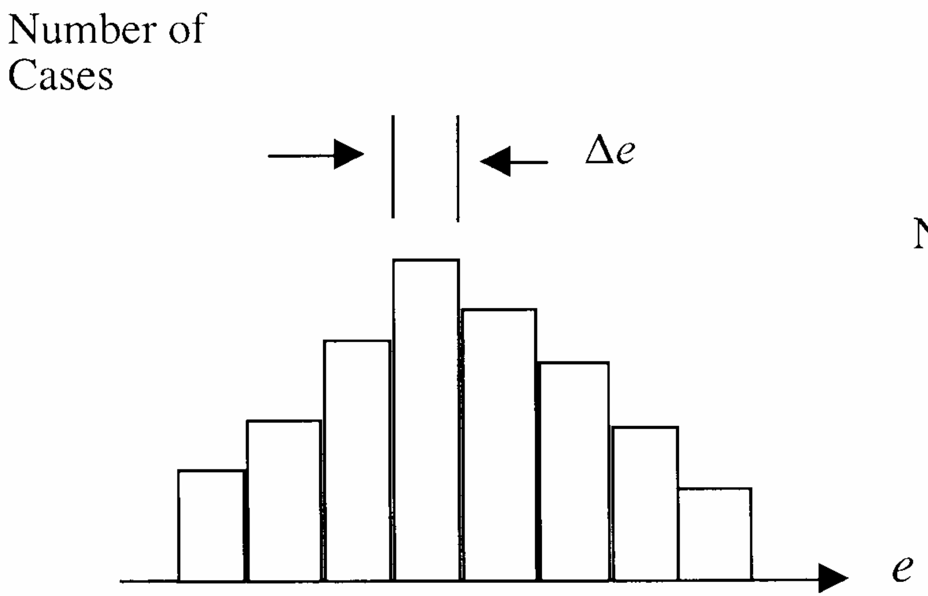
<u>Step 3</u> Generate a set of Dependent Variable Values

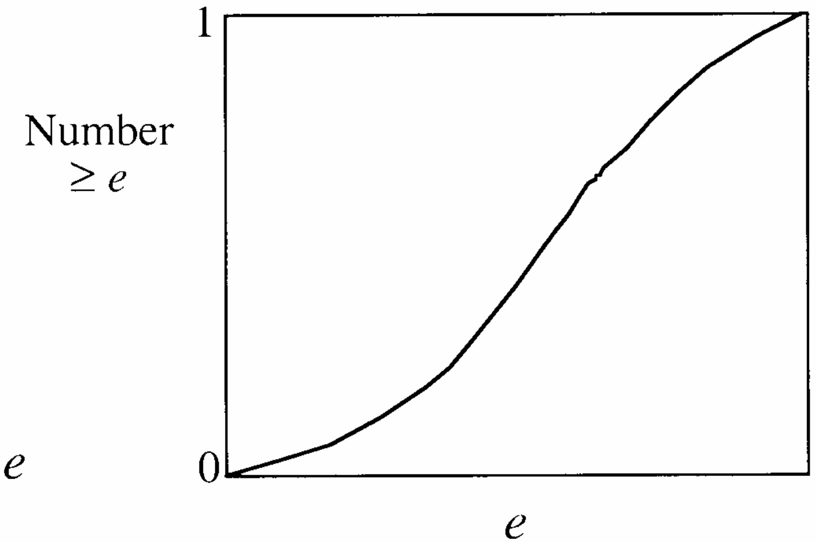


OUTLINE OF MONTE CARLO APPROACH, Continued

Step 4 Process the Output Data

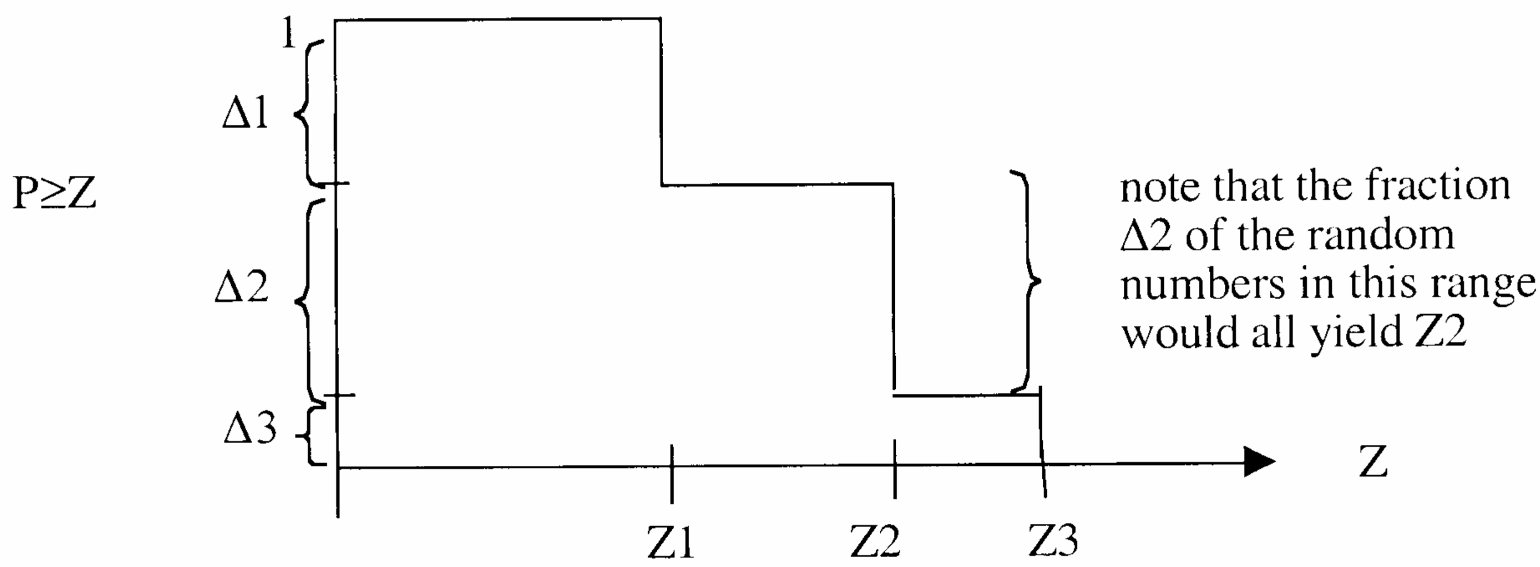
Calculate the average, $\bar{e}$, and variance, σ^2, of the N values of e_j and, if desired, sort and sum to obtain the PDF and CDF of e.





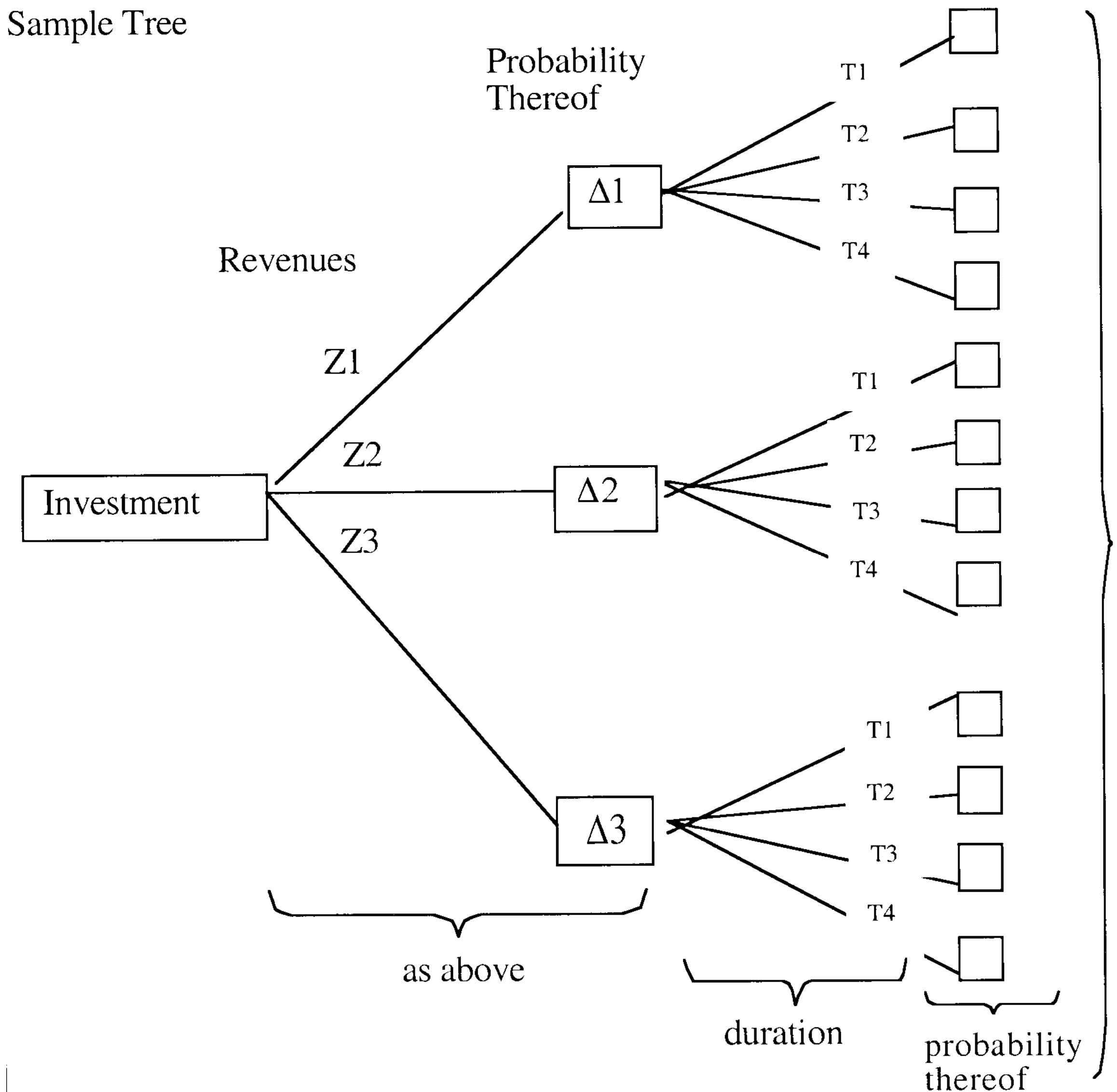
OUTLINE OF DECISION TREE APPROACH

Consider the complementary cumulative probability distribution function.



Note that the association of Δj with Zj is so simple that formal construction of P ≥ Z is seldom done.

OUTLINE OF DECISION TREE APPROACH, Continued



Use to calculate joint probabilities of present worth of all outcomes, their expected value and standard deviation from the mean, σ

ECONOMY OF SCALE AND LEARNING CURVE

These two concepts are firmly established semi-empirical precepts of engineering economics, and are central to the costing of most energy supply and end-use technologies (and a wide variety of other industrial systems).

Economy of scale refers to the general proposition that "bigger is cheaper" per unit output. In quantitative terms:

$$\left(\frac{C_i}{K_i}\right) = \left(\frac{C_o}{K_o}\right)\left(\frac{K_i}{K_o}\right)^{n-1}; \quad \text{or} \quad \frac{C_i}{C_o} = \left(\frac{K_i}{K_o}\right)^{n} \qquad \text{Eq. (24)}$$

where

C_i, C_o = cost of size *i* and reference (*o*) units, respectively

K_i, K_o = size or rating of subject units

n = scale exponent, typically ~ 2/3

Thus if a 50 MWe power station costs 2000 $/kWe, a 1000 MWe unit would be predicted to cost:

$$\left(\frac{C_{1000}}{K_{1000}}\right) = \left(2000\frac{\$}{\text{kWe}}\right)\left(\frac{1000}{50}\right)^{\left(\frac{2}{3}-1\right)} = \underline{737\$/\text{lWe}}\ ,$$

a substantial savings. This explains the steady increase in unit rating for steam, gas and water turbines to meet increased demand as time progresses, as shown in slide 6.

A simple example can be used to motivate n~2/3. Consider a spherical tank whose cost is proportional to surface area; then the surface-to-volume (i.e., cost-to-capacity) ratio is

$$\frac{C}{K} \sim \frac{S}{V} = \frac{4\pi R^2}{\frac{4}{3}\pi R^3} = \frac{3}{R} \sim \frac{1}{V^{1/3}} = V^{n-1}$$

OUTPUT OF POWER DEVICES: 1700-2000

Graph removed for copyright reasons. See Figure 5.4 in Tester, et al. *Sustainable Energy: Choosing Among Options.* Cambridge, MA: MIT Press, 2005.

The learning curve effect applies to the savings achieved by sequential mass production of a large number of identical units (same size or rating) i.e., "more is cheaper." Automobile engines are a good example.

Experience shows that one can often characterize the cost of the Nth unit as follows:

$$C_N = C_1 \bullet N^{-\alpha} \qquad \text{Eq. (25)}$$

with

$$\alpha = -\left(\frac{\ln \frac{f}{100}}{\ln 2} \right)$$

where C_1, C_N = cost of first and Nth units, respectively

$f/100$ = progress ratio: second (or 2^nth) unit is f percent as expensive as first (or 2^{n-1}st) unit; a typical value is ~85%

Thus, if the first first-of-a-kind production run photovoltaic panel costs 200 $/m²$, the last unit of a production run of 10^4 units would be predicted to cost:

$$C_{10^4} = \left(200\ \$/\mathrm{m}^2\right)10^{-4\alpha}$$

and

$$\alpha = -\left(\frac{\ln 0.85}{\ln 2}\right) = 0.234$$

so that

$$C_{10^4} = \underline{23\ \$/\mathrm{m}^2}$$

again a large decrease. Slide 46 illustrates this phenomenon for some technologies of current interest.

In addition to the unit cost of the nth unit in a mass-production run or in a sequence of increasing size, the average unit cost of all n items, first through last, is also of interest.

For a learning curve sequence the average cost is, to a good approximation:

$$\overline{C}_{1,N} = C_1 \left\{ \frac{N\alpha}{1+\alpha} \left\lfloor 1 - \frac{1}{N^{1+\alpha}} \right\rfloor + \frac{1}{2N} [1 + N^{\alpha}] \right\} \qquad \text{Eq. (26a)}$$

with a maximum error of -1.5% for $\alpha = 1/2$ ($f = 71\%$) and $N = 2$; the error decreases as N increases and for larger f.

For a sequence of *N* units each a factor of *S* larger than its immediate precursor:

$$\left(\frac{\bar{I}}{K}\right) \frac{\sum I}{\sum K} = \left(\frac{I}{K}\right)_1 \left(\frac{S^{nN} - 1}{S^n - 1}\right) \left(\frac{S - 1}{S^N - 1}\right) \qquad \text{Eq. (26b)}$$

where as before, *n* is the scale exponent.

These relations provide estimates of the total expenditure for subsidized installations before a competitive product is produced.

Note that for typical values of *n* and *f*, it generally does not pay to reduce size to increase number to satisfy a fixed total capacity.

TECHNOLOGY LEARNING CURVES

Graph removed for copyright reasons. See Figure 5.4 in Tester, et al. *Sustainable Energy: Choosing Among Options.* Cambridge, MA: MIT Press, 2005.

Cost improvements per unit installed capacity, in US(1990)$ per kW, versus cumulative installed capacity, in MW, for photovoltaics, wind and gas turbines.

FORD MODEL T: PRICE vs. CUMULATIVE PRODUCTION, 1909-23

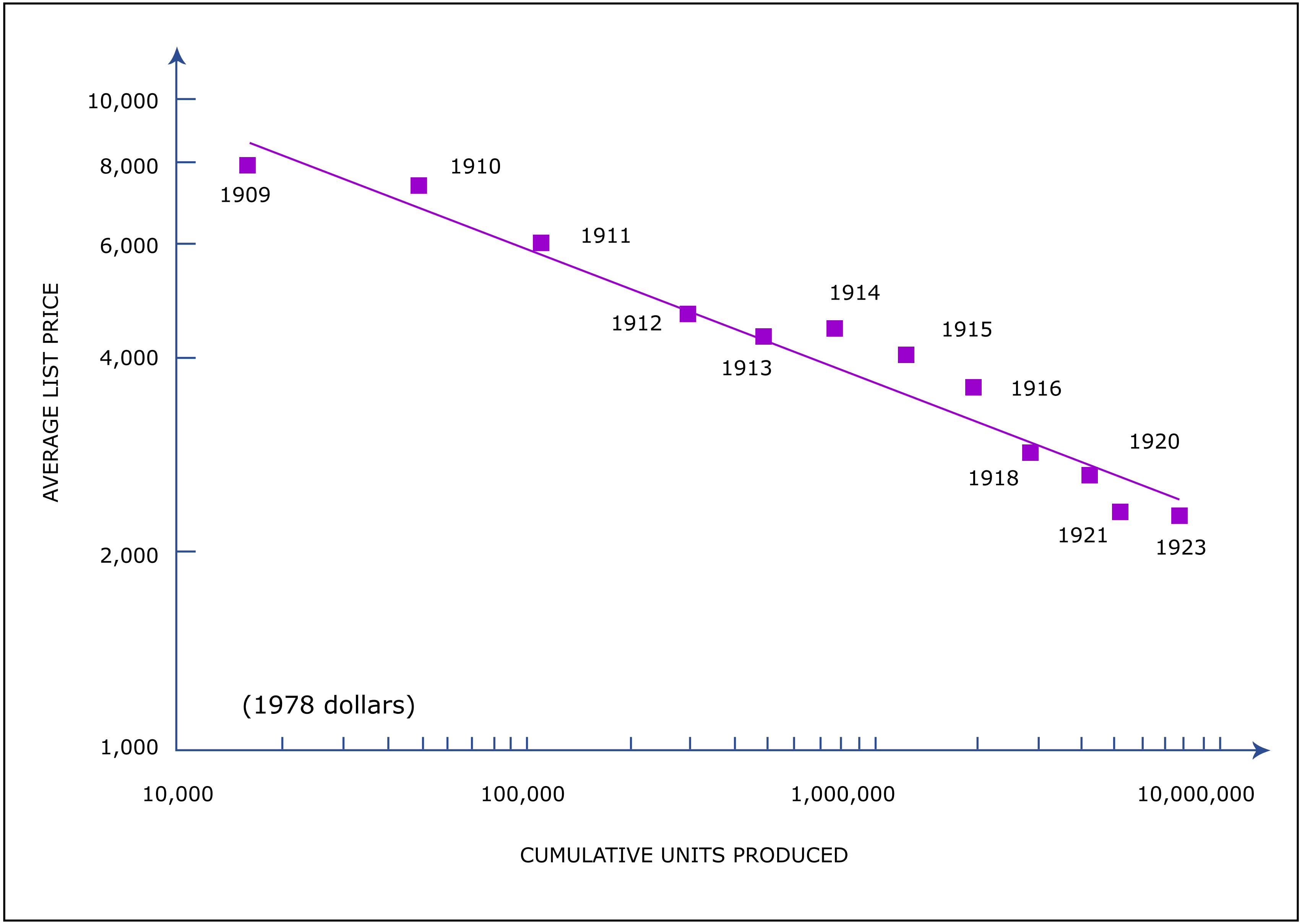


Figure by MIT OCW.

PHOTOVOLTAIC MODULES: PRICE vs. CUMULATIVE PRODUCTION, 1975-93

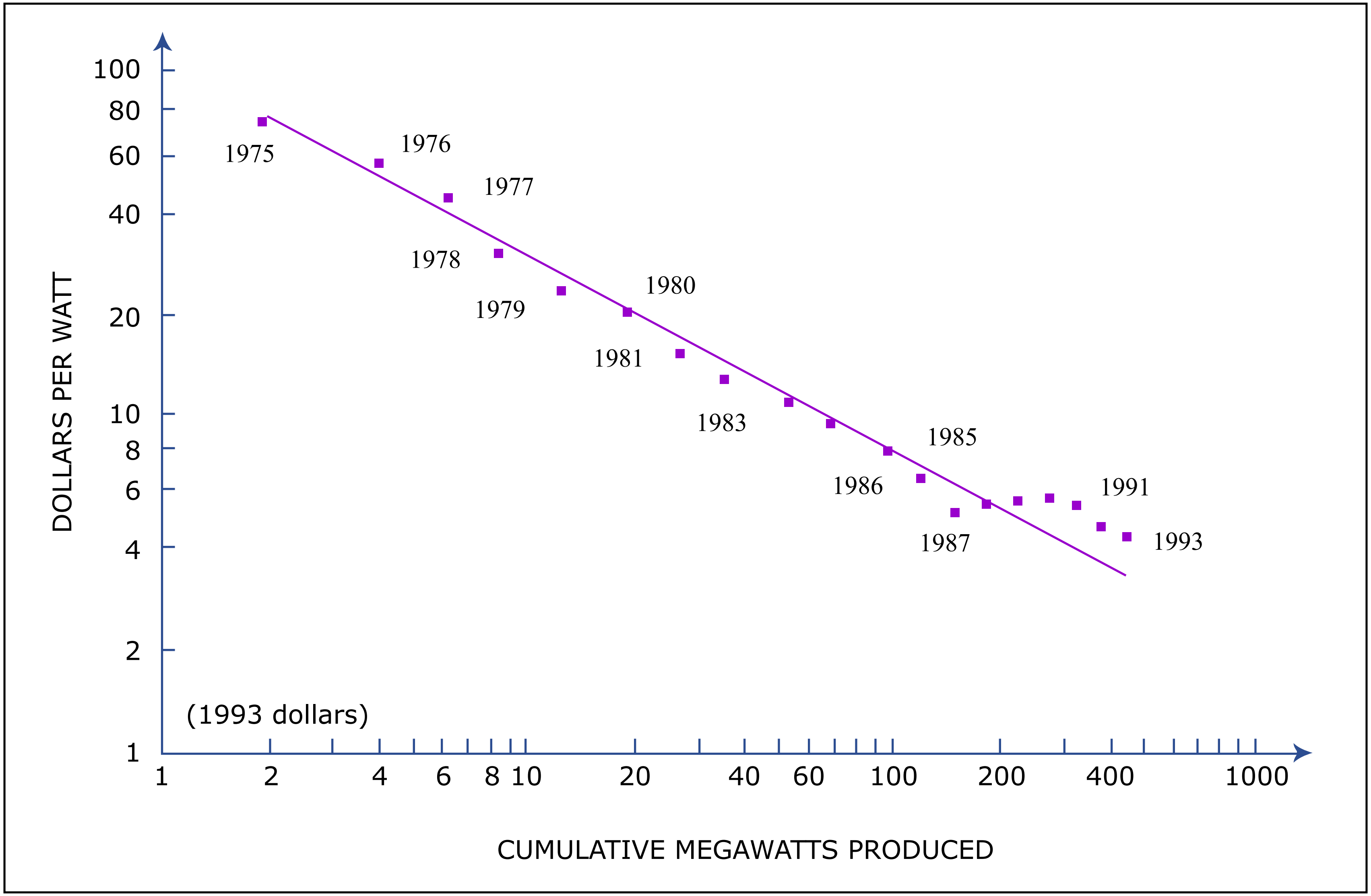


Figure by MIT OCW.

Economy of size and learning curve effects, while dignified by a mathematical formulation, are by no means "laws of nature" of the same credibility as the Carnot efficiency equation. Hence, one must be aware of several caveats regarding the use of such projections:

- At some point, size increases may require switching to new materials—for example, to accommodate higher stresses, in which case the economy-of scale relation has to be re-normalized.
- Larger size may lead to lower reliability (i.e., capacity factor) and therefore net unit cost of product may increase, i.e., there may well be dis-economies of scale.
- Learning curves apply to replication of the <u>same</u> design, by the <u>same</u> work force, in the <u>same</u> setting (e.g., factory), all of which are likely to change in the long run.

- Important factors such as materials resource depletion or technological innovation are not taken into account in an explicit manner.

- Shared costs of many units on a single site are also important: e.g., multi-unit stations save considerably on administrative infrastructure costs.

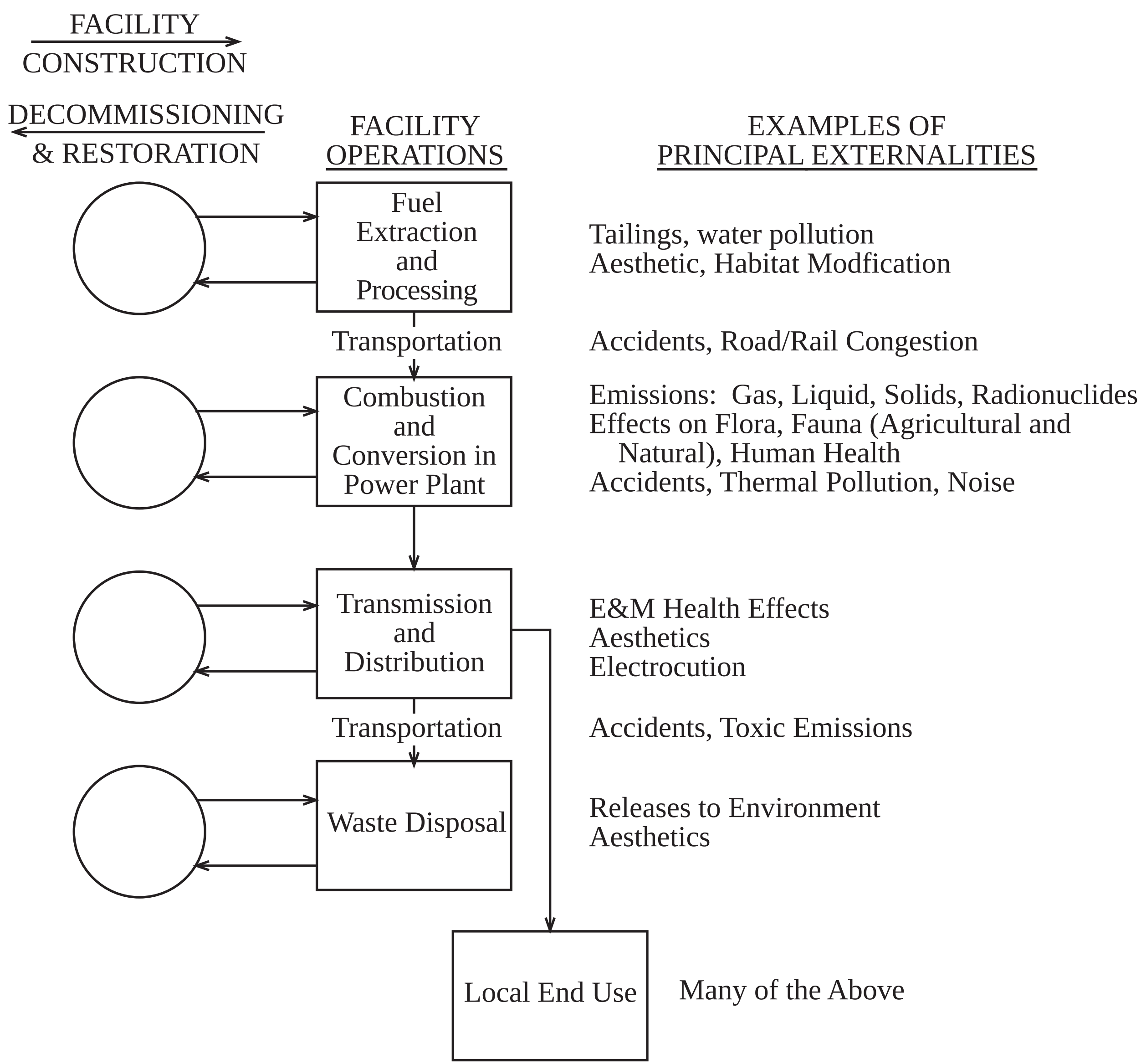
- Often both effects operate in series or parallel combination. For example, in nuclear fission and fusion reactor development, construction of a sequence of pilot/demonstration units of increasing size is usually envisioned, followed by replication and deployment of a fleet of identical large commercial plants.

WAYS OF INTERNALIZING EXTERNAL COSTS

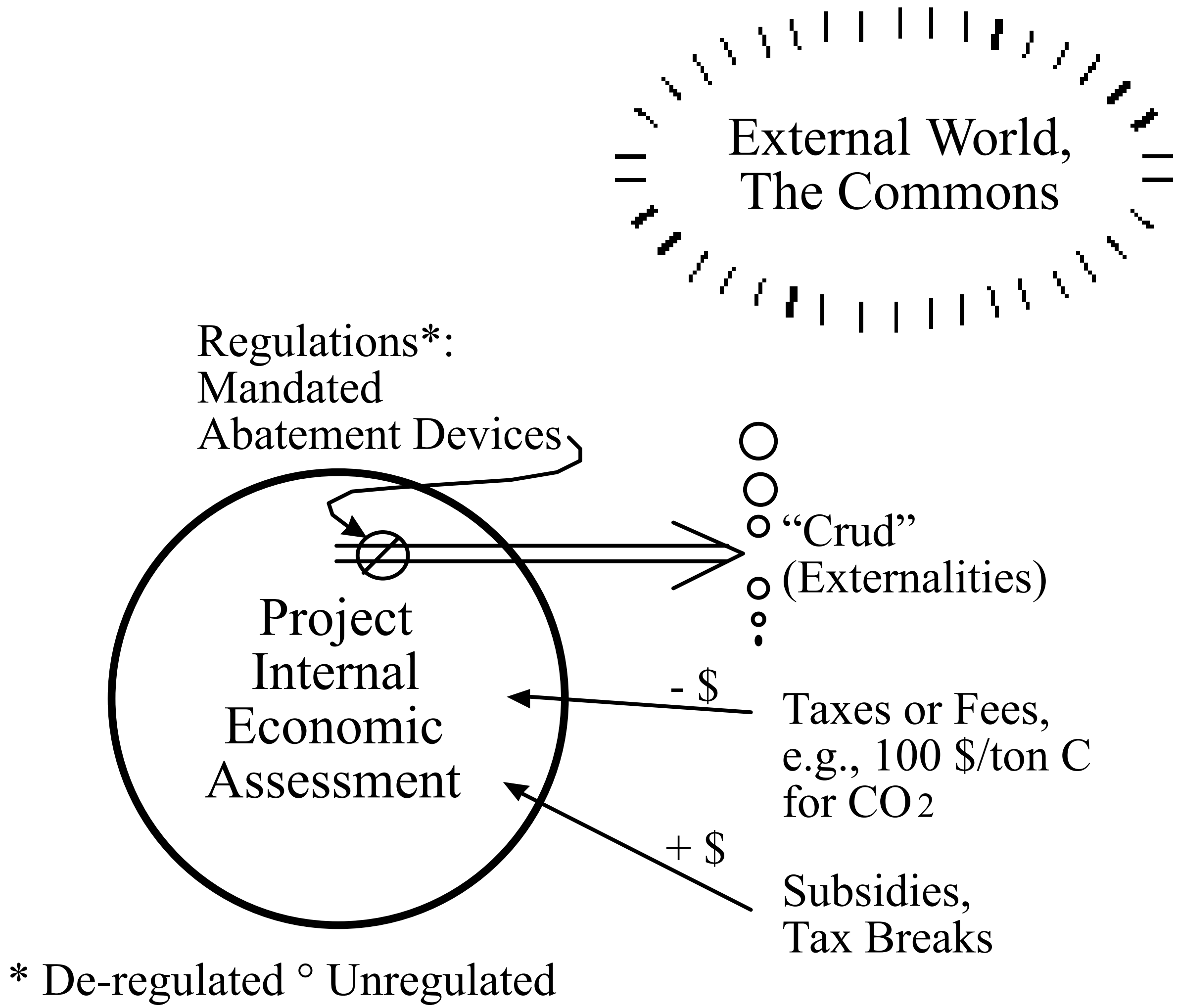
Definition of Externality: A cost of production of a good imposed upon an (external) party without corresponding benefits or compensation (e.g., costs of air pollution-related illnesses endured by persons downwind from a factory releasing toxic gases).

- Requiring Removal of External Effects (remediation & restoration)
- Requiring Prevention of External Costs (regulation)
- Requiring Compensation to Affected Parties

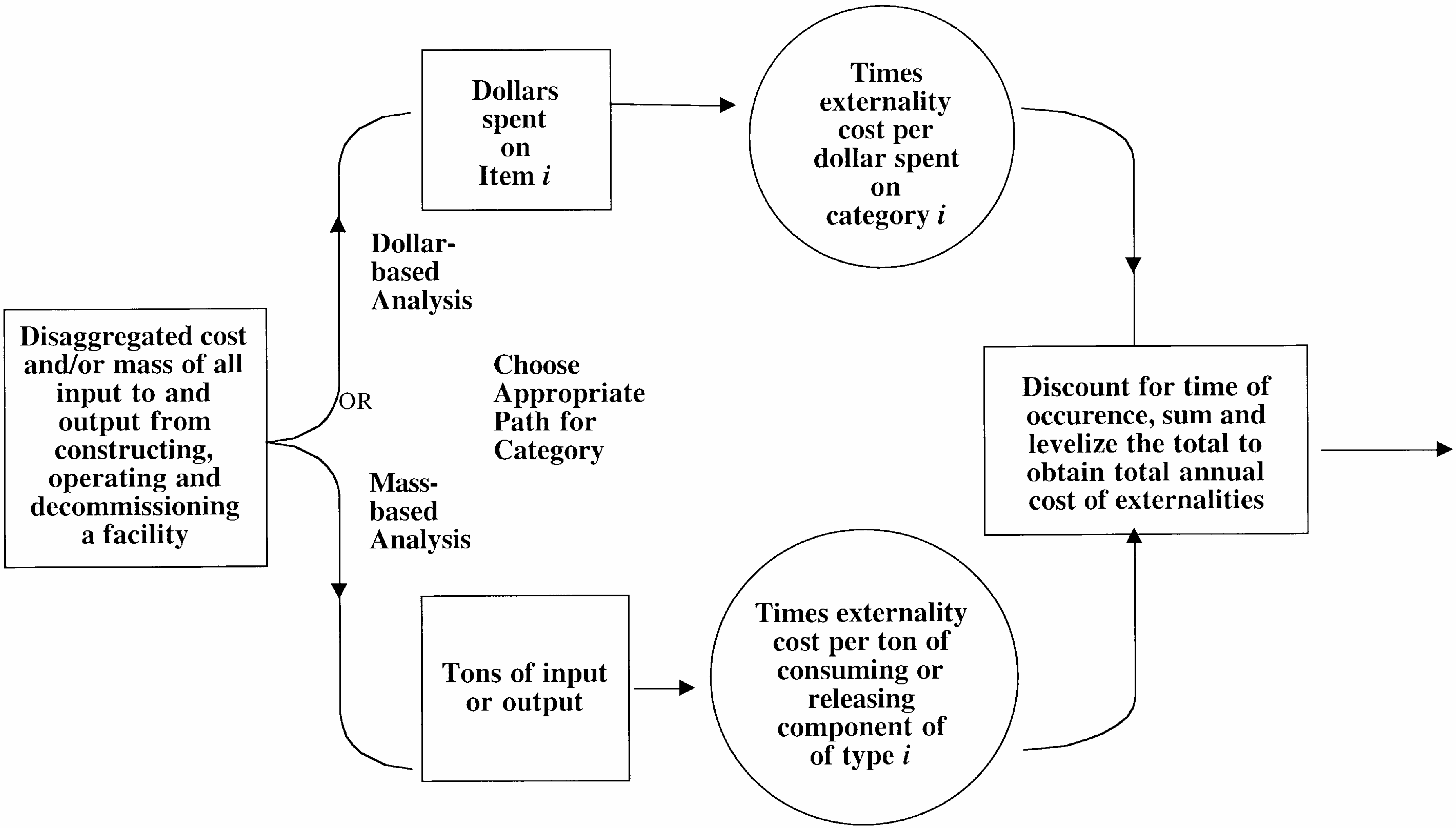
A GENERIC LIFECYCLE ROADMAP FOR EXTERNALITIES ASSESSMENT



SCHEMATIC OF OUR POINT OF VIEW FOR ECONOMIC ANALYSES



PROCEDURE FOR ASSIGNING COSTS TO EXTERNALITIES



RANGE OF EXTERNALITY STUDY ESTIMATES (<u>Including</u> Global Warming)

Graph removed for copyright reasons. See Figure 5.11 in Tester, et al. *Sustainable Energy: Choosing Among Options.* Cambridge, MA: MIT Press, 2005.

REPRESENTATIVE EXTERNALITY ASSESSMENT INPUTS

Units are Dollars Per Metric Ton

	State			
Emissions	NY PSC	MA DPU	NV PSC	CA PU
SO_2	900	1650	1720	4500
NOx	1960	7170	7500	7800
VOCs	-	5840	1300	3600
CO	-	950	1000	-
Particulates	350	4400	4600	2600
CO_2	2.2	24	24	29
CH_4	-	240	240	-
N_2O	-	4400	4600	-

REPRESENTATIVE EXTERNALITY ASSESSMENT OUTPUT

SUMMARY OF IMPACTS AND DAMAGE COSTS FOR **COAL** FUEL CHAIN:

Study	Impacts (deaths per TWh)		Damage Costs (in milli-Euro per kWh)					
	Public Fatalities	Occupational Fatalities	Public Health	Occupational Health	Environment	Global Warming	Major Accident	Study Total
Ottinger et al. 1991								22-55
Pearce et al. 1992			0.05		0.005	0.04		0.14
Pearce et al. 1995								0.11
Friedrich & Voss 1993			0.01-0.07		0.013-0.015			0.02-0.09
Ball 1994		0.04-0.14						
ORNL/RFF 1994			0.01-0.64	0.08	0-0.1	nq		0.7-1.4
Rowe et al. 1996			3 to 5		0.1	nq		3 to 5
ExternE 1995		0.13-0.23	4 to 13	1 to 2	0.2 to 0.8	10 to 18*		16 to 34
Rabl et al. 1996			5 to 14	nq	0.02	15		20 to 29
ExternE 1999			10 to 50		0.5 to 2	10 to 50		20 to 100

1 milli Euro ≈ 1 US mill = 0.1 US cent

REPRESENTATIVE EXTERNALITY ASSESSMENT OUTPUT, Continued

SUMMARY OF IMPACTS AND DAMAGE COSTS FOR A **NUCLEAR** FUEL CHAIN:

Study	Impacts (deaths per TWh)		Damage Costs (in milli-Euro per kWh)					
	Public Fatalities	Occupational Fatalities	Public Health	Occupational	Environmental Health	Global Warming	Major Accident	Study Total
Ottinger et al. 1991			4.9				18.5	23
Pearce et al. 1992			0.003-0.009			0.0012	0.002-0.006	0.007-0.017
Pearce et al. 1995						0.0012	0.006-0.044	0.006-0.044
Friedrich & Voss 1993			0.001-0.005		0-0.002		0.0005-0.004	0.002-0.01
Ball 1994	0.01-1.23	0.02-0.09						
ORNL/RFF 1994			0.012	0.08-0.09				0.09-0.1
Rowe et al. 1996								0.09
ExternE 1995	0.65	0.04	2.4	0.15				2.6
Dreicer et al. 1995	0.62	0.02	2.4	0.14			0.0005-0.023	2.5

Notes: Numbers have been rounded.
nq = not quantified
* at 0% discount rate

1 milli Euro ≈ 1 US mill = 0.1 US cent

SAMPLE CALCULATION

Consider a coal plant having the following characteristics:

Thermodynamic efficiency	0.36 MWe/MWth
Coal heating value	0.35 MWd (thermal)/MT coal
Coal carbon content	0.7 MT carbon/MT coal
Lifetime levelized cost at the busbar of electricity produced	6.5¢/kWhre

The added cost of product due to a carbon tax of $100/metric ton of <u>carbon</u> is then:

$$e_c = (100\$/\text{MTC})(100¢/\$)(0.7 \text{ MTC/MT coal})^*$$
$$(\text{MT coal}/0.35 \text{ MWDth})(\text{MWth}/0.36 \text{ MWe})^*$$
$$(1 \text{ d}/24 \text{ hr})(1 \text{ MWe}/1000 \text{ kWe})$$
$$= 2.3¢/\text{kWhre},$$

a 35% increase, which is quite significant, and would virtually eliminate the construction of new coal plants and hasten the shutdown of existing units.

SUMMARY OF EXTERNALITY VALUES* EXPRESSED IN cents/kWh GENERATED (x10 = mills/kWh)

	Exisiting Power Plants		New Power Plants			
Valuation Method	Existing Unscrubbed Coal Plant	Existing Scrubbed Coal Plant	CTU #2 Oil 0.3% S	CC Firm Gas	AFBC 0.5% S	IGCC 0.45% S
1. Ontario Hydro		0.41				
2. Pace University	10.3	4.0	2.6	0.77	2.6	2.1
3. Massachusetts DPU	7.7	5.2	4.0	1.4	3.6	3.0
4. CEC In-State	30.3	10.9	5.3	0.6	5.9	3.8
5. CEC Out-of-State	3.8	2.2	1.5	0.4	1.4	1.0
6. New York PSC	2.5	1.3	0.8	0.3	0.7	0.5
7. Nevada PSC	7.9	5.3	3.9	1.4	3.7	3.0

Compare to Total Busbar Cost of ~50 mills/kWh

* Excluding CO_2

"OFFICIAL" FIGURES FOR THE VALUE OF HUMAN LIFE*

Country	Cost in 1,000 ECU (1989) ...	*...of which* Market Cost	Method	Source
Belgium	300	300	Gross production costs & losses	Hansson and Marckham (1992)
Denmark	600	200	"	"
Germany	630	630	"	"
Finland	1,600	540	Willingness to pay	"
France	255	--	Life expectancy	"
United Kingdom	890	265	Willingness to pay	"
Luxembourg	330	330	Gross production costs & losses	"
Netherlands	85	85	Net production costs & loses	"
Norway	340	340	Gross production costs & loses	"
Austria	545	545	"	"
Portugal	12.5	12.5	"	"
Sweden	1,070	130	Willingness to pay	"
Switzerland	1,665	560	Social willingness to pay	"
Spain	145	97	Gross production losses	"
United States	2,350	495	Willingness to pay	"
United States	441	441	Gross production costs & losses	Le Net (1992)
France	344	315	"	"
Australia	407	407	"	"
New Zealand	155 to 451	122 to 181	"	"

* These percentages naturally also include the cost of material losses and injuries.

OVERLAP BETWEEN RANGES OF ENVIRONMENTALLY RELATED DAMAGE COSTS FOR SELECTED ELECTRICITY SUPPLY TECHNOLOGIES

Graph removed for copyright reasons.

Source: A. Stirling, "Regulating the Electricity Supply Industry by Valuing Environmental Effects," *Futures*, Dec. 1992, pp. 1024-47.

ENERGY BALANCE FOR ETHANOL – INPUTS FOR 1 GALLON ETHANOL

Corn Production	55,300 BTU
Fermentation/Distillation	74,300 BTU
Total	129,600 BTU
Output in Combustion:	76,000 BTU

Notes:

(1) Analysis applies to typical US Midwest conditions and practices; current technology throughout

(2) Production costs include fertilizer, operation of farm machinery

(3) For comparison, gasoline has ~120,000 BTU/gal

(4) In Brazil, using sugarcane and low-tech agriculture, the output/input ratio can be as high a 3

(5) For comparison, gasoline's output to input (for oil production, transportation and refining) is about 7

(6) In March 2000 the US EPA announced it would ban the gasoline additive MTBE and replace it with ethanol

APPROXIMATE ENERGY BALANCE FOR 1000 MWe NUCLEAR POWER PLANT

Energy to Construct: (and decommission)	4×10^9 kWhrth
Energy for Fuel (30 yrs)	7×10^9 kWhrth
Energy for Operations (30 yrs)	4×10^9 kWhrth
Total:	15×10^9 kWhrth
Electric Energy Output (30 yrs)	210×10^9 kWhre
Energy Ratio:	$\dfrac{\text{electric energy out}}{\text{thermal energy in}} = 14 \dfrac{\text{kWhre}}{\text{kWhrth}}$

Basis:

(1) 1000 MWe PWR operated for 30 yrs at 80% capacity factor

(2) Fuel enriched by gas centrifuge, 0.3 w/o tails

(3) Conversion between thermal and electrical energy: 3 kWhrth = 1 kWhre, in fuel cycle steps

(4) “Fuel” includes startup core, all front and back end steps

The main themes of this chapter are conceptually simple but devilishly complicated when it comes to the details of their practical application. Points to emphasize are:

- Money has a time value because of interest earned or paid, which requires that all cash flows be discounted from their point of occurrence in time: Slide 5 summarizes the basic conceptual framework. Once this is taken into account, options can be compared on a consistent basis. A simple but adequate way to do this using continuous compounding has been presented, leading to the concept of, and a prescription for, the single-valued levelized cost over the life of a project (slides 10 through 12). Market-based accounting, which includes monetary inflation, and constant dollar/real interest rate accounting, which excludes inflation are contrasted.

- Costs not reflected in the market price, "externalities", must be considered to account for detrimental effects on the common environment and public health, an important step in ranking technology <u>and</u> public policy options according to their true total life-cycle cost. The elements of an input-output analysis for this purpose are sketched.
- Economy of scale and learning curve effects are noted: bigger is cheaper, and so is more of the same.
- The universal need for an explicitly quantitative recognition of uncertainty is stressed.
- Conceptual difficulties with a purely monetary measuring system motivate moving beyond the methods of this chapter in the formulation of actual decision-making processes which reflect stakeholder concerns and offer greater likelihood of decision process convergence.