Nuclear Energy Systems Economic Evaluations: **Capital Cost** **Operations & Maintenance Cost**

Course 22.39, Lecture 18

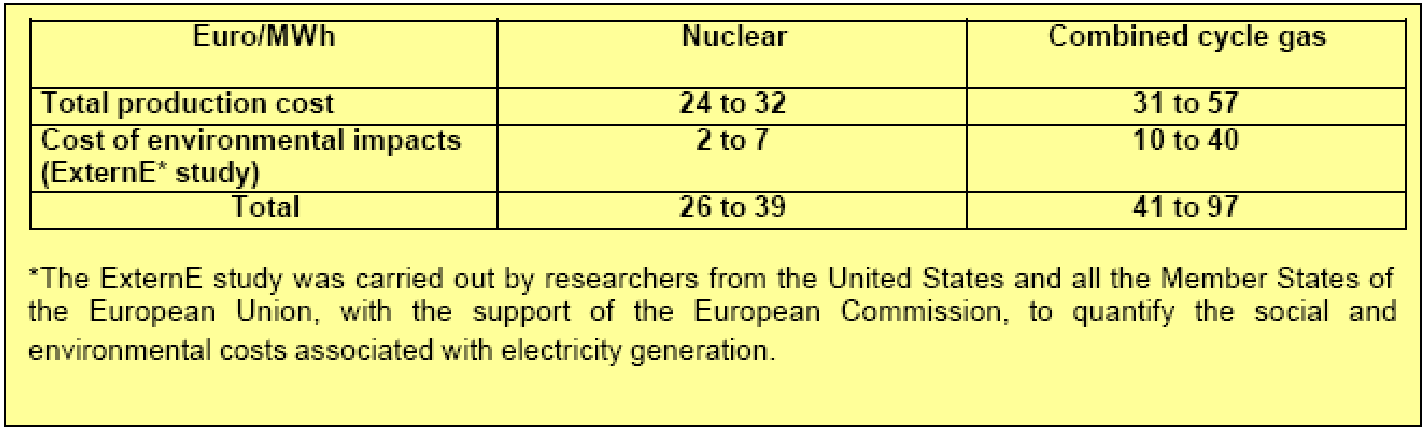
11/13/06

Professor Neil Todreas

How to Think about Economics (and deal with economists)

Externalities are not generally accounted for.
The playing field is not level.

- Carbon penalties
- Energy security
- Clean air



Euro/MWh	Nuclear	Combined cycle gas
Total production cost	24 to 32	31 to 57
Cost of environmental impacts (ExternE* study)	2 to 7	10 to 40
Total	26 to 39	41 to 97

*The ExternE study was carried out by researchers from the United States and all the Member States of the European Union, with the support of the European Commission, to quantify the social and environmental costs associated with electricity generation.

Courtesy of Tyler Ellis. Used with permission.

Tyler Ellis, "A Sustainable Nuclear Energy Systems Strategy for The United States of America," MIT Dept. of Nuclear Science and Engineering, Oct. 18, 2006.

Also see: *Nucleonics Week*, July 26, 2001, pp. 10-11
http://www.externe.info
http://externe.jrc.es

Dealing with economists (cont.)

The poor nuclear construction/operation experience of the 20th century has stung them. Whereas

- engineers are typically willing to accept projected improvements which stem from new design/operation regimes,
- economists await demonstration of improved cost performance from first mover construction and operation experience.

Hence MIT base case values became:

Overnight cost	$2000/kWe
O & M cost*	$ 15¢/kWe-hr (includes fuel)
Construction period	5 years
Capacity factor	85%
Plant life	40 years

*MIT base O&M case is 25% reduction of non-fuel costs from recent $ 18¢/kWe-hr average fleet performance.

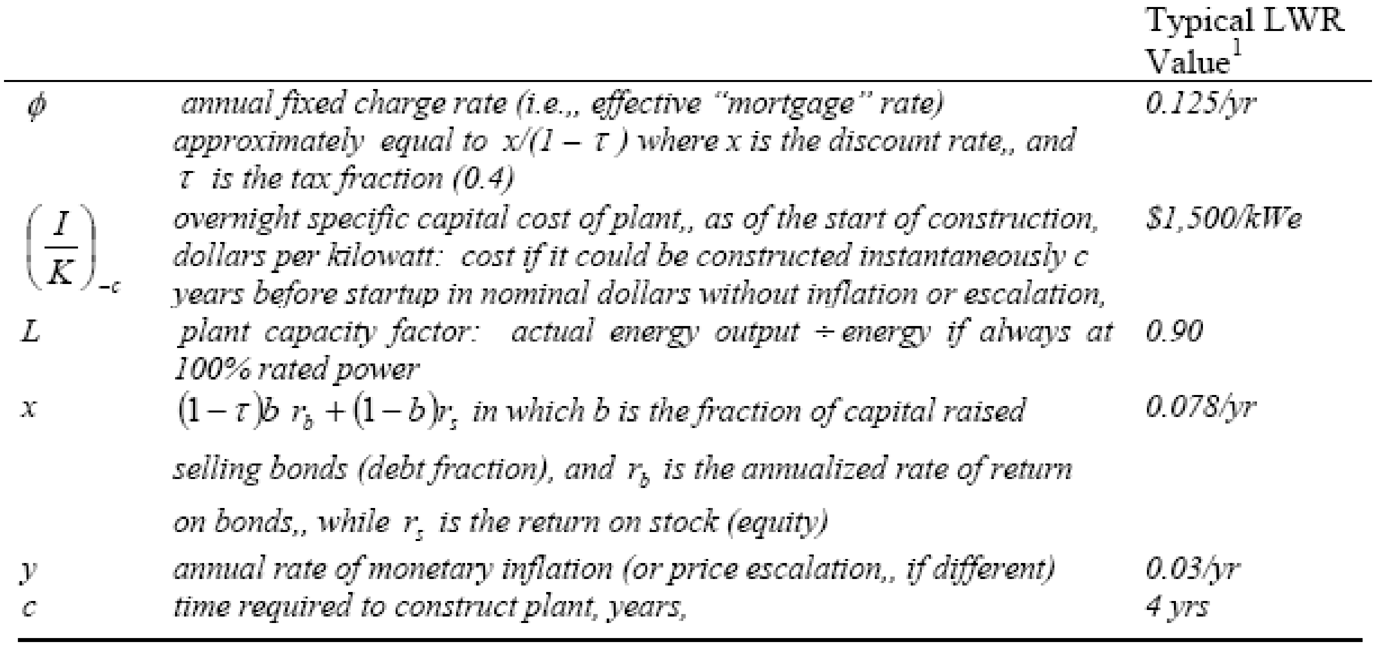
COE Issues

- Capital Cost (overnight and construction period)
- Financing Model
- O & M Cost
- Plant Size
- Fuel Cycle Cost

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.7

Capital Related Costs (Simplified expression of capital cost component contributing to Lifetime-Levelized Busbar Cost of Electric Energy

$$\frac{1000\phi}{8{,}766L}\left(\frac{I}{K}\right)_{-c}\left[1+\frac{x+y}{2}\right]^{c}$$



		Typical LWR Value[1]
ϕ	*annual fixed charge rate (i.e.,, effective "mortgage" rate) approximately equal to x/(1 – τ) where x is the discount rate,, and τ is the tax fraction (0.4)*	*0.125/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 nominal dollars without inflation or escalation,*	*\$1,500/kWe*
L	*plant capacity factor: actual energy output ÷ energy if always at 100% rated power*	*0.90*
x	$(1-\tau)b\ r_b+(1-b)r_s$ *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)*	*0.078/yr*
y	*annual rate of monetary inflation (or price escalation,, if different)*	*0.03/yr*
c	*time required to construct plant, years,*	*4 yrs*

Capital Cost Component for an Existing LWR Plant *41 mills/kw-hre*

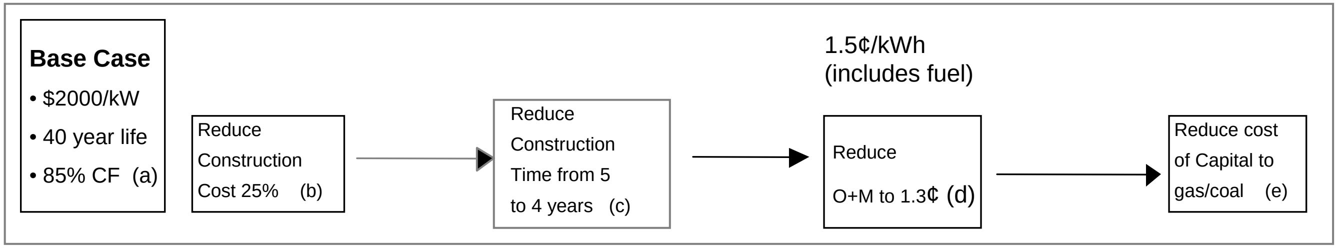
Driscoll, M.J., Chapter 5 from "**Sustainable Energy - Choosing Among Options**" by Jefferson W. Tester, Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. MIT Press, June 2005

Cost Parameters

$$40\ \frac{mills}{kWe-hr}\times 0.1\frac{cents}{mill}=4.00\frac{¢}{kWe\text{-}hr}$$

$$4.00\frac{¢}{kWe\text{-}hr}\times\frac{0.01\,\$/¢}{0.001\frac{\mathrm{MW}}{\mathrm{kW}}}=40\frac{\$}{MWe-hr}$$

MIT Study Results



Base Case

- $2000/kW
- 40 year life
- 85% CF (a)

Reduce Construction Cost 25% (b)

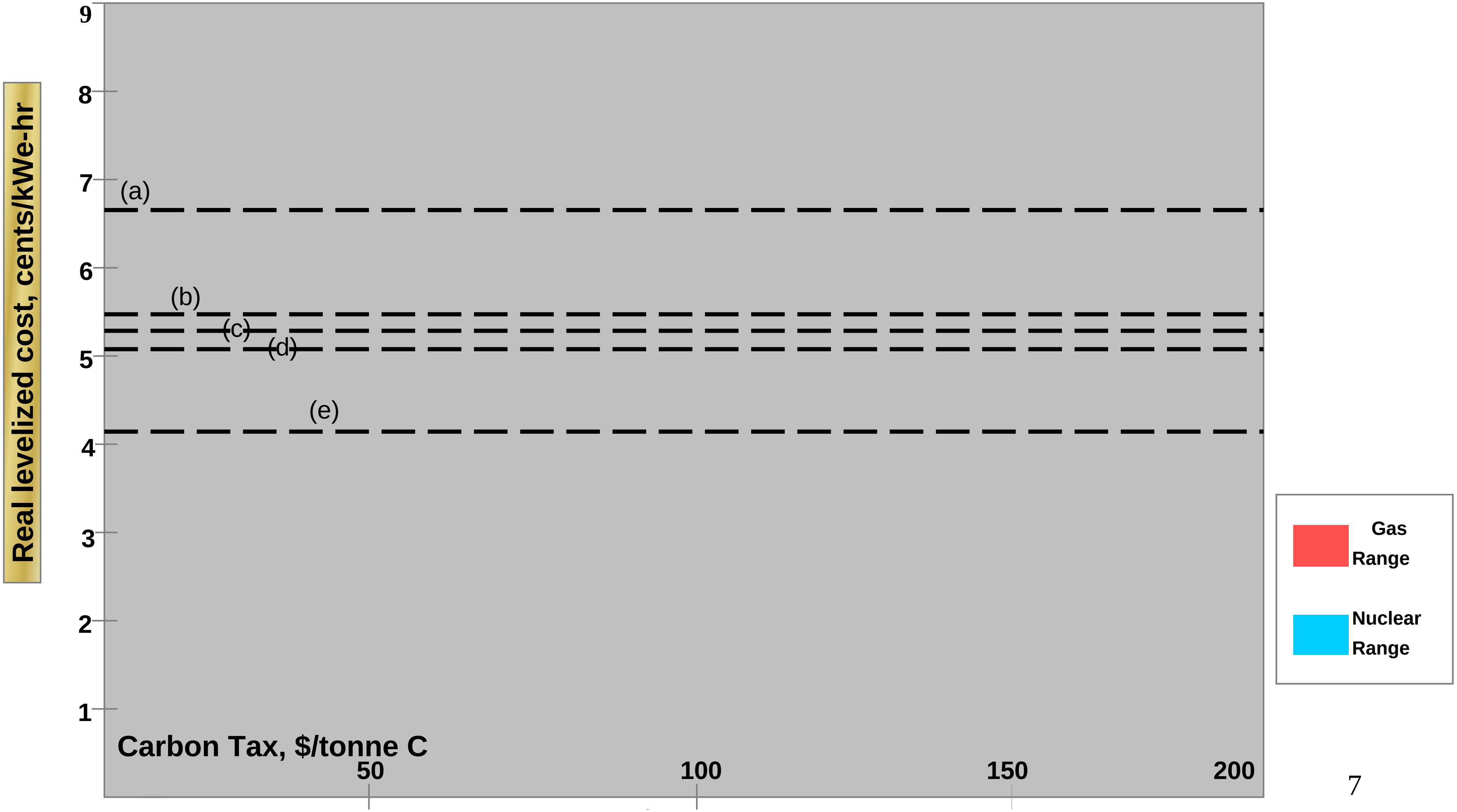
Reduce Construction Time from 5 to 4 years (c)

1.5¢/kWh (includes fuel)

Reduce O+M to 1.3¢ (d)

Reduce cost of Capital to gas/coal (e)

	Nuclear	Gas
Equity/Debt	50/50%	40/60%
Equity (nominal net of income tax)	15%	12%
Debt (Nominal)	8%	8%
Inflation	3%	3%
Income Tax Rate (after expenses, interest + tax depreciation)	38%	38%



N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.5

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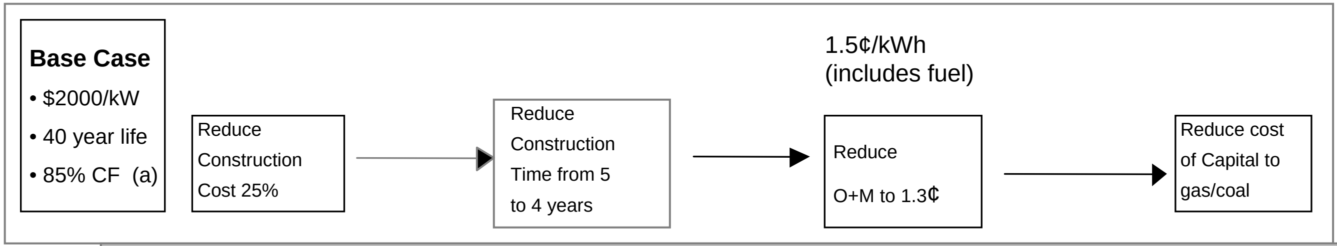

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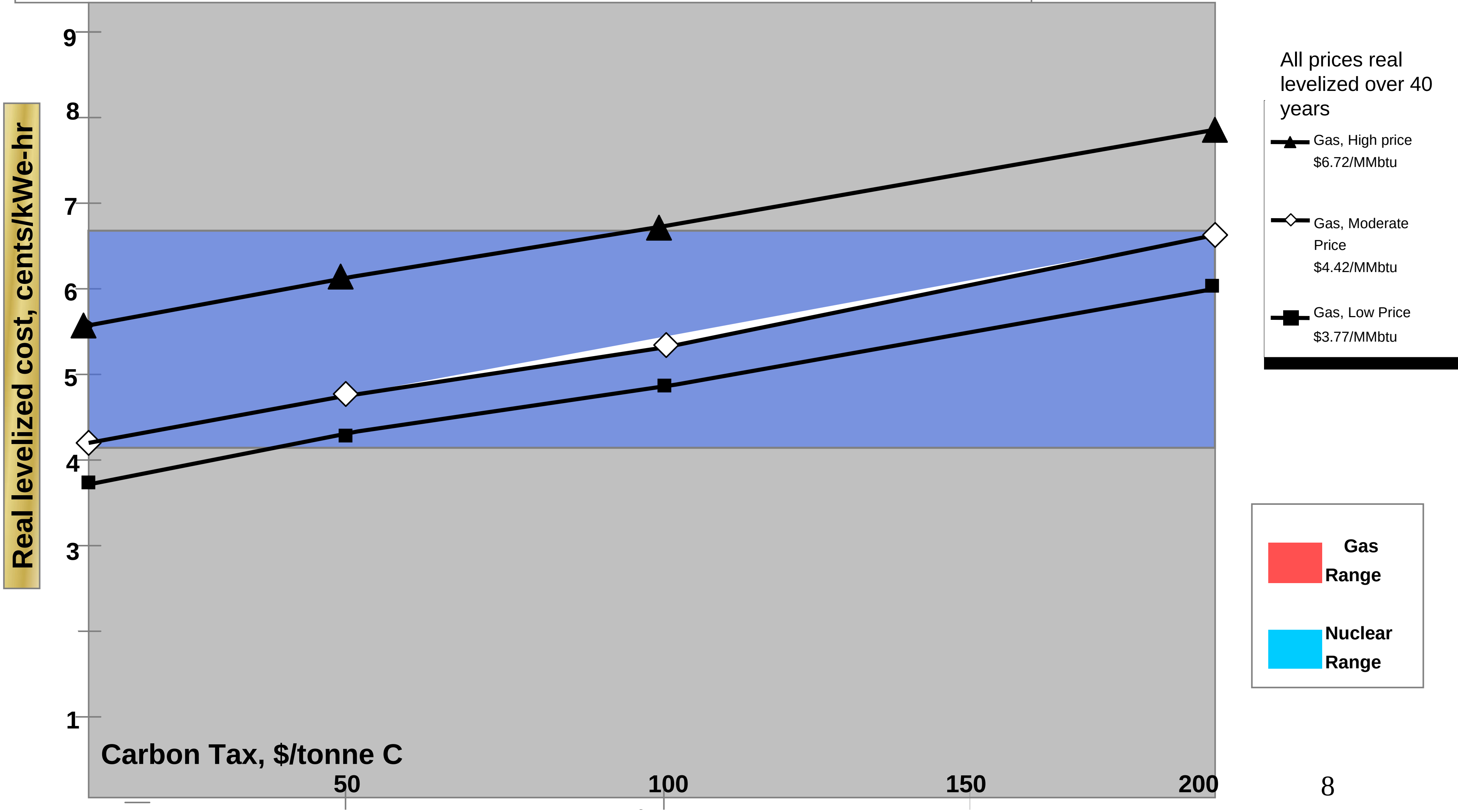
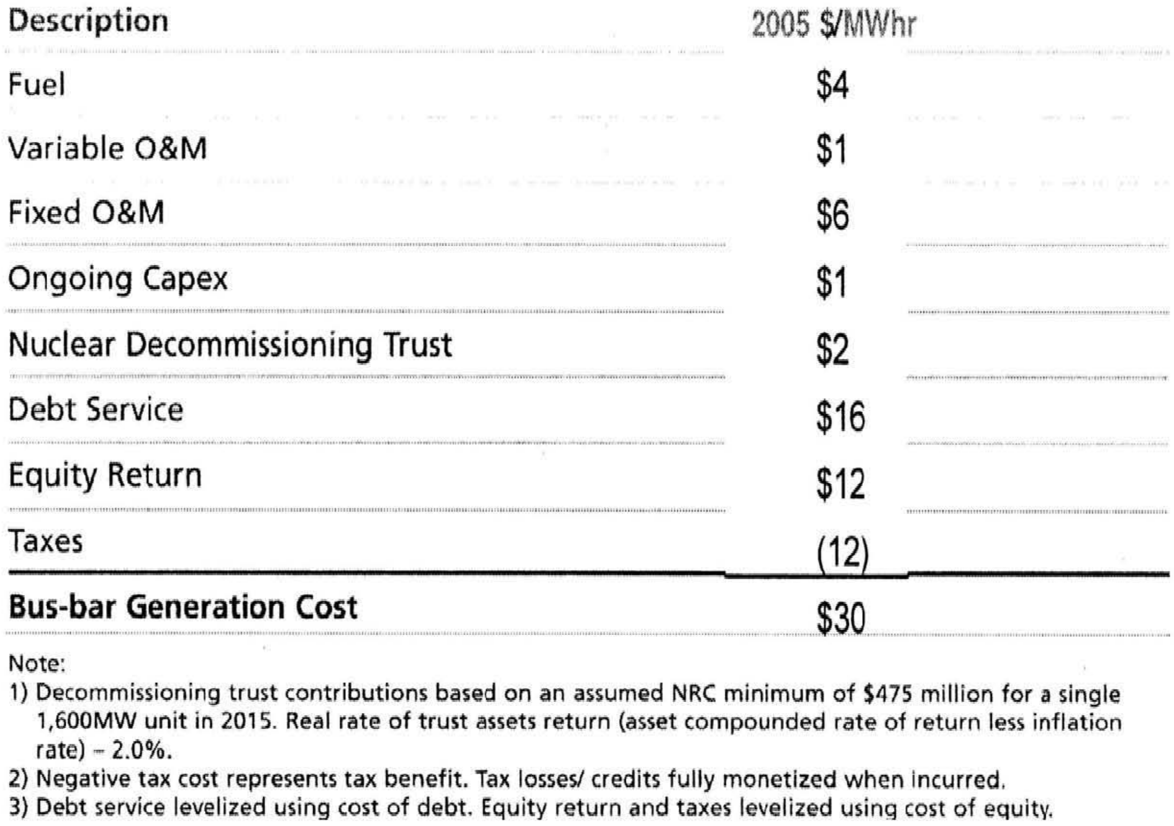


All prices real levelized over 40 years

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.6

UniStar Nuclear Business Model

The UniStar Nuclear Business Model provides a compelling investment opportunity. For a fleet of units with a leveraged overnight capital cost of $1,998/kw and a return on equity at risk of 15%, the following take reflects the approximate resulting bus bar cost structure:



Description	2005 $/MWhr
Fuel	$4
Variable O&M	$1
Fixed O&M	$6
Ongoing Capex	$1
Nuclear Decommissioning Trust	$2
Debt Service	$16
Equity Return	$12
Taxes	(12)
Bus-bar Generation Cost	$30

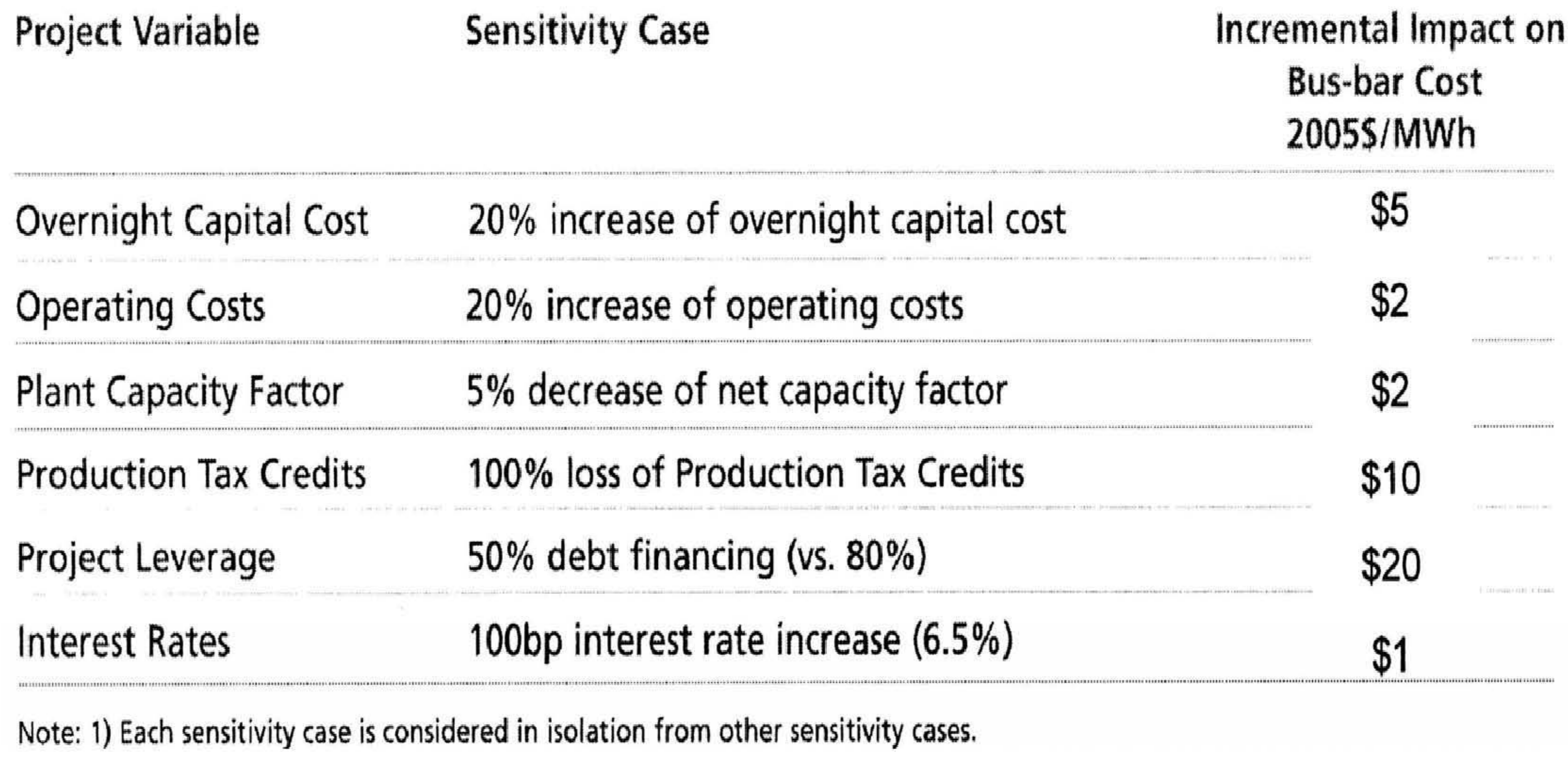
Note:

1) Decommissioning trust contributions based on an assumed NRC minimum of $475 million for a single 1,600MW unit in 2015. Real rate of trust assets return (asset compounded rate of return less inflation rate) – 2.0%.
2) Negative tax cost represents tax benefit. Tax losses/ credits fully monetized when incurred.
3) Debt service levelized using cost of debt. Equity return and taxes levelized using cost of equity.

N.E. Todreas, "Perspectives on the Economics of Nuclear Power from the MIT Study," NE ANS Symposium, Troy, NY 3/30/2006, p.21

UniStar Business Model (cont.)

The robustness of the investment opportunity is suggested by the following sensitivity analysis:



Project Variable	Sensitivity Case	Incremental Impact on Bus-bar Cost 2005$/MWh
Overnight Capital Cost	20% increase of overnight capital cost	$5
Operating Costs	20% increase of operating costs	$2
Plant Capacity Factor	5% decrease of net capacity factor	$2
Production Tax Credits	100% loss of Production Tax Credits	$10
Project Leverage	50% debt financing (vs. 80%)	$20
Interest Rates	100bp interest rate increase (6.5%)	$1

Note: 1) Each sensitivity case is considered in isolation from other sensitivity cases.

N.E. Todreas, "Perspectives on the Economics of Nuclear Power from the MIT Study," NE ANS Symposium, Troy, NY 3/30/2006, p.22

Overnight Capital Cost

(From Appendix to Chapter 5, MIT Study)

		$ Year	Construction Time Years	Financing	Income Tax	Contingen-cy
USEIA (Jan 03)	**Reference Case** **$2044/kWe in 2010** **$1906/kWe in 2025**	**2001**	**5**		✓	✓
	Advanced Cost Case **$1535/kWe in 2012** **$1228/kWe in 2025**	**2001**	**5**		✓	✓
DOE – 2010 Roadmap (Oct 01)	**$1000 - 1600/kWe**	**2000**	**4.5**			
NEA (2001)	**USA** **$1831/kWe**	**2002**	**4**			✓
	OECD **$1831 - 2737/kWe**	**2001**	**4-9**			
FINLAND	**$1600/kWe**	**2002**	**5**	**100% Debt at 5% Real Interest**	**None**	
JAPAN	**Onagawa 3 (BWR) - $2409/kWe** **K-K 6 (ABWR) - $2020/kWe** **K-K 7 (ABWR) - $1790/kWe**	**2002**				
KOREA	**Yonggwang 5 + 6 - (KSNP-PWRs)** **$1800/kWe**	**2002**		**100% Debt**		
BROWN'S FERRY (Restart)	**$1280/kWe**	**2002**		**100% Debt at 80 basis points above 10 yr Treasury**	**None**	
SEABROOK (Sale)	**$730/kWe**	**2002**		**Plus $25.6MM for components and $61.9MM for fuel**		

N.E. Todreas, "Perspectives on the Economics of Nuclear Power from the MIT Study," NE ANS Symposium, Troy, NY 3/30/2006, p.8

Overnight Capital Cost

(post MIT report 7/03)

1) Univ. of Chicago (8/04) $1200-$1500/kWe
   - ABWR & AP 1000/SWR 1000 + $300/kWe FOAK

2) French DIDEME (12/03)/E. Proust (5/05) $1283 €/kWe

3) J. Turnage (UniStar) (1/06) $1998/kWe
   - Return on equity 15%
   - Equity 20%/Debt 80%

4) R. Matzie (Westinghouse) (3/06) $1400-1600/kWe
   - Twin 1090 MWe units

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.9

Challenges

(from Turnage, 2005)

There remain a number of challenges:

- Rulemaking
- Public perception (how deep?)
- Financing
- Infrastructure
- Qualified labor pool
- Issues with the back end of the fuel cycle

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.19

COE Differences (France vs. USA)

Finance model

- US – distinguishes between equity and debt (different costs & loan payback period)
- French – uniform discount rate (real Weighted Average Cost of Capital [WACC] before tax)

O & M assumption

- US – 2nd best operating plant quartile (base case)
- France – EPR projected gains in availability, rating, cost performance

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.10

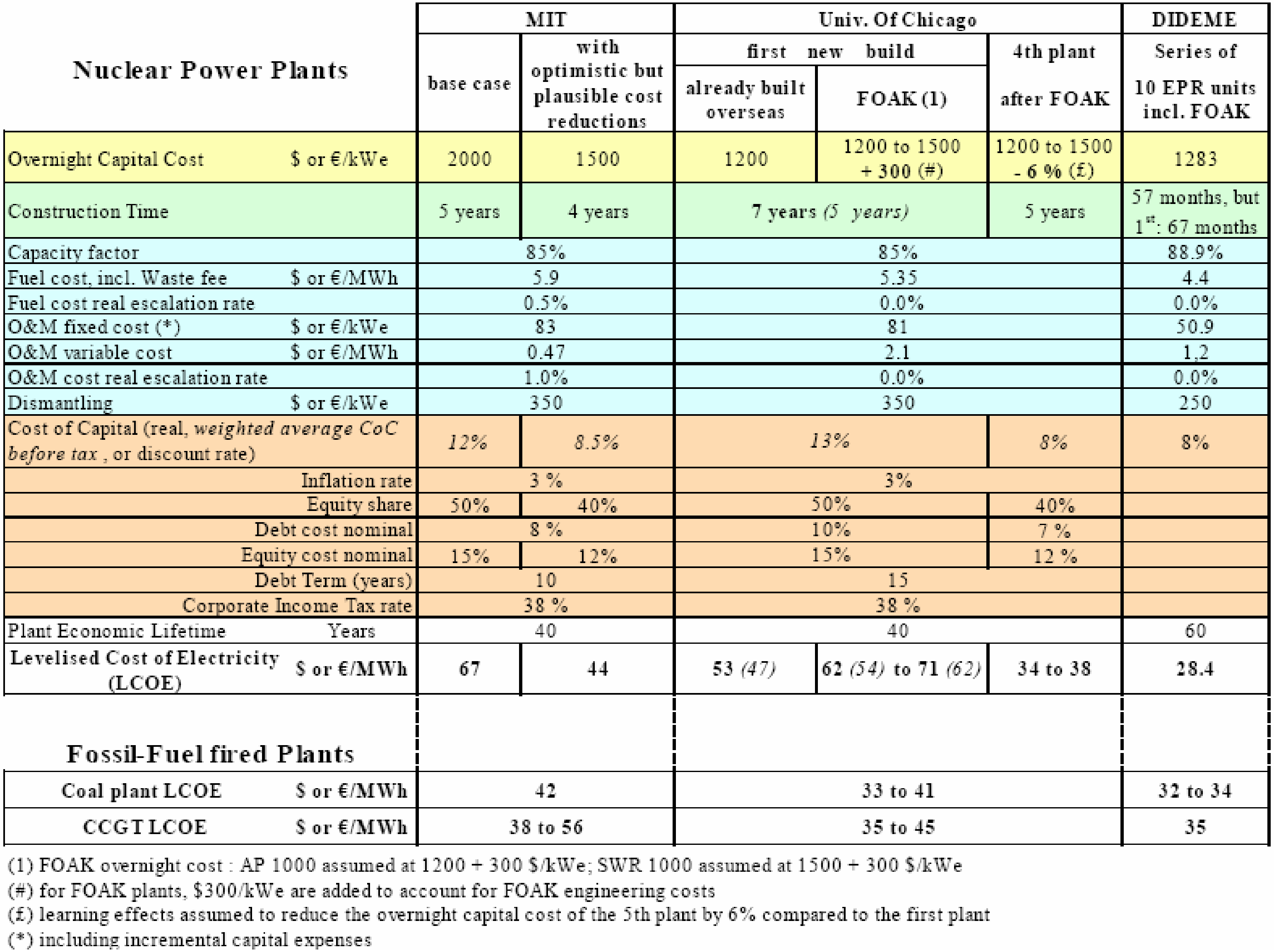
Financing Assumptions and Technical-Economic Parameters Adopted for Nuclear Power Plant Economic Studies (Proust 2005)

Nuclear Power Plants		**MIT**		**DIDEME**
		base case	**with optimistic but plausible cost reductions**	**Series of 10 EPR units incl. FOAK**
Overnight Capital Cost	$ or €/kWe	2000	1500	1283
Construction Time		5 years	4 years	57 months, but 1st: 67 months
Capacity factor		85%		88.9%
Fuel cost, incl. Waste fee	$ or €/MWh	5.9		4.4
O&M fixed cost (*)	$ or €/kWe	83		50.9
Cost of Capital (real, *weighted average CoC before tax*, or discount rate)		*12%*	*8.5%*	8%
Inflation rate		3 %		
Equity share		50%	40%	
Debt cost nominal		8 %		
Equity cost nominal		15%	12%	
Debt Term (years)		10		
Corporate Income Tax rate		38 %		
Plant Economic Lifetime	Years	40		60
Levelised Cost of Electricity (LCOE)	**$ or €/MWh**	**67**	**44**	**28.4**
Fossil-Fuel fired Plants				
Coal plant LCOE	**$ or €/MWh**	**42**		**32 to 34**
CCGT LCOE	**$ or €/MWh**	**38 to 56**		**35**

(*) including incremental capital expenses

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.11

Financing Assumptions and Technical-Economic Parameters Adopted for Nuclear Power Plant Economic Studies (Proust 2005)



Nuclear Power Plants		MIT		Univ. Of Chicago			DIDEME
		base case	with optimistic but plausible cost reductions	first new build		4th plant	Series of
				already built overseas	FOAK (1)	after FOAK	10 EPR units incl. FOAK
Overnight Capital Cost	$ or €/kWe	2000	1500	1200	1200 to 1500 + 300 (#)	1200 to 1500 - 6 % (£)	1283
Construction Time		5 years	4 years	7 years *(5 years)*		5 years	57 months, but 1^{st}: 67 months
Capacity factor		85%		85%			88.9%
Fuel cost, incl. Waste fee	$ or €/MWh	5.9		5.35			4.4
Fuel cost real escalation rate		0.5%		0.0%			0.0%
O&M fixed cost (*)	$ or €/kWe	83		81			50.9
O&M variable cost	$ or €/MWh	0.47		2.1			1,2
O&M cost real escalation rate		1.0%		0.0%			0.0%
Dismantling	$ or €/kWe	350		350			250
Cost of Capital (real, *weighted average CoC before tax* , or discount rate)		*12%*	*8.5%*	*13%*		*8%*	8%
Inflation rate		3 %		3%			
Equity share		50%	40%	50%		40%	
Debt cost nominal		8 %		10%		7 %	
Equity cost nominal		15%	12%	15%		12 %	
Debt Term (years)		10		15			
Corporate Income Tax rate		38 %		38 %			
Plant Economic Lifetime	Years	40		40			60
Levelised Cost of Electricity (LCOE)	**$ or €/MWh**	**67**	**44**	**53** *(47)*	**62** *(54)* **to 71** *(62)*	**34 to 38**	**28.4**
Fossil-Fuel fired Plants							
Coal plant LCOE	**$ or €/MWh**	**42**		**33 to 41**			**32 to 34**
CCGT LCOE	**$ or €/MWh**	**38 to 56**		**35 to 45**			**35**

(1) FOAK overnight cost : AP 1000 assumed at 1200 + 300 $/kWe; SWR 1000 assumed at 1500 + 300 $/kWe

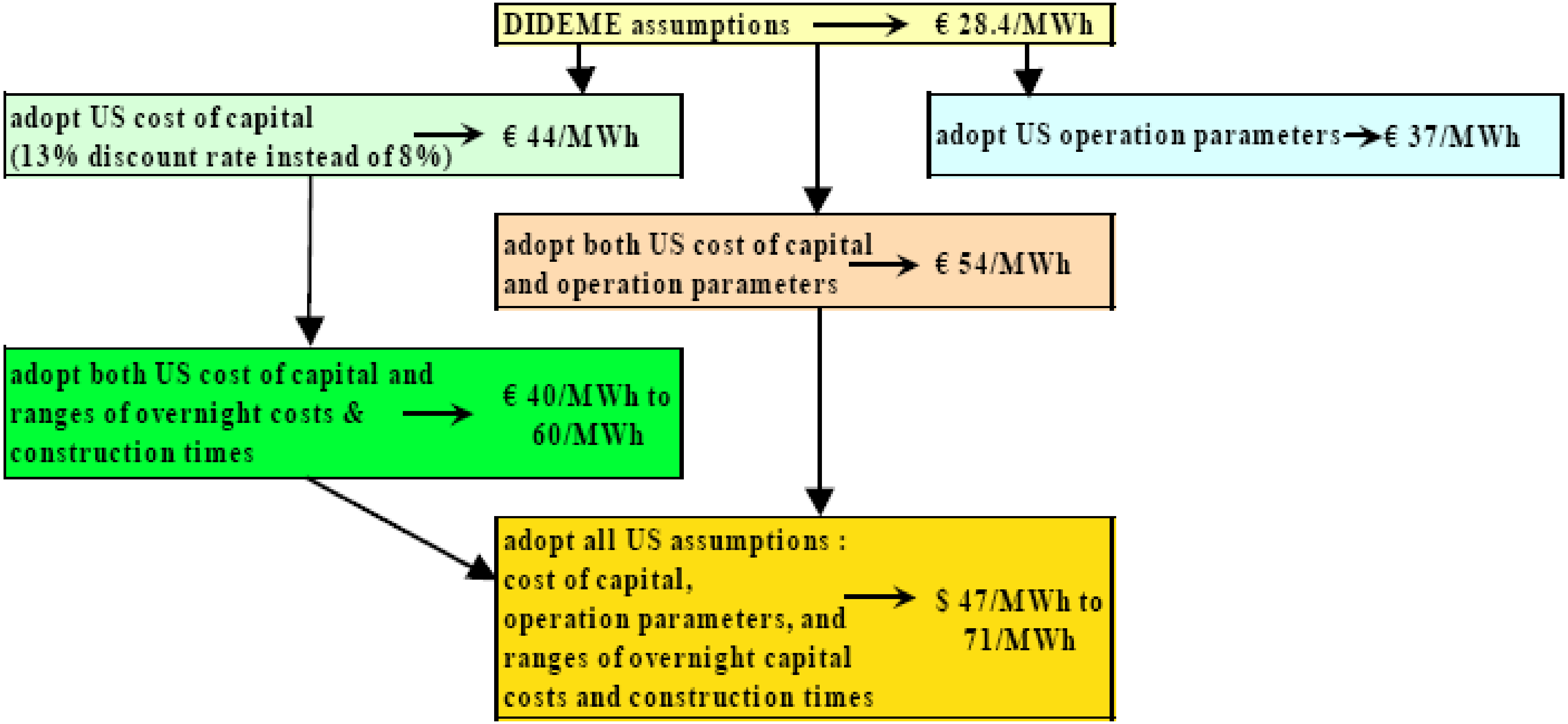
(#) for FOAK plants, $300/kWe are added to account for FOAK engineering costs

(£) learning effects assumed to reduce the overnight capital cost of the 5th plant by 6% compared to the first plant

(*) including incremental capital expenses

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.12

Explaining how to go from the nuclear MWh cost found by the French DIDEME study to the cost range given in the University of Chicago 2004 economic study (Proust, 2005)



DIDEME assumptions → € 28.4/MWh

adopt US cost of capital (13% discount rate instead of 8%) → € 44/MWh

adopt US operation parameters → € 37/MWh

adopt both US cost of capital and operation parameters → € 54/MWh

adopt both US cost of capital and ranges of overnight costs & construction times → € 40/MWh to 60/MWh

adopt all US assumptions : cost of capital, operation parameters, and ranges of overnight capital costs and construction times → $ 47/MWh to 71/MWh

N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.13

Elements of Capital Cost
ALMR (1994 $)

Overnight Cost		
• **Base construction**	**72%**	**84%**
• **Contingency**	**12%**	
Interest during Construction	**16%**	
	100%	

	Nuclear Island	**BOP**	**Total**
Total Capital Cost	**0.73**	**0.27**	**1.00**
• **Overnight Cost**	**0.61**	**0.23**	**0.84**
Interest During Construction	**0.12**	**0.04**	**0.16**
• **Overnight Cost**	**0.61**	**0.23**	**0.84**
• • **Base Construction Cost**	**0.51**	**0.21**	**0.72**
Total Contingency	**0.10**	**0.02**	**0.12**
• • **Base Construction Cost**	**0.51**	**0.21**	**0.72**
Direct Cost	**0.36**	**0.13**	**0.49**
Indirect Cost	**0.15**	**0.08**	**0.23**

Elements of Capital Cost (Cont.)
(ALMR (1994 $)

	Nuclear Island	BOP	Total	
Direct Cost	**0.36**	**0.13**	**0.49**	
Acct 20 Land + Land Rights	**0**	**0.006**	**0.006**	
Acct 21 Structures + Improvements	**0.071**	**0.02**	**0.091**	
Acct 22 Reactor Plant Equip	**0.27**	**0**	**0.27**	
Acct 220 NSSS	**0.25**	**0**	**0.25**	**0.27**
Acct 221-228	**0.02**	**0**	**0.02**	
Acct 23 Turbine Plant Equip	**0.0009**	**0.063**	**0.064**	
Acct 24 Electric Plant Equip	**0.013**	**0.019**	**0.032**	
Acct 25 Misc. Plant Equip	**0.008**	**0.010**	**0.018**	
Acct 26 Main Cond Heat Reject System	**0**	**0.011**	**0.011**	

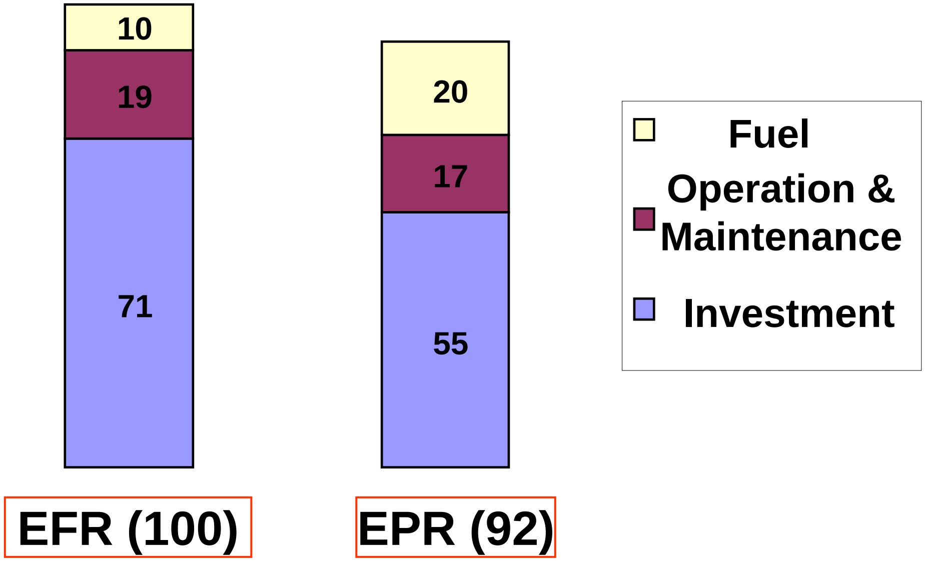
Elements of Capital Cost (Cont.)
(ALMR (1994 $)

Acct 220 NSSS	**0.25**	
220 A.211 Reactor Vessels	**0.017**	**0.175***
220 A.22 Heat Transport Systems	**0.114**	
220 A.26 Other Equipment – inert gas, storage, purification, leak detection, impurity	**0.030**	
220 A.27 I + C	**0.014**	
220 A.211 Heat Transport Systems	**0.114**	
.221 Primary System	**0.031**	**0.114**
.222 Intermediate Heat Transport System	**0.032**	
.223 Steam Generator	**0.051**	
220 A.26 Other equip	**0.030**	
.261 Inert gas	**0.00099**	**0.030**
.264 Na storage, relief, Makeup	**0.0011**	
.265 Na purification	**0.0043**	
.266 Na leak detection	**0.0017**	
.268 Maintenance equip	**0.017**	
.269 Impurity monitoring	**0.0042**	

*Not an inclusive list of NSSS accounts

The economy of FBRs

Comparaison of EFR and EPR generating costs (kWh)



→ Cost investment reduction of FBRs is an important R&D axis

Management cost of waste should be taken into account:

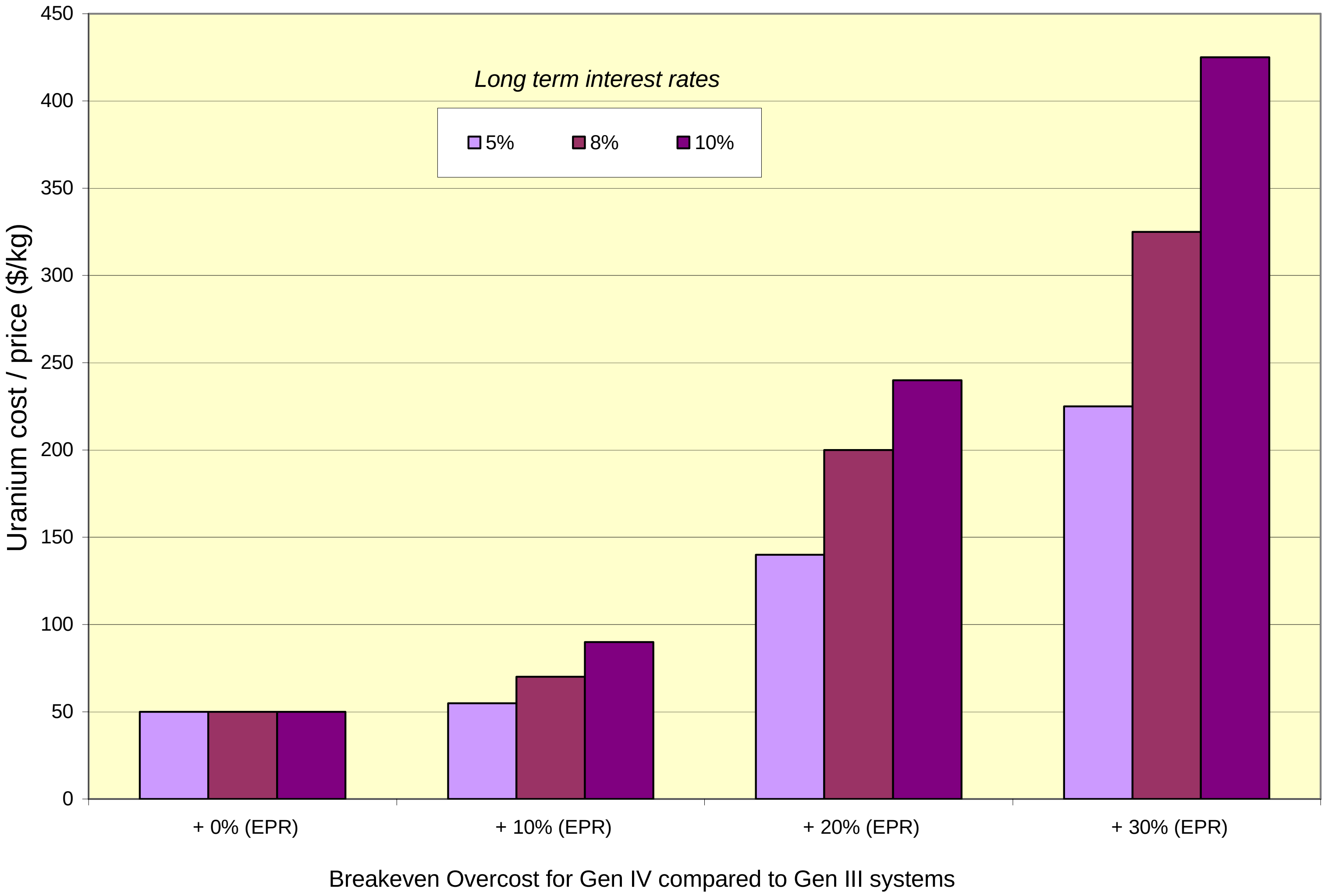
- FBRs have the potential of managing all their waste,

- LWRs may require a second stratum of dedicated reactors (ADS or critical burner reactors), the cost of which should be integrated in the production cost of LWRs

Courtesy of J. L. Carbonnier, CEA. Used with permission.

J.L. Carbonnier, “Merits of Fast Reactors,” Int. Symp.: Rethinking the Nuclear Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, p.11

Competitiveness of Gen IV systems

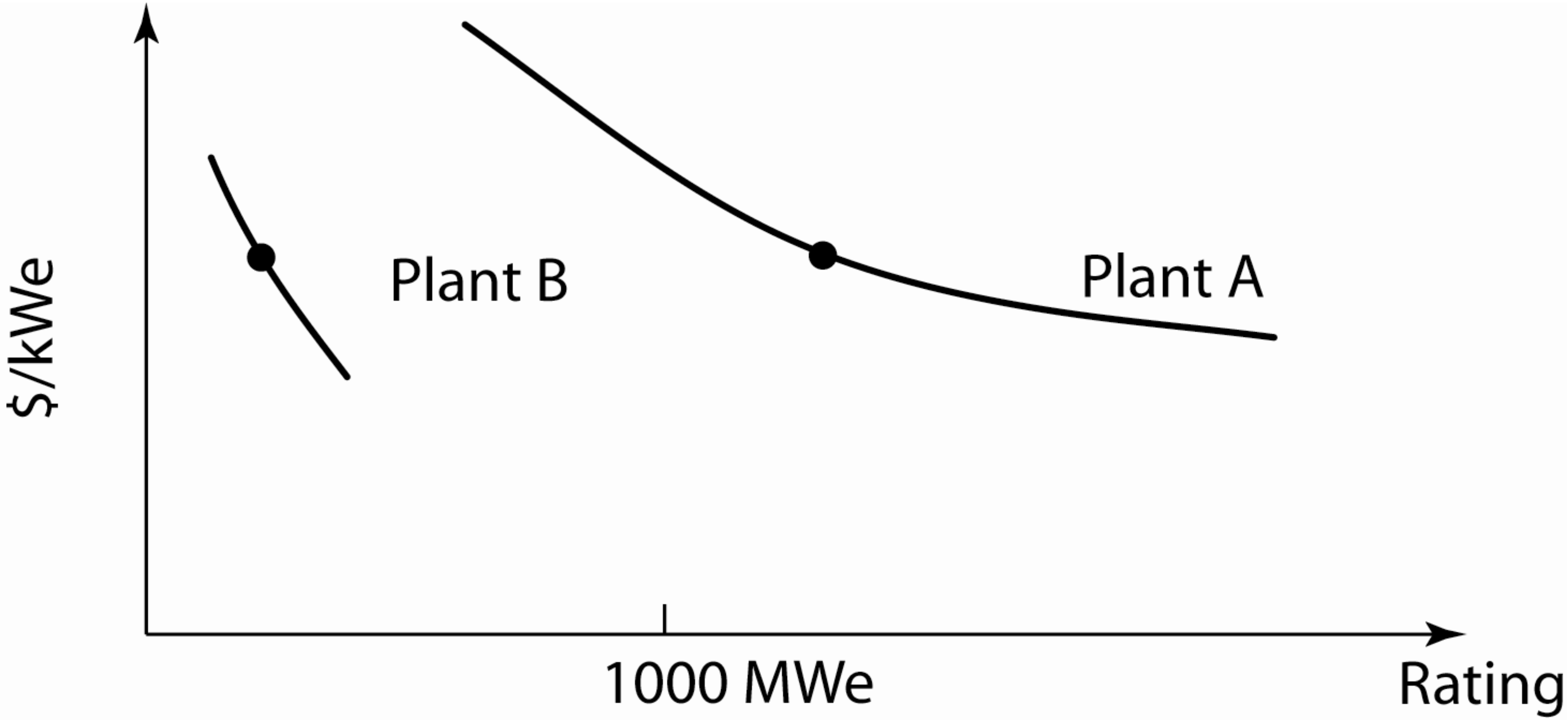


Courtesy of J. L. Carbonnier, CEA. Used with permission.

J.L. Carbonnier, "Merits of Fast Reactors," Int. Symp.: Rethinking the Nuclear Fuel Cycle, Cambridge, Mass., Oct. 30-31, 2006, p.12

Plant Size

Economics of Scale versus Economics of Serial Production



N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.14

Economy of Scale

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

$$\frac{C_i}{C_o} = \left(\frac{K_i}{K_o}\right)^n; \quad or \quad \left(\frac{C_i}{K_i}\right) = \left(\frac{C_o}{K_o}\right)\left(\frac{K_i}{K_o}\right)^{n-1} \qquad (5.25)$$

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 predicated to cost:

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

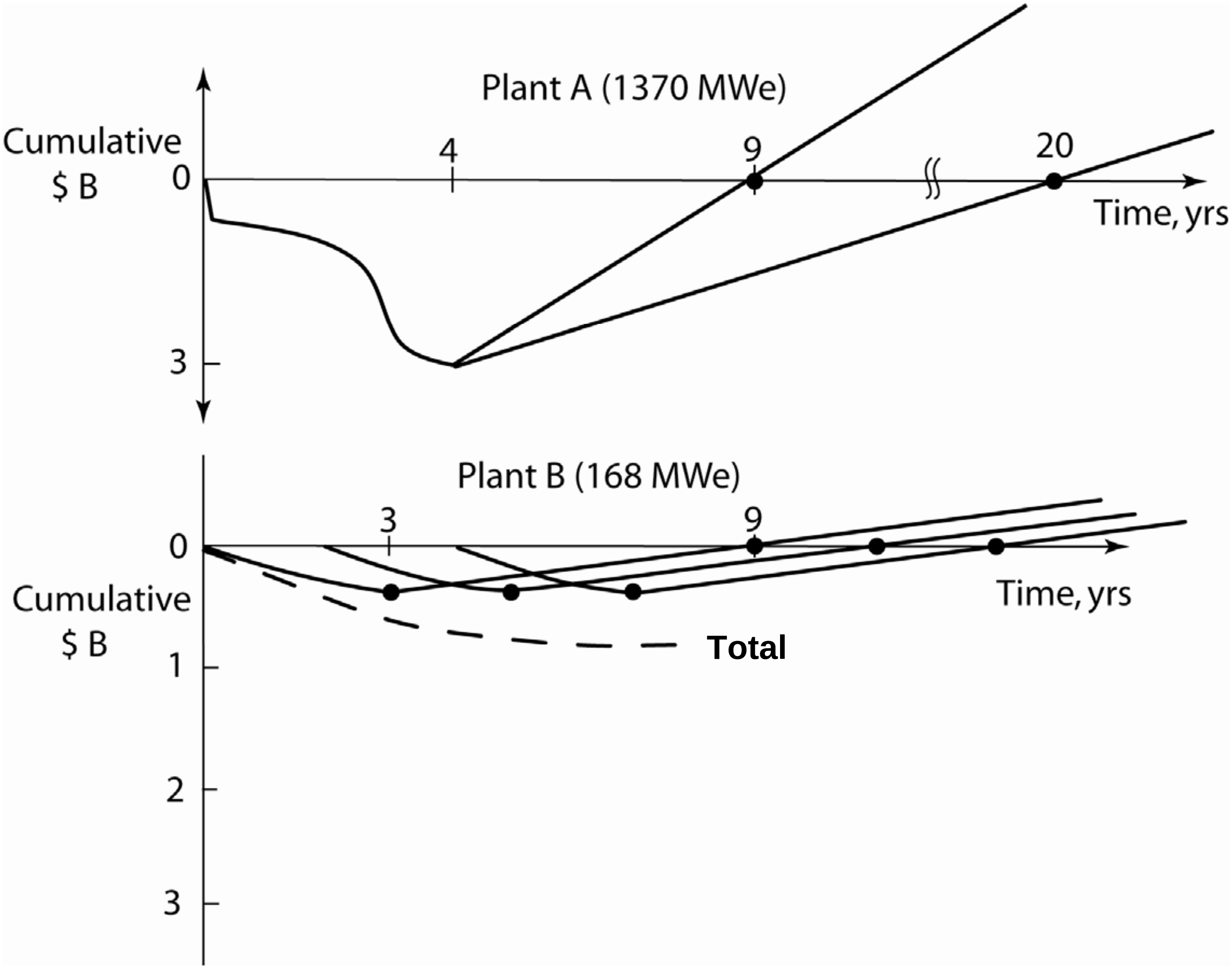
Driscoll, M.J., Chapter 5 from “**Sustainable Energy - Choosing Among Options**" by Jefferson W. Tester, Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. MIT Press, June 2005

Caveats Using Economy of Scale Projections

1) Learning curves apply to replication of the same design, by the same work force, in the same setting (e.g., factory), all of which are likely to change in the long run.
2) 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.
3) Important factors such as materials resource depletion or technological innovation are not taken into account in an explicit manner.
4) 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 renormalized.
5) Shared costs of many units on a single site are also important: e.g., multi-unit stations save considerably on administrative infrastructure costs.

Driscoll, M.J., Chapter 5 from "**Sustainable Energy - Choosing Among Options**" by Jefferson W. Tester, Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. MIT Press, June 2005

Capital Flow



N.E. Todreas, “Perspectives on the Economics of Nuclear Power from the MIT Study,” NE ANS Symposium, Troy, NY 3/30/2006, p.15

Potential Economic Advantages of Smaller Nuclear Plants

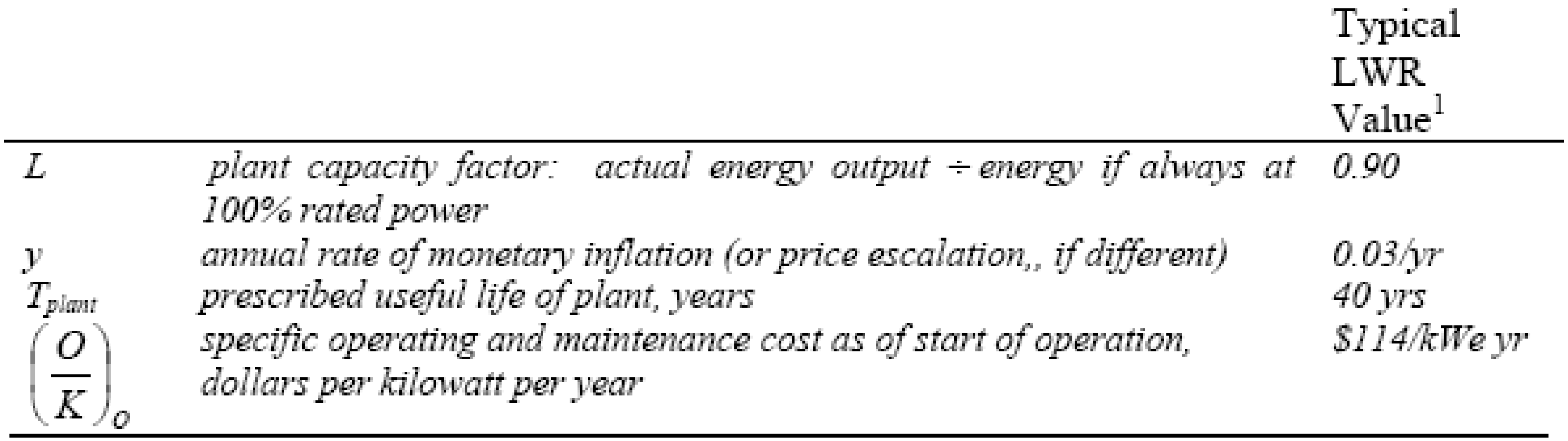
John Taylor	**Hayns & Shepherd**
1. New capacity planning flexibility **2. High content of repetitive factory fabrication with unit standardization** **3. Shorter construction period** **4. Potential market much larger** **5. Reduced financial risk resulting in lower financing rates** **6. Lower costs of first-of-a-kind engineering in multi-modular systems**	**1. Reduction in planning margin** **2a) Increased factory fabrication** **2b) More replication** **3. Reduced construction time** **4. Better match to demand** **5. Smaller front end investment** **6. Bulk ordering**
• More rapid return on investment from single module **• “Packaging” flexibility**	**• Multiple units at a single site** **Improved availability (fast and efficient repair/replacement of defective modules)** **• Faster progression along learning curve** **• Increased station lifetime (easier refurbishment)** **• Elimination of some engineered safety systems and the downgrading (in terms of safety) of some other plant features** **• Design appropriate to the size**

John J. Taylor, “Economic and Market Potential of Small Innovative Reactors,” Rice University, Houston, Texas, March 19-21, 2001

M.R. Hayns & J. Shepherd, “Reducing Cost by Reducing Size,” IAEA Specialist Meeting, Helsinki, 3-6 Sept. 1990

Operating & Maintenance (O&M) Cost Calculation

$$\frac{1000}{8{,}766L}\left(\frac{O}{K}\right)_O\left[1+\frac{yT_{plant}}{2}\right]$$



		Typical LWR Value[1]
L	*plant capacity factor: actual energy output ÷ energy if always at 100% rated power*	*0.90*
y	*annual rate of monetary inflation (or price escalation,, if different)*	*0.03/yr*
T_{plant}	*prescribed useful life of plant, years*	*40 yrs*
$\left(\frac{O}{K}\right)_O$	*specific operating and maintenance cost as of start of operation, dollars per kilowatt per year*	*$114/kWe yr*
	O & M Cost Component for an Existing LWR Plant	*22 mills/kwhre*

Driscoll, M.J., Chapter 5 from "**Sustainable Energy - Choosing Among Options**" by Jefferson W. Tester, Elisabeth M. Drake, Michael W. Golay, Michael J. Driscoll, and William A. Peters. MIT Press, June 2005

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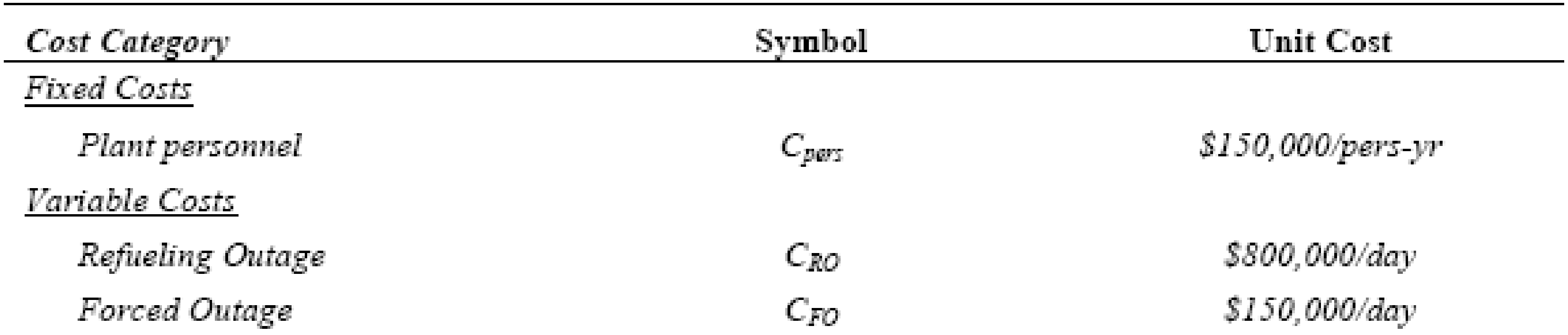
US O&M Performance (including fuel)

the 1990s	Fleet Average	> $20 / MWe-hr
by 2001	Fleet Average Lowest Quartile	$ 18 / MWe-hr $ 13 / MWe-hr

Elements of $(O/K)_o$ Cost



Cost Category	**Symbol**	**Unit Cost**
Fixed Costs		
Plant personnel	C_{pers}	*$150,000/pers-yr*
Variable Costs		
Refueling Outage	C_{RO}	*$800,000/day*
Forced Outage	C_{FO}	*$150,000/day*
Plant Upgrade/Repair Projects	-	***in the $ Millions***

Source: C.A. Shuffler, “Optimization of Hydride Fueled Pressurized Water Reactor Cores,” M.S. Thesis, MIT, Dept. of Nuclear Science & Engineering, p. 135, Sept. 2004, as amended by N. Todreas 11/2006

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