An Evaluation of the Real Option of Starting to Build a Nuclear Power Plant in Chile in 2020

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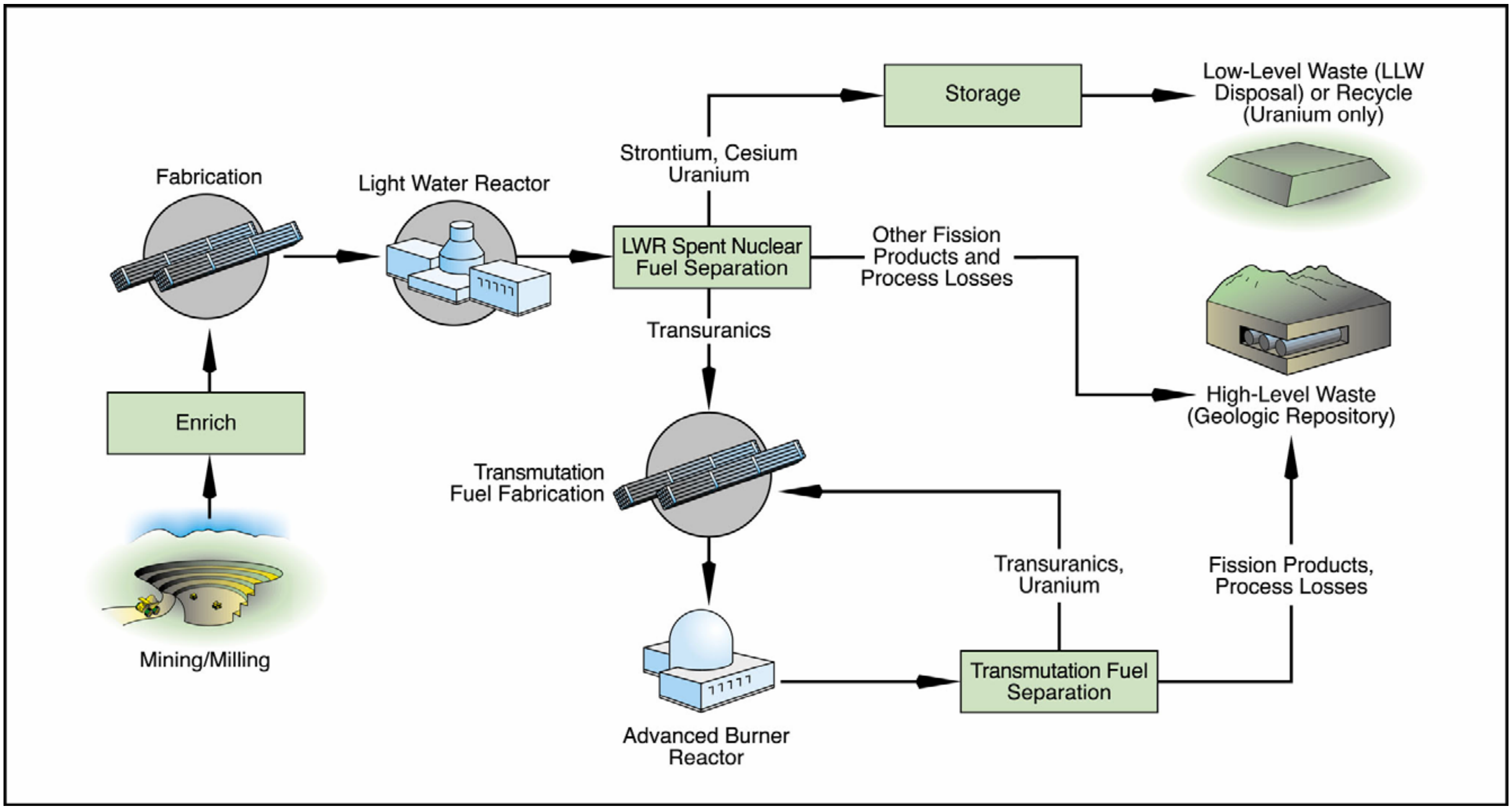
Outline of Presentation:

1. Generating Electricity with Nuclear Power
2. The Costs of Nuclear Power
3. The Nuclear Fuel Cycle
4. A Comparison of Nuclear with Natural Gas
5. Sample value of a Real Option of building a nuclear power plant in Chile in 2020

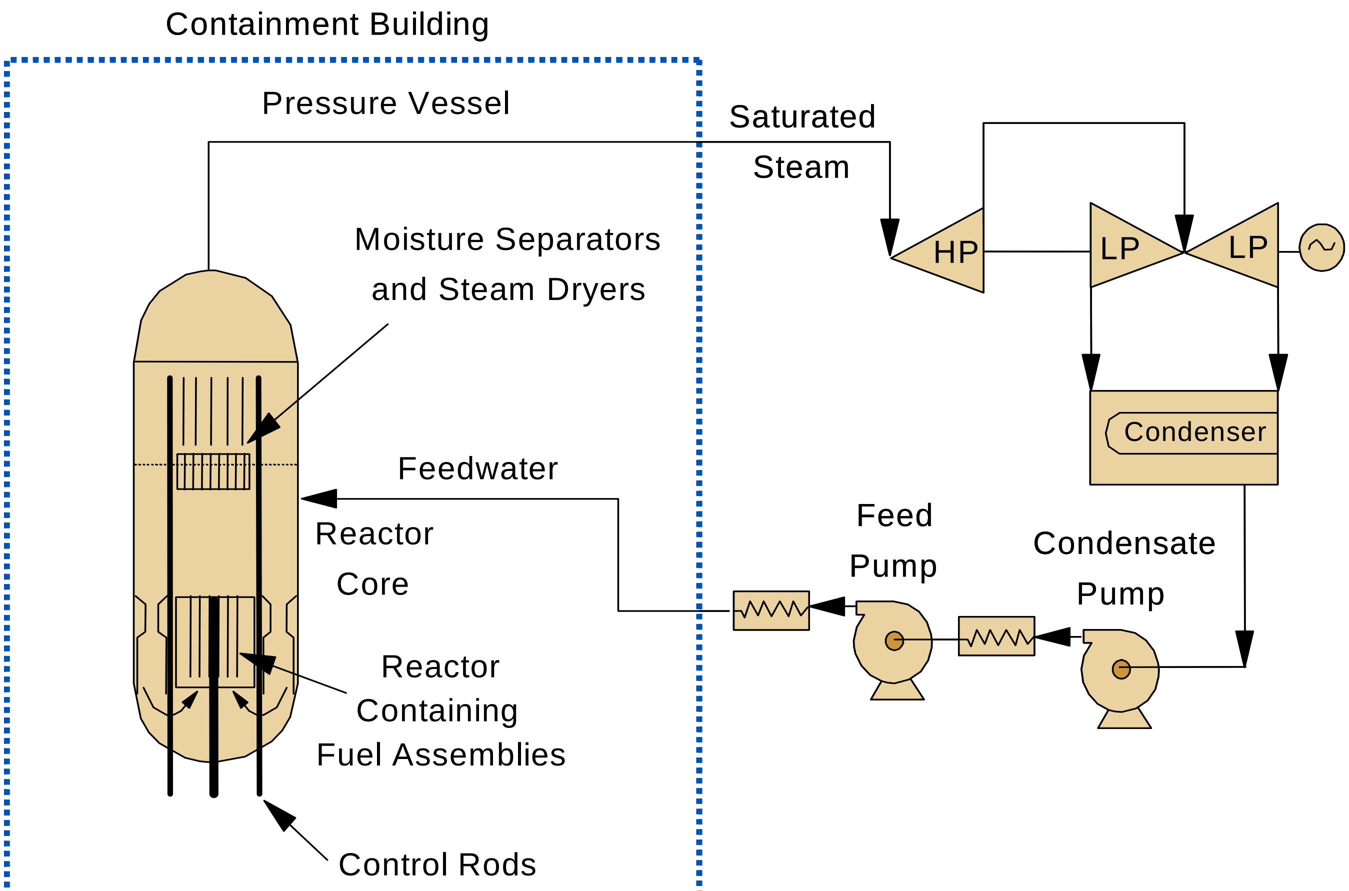
Bottom line: **Spend about $20 M over 6 years to determine whether to license a nuclear power plant in Chile, starting in 2014.**

Generating Electricity with Nuclear Power in a Closed Nuclear Fuel Cycle

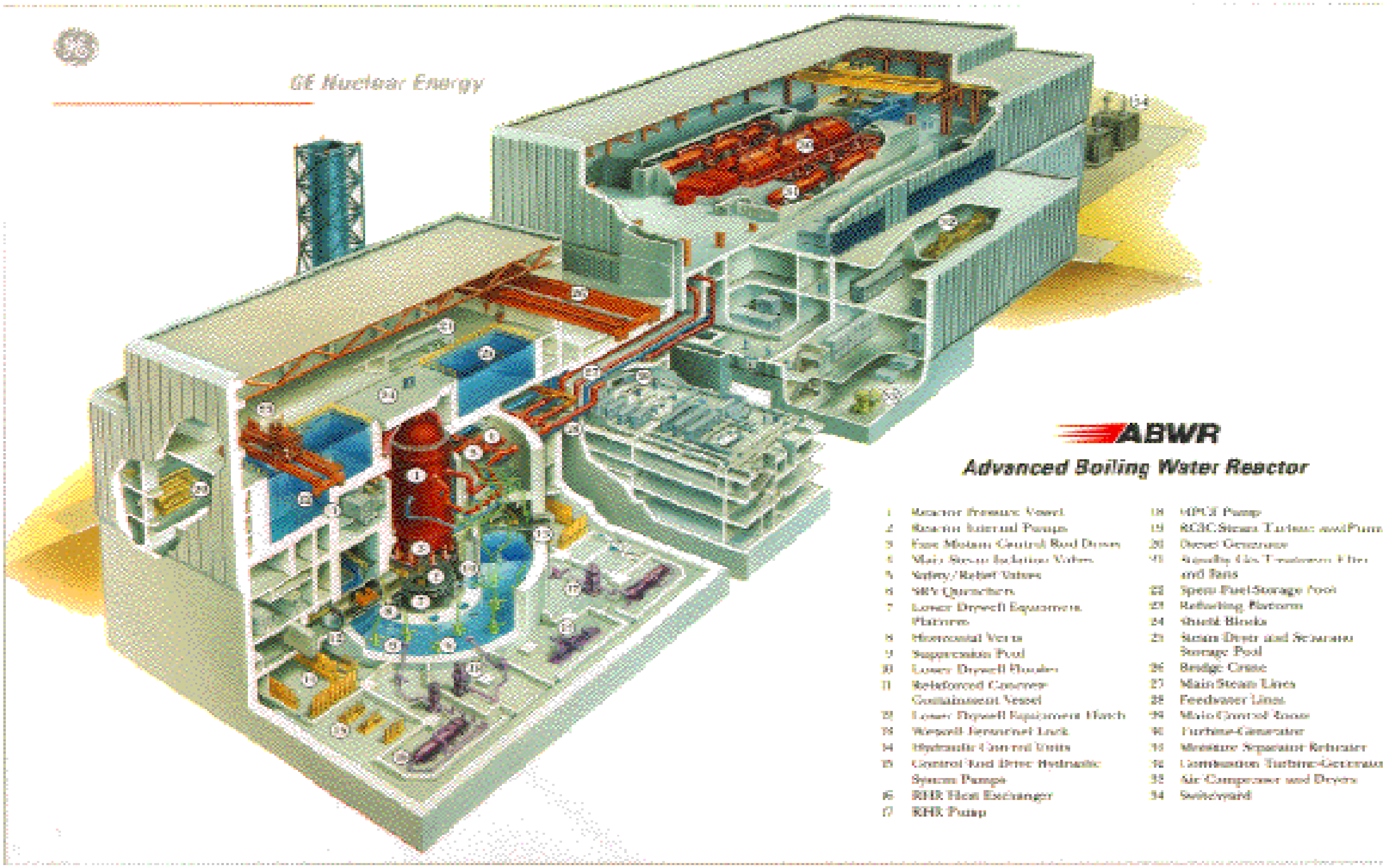


Generating Electricity with a Boiling Water Reactor (BWR), e.g., from General Electric (GE)

Reactor Turbine-Generator



GE's Advanced Boiling Water Reactor:



Sept 25, 2007: ABWR to be built in Texas

Approval Is Sought to Build Two Reactors in Texas

By MATTHEW L. WALD
Published: New York Times, September 25, 2007

WASHINGTON, Sept. 24 — In a bid to take the lead in the race to revive the nuclear power industry, an energy company will ask the federal Nuclear Regulatory Commission (NRC) on Tuesday for permission to build two reactors in Texas. It is the first time since the 1970s and the accident at Three Mile Island that an American power company has sought permission to start work on a new reactor.

The company, NRG Energy, wants to be the first to pour concrete, allowing it to qualify for the maximum federal benefits, said David Crane, its chief executive. NRG is planning to build a two-unit General Electric Advanced Boiling Water Reactor in Texas with Toshiba leading the construction. The project has an estimated cost of $6 to $7 billion.

U.S. Nuclear Subsidies in the *Energy Policy Act of 2005:*

(1) "Regulatory Insurance": If NRC licensing takes longer than anticipated; $500 M for the first 2 units, $250 M for the next 4 units, $0 for all others

(2) Tax Credits: $18/MWh for 8 years if Construction and Operating License applied for before Dec 31, 2008

(3) Loan Guarantees: Backs up 80% of the cost of construction; $4 B for "advanced energy technologies," but currently doesn't cover nuclear power; maybe later. . .

ABWRs built in Japan and Taiwan:

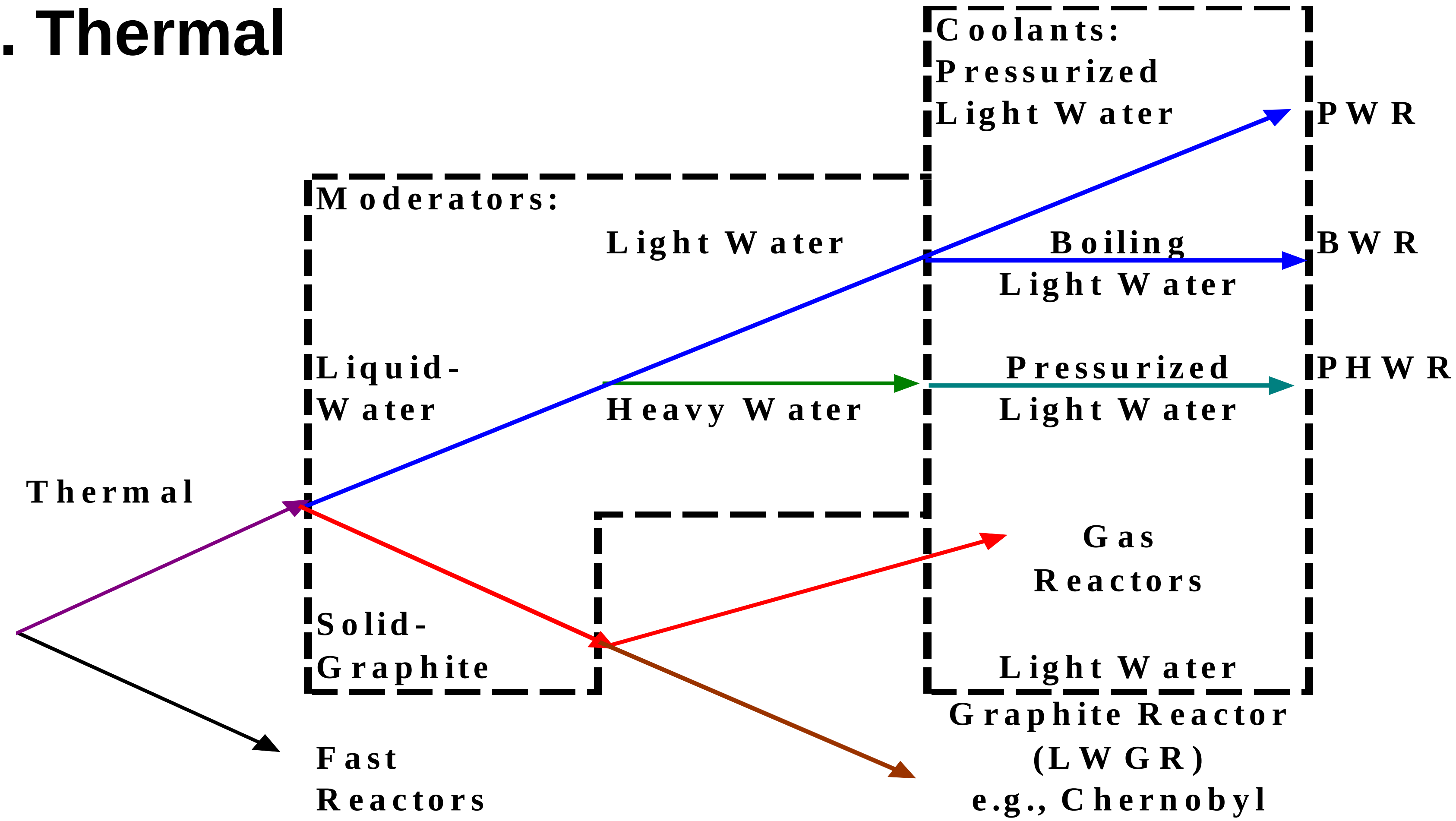
Country	Name	Unit	Capacity (Mwe)	Status	Construct Start	Commercial Op	Constr Time (yrs)
Japan	Kashiwazaki Kariwa	6	1356	Operating	11/3/1992	11/7/1996	4.01
Japan	Kashiwazaki Kariwa	7	1356	Operating	7/1/1993	7/2/1997	4.01
Japan	Hamaoka	5	1380	Operating	3/1/1999	1/18/2005	5.89
Japan	Shika	2	1358	Operating	8/1/2001	3/15/2006	4.62
Japan	Shimane	3	1373	Construction	9/1/2005		
Taiwan	Lungmen	1	1350	Construction	10/1/1997		
Taiwan	Lungmen	2	1350	Construction	10/1/1997		

Characterizing Nuclear Reactors

1. Fast v. Thermal

2. Moderators

3. Coolants



Number of Reactors Operating and under Construction:

Light Water Reactors (LWR)	In	Under
Pressurized Water Reactors	Operation	Construction
PWR (Former "Western")	213	8
WWER (Former "Eastern")	51	9
Advanced PWR (Gen III)	0	1
Boiling Water Reactors (BWR)	89	0
Advanced BWR (Gen III)	4	3
Pressurized Heavy Water Reactors	42	6
Gas Reactors	18	0
Water-Graphite Reactors	16	1
Fast Reactors	2	2
Total Reactors	**435**	**30**

“Generation III” Reactor Types in U.S. Market:

Type	Tech	Supplier	Size (MWe)	Operating	Construction
ABWR	BWR	GE, Toshiba, Hitachi (U.S.-Japan)	1,371-1,465	4	3
ESBWR	BWR	GE (U.S.)	1,550	0	0
VVER-1000	PWR	AES (Russia)	950-1,000	1	5
AP-1000	PWR	West-Toshiba (U.S.-Japan)	1,000	0	0
EPR	PWR	Areva (EU)	1,600	0	1
APWR	PWR	Mitsubishi (Japan)	1,700	0	0

Construction costs of a ABWR (2005 $):

ABWR in NEA (2000, p. 99) all costs updated to millions of 2005 US dollars	Total Cost (in M$)	$/kWe at r = 10%
Plant Size in MWe, *N* = 1,440 (gross) and 1,400 (net)	**1,400**	**1,400**
Pre-Construction Costs (Account 10)	**$50**	**$36**
Capitalized Direct Costs (Accounts in the 20 series)		
Buildings, Structures, & Improvements on Site (Acct 21)	$485	$346
Reactor Plant equipment (Acct 22)	$586	$419
Turbine/Generator Plant equipment (Acct 23)	$259	$185
Electrical equipment (Acct 24)	$169	$121
Water intake and heat rejection plant (Acct 25)	$51	$36
Miscellaneous plant equipment (Acct 26)	$51	$36
Special materials (Acct 27)	$0	$0
Capitalized Direct Costs (Account 20)	**$1,601**	**$1,143**
DIRECT = (Account 10+Account 20)	**$1,651**	**$1,179**

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DIRECT = (Account 10+Account 20)	**$1,651**	**$1,179**
DIRECT to BASE (Indirect) Multiplier	1.420	1.420
BASE (Direct + Indirect)	**$2,345**	**$1,675**
Contingency Multiplier	1.070	1.070
Overnight Cost	**$2,509**	**$1,792**
Interest During Construction (IDC) Multiplier	1.300	1.300
Total Capital Investment Cost (TCIC)	**$3,261**	**$2,330**
TCIC for 2 Block 2,800 MWe Plant	**$6,523**	**$2,330**

AEO (2007) Costs & Parameters: Gen III LWR

Values from AEO (2007, Table 39, p. 77)	Units	ALWR r = 10%	ALWR r = 15%
Net Electrical Capacity	MWe	1350	1350
Average Capacity Factor	%	90%	90%
Plant Economic and Operational Life	Years	40	40
Construction Lead Time	Years	6.000	6.000
Real Cost of Capital for IDC & Amortization	%/year	10.00%	15.00%
Costs			
Overnight Cost (includes contingency)	M 2005 $	$2,081	$2,081
TOTAL (including Interest During Construction)	M 2005 $	$2,705	$3,017
Variable O&M	$/MWh	$0.47	$0.47
Fixed O&M	$/kW	$63.88	$63.88

AEO (2007) Levelized Costs for a Gen III LWR:

Values from AEO (2007, Table 39, p. 77)	Units	ALWR r = 10%	ALWR r = 15%
Costs			
Capital (including IDC)	$/MWh	**$35.07**	**$57.59**
Operation	$/MWh	**$8.57**	**$8.57**
Fuel Cycle - Front End	$/MWh	**$7.67**	**$7.67**
Fuel Cycle - Back End (Waste or Carbon)	$/MWh	**$1.00**	**$1.00**
Levelized Cost	$/MWh	**$52.30**	**$74.82**

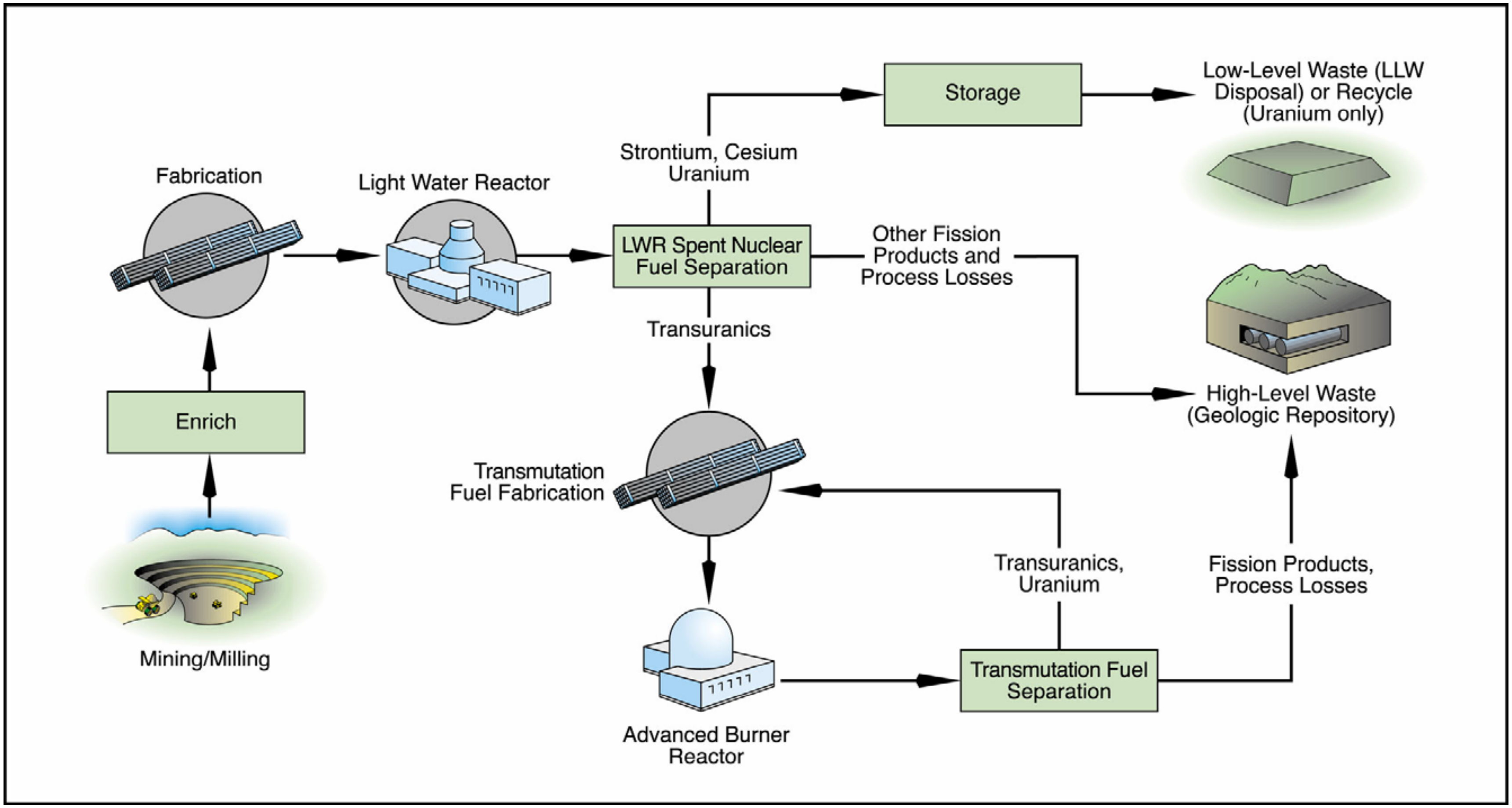
“Fuel Cycle - Front-End” Costs:

I have discussed “Generating Electricity with Nuclear Power” and “The Costs of Nuclear Power.”

In the previous slide, the cost of the “Fuel Cycle – Front-End” was $7.67/MWh.

I now discuss how this value is derived in the next section: “The Nuclear Fuel Cycle”

Generating Electricity with Nuclear Power in a Closed Nuclear Fuel Cycle



The Two Faces of the Nuclear Fuel Cycle: "The Front End" and "The Back End"

(1) "The Front End"

- **(1.1) Uranium Mining and Milling**
- **(1.2) Uranium Conversion and Enrichment**
- **(1.3) Nuclear Fuel Fabrication**

(2) "The Back End"

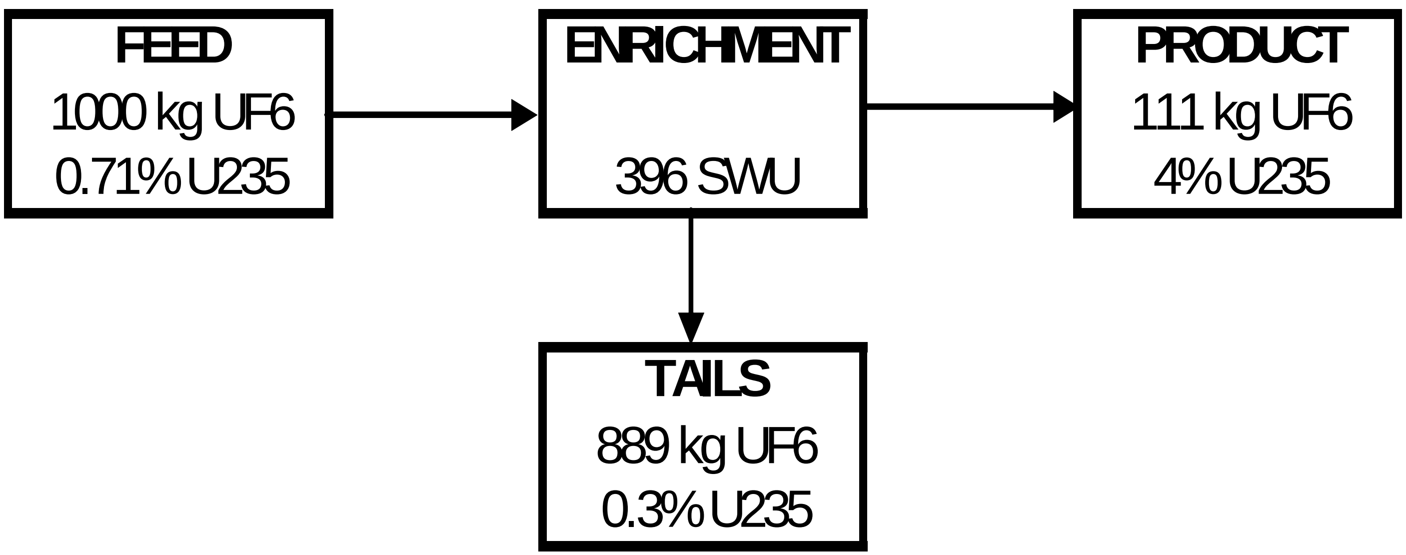
- **(2.1) Optional Reprocessing & Recycle**
- **(2.2) Low Level Waste Storage**
- **(2.3) High Level Waste Storage**

Which Countries have Uranium Reserves?

	Percent of World's Uranium Reserves	GW of Nuclear	Enrichment
South Africa	10%	1.8	SOON
Brazil	6%	1.9	YES
USA	5%	99.3	YES
Russia	4%	21.7	YES
Australia	24%	0	NO
Canada	22%	12.6	NO
Kazakhstan	13%	0	NO
Namibia	6%	0	NO
Uzbekistan	6%	0	NO
Niger	5%	0	NO

Enrichment is measured by the "Separative Work Unit" or SWU.

Enrichment can also be used for the manufacture of nuclear weapons.



Which countries have fuel cycle facilities?

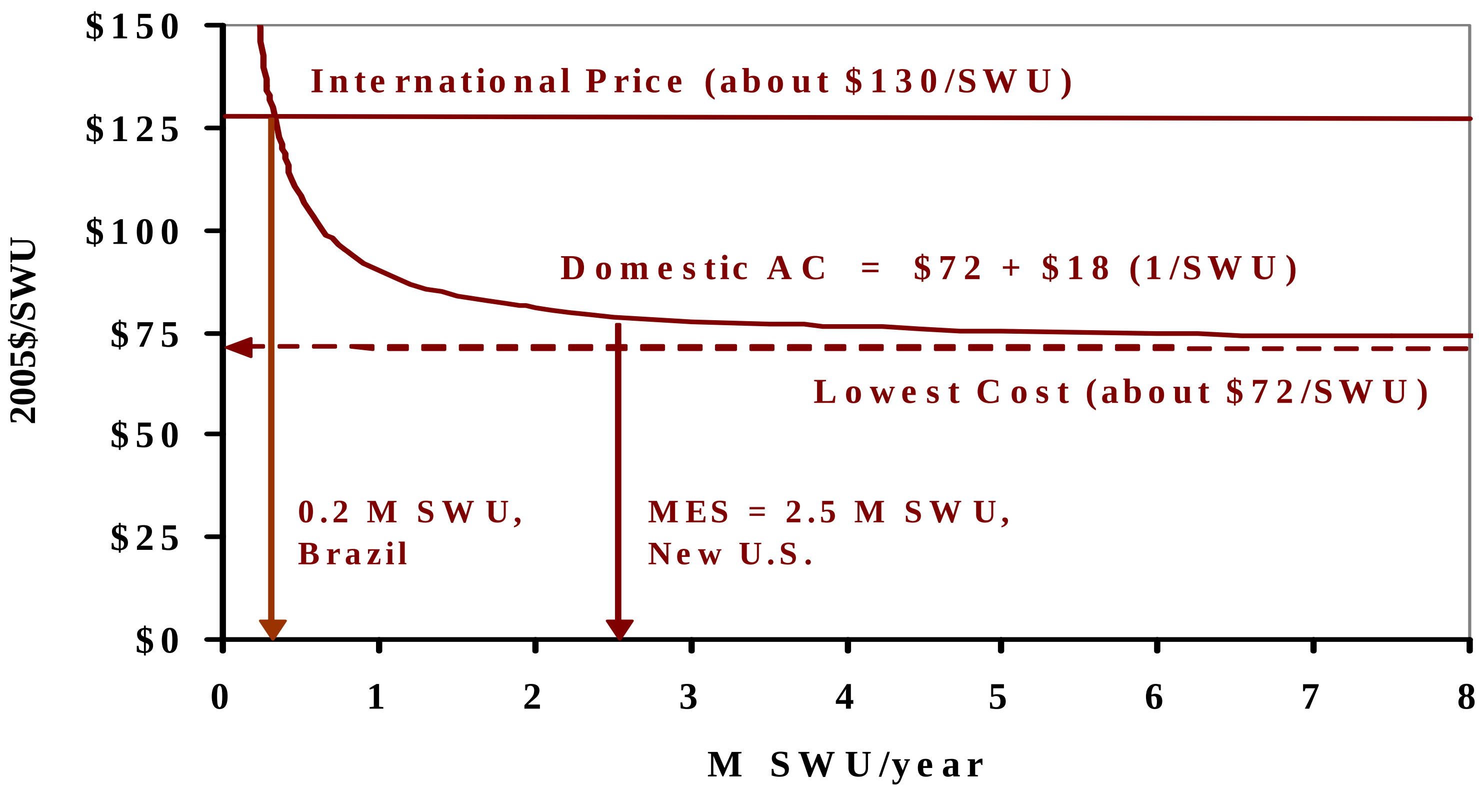
	Enrichment + Fuel Fab		LEU Fuel Fab Only		Neither	
> 5 GW	USA	Germany	Korea	Spain	Ukraine	
	France	China	Canada	Belgium	Taiwan	
	Japan	UK	Sweden			
	Russia	India				
< 5 GW	Brazil		Argentina		Armenia	Mexico
	Pakistan				Bulgaria	Romania
	Iran	(No Fab)			Czech	Slovakia
	Netherlands	(No Fab)			Finland	Slovenia
	S. Africa	(by 2017)			Hungary	Suisse
					Lithuania	

Which States have commercial enrichment facilities? And soon Brazil!

Country	Technology	Owner	Capacity (12/1995)	Mkt. Share	Capacity (12/2005)	Mkt. Share
Russia	Centrifuge	Tenex	14,000	29	20,000	42
US	Diffusion	USEC	19,200	39	8,000	17
France	Diffusion	Eurodif	10,800	22	10,800	23
Urenco	Centrifuge	Urenco	3,375	7	7,400	15
Japan	Centrifuge	JNFL	800	2	900	2
China	Diff & Cent	CNNC	500	1	800	2
Total Commercial SWU Capacity			**48,675**	**100**	**47,900**	**100**

Source: Ux Consulting Company, LLC. http://www.uxc.com/

What are the commercial incentives to enrich uranium in a "non-fuel cycle state"?



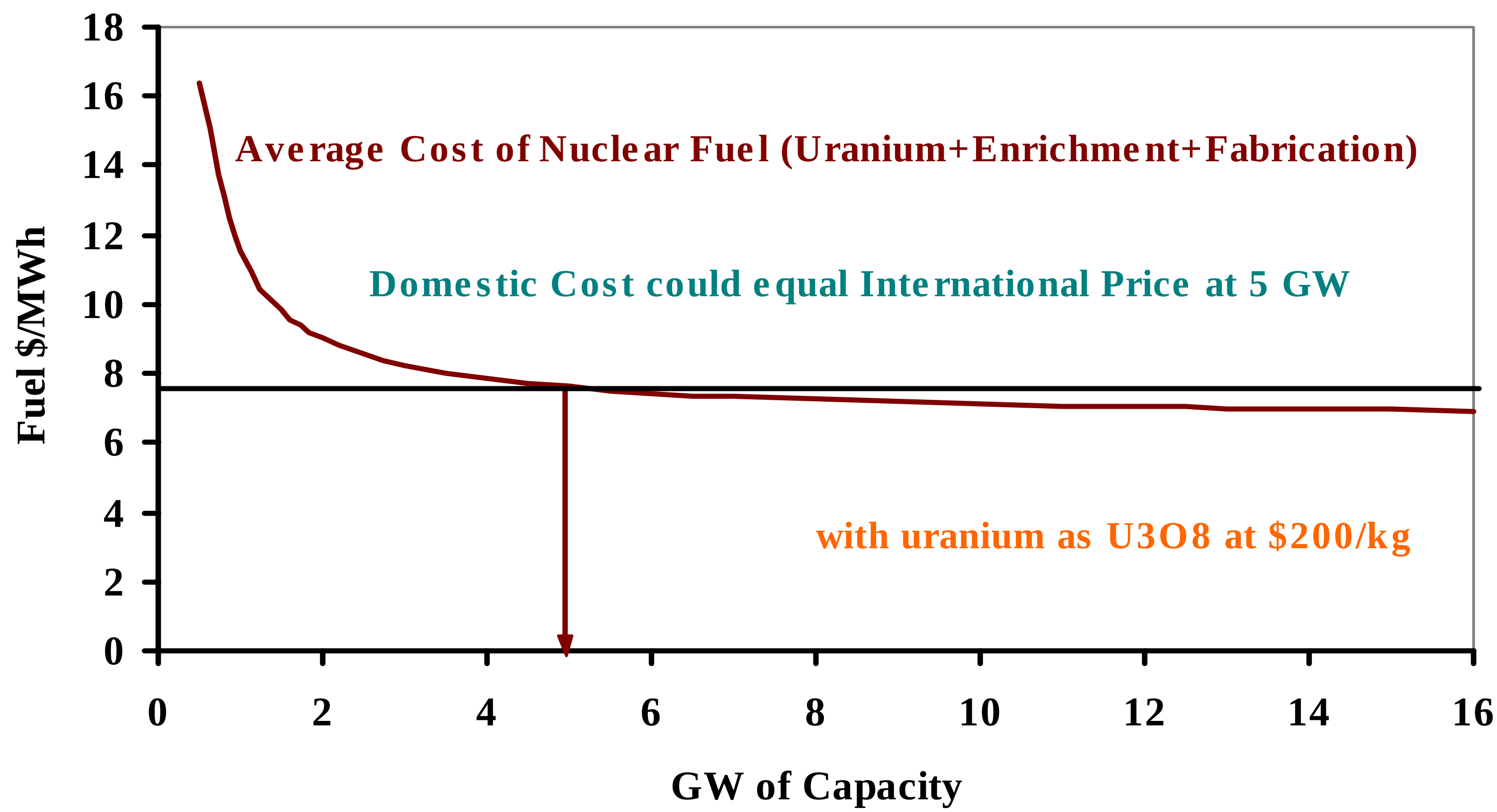
What is the price of nuclear fuel?

Cost	Uranium plus Conversion	Enrichment	Fuel Fab	Total ($M)	Average Fuel Cost
($M/year)	**$40.21** +	**$14.30** +	**$6.07** =	**$60.58**	**$7.67 /MWh**
% of Total	66%	24%	10%	100%	
Prices	$206 /kg	$130 /SWU	$250 /kg		
Quantities	195,196 kg	110,000 SWU	24,265 kg		7,900 GWh
Quantities	724 kg	408 SWU	90 kg		
	FEED 0.71% feed assay →	**ENRICHMENT** 0.3% tails assay →	**PRODUCT** 4% product assay →	**ELECTRICTY** 1,000 MW 90% Capacity Factor	

↓ **TAILS**

http://www.wise-uranium.org/nfcue.html

What are the costs of the "non-fuel cycle state" (e.g., Chile) assuring its own supply at today's uranium and enrichment prices?



What is the price of the back end of the nuclear fuel, i.e., of managing spent nuclear fuel?

(1) Assume it is $1/MWh, which is what is done in the U.S.

(2) Great uncertainty in knowing the “true cost”

(3) Assume that a “fuel-cycle” state (e.g., U.S., Brazil?) will “Take-Back” used nuclear fuel for a fee (e.g., $3/MWh).

US DOE GNEP's Proposed Vision

(1) **Encourage international adoption of nuclear power to reduce CO_2 emissions**

(2) **Develop international capacities so "fuel-cycle" states can assure fuel supplies to "non-fuel-cycle" states, and take-back used fuel for reprocessing**

(3) **Develop technologies that reduce nuclear waste in geologic repositories**

(4) **Develop reprocessing technologies that reduce proliferation risk**

Next, is nuclear power economically competitive in Chile?

(1) First, nuclear electricity costs are compared to electricity generated by Combined-Cycle Natural Gas Turbines (CCGT)

(2) Second, simulated volatile natural gas prices are used to generate Net Present Value (NPV) probability distributions

(3) Third, given the uncertainty of social surplus, what is the value today of being able to take future action?

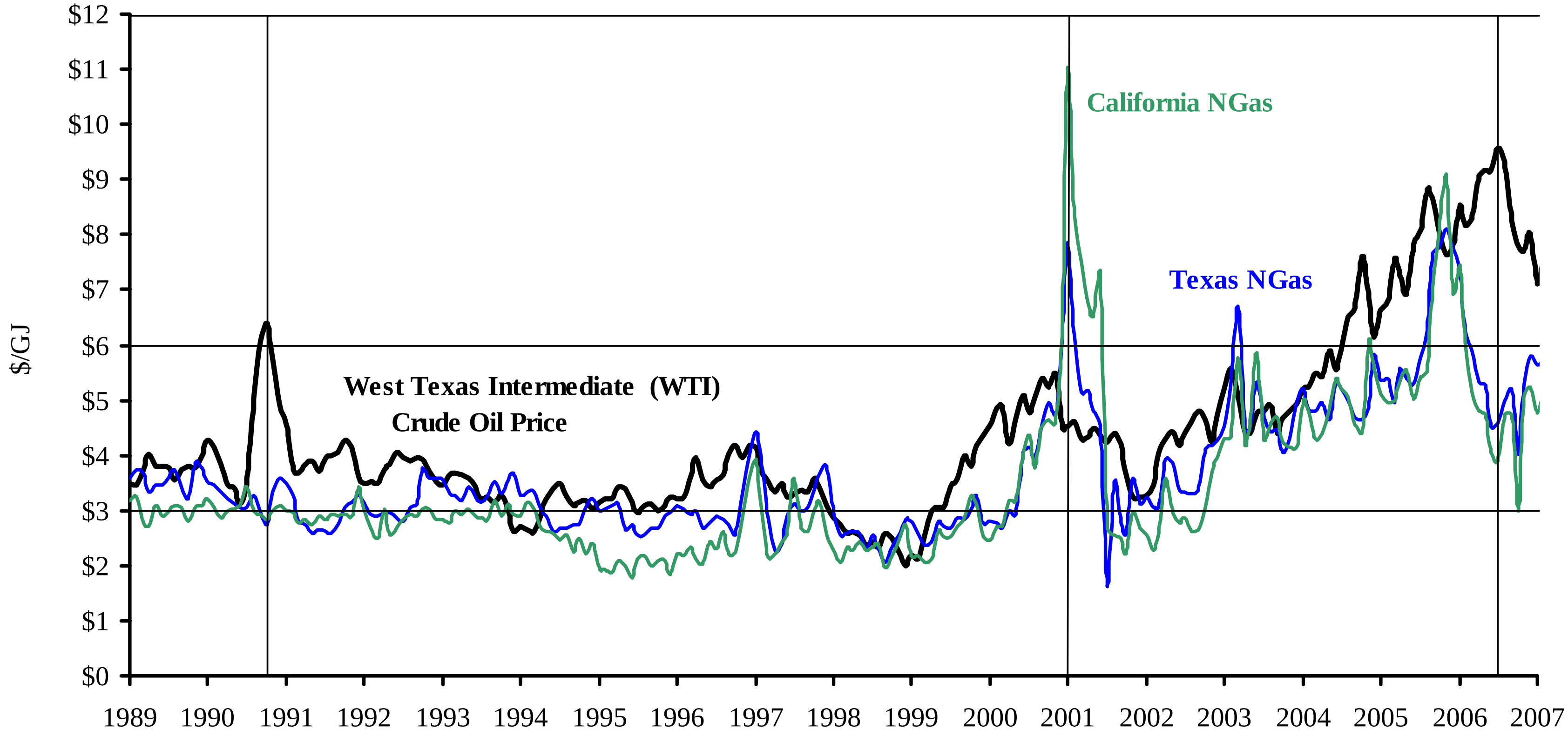
Comparing an ALWR with a CCGT (at a natural gas price of $6/GJ, or $6.38/MBtu):

Comparing with CCGT ($2005) **Values from AEO (2007, Table 39, p. 77)**	Units	**ALWR** **r = 10%**	**CCGT** **r = 10%**
Natural Gas Price ($/GJ=0.94x $/MBTU)	$/GJ		$6.00
Carbon Price ($/tonne)	$/tonne		$45
Carbon per MWh	kg/MWh	0.00	94.87
Heat Rate	BTU/kWh	10,400	6,333
Net Electrical Capacity	MWe	1350	1350
Average Capacity Factor	%	90%	90%
Plant Economic and Operational Life	Years	40	40
Construction Lead Time	Years	6.000	3.000
Real Cost of Capital for IDC & Amortization	%/year	10.00%	10.00%

Comparing Levelized Costs of an ALWR with a CCGT: In this example, nuclear is not competitive without carbon taxes. But this doesn't highlight the importance of the volatility of the price of natural gas.

Comparing with CCGT ($2005) Values from AEO (2007, Table 39, p. 77)	Units	ALWR r = 10%	CCGT r = 10%
Costs			
Capital (including IDC)	$/MWh	$35.07	$8.85
Operation	$/MWh	$8.57	$3.28
Fuel Cycle - Front End	$/MWh	$7.67	$38.00
Fuel Cycle - Back End (Waste or Carbon)	$/MWh	$1.00	$4.27
Levelized Cost without Carbon Tax	$/MWh	$52.30	$50.13
Levelized Cost with Carbon Tax	$/MWh	$52.30	$54.40

But Oil and Natural Gas Prices are Volatile!



The Net Present Value (NPV) of Nuclear Power is uncertain, because the Price of Natural Gas is uncertain!

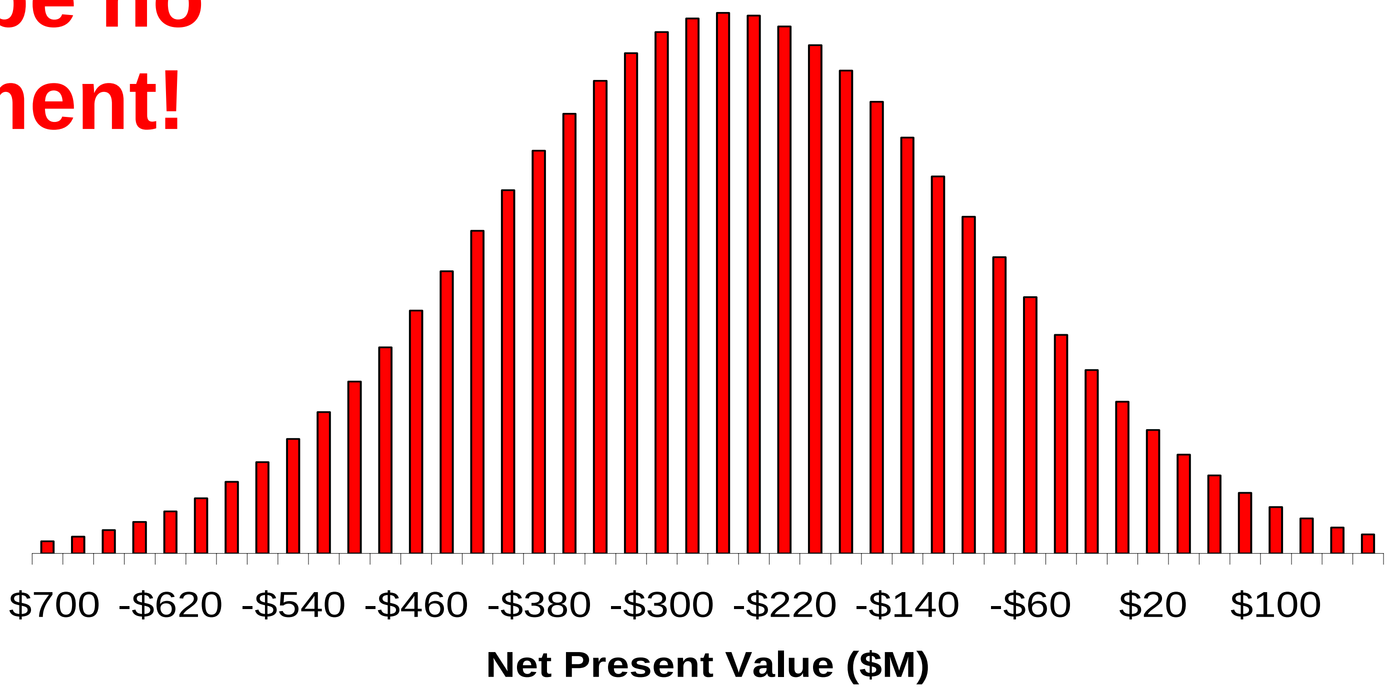
Here, Natural Gas Prices follow each other:

$P(t) = \$0.88 + 0.82 \times P(t-1) + \text{error}$

Cash Flow Analysis (Millions of 2005 dollars)	Without C Tax	With C Tax
Electricity Price = CCGT Cost	$50.13	$54.40
Net Present Value at 10% real	$232	$495
Net Present Value at 15% real	-$514	-$257

This variation in the price of natural gas yields a mean NPV is -$257M with a high variance, such that there is only a 10% probability of a positive NPV.

Under standard NPV analysis, there would be no investment!



But consider the project as a series of Real Options, where investors can quit or continue:

For example, consider 3 Real Options (Project Stages):

(1) Select Site, Supplier, and Technology

(worth about $20 M to buy Option 2)

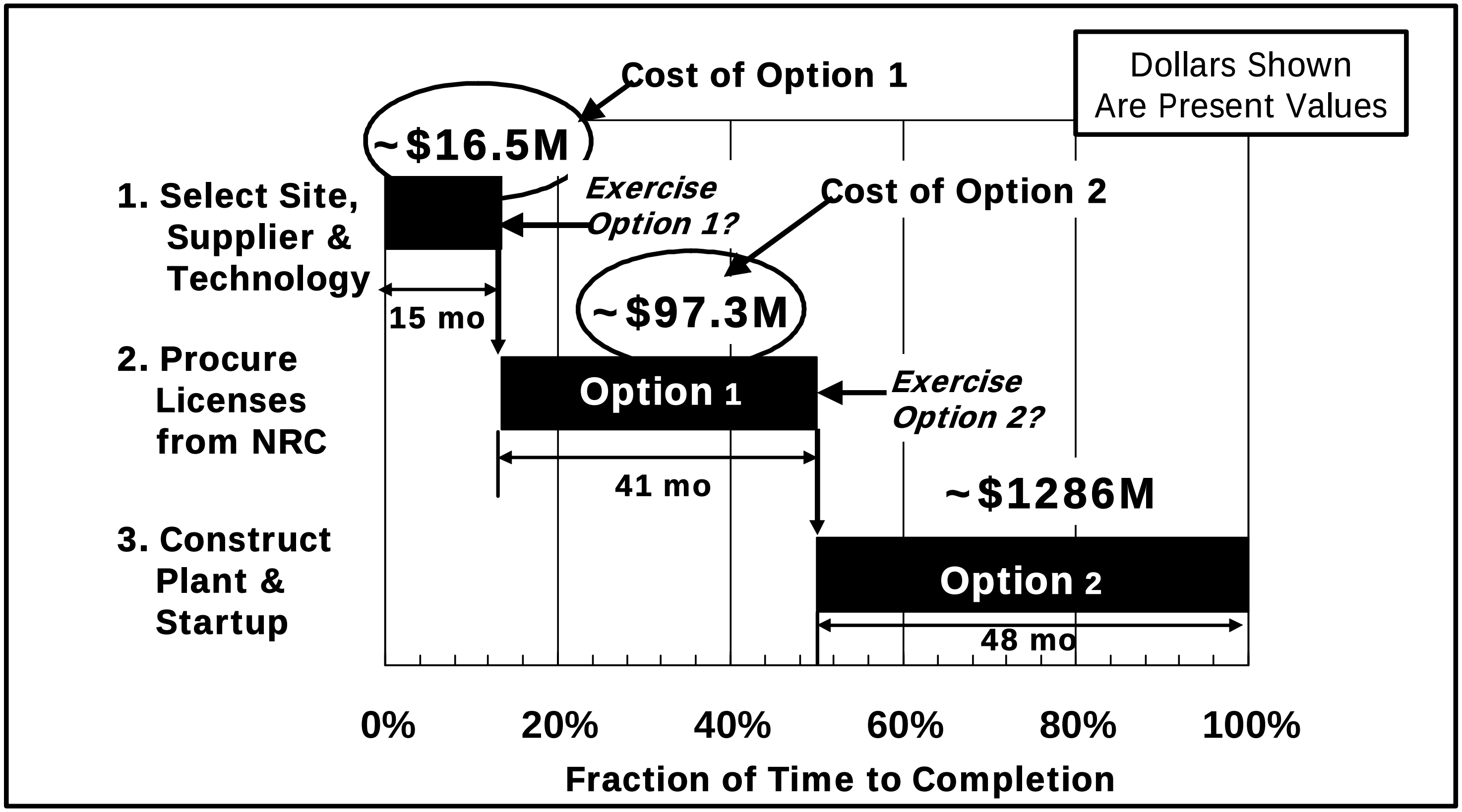
(2) License the Site, Supplier, and Technology

(worth about $100 M to buy Option 3)

(3) Build Nuclear Power Plant

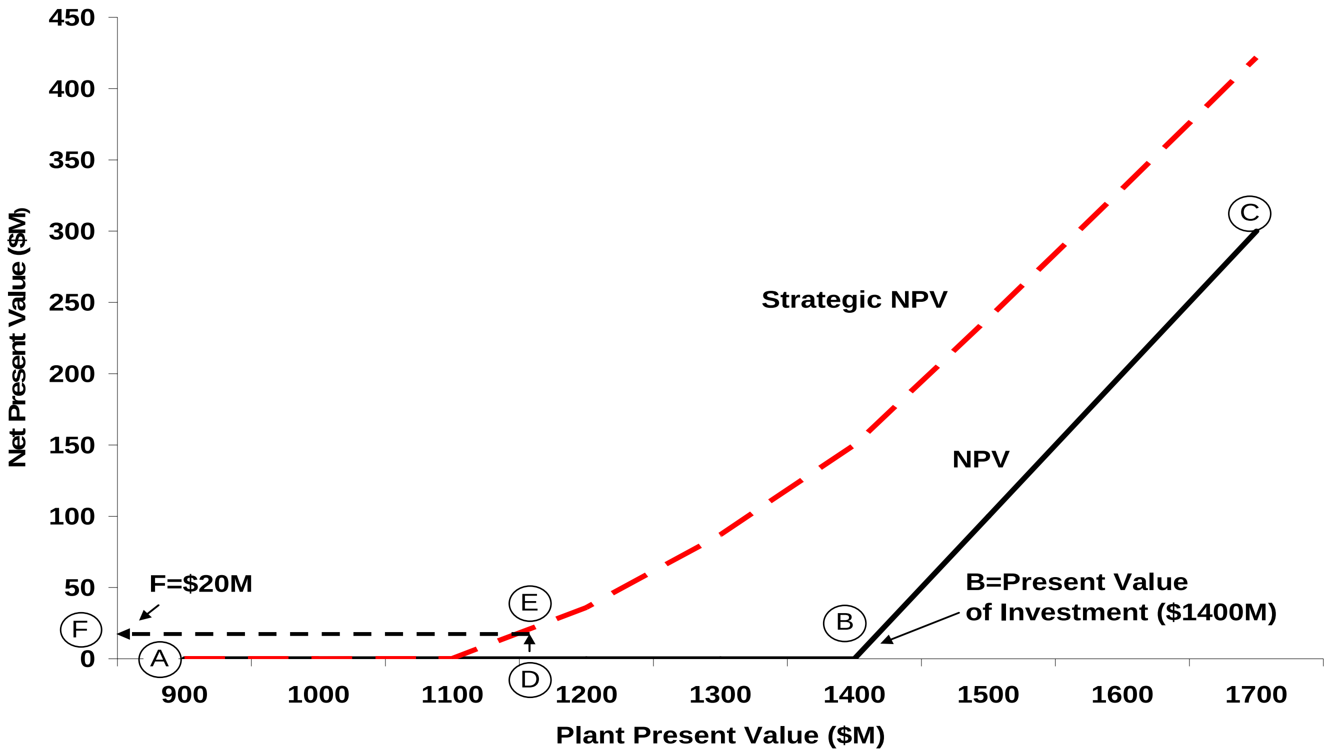
(costs about $3,000 M to build Option 3)

Consider Rothwell (2004, 2006) and Graber and Rothwell (2006) analysis of the value of building an ABWR in Texas (note, NRG exercised Option 1 on September 24, 2007):



What is the value of investing in the First Option? **Here it is about $20 M.**

The value of the Second Option can be shown to be **about $100 M.**



What is the Real Option conclusion?

This Real Options analysis implies that if agreements can be concluded

(1) with appropriate Site(s) and Owner(s),

(2) with appropriate Technology(ies) and Supplier(s),

(3) and under an appropriate Regulatory Regime,

public and private investors should be willing to spend about $20 M (final value to be estimated!) to determine whether to apply for a license for an appropriate nuclear power plant in Chile.

If the first license will require 6 years, the first phrase should be completed in 6 years, i.e., before 2014.

References:

Rothwell (2004) "Triggering Nuclear Development: What Construction Cost Might Trigger New Nuclear Orders in Texas?" *Public Utilities Fortnightly* (May): 46-51.

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Graber and Rothwell (2006). "Valuation and Optionality of Large Energy Industry Capital Investments," *Cost Engineering* 48, 8 (2006): 20-26.