



# Sustainable Energy

## Lecture 5: Environmental Economics

# The Value of Money

- **Time Value of Money: Interest**
  - Interest can be compounded discretely or continuously.
  - Using continuous interest calculations simplifies the solving of differential equations.
  - The future worth,  $F$ , of a present amount,  $P$  after  $t$  years at the rate  $I$  per year is:
    - $F = P e^{it}$
  - The present worth of a discrete cash flow in the future is:
    - $F = P e^{-it}$

# Interest.....continued

- **It is possible to correct for the time value of money by expressing all costs in terms of their present worth and then computing an overall sum extended for a specified T-year time horizon.**
- **Lifetime levelized cost**
  - **A levelized (uniform) annual rate of expenditure (\$/yr) can be calculated by equating present worth over a specified T-year time horizon.**

# Interest....continued

- **Estimating the cost of electricity generation**
  - **Capital-Related Costs + Operating and Maintenance Costs + Fuel Costs**
  - **1998 Production Costs of energy in the US**
    - Nuclear 2.13 cents/kwhe
    - Coal 2.07
    - Gas 3.30
    - Oil-fueled 3.24

# Levelized energy costs

MILLS  
KWH  
IN  
7/1/96  
Constant  
Dollars

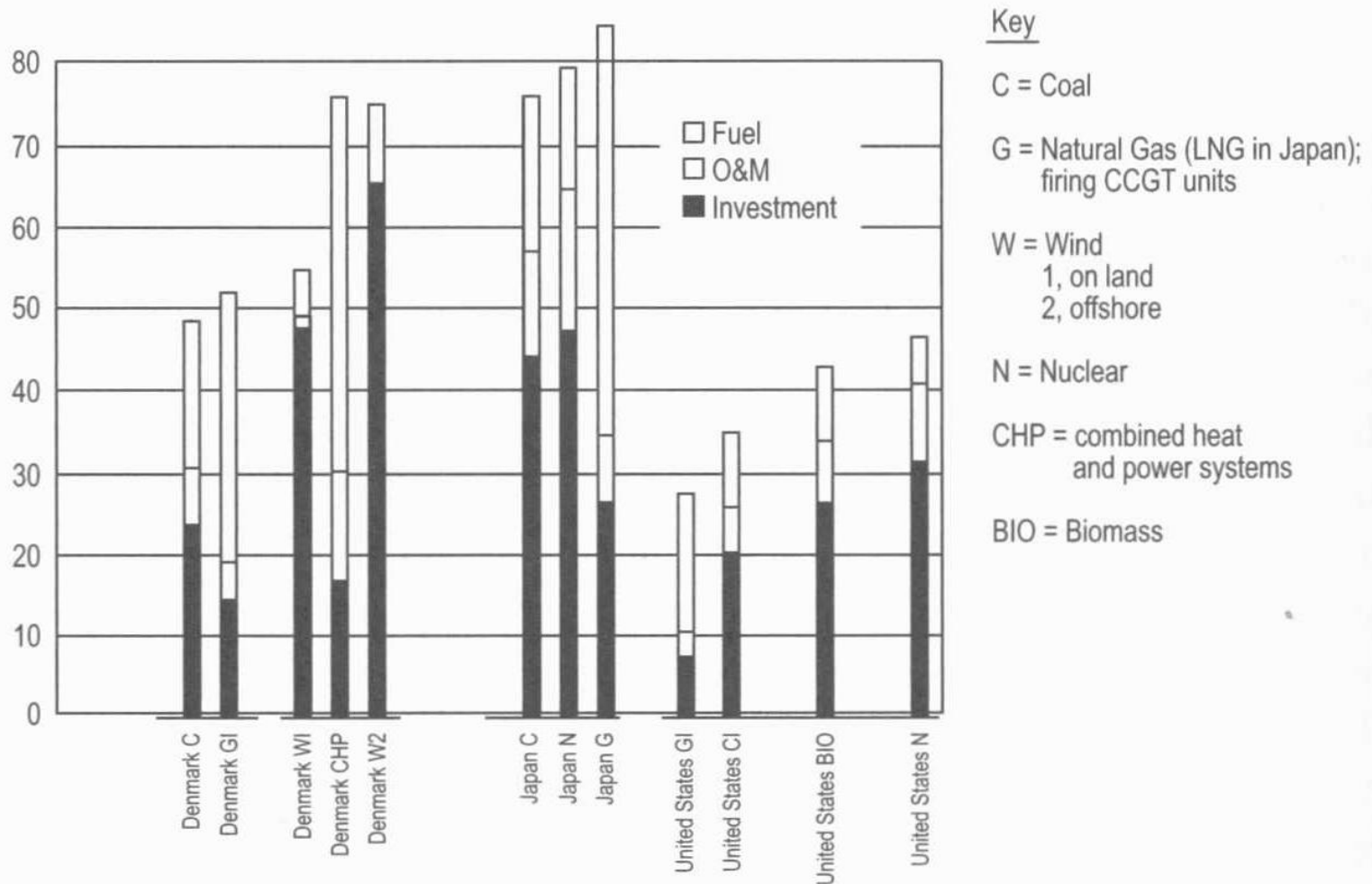


Figure 5.3. Levelized electricity generation (busbar) cost projections (at 10%/yr real discount rate). Adapted from: OECD/IEA (1998b).

# Table 5.3

**Table 5.3. 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:**

$$\frac{100 \phi}{8,766 \cdot L} \left( \frac{I}{K} \right)_{-c} \left[ 1 + \frac{x+y}{2} \right]^c$$

**Plus Operating and Maintenance (O&M) Costs:**

$$+ \frac{100}{8,766 \cdot L} \left( \frac{O}{K} \right)_o \left[ 1 + \frac{yT}{2} \right]$$

**Plus Fuel Costs:**

$$+ \begin{cases} \text{Nuclear} & \left[ \frac{100}{24} \frac{F_o}{\eta B} \right] \left[ 1 + \frac{yT}{2} \right] \\ \text{or} \\ \text{Fossil} & \left[ \frac{0.0034 f_o}{\eta} \right] \left[ 1 + \frac{yT}{2} \right] \end{cases}$$

where:

		Typical LWR Value
$L$	= plant capacity factor: actual energy output ÷ energy if always at 100% rated power	0.80
$\phi$	= annual fixed charge rate (i.e., effective "mortgage" rate) = $x/(1 - \tau)$ where $x$ is the discount rate, and $\tau$ 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
$\left( \frac{I}{K} \right)_{-c}$	= overnight 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	\$1,400/kWe

# Table 5.3 continued

Table 5.3. continued

$y$	=	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
$\eta$	=	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	\$2,000/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:

$$e_b = \begin{array}{ccccccccc} & & \text{Cap} & + & \text{O\&M} & + & \text{Fuel} & & \\ & = & 4.1 & + & 2.2 & + & 0.9 & = & 7.2 \text{ cents/kWhre} \end{array}$$

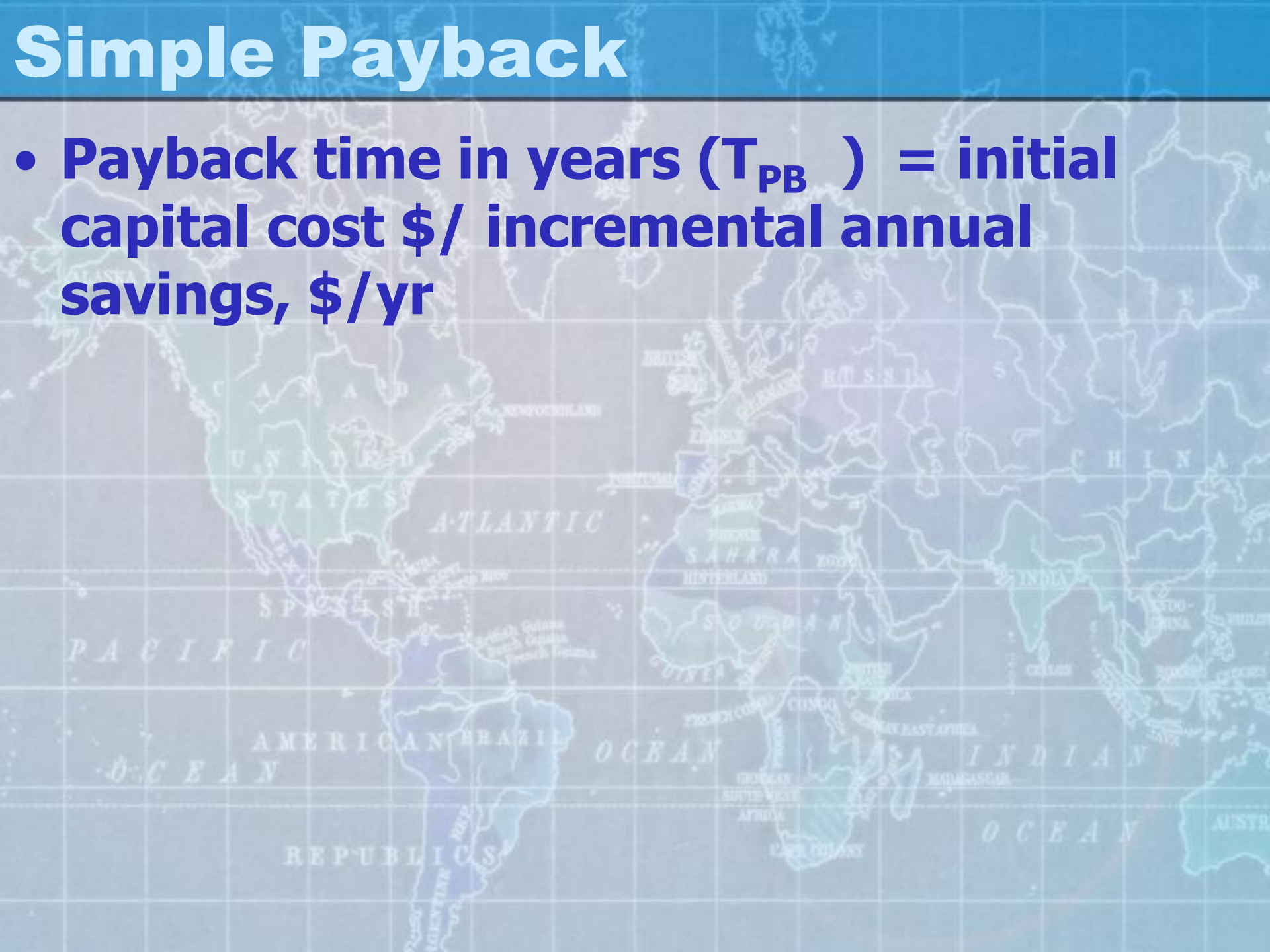
\*Note that these costs represent only the cost of generating the electricity (i.e., excluding transmission and distribution). These costs are lifetime-average (i.e., "levelized") costs for a new plant starting operations today.

# Current versus Constant-Dollar Comparisons

- **Business people and engineers use then-current (market) dollars and “nominal” interest rates**
- **Economists often use constant dollar estimate (inflation is not considered, “real” interest rates).**
- **Current dollar estimates always are higher than constant-dollar cost estimates.**

# Simple Payback

- **Payback time in years ( $T_{PB}$ ) = initial capital cost \$/ incremental annual savings, \$/yr**



# Economy of Scale

- **Economy of Scale – bigger is cheaper per unit output.**
- **Learning Curve – savings are achieved by mass production of a single product. As the product is made the cost of producing items decreases with time.**

# Learning Curve

Experience shows that one can often characterize the cost of the  $N$ th unit as follows:

$$C_N = C_1 \cdot N^{-\alpha} \quad (5-20)$$

with:

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

where:

$C_1, C_N$  = cost of first and  $N$ th units, respectively

# Learning Curve costs

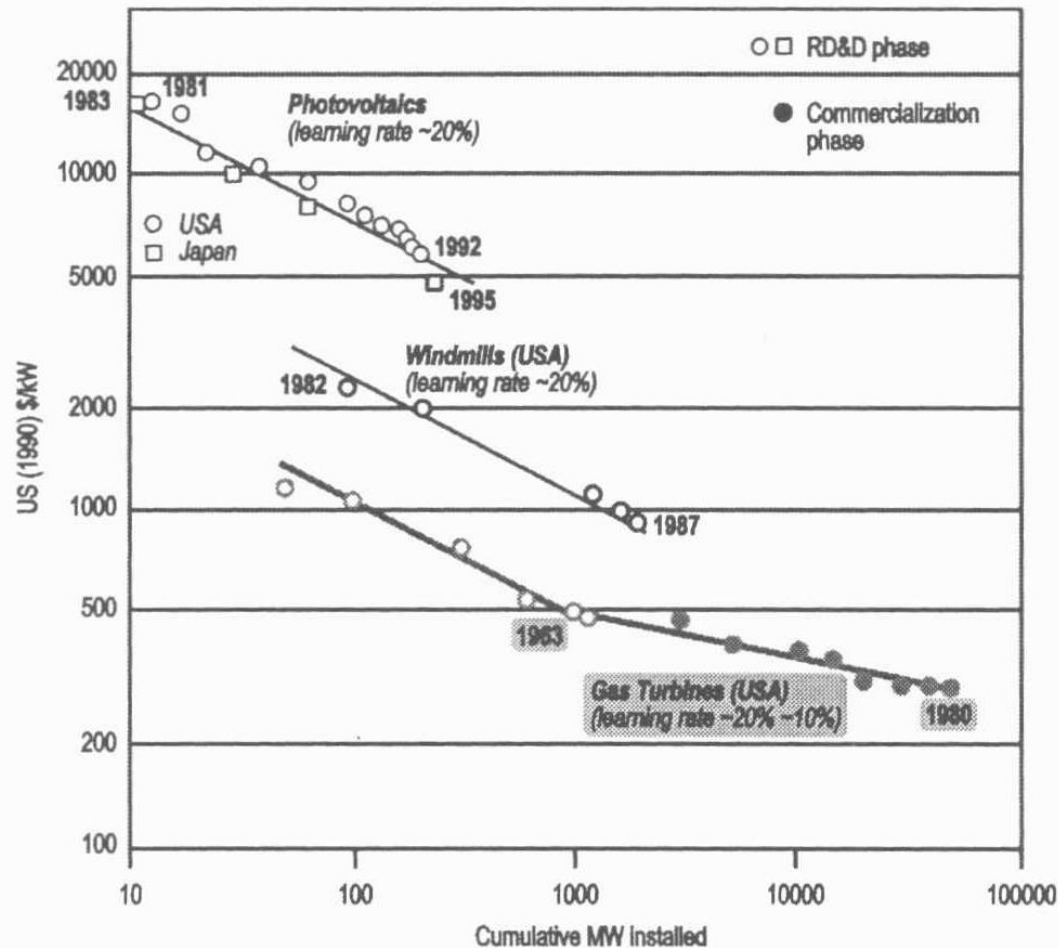


Figure 5.5. Technology learning curves: Cost improvements per unit installed capacity, in (1990) US\$ per kW, versus cumulative installed capacity, in MW, for photovoltaics, wind and gas turbines. Source: Nakicenovic et al. (1998). Reprinted with permission of Cambridge University Press.

# Economy of Scale/equations

$$\left(\frac{C_i}{K_i}\right) = \left(\frac{C_o}{K_o}\right) \left(\frac{K_i}{K_o}\right)^{n-1} ; \text{ or } \frac{C_i}{C_o} = \left(\frac{K_i}{K_o}\right)^n \quad (5-19)$$

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  $\sim 2/3$

Thus, if a 50 MWe power station costs 2,000 \$/kWe, a 1,000 MWe unit would be predicted to cost:

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

# Allowing for Uncertainty

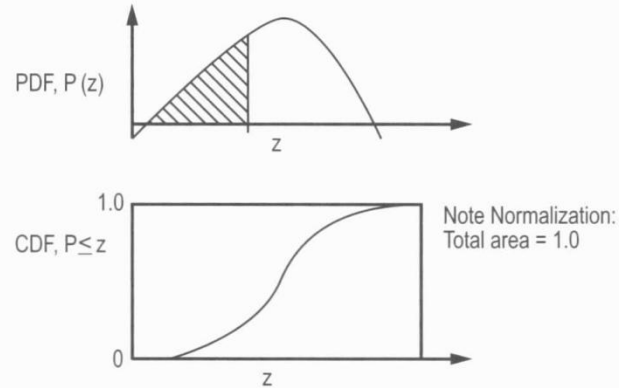
- Use standard deviation to bracket the uncertainty of costs
- The Monte Carlo Method
  - Concoct a PDF and integrate to develop a CDF distribution.
  - Randomly select a data input set for your variables.
  - Calculate the results many times and obtain the average outcome and variances.

# Uncertainty....continued

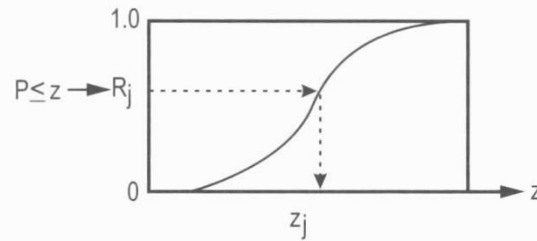
- **Decision Tree Method**
  - **Similar to the Monte Carlo method but more restricted.**
  - **You are selecting the most likely scenarios from the potential list.**
  - **Calculate probabilities/outcomes from this shortened list.**

# Monte Carlo Method

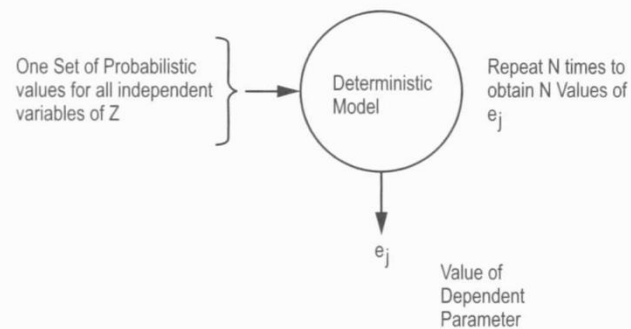
Step 1: Concoct a PDF and integrate under it to develop a CDF distribution.



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



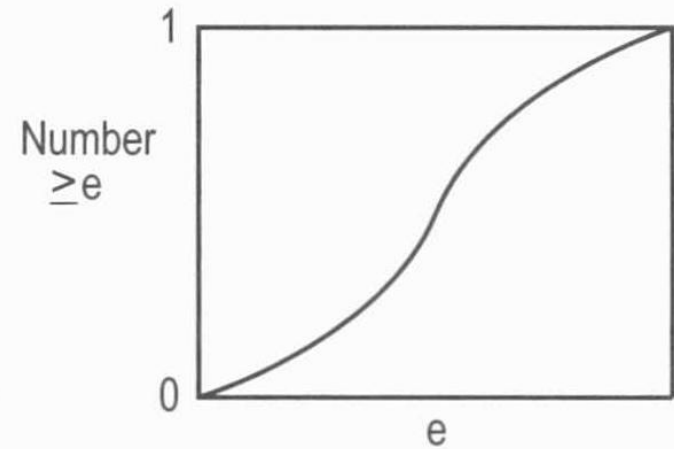
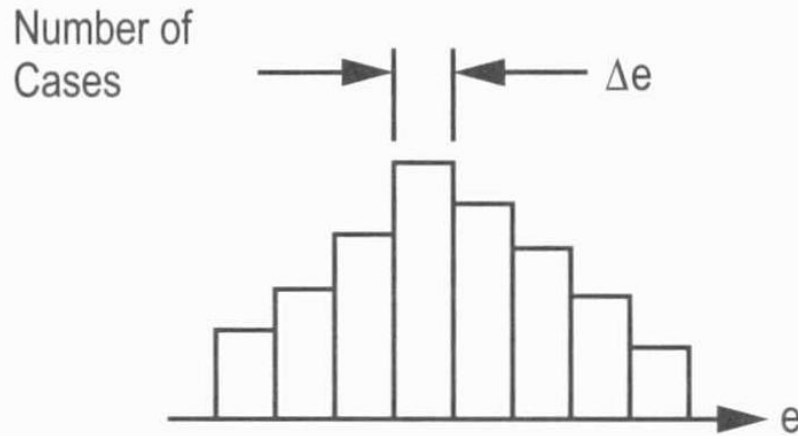
Step 3: Generate a set of dependent variable values



# Monte Carlo continued.....

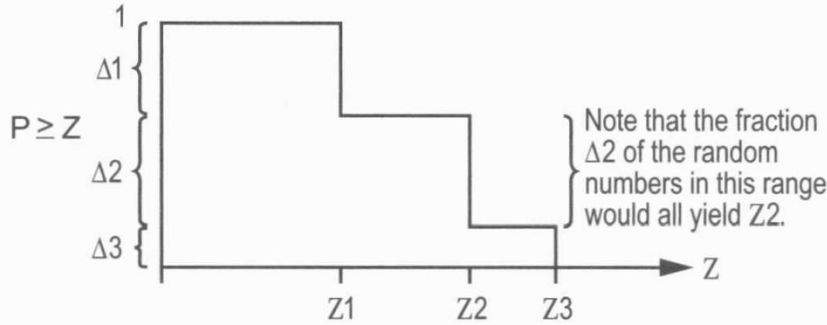
Step 4: Process the output data

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

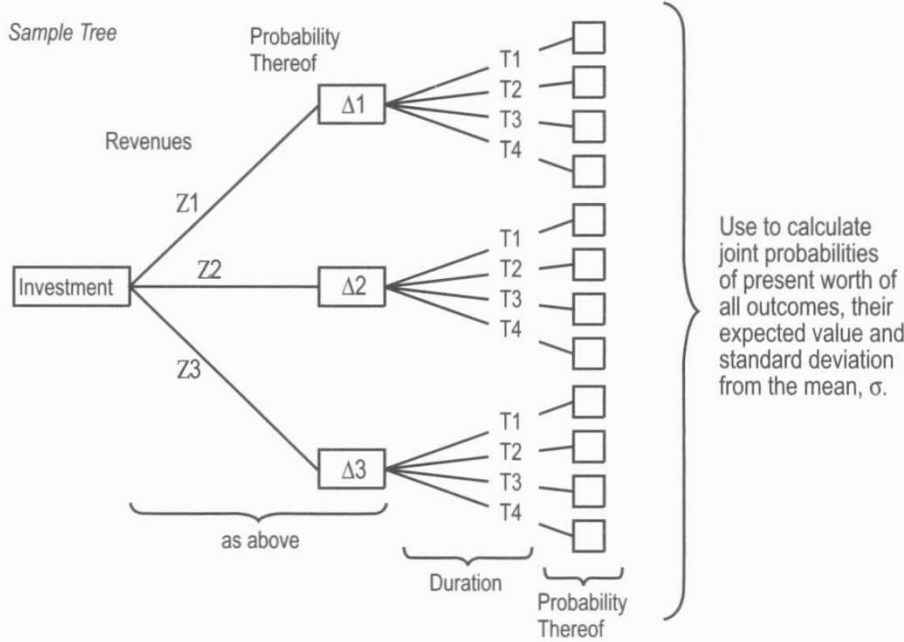


# Decision Tree Method

Consider the complementary cumulative probability distribution function.

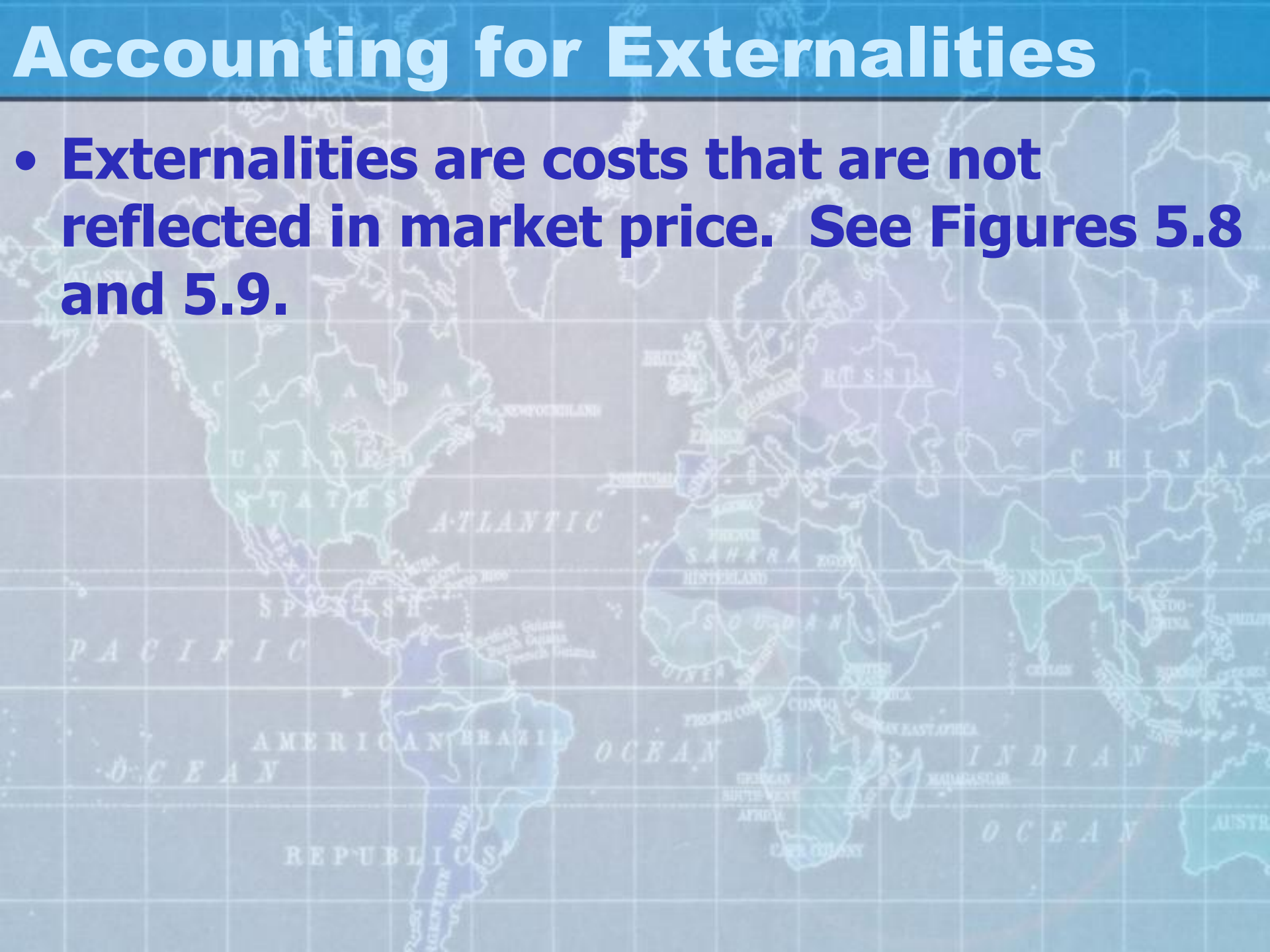


Note that the association of  $\Delta_j$  with  $Z_j$  is so simple that formal construction of  $P \geq Z$  is seldom done.



# Accounting for Externalities

- Externalities are costs that are not reflected in market price. See Figures 5.8 and 5.9.



# Externalities

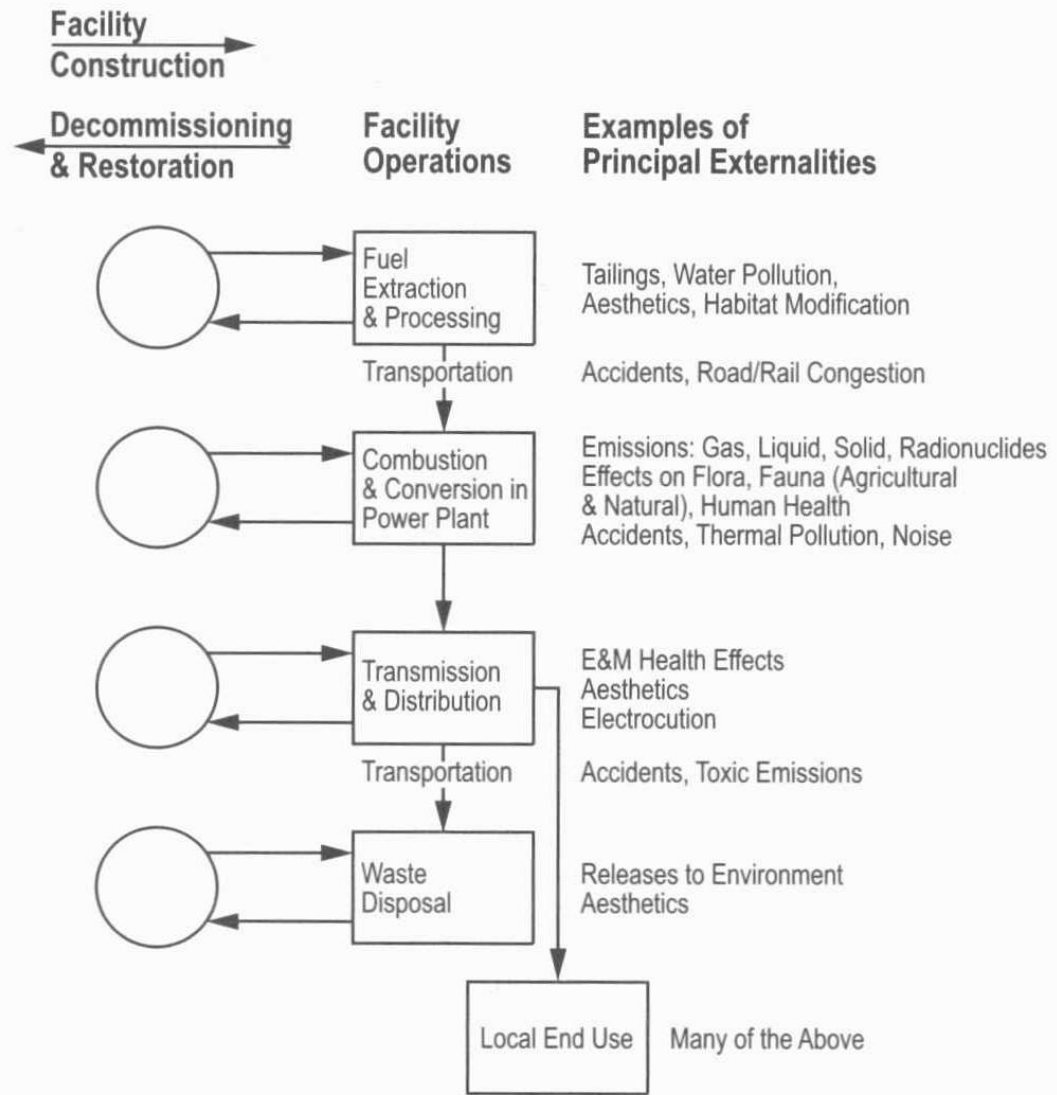


Figure 5.8. A Generic lifecycle roadmap for externalities assessment.

# Estimating Costs of Externalities

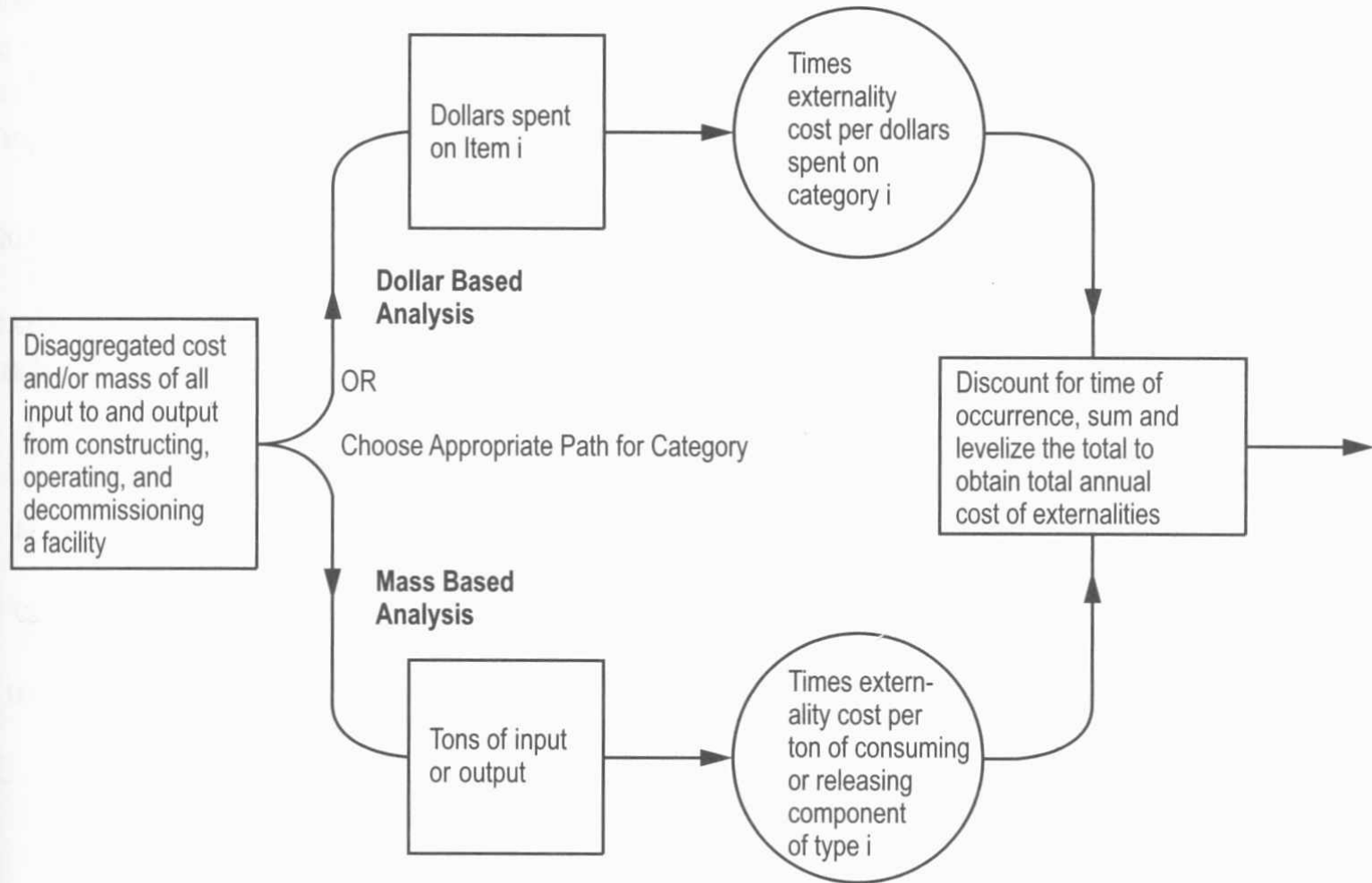


Figure 5.9. Procedure for assigning costs to externalities.

# Costs of Externalities

**Table 5.5. Representative Externality Assessment Inputs**

	State			
	NY PSC	MA DPU	NV PSC	CA PU
SO <sub>2</sub>	900	1,650	1,720	4,500
NO <sub>x</sub>	1,960	7,170	7,500	7,800
VOCs	—	5,840	1,300	3,600
CO	—	950	1,000	—
Particulates	350	4,400	4,600	2,600
CO <sub>2</sub>	2.2	24	24	29
CH <sub>4</sub>	—	240	240	—
N <sub>2</sub> O	—	4,400	4,600	—

Units are dollars per metric ton

Source: Economic Research Associates (1992).

# Costs of Externalities

**Table 5.6. 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)					Study Total
	Public Fatalities	Occupational Fatalities	Public Health	Occupational Health	Environ- ment	Global Warming	Major Accident	
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			3–5		0.1	nq		3–5
ExternE 1995		0.13–0.23	4–13	1–2	0.2–0.8	10–18*		16–34
Rabl et al. 1996			5–14	nq	0.02	15		20–29
ExternE 1999			10–50		0.5–2	10–50		20–100

Notes: Numbers have been rounded.

nq = not quantified

\*at 0% discount rate

1 milli Euro ≈ 1 US milli Dollar = 0.1 US cent

Source: Wilson et al. (1999).

**Table 5.6. Representative Externality Assessment Output**

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