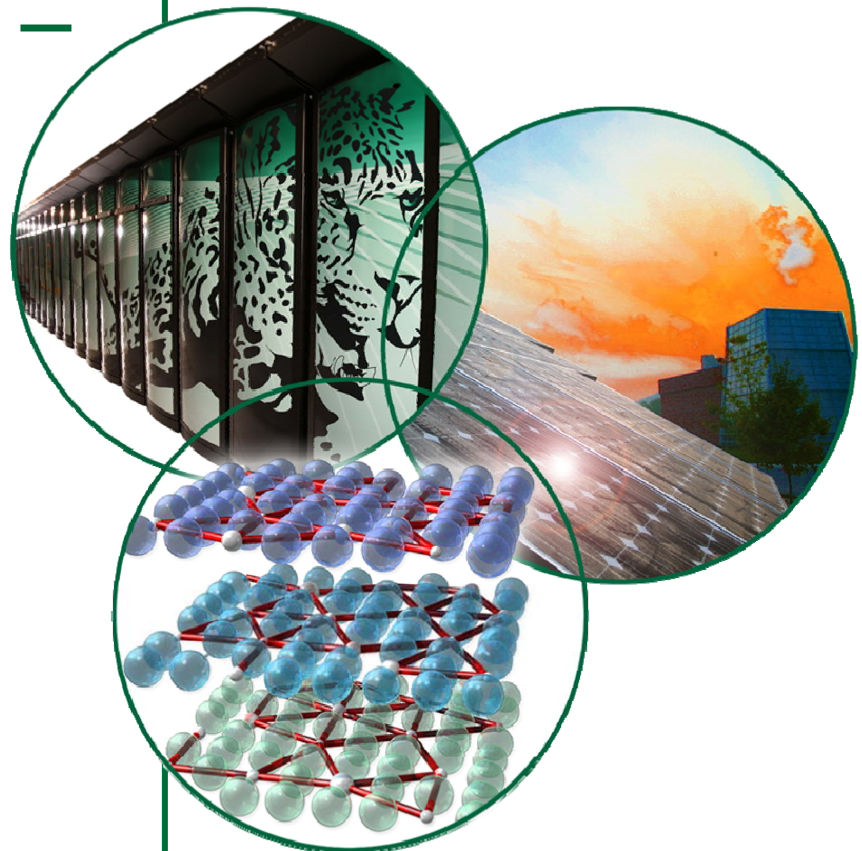
Reactor and Fuel Cycle Economics – Can Nuclear Power Compete?



Kent A. Williams
Nuclear Science and Technology Division

Nuclear Nonproliferation Summer Seminar Series

NSTD Seminar Series

Monday, August 3, 2009
Bldg 5700, Rm D307

U.S. DEPARTMENT OF ENERGY

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

Today's Agenda

- **Introductory background**
- **Very short course in economic terminology and modeling methodology**
- **Discussion of nuclear costs today**
- **Results of a study looking at nuclear futures**
- **Competitiveness vis-à-vis fossil sources**
- **Examination of antinuclear claim that conservation and renewables can replace coal and nuclear**
- **Where does nuclear energy's advantage really lie?**

Not Everyone Is In Favor Of The "Nuclear Renaissance"

- **Antinuclear power organizations now attacking nuclear power and its fuel cycle on three fronts**
  - **Nuclear proliferation**
  - **Susceptibility to terrorist attack**
  - **Cost competitiveness with other low-carbon energy sources**
- **Operational safety of U.S. nuclear plants not really a big issue for interveners anymore**
- **In the last few months antinuke NGOs have issued several reports citing cost as major issue**
- **Antinukes also contest sustainability of nuclear power**
  - **Coal no longer considered acceptable generation source**
  - **Emphasis is on renewables and conservation**

Cost Is An Issue For Other Reasons

- **Regulated utilities must show prior to construction that investment in nuclear is prudent**
- **Some regulated utilities want to begin collecting payments (rate base) prior to plant completion**
- **A nuclear plant investment can be a very significant fraction of the utility's capitalization**
- **Higher cost means higher risk, hence higher financing costs**
- **Cost of NPPs and their fuel cycle an important factor to developing countries wanting nuclear power (non-proliferation consideration)**

A Little History: ORNL Has Been Involved In The Area Of Nuclear Economics For Over 30 Years

- **"Level playing field" comparison of competing advanced nuclear reactor concepts**
- **Comparison of projections for nuclear generating costs vis-à-vis other generation sources**
- **Economic evaluation of fuel cycle alternatives ("open" vs "closed" fuel cycles)**
- **Socioeconomic costs of energy production**
- **Preparation of cost databases for reactors and multiple steps of the nuclear fuel cycle**

Now For A Quick Course In Electrical Generation Economics

- **The measures or "figures-of-merit" for generation economics**
- **The economic life cycle of an NPP**
- **Annualization and levelization of projected costs as a means of simplification for modeling purposes**
- **The four components of levelized unit energy cost (LUEC)**
  - **Capital recovery**
  - **Nonfuel Operations and Maintenance (O&M)**
  - **Nuclear fuel**
  - **Decontamination and Decommissioning (D&D)**

Two Important Economic "Figures-of-Merit" for Nuclear Power Plants

- **Capital at Risk ("All-in" Project Cost)**
  - **Total of all costs incurred before commercial electricity production starts**
  - **Often expressed in $/kW(e) (dollars per unit of electrical capacity)**
  - **These costs are sometimes called "up front" costs**
- **Levelized Unit Electricity Cost (LUEC)**
  - **Expressed in $/megawatt-hour ($/MWh) or mills/kilowatt-hour**
  - **Four major components**
    - **Capital recovery**
    - **Nonfuel Operations and Maintenance (O&M)**
    - **Fuel Cycle**
    - **Contribution to Decontamination and Decommissioning Fund**
  - **Sometimes called "busbar generation cost"**
  - **Generation "Cost" not the same as "price" charged by utility**
- **These figures-of-merit used for actual projects as well as for cost projections**

Capital at Risk (Total Capital Cost)

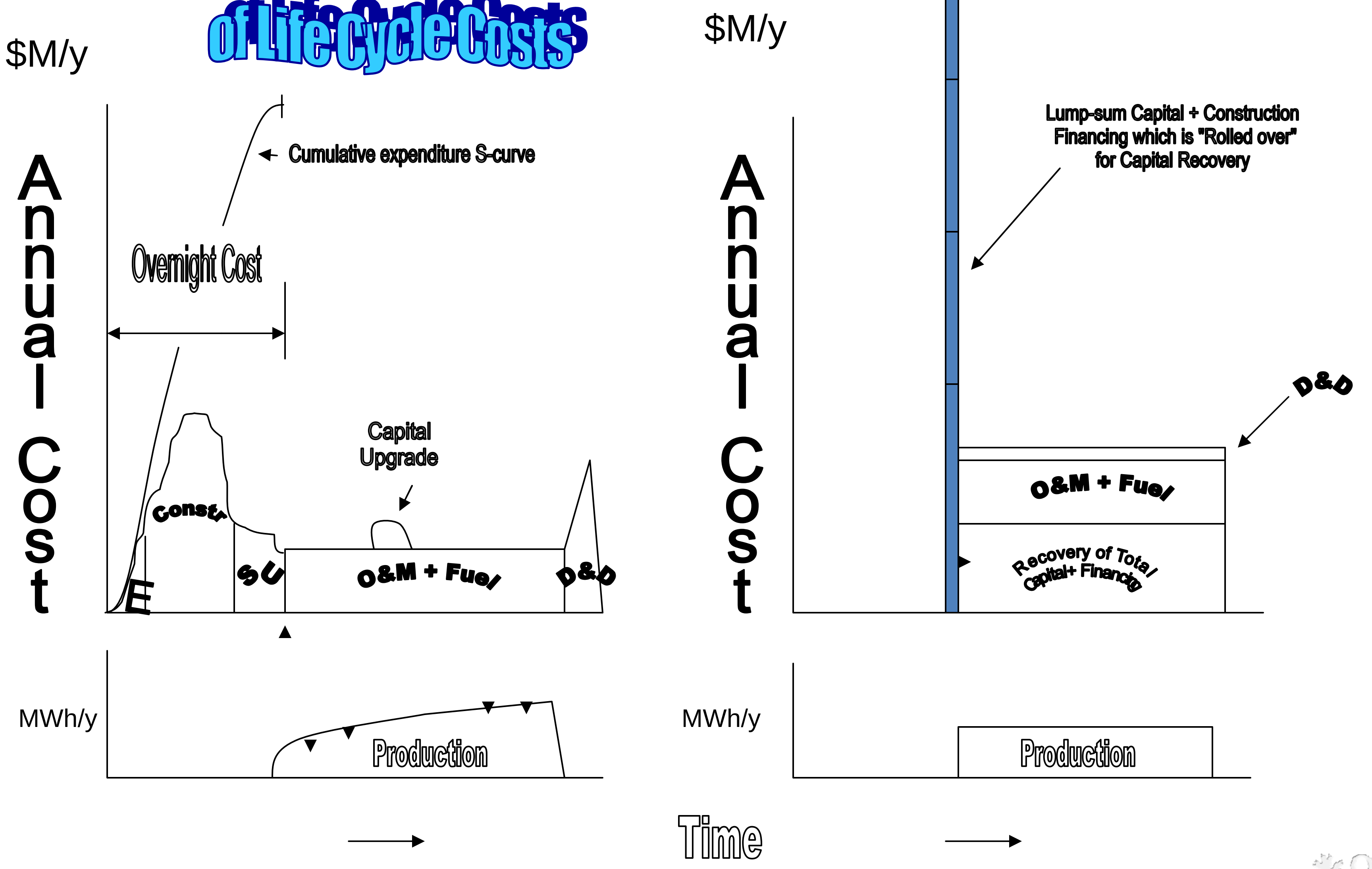
- **Four major components**
  - **"Overnight Cost" (Engineering, Licensing, Procurement, Construction, & Contingency)**
  - **Owner's cost (major component is precommercial start-up)**
  - **Interest during construction (interest on money borrowed prior to start of commercial operation)**
  - **Sometimes the Initial Fuel Load**

- **For projects with "high-risk" financing and/or long construction times, interest during construction can become a significant fraction of the total capital cost. "TIME IS MONEY!"**

For Future Cost Modeling Purposes Cost Annualization and Levelization Simplifys The Analysis and Rolls Up All Elements Of The Life Cycle Cost Into A Few Numbers

- **Useful for technologies where cost detail is limited, i.e. Generation IV**
- **Avoids having to deal with complex year by year cash flows**
- **Assumes the "investment at risk" is recovered over the operating life of the plant (amortization)**
- **Assumes throughput or production rate of plant is constant over life**
- **Assumes O&M and fuel costs are the same (in constant dollars) over the life of the plant (sum of recurring O&M and fuel cost often called the "production cost")**
- **Assumes sinking (escrow) fund over plant life to accumulate amount needed for D&D at end of life**
- **The following figure shows this schematically**

Levelization of Life Cycle Costs



Subcategories For Recurring Costs (O&M and Fuel)

- **Nonfuel O&M**
  - **Staffing**
  - **Maintenance materials**
  - **Consumables including utilities**
  - **Subcontracts (such as refueling crew)**
  - **Insurance and regulation**
  - **Capital upgrades/ replacements**
  - **Radwaste disposal**
  - **Other overheads**

  - **Typically expressed in $M/year**

- **Fuel Cycle Costs (LWR)**
  - **Uranium ore**
  - **Conversion (U_3O_8 to UF_6)**
  - **Enrichment**
  - **Tails conversion/disposition**
  - **Fuel fabrication**
  - **Spent fuel storage**
  - **Spent fuel disposal (open)**
  - **Reprocessing & disposal of all associated wastes (closed)**
  - **Costs and credits for reprocessing products (REPU, Pu, etc.)**

  - **Typically expressed in $/kgHM**

Energy Generation Calculation

- **The model requires the average annual electricity generation in kWh/year or MWh/year**

- **KWh/year = [capacity in MW(e)] × (capacity factor) × 1000 × (8760 h/year)**

- **Capacity factor is a crucial cost driver!**

- **Average capacity factor is % of time plant is actually producing electricity**

Calculation of LUEC ($/MWh)

- **Capital at risk is annualized and levelized via a "fixed charge rate" or "capital recovery factor"**
- **CRF = $i / [(1- i)^n - 1]$**
  - **i = interest rate (inflation free)**
  - **n = plant operating life in years**
- **CRF is multiplied by the total capital at risk to calculate the required annual ($M/year) amount to pay back interest (return to investors) plus principal**
- **Basically the same as a home mortgage**
- **Interest rate is a crucial factor (5% real typical of regulated utility, 10% real typical of "merchant plant")**
- **Result of this calculation is annual payback amount in $M/year over life of plant**

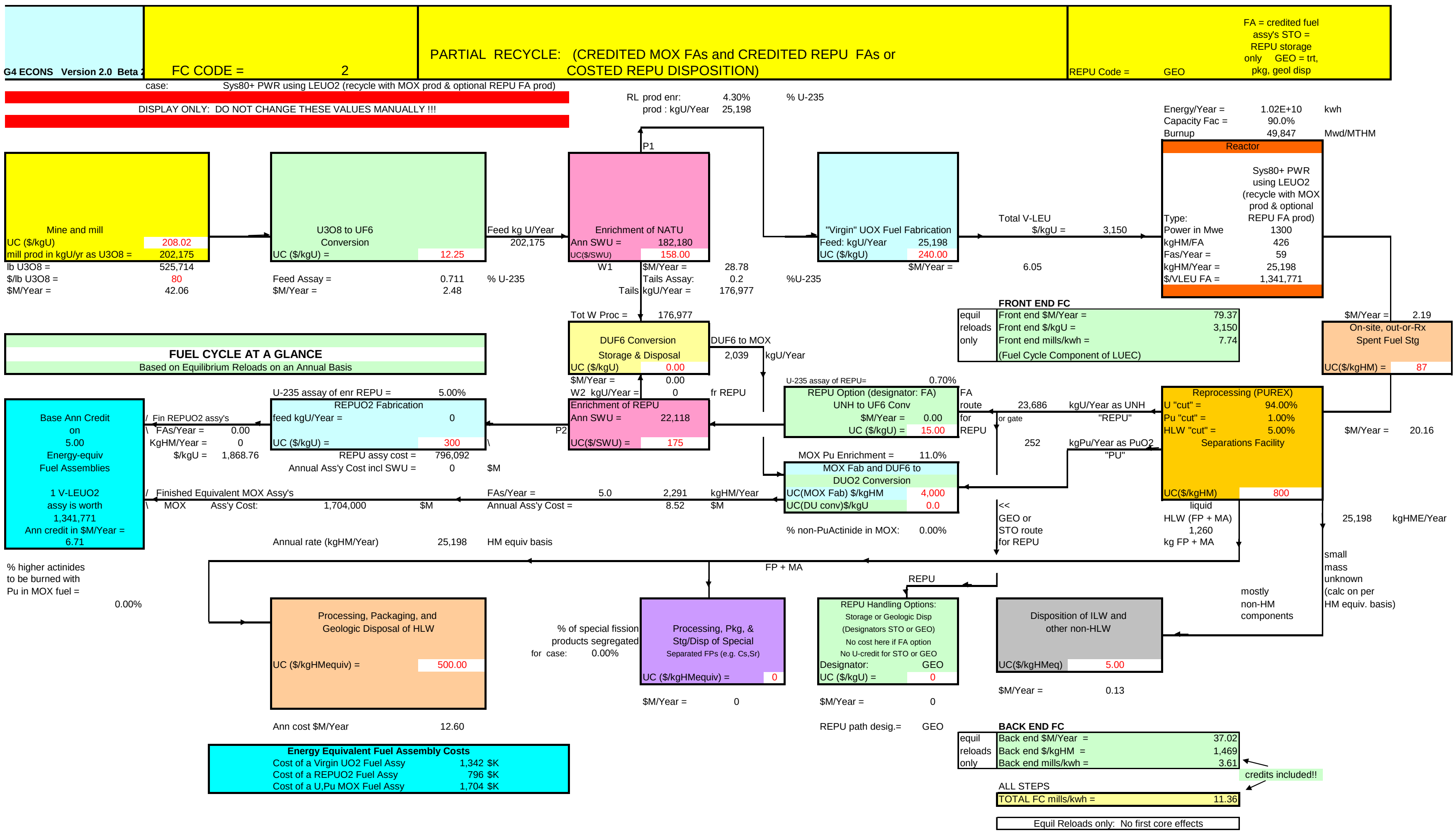
Calculation Of LUEC (continued)

- **LUEC = ([annual capital recovery + annual O&M + annual fuel + annual D&D fund pymt])/[annual electricity production]**

- **G4-ECONS is an EXCEL-based model developed by ORNL for the Generation IV Reactors Program which performs all of the life cycle and economic calculations needed to develop the LUEC**

- **The fuel cycle part of G4-ECONS is the most complex part and requires fuel cycle material balance data (next slide)**

Example Fuel Cycle Output from G4-ECONS (LWR with Partial Recycle)



General Observations On The Levelized Unit Electricity Cost From Nuclear Power

- **Recovery (or amortization) of the "capital at risk" is the largest component of the LUEC (50% or higher, depending on economic life and financing assumptions)**
- **The fuel cycle cost component is likely to stay at 20% or less of LUEC, even with spent fuel recycle or increasing uranium prices (NUCLEAR'S "TRUMP CARD"!)**
- **The O&M cost component is likely to be 30% or less of the LUEC, with staffing costs being the largest contributor**
- **The annual contributions to the D&D sinking fund (D&D component) should be 2% or less of the LUEC**
  - **Acceptable scope of D&D defined by NRC**

Example Breakdown Of LUEC From G4-ECONS (2001 Data For PWR)

G4 ECONS Version 2.0 Beta 2

Case: **Sys80+ PWR using LEUO2 (recycle with MOX prod & optional REPU FA prod)**

Strategy 2

Worksheet name: LUEC Summary

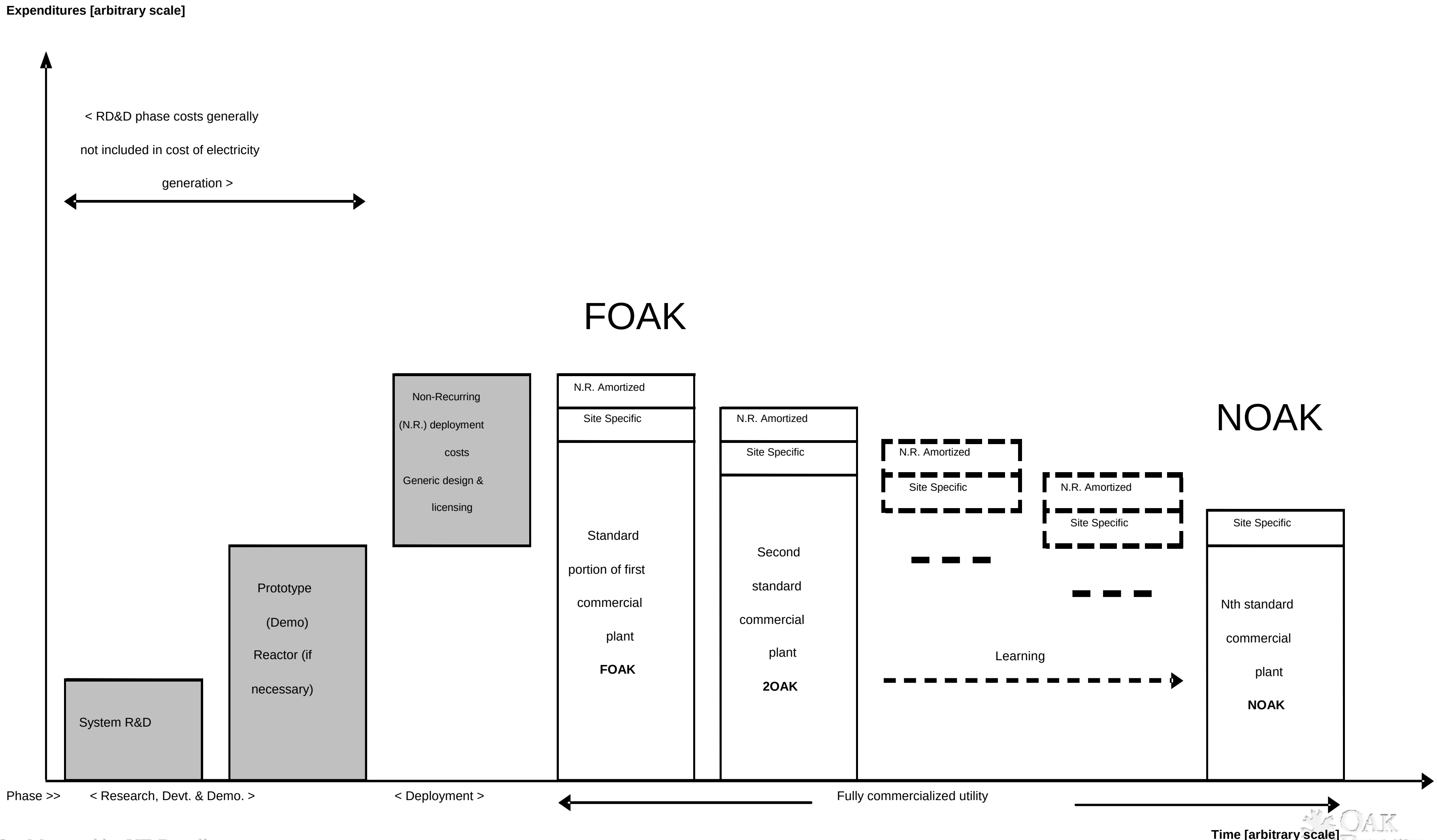
Total Reactor and Fuel Cycle System

Summary of Model Results		
Discount Rate =	5.00%	
	Annualized Cost in $M/Year	Mills/kwh or $/MWh
Capital (Including 1st Core and Financing)	147.07	14.35
Operations Cost	78.47	7.66
Fuel Cycle - Front End	79.37	7.74
Fuel Cycle - Back End	39.54	3.86
D&D Sinking Fund	0.85	0.08
TOTAL LUEC	**345.29**	**33.69**

Some Other Considerations For New Reactor Types

- **Not all costs are captured in the LUEC**
  - **R&D**
  - **Prototype**
  - **Design certification**
- **Reactor Nth-of-a-kind (NOAK) cost of most interest for long range planning**
- **Most current projects will be first-of-a-kind (FOAK)**
- **Learning curves can be used to go from FOAK to NOAK cost (or vice versa)**

Deployment Timeline For A Generic Gen IV Reactor Design



Some Utility LUEC Projections For Current LWR Projects

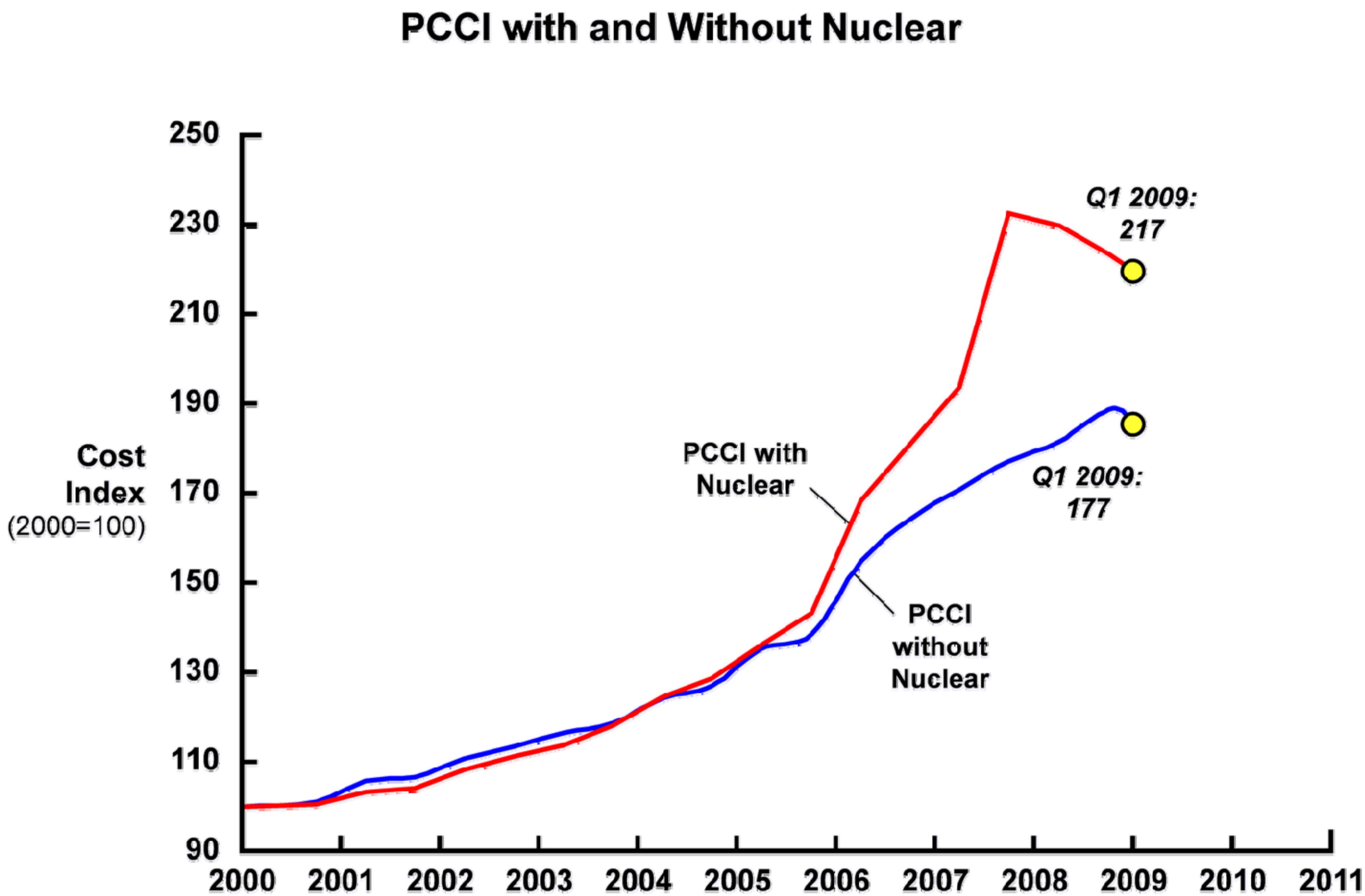
- **Often expressed in 40–60 year constant dollar levelized average $/MWh**
- **Capital contribution could be $25 to $60/MWh**
- **Fuel cycle contribution likely less than $10/MWh**
- **O&M likely in $10 to $20/MWh range**
- **D&D likely less than $1/MWh**
- **Total range of $40 to $90/MWh (low end of range disputed by antinukes)**
- **Capital cost and capacity factor (performance) are the major drivers**

Capital Cost Projections For Some Real Projects

- **Two 1117 MW(e) AP-1000 PWRs (Summer, South Carolina)—$4400/KW(e) "all-in" cost including inflation**
- **One 1600 MW(e) EPR (Olkiluoto, Finland)—$4200/kW(e) "all-in" cost**
- **Two 1350 MW(e) Toshiba LWRs (South Texas Project)—$3700/kW(e) "all-in" cost**
- **One 1600 MW(e) EPR (Calvert Cliffs, MD)—$5000 to $6000/kW(e) "all-in" cost**
- **Two 1100 MW(e) AP-1000 PWRs (Levy County, FL)—$7000 to $8000/kW(e) "all-in" including inflation and transmission system upgrades and new lines**
- **Two 1100 MW(e) AP-1000 PWRs (Turkey Point, FL)—$3100 to $4540/kW(e) "overnight" or $5500 to $8000/kW(e) "all-in" including varying degrees of cost escalation and transmission additions**
- **In many respects, these are FOAK projects**

Some Comments On Capital Cost

- Five years ago total capital costs were projected to be $2000 to $3000/kW(e) (constant dollars)
- Today's latest projections are $3500/kW(e) and above
- Increase is due to
  - Escalation in commodity prices (steel, concrete, etc.)
    - This is backing off somewhat due to economy
  - Shortage of skilled labor force for nuclear construction
  - Shortage of qualified vendors for major equipment items
  - Anticipated higher risk financing
  - Costs of re-establishing nuclear industry in United States
  - Schedule slips due to regulatory and procurement difficulties
- Other types of baseload power generation plants are also seeing capital cost increases (coal, natural gas)
  - Pulverized coal now >$2000/kW(e) without CCS
  - IGCC coal $/kW(e) likely to be close to nuclear



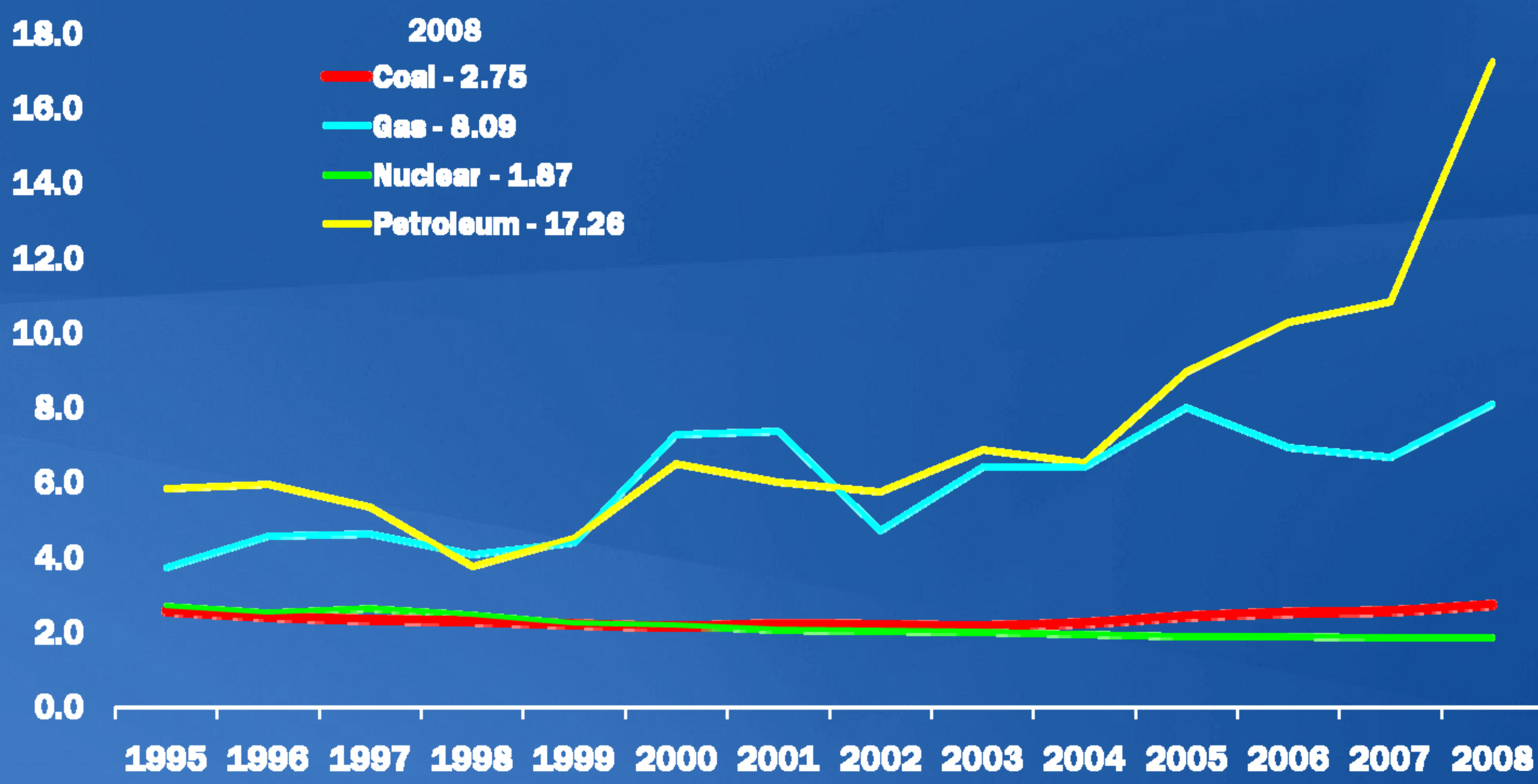
Source: IHS Cambridge Energy Research Associates.
80417-1_0605

Comments On O&M and Fuel Cycle Costs

- **O&M**
  - **In last 20 years annual O&M cost has decreased (in constant dollars)**
  - **Mainly due to smaller staffs**
  - **Last few years have seen increase in security staffing**
  - **Better operations have increased capacity factors**
- **Fuel (Projected Unit Costs for Fuel Cycle Components): long term Low/Medium/High**
  - **Uranium ore ($/kgU) 25/60/240**
  - **Conversion ($/kgU) 5/10/15**
  - **Enrichment ($/SWU) 80/105/130**
  - **Tails conversion/disp ($/kgDU) 5/10/50**
  - **Fuel fabrication ($/kg EU) 200/240/300**
  - **Dry cask storage ($/kgHM) 100/120/300**
  - **Spent fuel disposal ($/kgHM) 400/1000/1600 (1 mill/kWh ~ 380)**
  - **Aq reprocessing not including HLW disposal ($/kgHM) 500/1000/1500**
  - **Transportation costs small except for spent fuel**
  - **With material balance information, one calculates $/MWh and overall $/kgHM cost**

U.S. Electricity Production Costs

1995–2008, *In 2008 cents per kilowatt-hour*



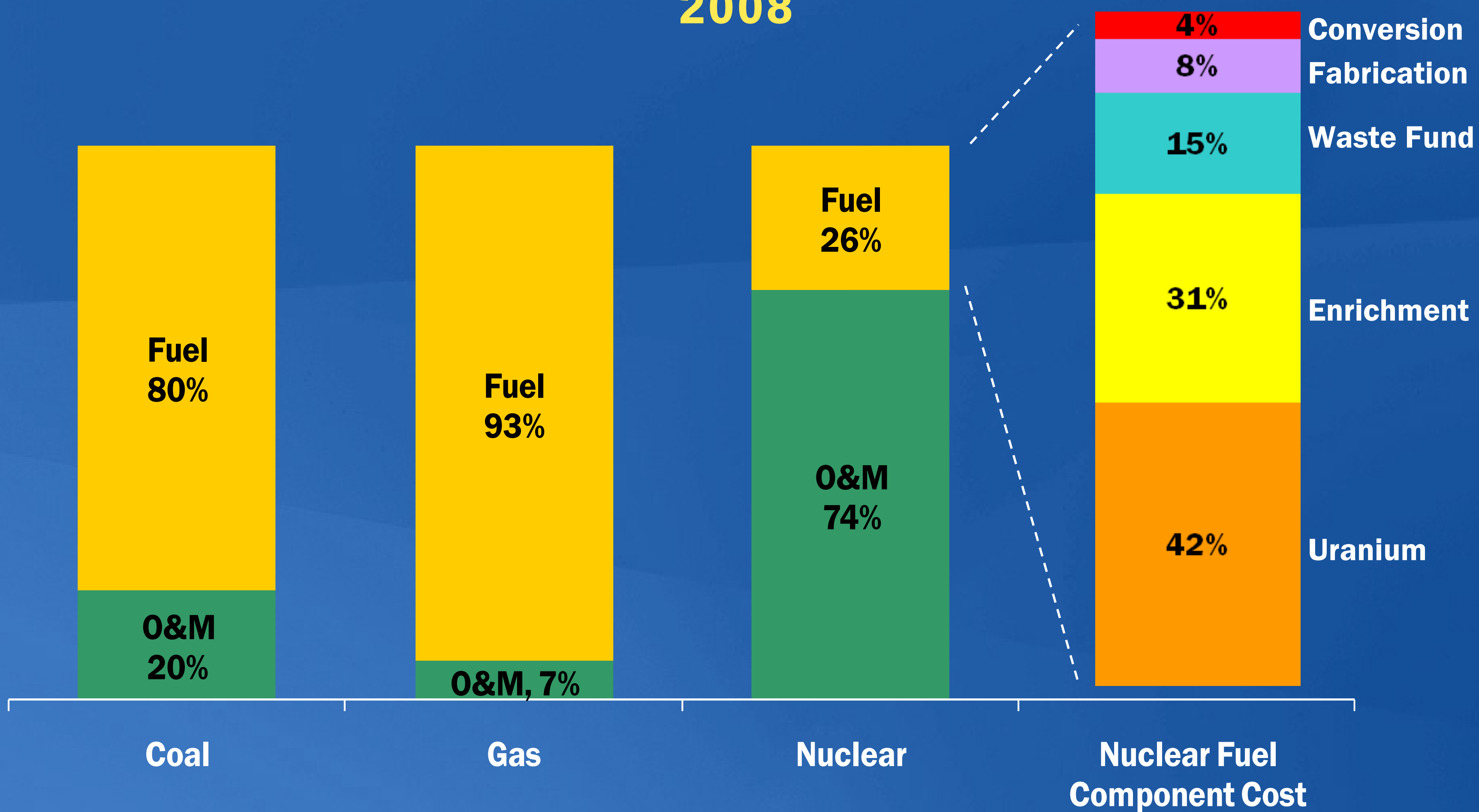
Production Costs = Operations and Maintenance Costs + Fuel Costs. Production costs do not include indirect costs and are based on FERC Form 1 filings submitted by regulated utilities. Production costs are modeled for utilities that are not regulated.

NEI

Source: Ventyx Velocity Suite
Updated: 5/09

Fuel as a Percentage of Electric Power Production Costs (Capital Recovery of Reactor Not Included)

2008



Source: Ventyx Velocity Suite; Energy Resources International, Inc.
Updated: 7/09

FYI: West Knox residential rate ~ 90$/MWh

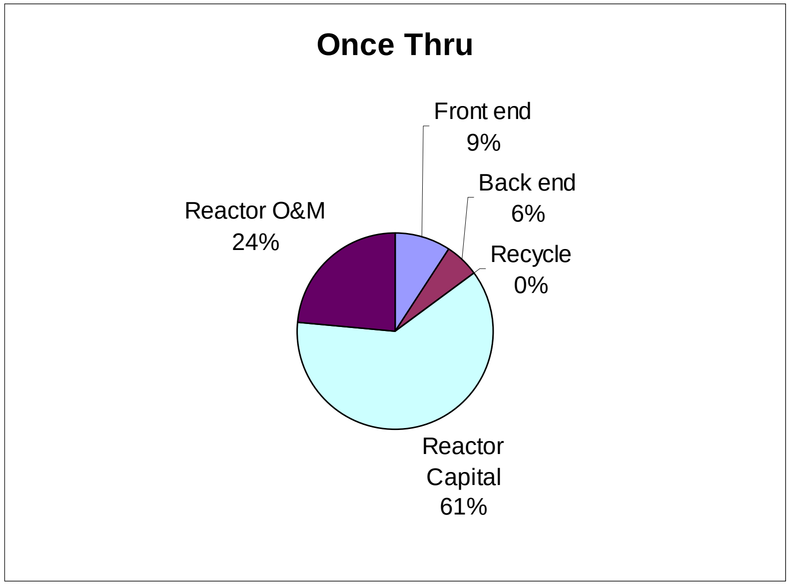
Competitiveness of Nuclear

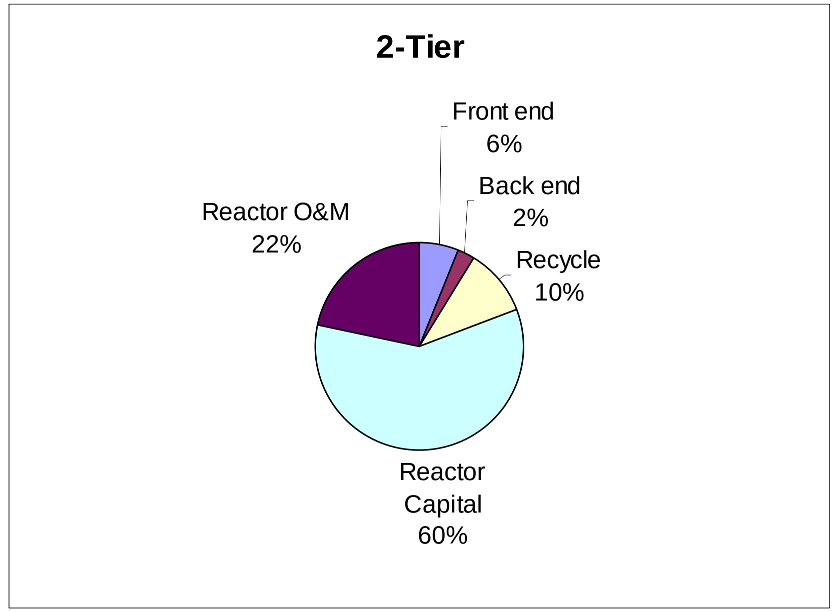
- Despite rising capital costs, nuclear is becoming more competitive because of
  - High capacity factors of ~90% (reliable baseload generation source)
  - Nuclear power cost is relatively insensitive to fuel cost (mainly uranium ore and uranium enrichment)
  - Increasing costs of other fossil fuels (fuel is the largest component of the LUEC for the fossil options)
  - If carbon costs (C tax, carbon capture & control cost, or "cap&trade" costs) are added to fossil generation cost, the competitiveness of nuclear increases markedly

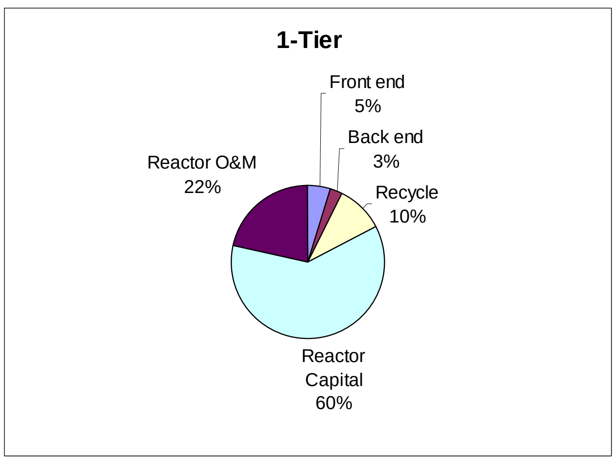
Scenario Analysis: New Power Plants New England IPO Study

Technology	MW	Heat Rate (Btu/kWh)	Availability (%)	Plant Cost (2006$/KWe)	Source
IGCC w/o CO2 Capture	600	8,600	80	2500-3500	EPA, EPRI, MIT, DOE
IGCC with 90% CO2Capture	500	9,750	80	2900-3900	EPA, EPRI, UN, MIT
NG Combined Cycle	400	6,500	90	800-1000	GE
NG Comb Turbine	100	8,500	90	500-700	GE
Nuclear	1080	10,000	90	3000-5000	Westinghouse, NEI
Fuel Cell*	1	8,000	95	3500-4000	Fuel Cell Energy
Biomass	40	14,000	90	2500-3500	CT Plants, NH DES
Small Hydro	5	N/A	90	3000-4000	NE Developer
Landfill Gas	5	10,500	90	2000-2500	NE Plants
CHP*	5	9,750	90	1000-1500	Solar Turbines
Photovoltaics	1	20%**	98	4000-6000	UMASS RERL
Wind Onshore	1.5	N/A	90	1500-2000	UMASS RERL Levitan
Wind Offshore	3.5	N/A	90	2000-2500	UMASS RERL Levitan
Imports	N/A	N/A	N/A	2000-4000	Canadian Developer

What About Fuel Recycle? — Breakdown of Nuclear Power Total Levelized Unit Electricity Cost (LUEC)







Once-through Total LUEC (breakdown typical of today's LWRs)	42.3 $/MWh
1-Tier Total LUEC	48.3 $/MWh
2-Tier Total LUEC	47.9 $/MWh

Nominal or "Medium" Case

"Front-end", "Back-end", and "Recycle" refer to steps of fuel cycle

Levelized Unit Electricity Cost (LUEC) From Various Generation Technologies ($/MWh or mills/kWh)

Table 8-5. Tablular representation of the low, nominal, and high LUECs for baseload generation technologies.

Assumptions	TECHNOLOGY	Overall LUEC (LOW) $/MWh	Overall LUEC (NOM) $/MWh	Overall LUEC (HIGH) $/MWh	Fuel Comp of LUEC (LOW) $/MWh	Fuel Comp of LUEC (NOM) $/MWh	Fuel Comp of LUEC (HIGH) $/MWh
All LWR generation	Nuclear (OT)	24.65	42.29	80.07	3.53	6.51	13.21
37.1% of Gen by FRs	Nuclear (1-Tier)	26.43	48.26	93.84	4.24	8.22	14.73
25.7% of Gen by FRs	Nuclear (2-Tier)	26.67	47.86	91.93	4.81	9.13	16.59
Pulverized Coal Tech	Coal (No C Tax)	23.55	39.91	105.76	10.94	14.59	36.46
Pulverized Coal Tech	Coal (w/ C-Tax)	27.79	73.87	190.65			
CCGT Technology	Nat Gas (No C-Tax)	27.61	65.65	107.16	20.9	52.24	83.58
CCGT Technology	Nat Gas (w/ C-Tax)	30.09	85.47	156.72			

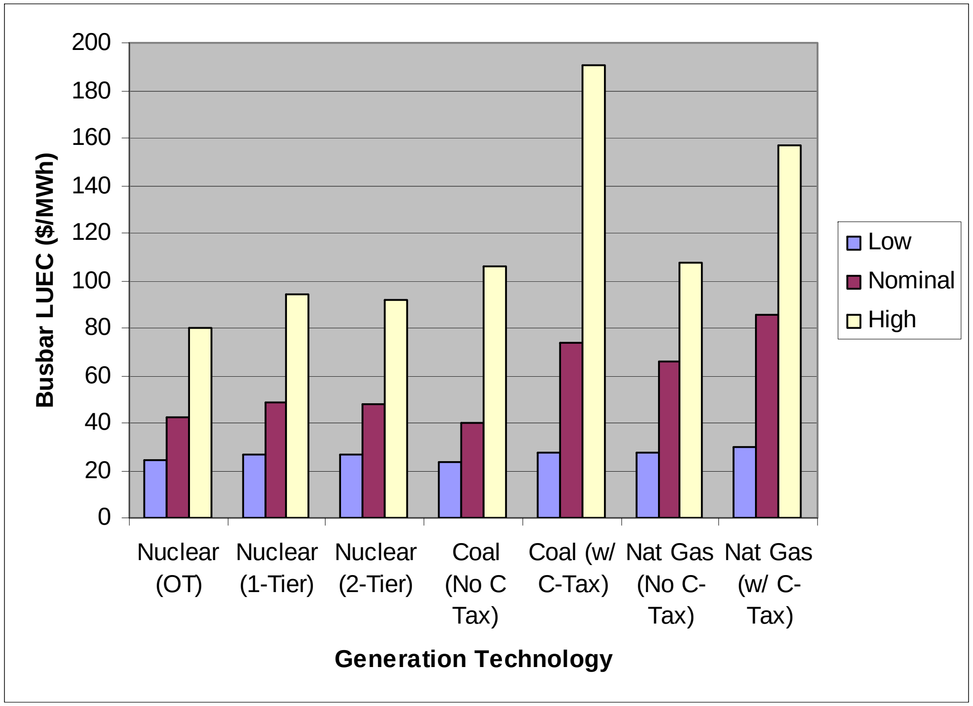


Figure 8-11. Graphical representation of the low, nominal, and high LUECs for baseload generation technologies.

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Same LUEC Study With Uncertainty Analysis

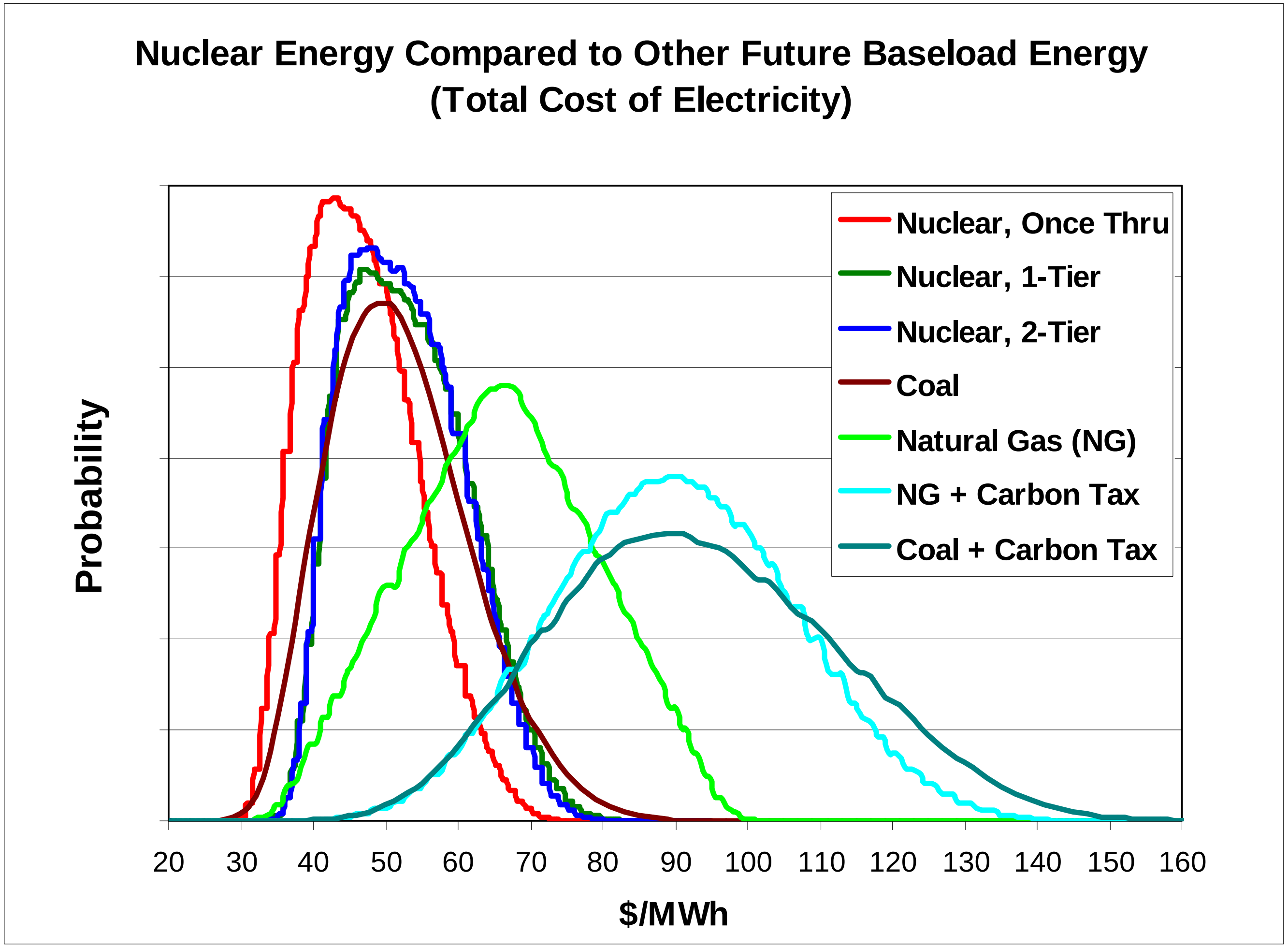


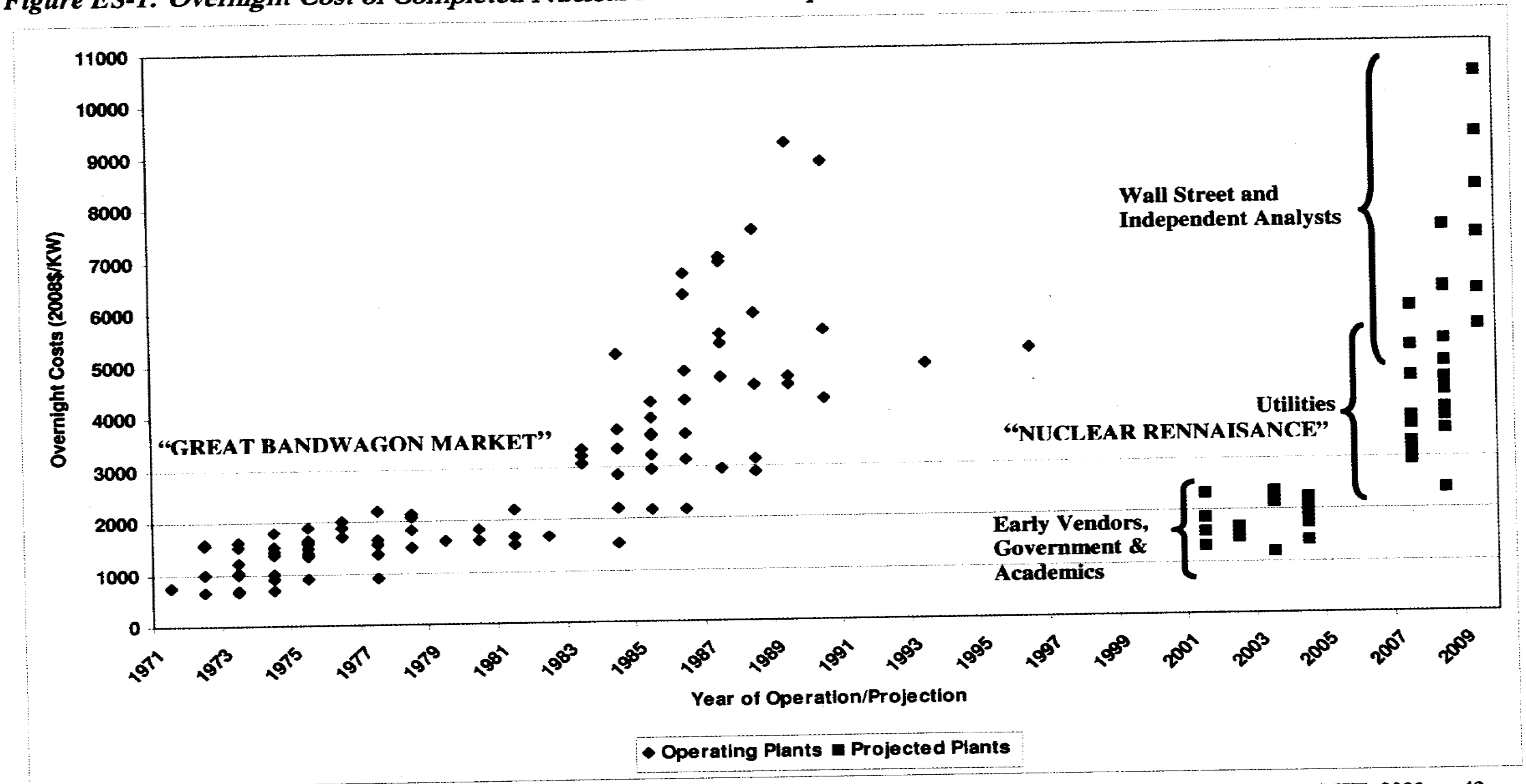
Figure 8-12. Total cost of energy for all generation technologies.

Problems With Most Antinuclear NGO Studies

- **Most assume that nonhydro renewables (solar, wind, biomass, geothermal) and/or conservation can replace BASELOAD nuclear and coal**
  - **Solar and wind most often touted**
  - **These are intermittent or have capacity factors <<< coal or nuclear**
  - **Electrical power grid will have difficulty accommodating high renewable portfolio (distances, AC/DC interfaces, stability)**
  - **Expensive natural gas power or electricity storage needed to back-up most renewables**
  - **Electrical energy storage methods expensive or need a lot more R&D (batteries, capacitors, flywheels, pumped storage, molten salt tanks)**
  - **Geothermal has most potential for baseload, but high front-end costs**
- **Most assume that industry has learned nothing from "first nuclear era" (1960s through 1990s) and that all mistakes and problems will be repeated**
- **Some studies not concerned by reduced standard of living associated with loss or major reduction of reliable baseload electricity**
- **"Carbon footprint" or "life cycle analyses" for nuclear often based on old or obsolete data**
- **Land use issues are often ignored**
- **Nuclear touted as nonsustainable from U-resource standpoint despite huge potential for recycle and breeding**

Figure from June 09 Vermont Law School (Cooper) Report

Figure ES-1: Overnight Cost of Completed Nuclear Reactors Compared to Projected Costs of Future Reactors



Sources: Koomey and Hultman, 2007, Data Appendix; University of Chicago 2004, p. S-2, p. S-8; University of Chicago estimate, MIT, 2003, p. 42; Tennessee Valley Authority, 2005, p. I-7; Klein, p. 14; Keystone Center, 2007, p.42; Kaplan, 2008 Appendix B for utility estimates, p. 39; Harding, 2007, p. 71; Lovins and Shiekh, 2008b, p. 2; Congressional Budget Office, 2008, p. 13; Lazard, 2008, Lazard, p. 2; Moody's, 2008, p. 15; Standard and Poor, 2008, p. 11; Severance, 2009, pp. 35-36; Schlissel and Biewald, 2008, p. 2; Energy Information Administration, 2009, p. 89; Harding, 2009. PPL, 2009; Deutch, et al., 2009, p. 6. See Bibliography for full citations.

The High "Energy Density" Of Nuclear Is Its Greatest Attribute On A Planet That Is Becoming Increasingly Crowded

- **Fuel requirements in kWh per kg of fuel**

– Hardwood	1
– Coal	3
– Heavy oil	4
– Natural gas	6
– Natural U fuel	50,000
– Low-enriched UOX	250,000
– Uranium with reprocessing	3,500,000
– Plutonium with reprocessing	5,000,000

- **Other measurable resource attributes (land area, volumes of wastes, etc.) are also reduced with nuclear**
- **The following "cube analysis" illustrates this**

“Cube Analysis”: Impacts For A Fixed Amount Of Annual Electricity Generation

- **7.89 billion kilowatt-hours per year!**

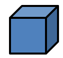
Coal

Nuclear

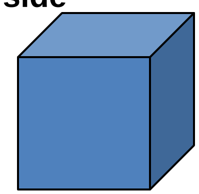
Wind

Nuclear Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A 1000-MW(e) PWR at 90% Capacity Factor (REACTOR SITE)

- **Primary energy generation (UOX fuel assemblies) annual volume:**
  - **A cube of stacked UOX fuel assembly sections 2 m on a side (or 6.4 ft/side)**



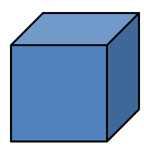
  - **Energy density of >10^9 kWh/cubic m**
- **Water use (annual water evaporated from cooling towers) annual volume:**
  - **A cube of water (liquid) 250 m on a side (823 ft on a side)**



- **Land use for one 1000 MW(e) unit:**

250 to 1000 acres

- **Annual low level waste generation**



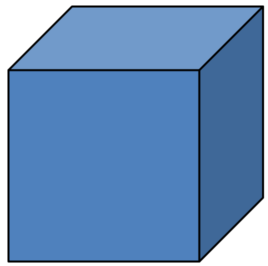
  - **Annual volume: All LLW generated would require a cube <5 m on a side (~15 ft on a side). Steel boxes are shipped offsite.**
  - **Compaction could reduce by 50% or more**

One Unit Generates 7.89 $\times$ 10^9 kWh/year

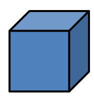
PWR FUEL ASSEMBLY

Nuclear Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A 1000-MW(e) PWR At 90% Capacity Factor (ASSOCIATED FRONT-END FUEL CYCLE: ONCE-THROUGH)

- Mining:
  - Medium grade ore from pit or underground mine (0.3 without U)
  - Cube of loose rock 115 ft or 35 m on a side (some fraction ends up as mill tailings
  - Land disturbed 58 acres/year

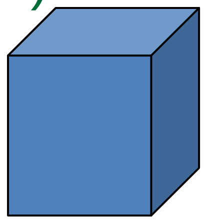


- Yellowcake (U_3O_8 from mill)
  - Cube of stacked 55 gal drums of U_3O_8 powder 17 ft or 5.3 m on a side
- Conversion of U_3O_8 to UF_6 has negligible footprint
  - Fluorine or HF used is regenerated later

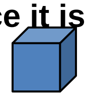


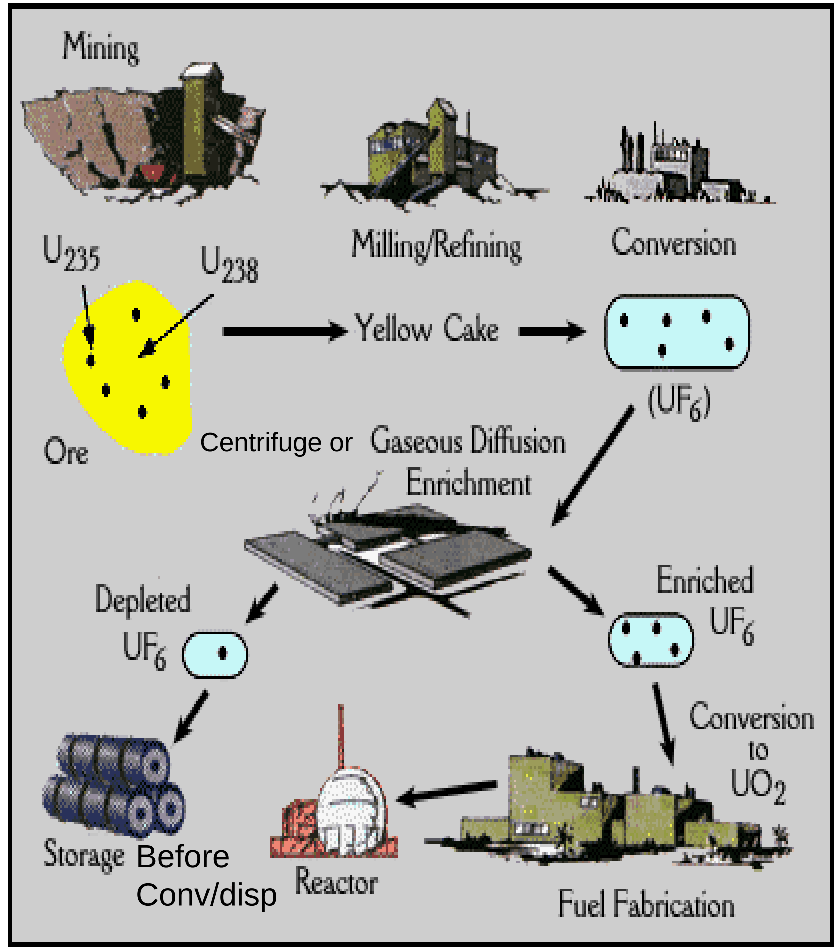
Nuclear Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A-1000 MW(e) PWR At 90% Capacity Factor (ASSOCIATED FRONT-END FUEL CYCLE: ONCE-THROUGH)

- **Uranium Enrichment Step**
  - **120,000 SWUs required**
  - **Gas Centrifuge Process assumed used**
  - **Enrichment plant needs 6.1 million kWh/year**
  - **Assuming available electricity is 50% coal**
  - **A cube of gaseous CO_2 124 m or ~400 ft on a side is generated**
  - **This gives a fair appraisal of the nuclear fuel cycle's carbon footprint during operations**



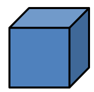
- **Handling of Tails (Depleted UF_6) from Enrichment Process**
  - **~90% of "natural" UF_6 fed to enrichment process ends up as tails**
  - **For ES&H reasons, DUF_6 will be converted to U_3O_8 and drummed for ultimate shallow geological disposal. Cube of stacked drums would be 16 ft or 5.11 m on a side**
  - **DU_3O_8 should remain retrievable, since it is future fuel for breeder reactors!!**



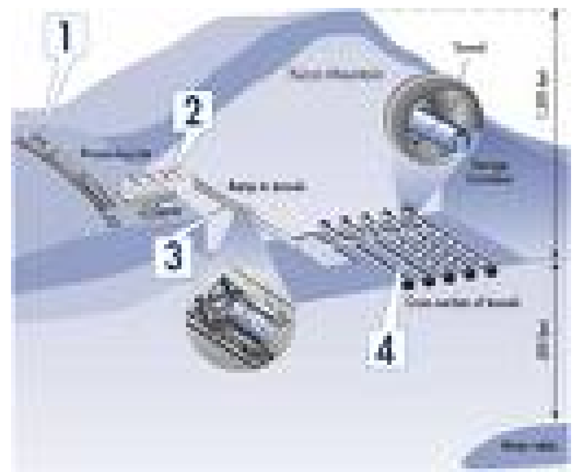


Nuclear Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A-1000-MW(e) PWR At 90% Capacity Factor (ASSOCIATED BACK-END FUEL CYCLE: ONCE-THROUGH)

- **Spent fuel storage in dry casks**
  - **2 PWR casks/year required (21 assemblies each)**
  - **< 500 ft^2 of pad required per cask**
  - **Casks occupy a volume equivalent to a cube 9.2 ft or 2.8 m on a side**

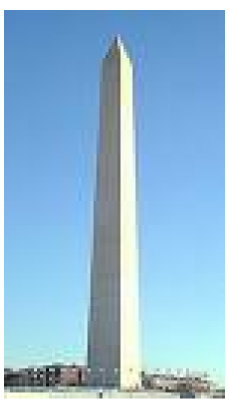


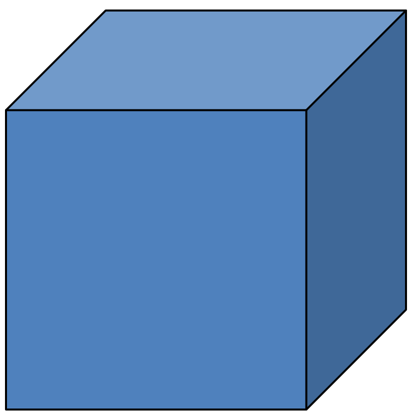
- **Geologic repository disposal of spent fuel (assume cask is disposal package)**
  - **0.34 acres of underground tunnel area required**
  - **40 acres of land "set aside" required**

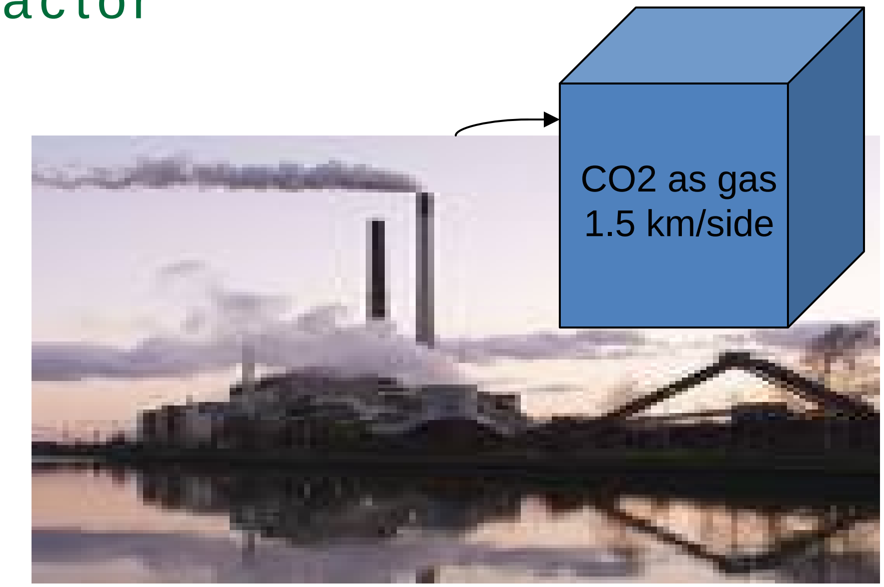


Coal-Fired Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A 1125-MW(e) Pulverized Coal Burner at 80% Capacity Factor

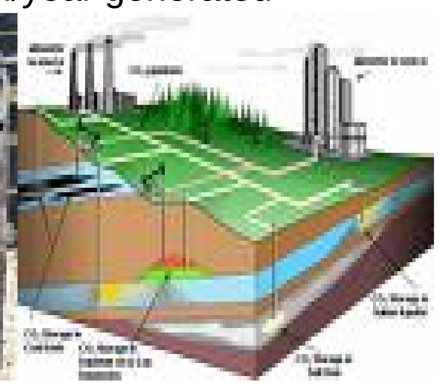
- **Coal consumption**
  - **Eastern coal with heat value 13,000 BTU/lb assumed**
  - **2.88 million tons of coal/year**
  - **29,000 100-ton capacity RR cars/year**
  - **290 100-car unit trains/year**
  - **Cube of loose coal 470 ft or 143 m on a side!**





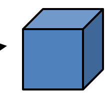


7.89 billion kWh/year generated

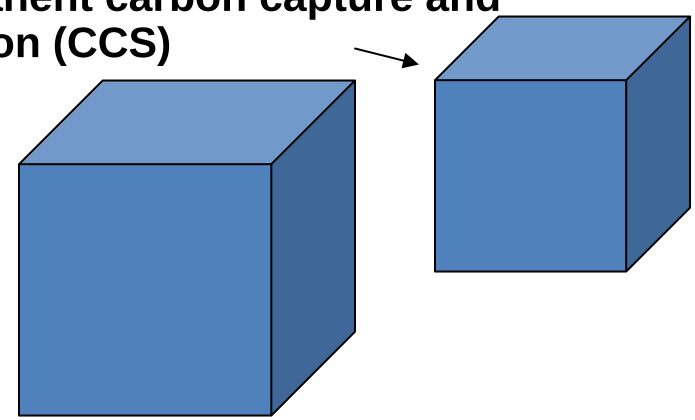


Coal-Fired Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A 1125-MW(e) Pulverized Coal Burner at 80% Capacity Factor

- **Waste products**
  - **SOx, NOx, Hg, particulates assumed mostly removed prior to stack discharge**
  - **Ash (coal is assumed to be 7% ash before combustion)**
    - **Ash solids would occupy equivalent cube 164 ft or 50 m on a side**



  - **Gaseous CO_2**
    - **3.4 billion cubic meters of CO_2 generated per year: a cube 1.5 km or 0.9 miles on a side!**
  - **Liquid CO_2 (assumed to be the form for permanent carbon capture and below ground or bottom-of-ocean sequestration (CCS)**
    - **Would occupy a cube 600 ft or 185 m on a side**
  - **Water used to cool plant (evaporated water)**
    - **Would occupy a cube 230 m or 750 ft on a side**

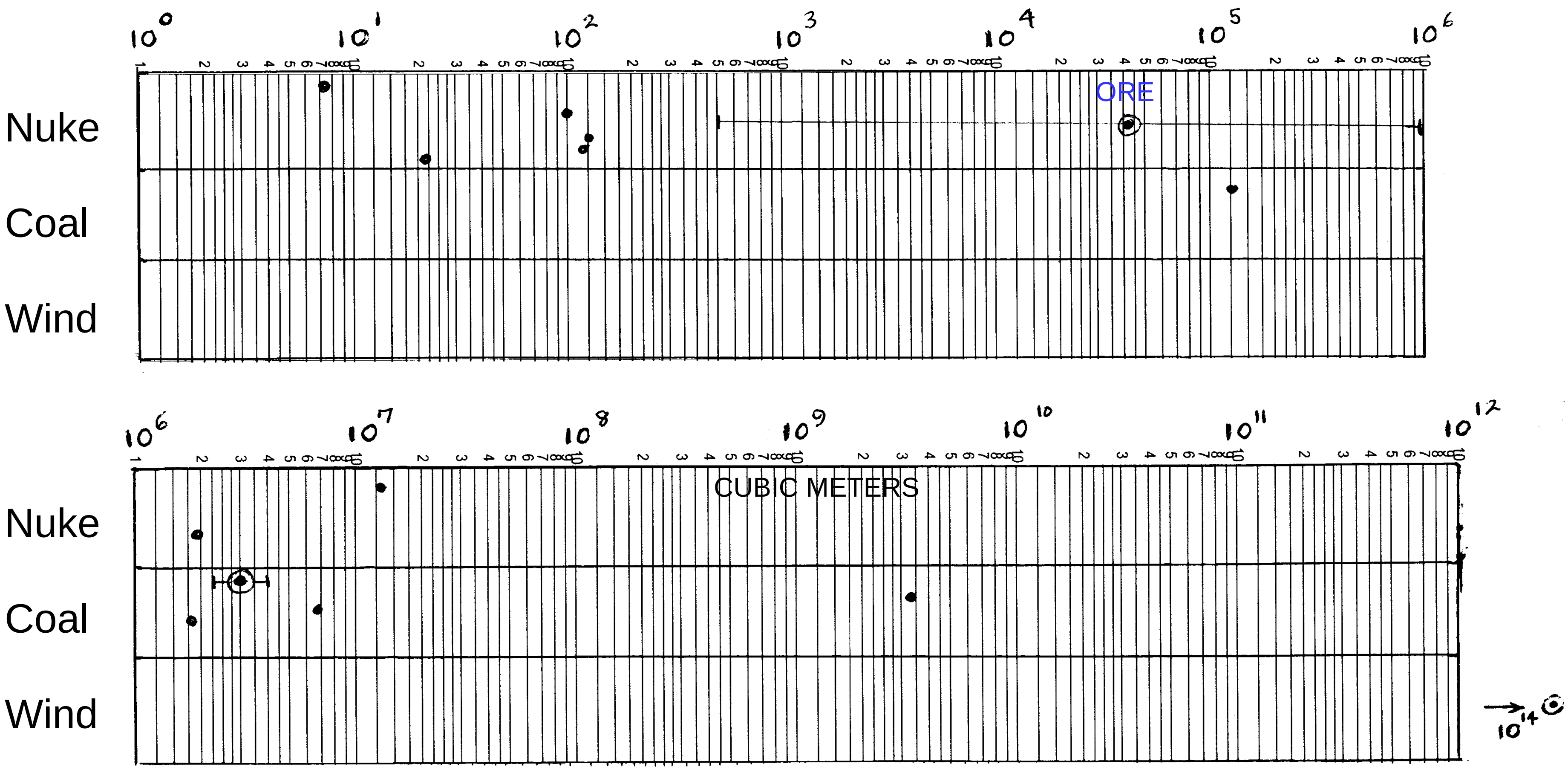


  - **Land use or disturbance**
    - **<1 km^2 required for coal plant**
    - **Mining of coal disturbs 0.91 sq mi per year (average of pit, strip, and underground mining)**

Wind Farm Power Plant Requirements and Attributes: 1-Year's Worth Of Electricity Generation For A 3600-MW(e) Multi-turbine Facility At 25% Capacity Factor

- **7.89 million kWh generated per year on the average**
- **Assume wind turbines are 1.5 MW(e) capacity each**
- **2400 wind turbines required**
- **Fthenakis & Kim "Land Use" report gives land requirement of 190,000 m^2/MW capacity**
- **This translates to 264 sq mile or a square 16 miles on a side**
- **One long row could be over 1000 miles!**

Summary of Volumetric Impacts



Energy Density From Natural Source in kWh Per Cubic Meter

- **“Once-through” nuclear (geologic medium with U)** — **10^3 to 10^7**
- **Fossil–Coal** — **2000–3000**
- **Wind (moving air)** — **10^{-5} to 10^{-4}**

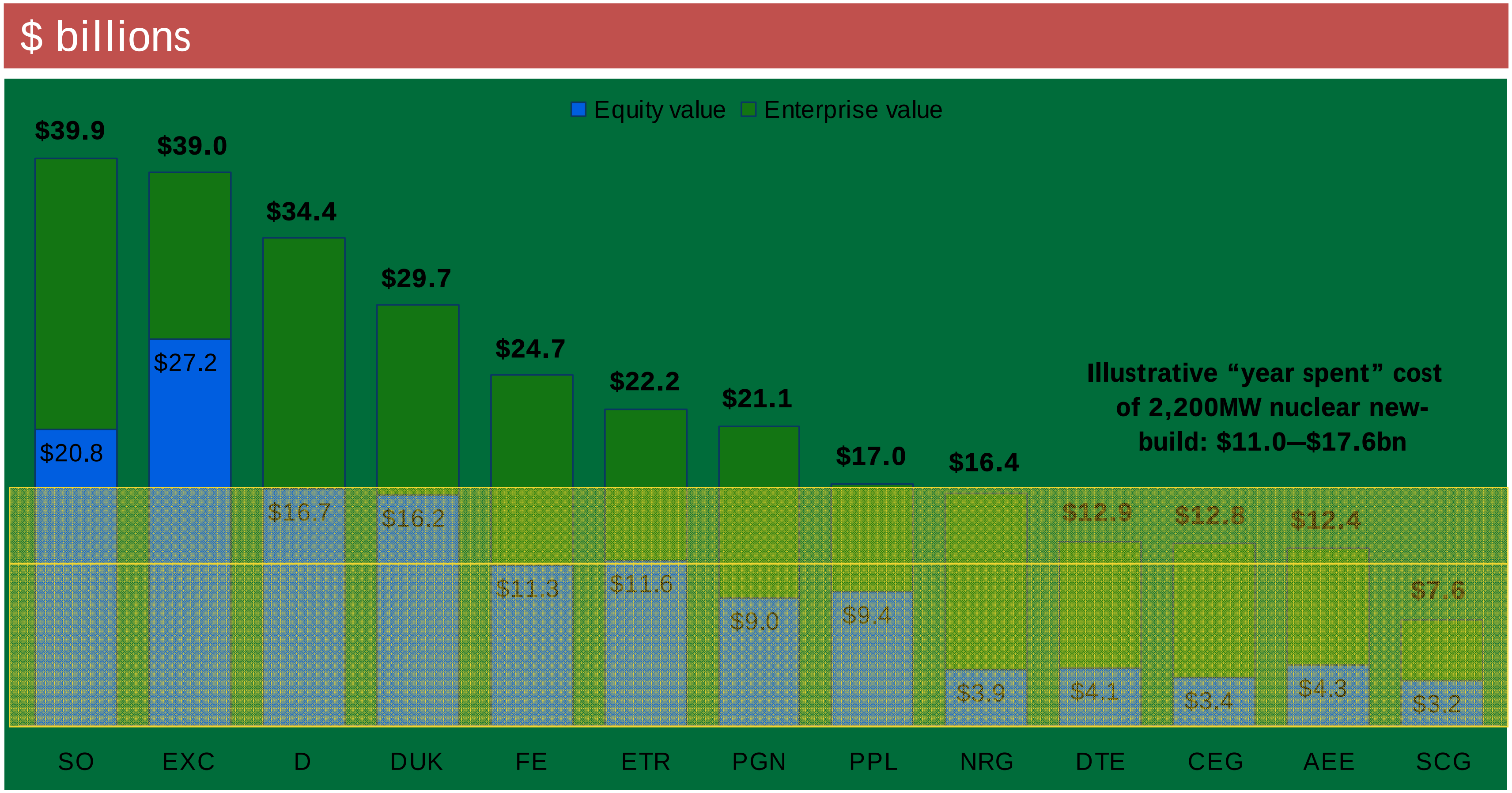
Land Use Summary

- Nuclear
  - Powerplant — 250 to 1000 acres
  - Fuel cycle land disturbance — ~100 acres/year
- Coal
  - Powerplant — Similar to nuclear
  - Land disturbance — ~600 acres/year
- Wind
  - Plant (wind farm) — 1.7×10^5 acres

Summary

- First projects will be expensive; financing is major issue
- Carbon tax or “cap and trade” will help relative economics of nuclear
- Conservation and renewables cannot replace nuclear and coal
- High energy density of nuclear lessens impacts on environment
- Availability of nuclear fuel should not be problem
- Fuel cycle costs are not main cost driver

Nuclear developer capitalization relative to cost of new-build



Source: FactSet as of 3/13/09 J.P.Morgan