GTSP

Global Energy Technology Strategy Program

Nuclear Energy in a Climate-constrained World

Global Energy Technology Strategy Program (GTSP) Annual Meeting

Sonny Kim and Jae Edmonds

May 29, 2008

Battelle

JGCRI Joint Global Change Research Institute

UNIVERSITY OF MARYLAND

Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Acknowledgements

Kathryn McCarthy at the Idaho National Laboratory (INL) for supporting our analysis on the role of nuclear energy for addressing climate change.

GTSP
Global Energy Technology Strategy Program

Contents

- Motivation for Nuclear Power
- Modeling the Nuclear Energy System
- Reference and Climate Scenario Results
- Value of Nuclear Energy for Addressing Climate Change
- Challenges for the Greater Use of Nuclear Energy
- Conclusions

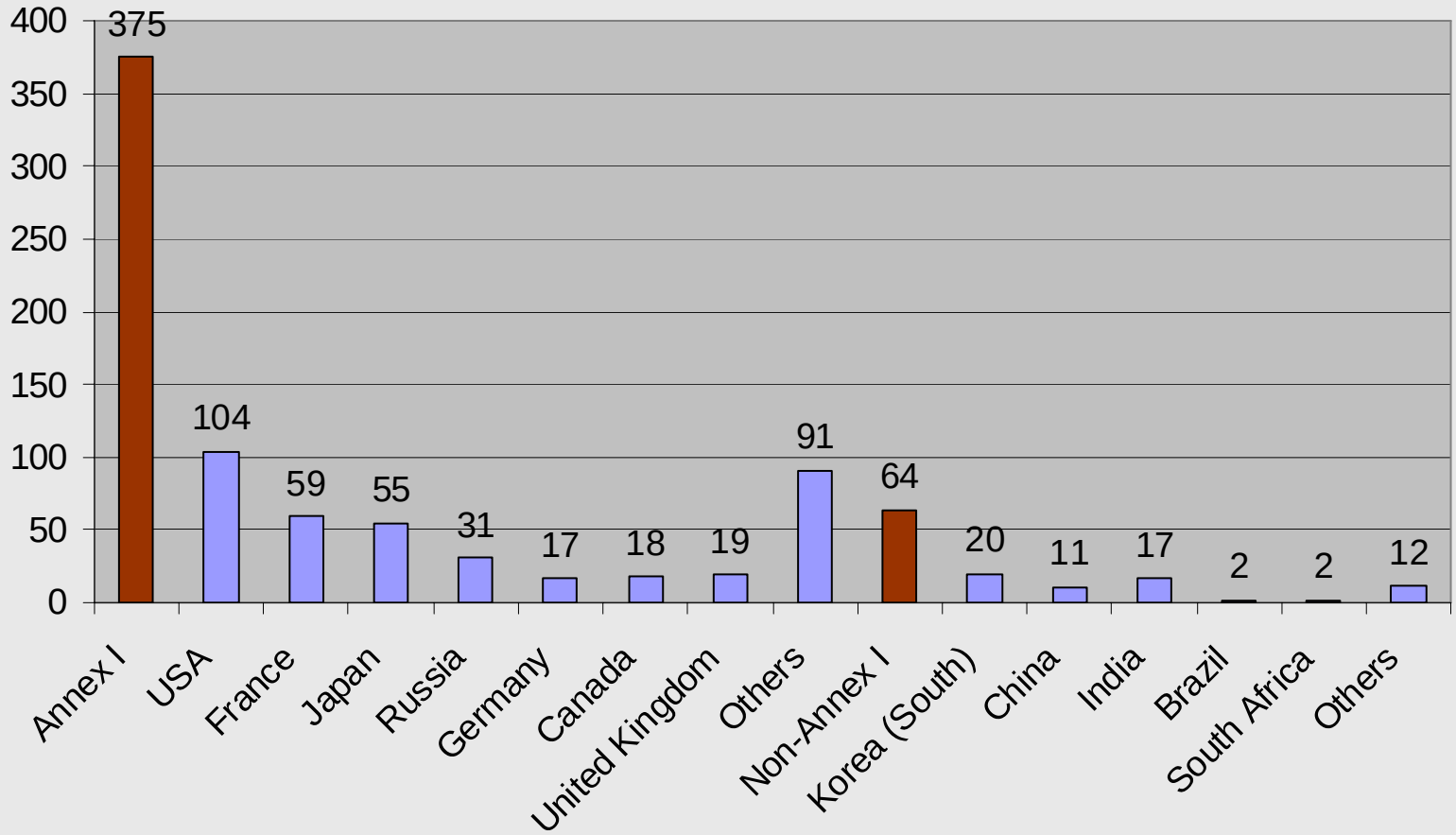
GTSP
Global Energy Technology Strategy Program

Motivation for Nuclear Power

- Nuclear power does not emit GHGs in the production of electricity.
- Nuclear power supplies baseload electricity without intermittency.
- Nuclear power currently supplies 16% of global electricity.
- Nuclear power is a mature and widely distributed global technology.
- What is the role of nuclear energy in the global energy system for addressing climate change?

Currently Operating Nuclear Reactors

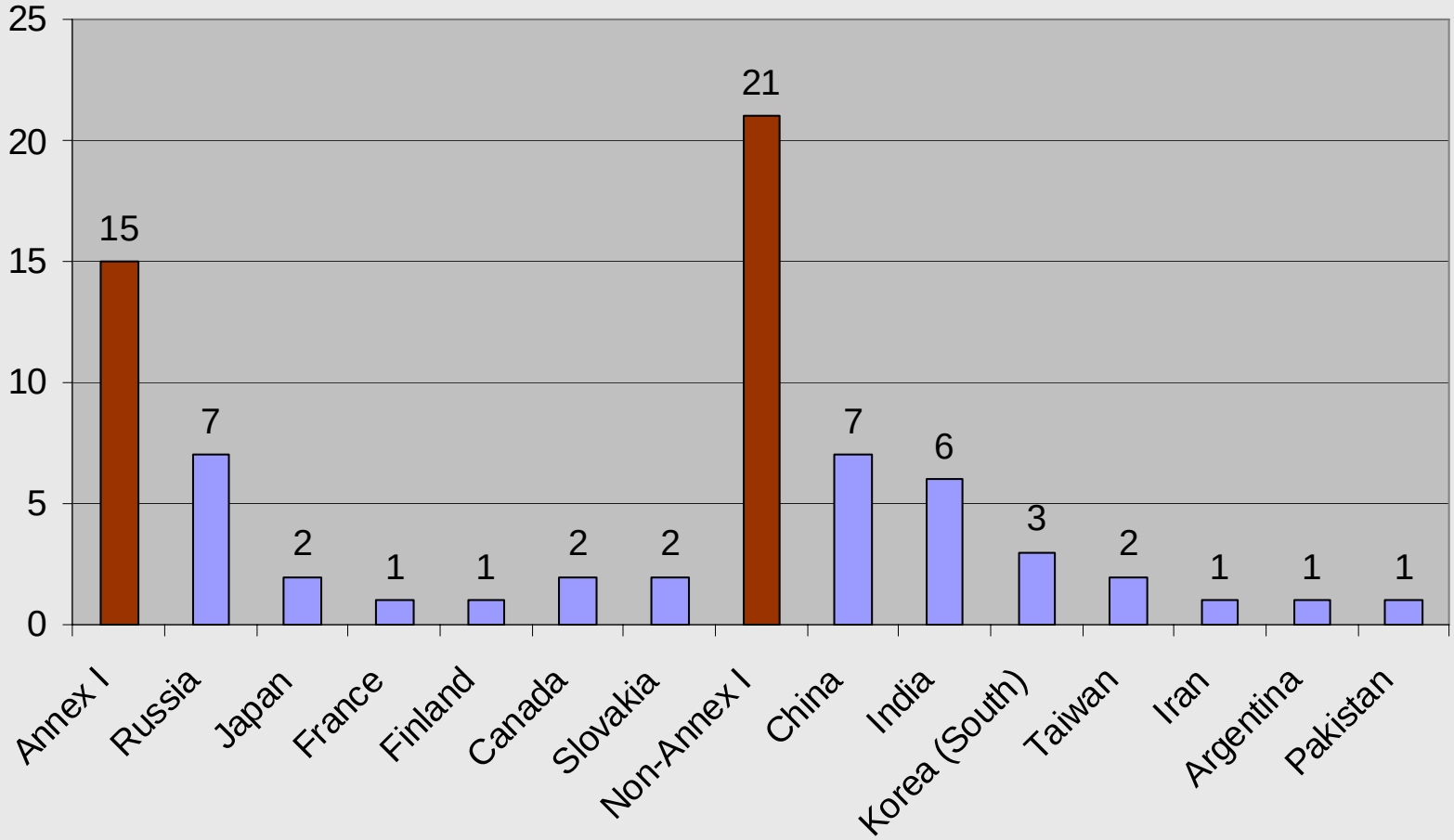
Total: 439 Annex I: 375 Non-Annex I: 64



Annex 1: OECD (less Korea & Mexico), Former Soviet Union & Eastern Europe
Non-Annex I: Rest of the World
(www.world-nuclear.org/info/reactors.html)

Nuclear Reactors Currently Under Construction

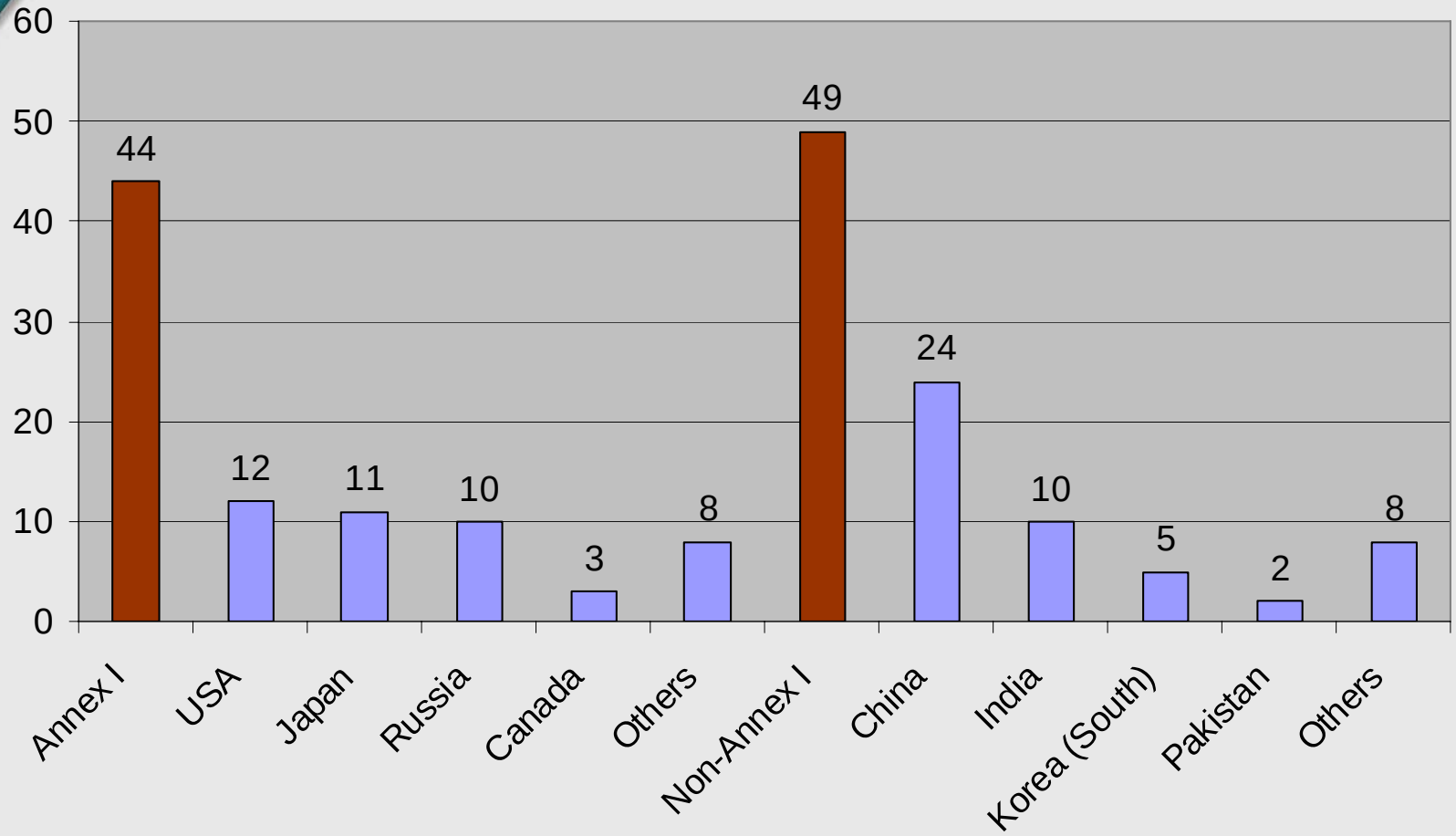
Total: 36 Annex I: 15 Non-Annex I: 21



(www.world-nuclear.org/info/reactors.html)

Planned Nuclear Reactors

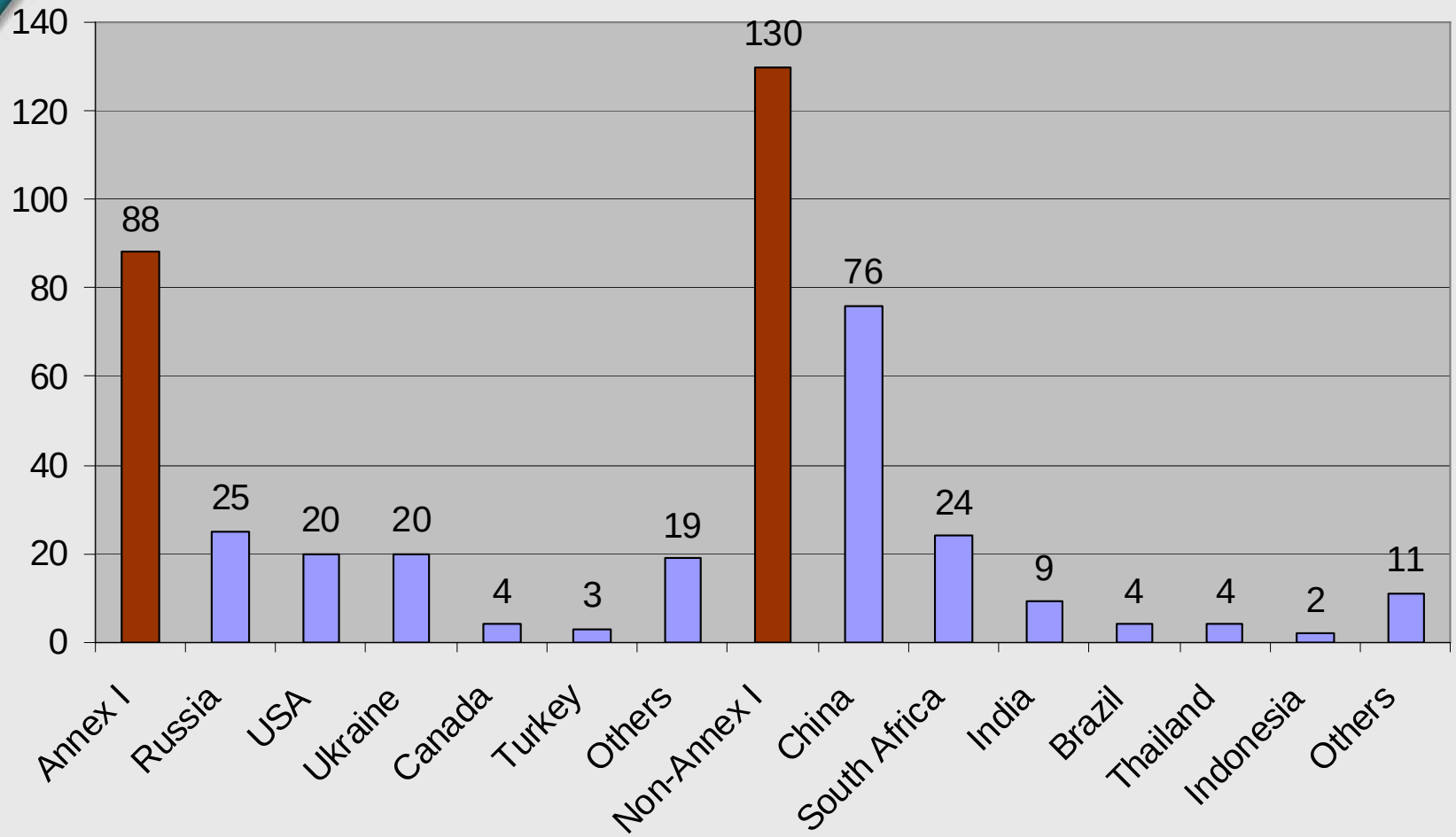
Total: 93 Annex I: 44 Non-Annex I: 49



Planned = Approvals, funding or major commitment in place, mostly expected in operation within 8 years, or construction well advanced but suspended indefinitely (www.world-nuclear.org/info/reactors.html).

Proposed Nuclear Reactors

Total: 218 Annex I: 88 Non-Annex I: 130



Proposed = clear intention or proposal but still without firm commitment (www.world-nuclear.org/info/reactors.html).

Global Distribution of Nuclear Reactors

- Currently Operating: 439 reactors in 30 countries
  - Annex I : 375 (85%)
  - Non-Annex I: 64 (15%)
- Currently Under Construction, Planned and Proposed: 347 reactors in 35 countries
  - Annex I : 147 (42%)
  - Non-Annex I: 200 (58%)
  - China has 107 or 31% of the total, Russia has 42 (12%), US has 32, India has 25, and South Africa has 25. Top 5 countries total 231.
- Potential Total Reactors: 786
  - Annex I : 522 (65%)
  - Non-Annex I: 264 (35%)

ObjECTS-MiniCAM
Nuclear Energy System

Resources:

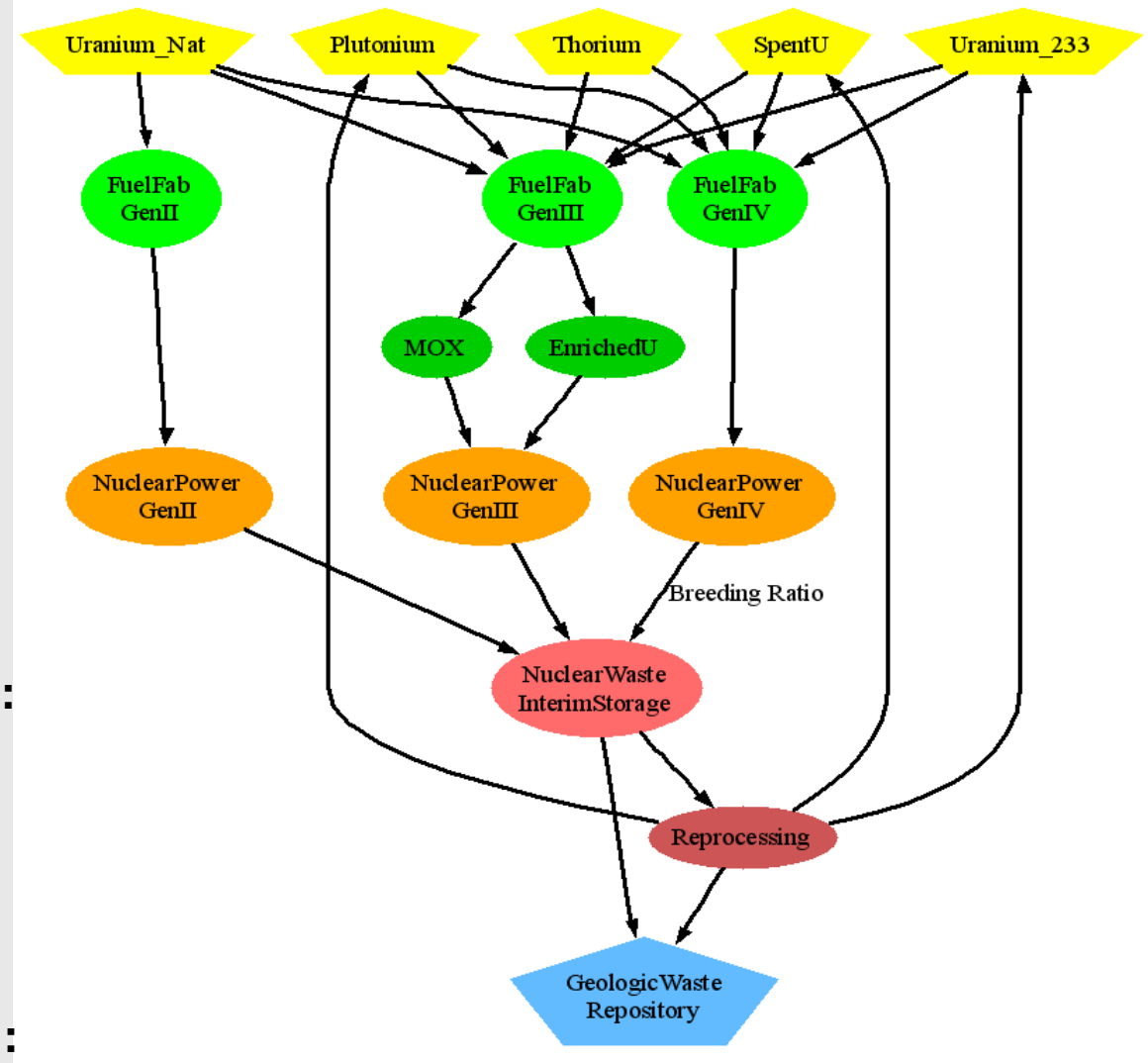
Fuel Fabrication:

Reactors:

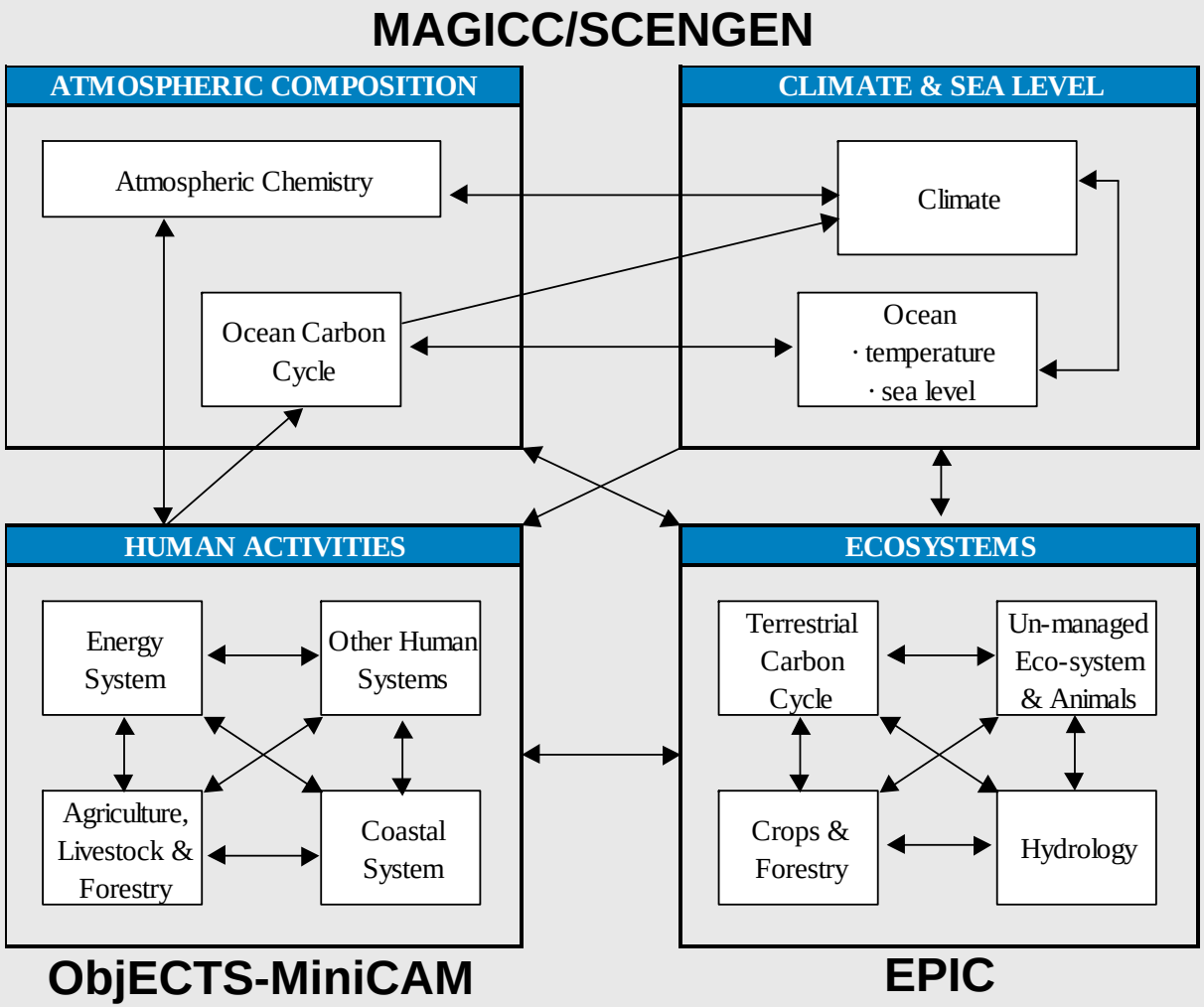
Interim Storage:

Reprocessing:

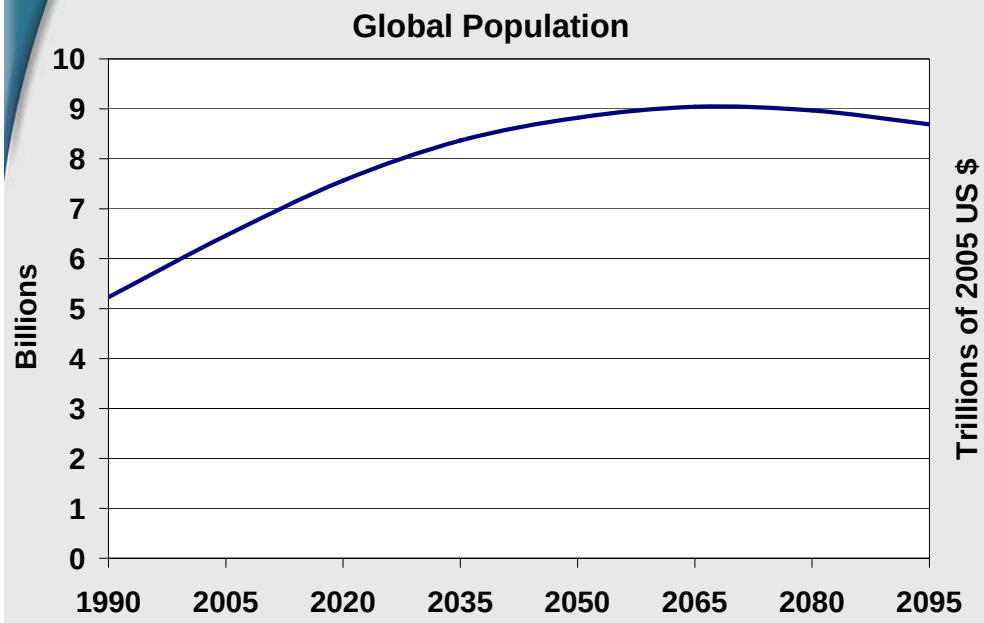
Waste Disposal:

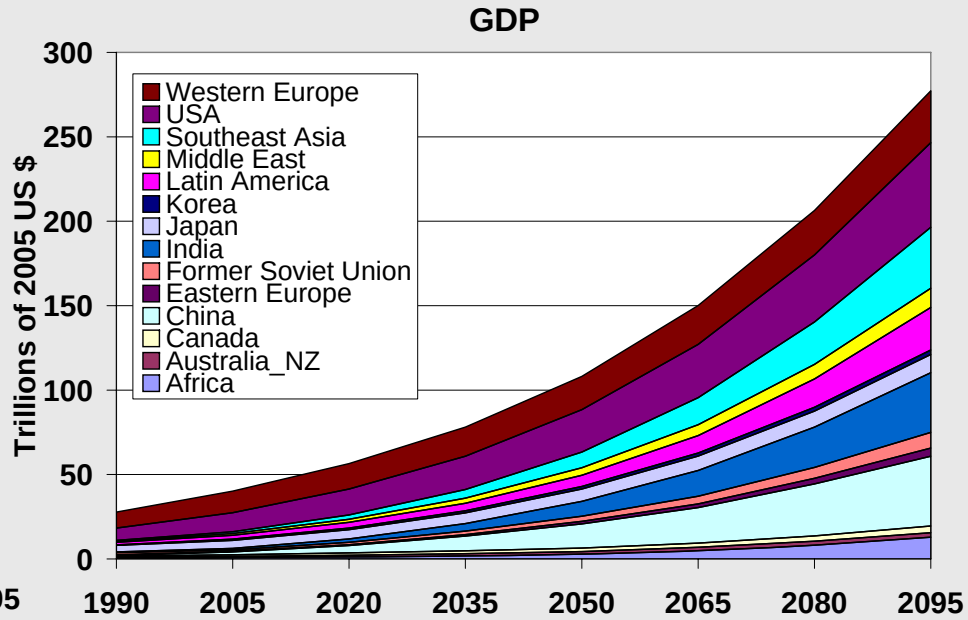


The Integrated Assessment Framework



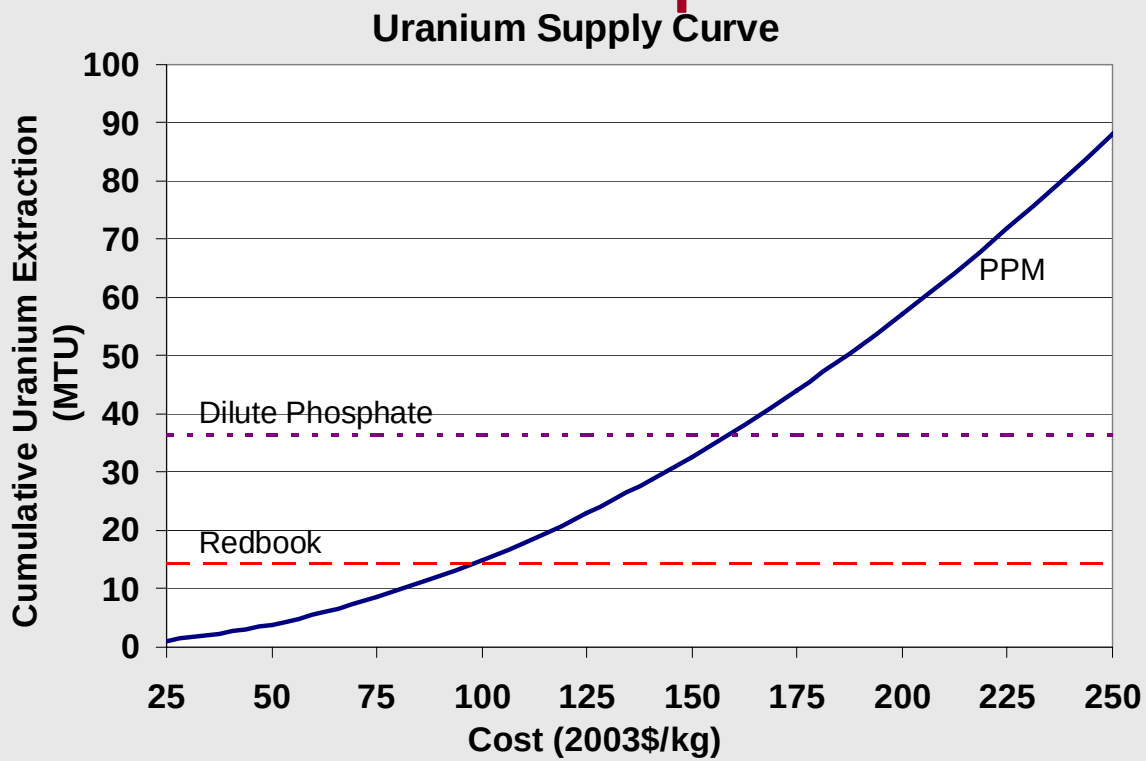
Global Population & GDP Reference Scenario





(Based on US DOE CCSP Scenario)

Natural Uranium Resource Assumption



Redbook, 2003. *Uranium 2003: Resource, Production and Demand*, IAEA and OECED/NEA.

Reference Scenario
Nuclear Energy System

- Nuclear Reactors
  - Legacy Reactors (Gen II)
  - Advanced Light-Water Reactor (Gen III)
- Once-Through Fuel Cycle
- Direct Disposal of Spent Fuel
- Unconstrained Waste Disposal with a Fixed Charge

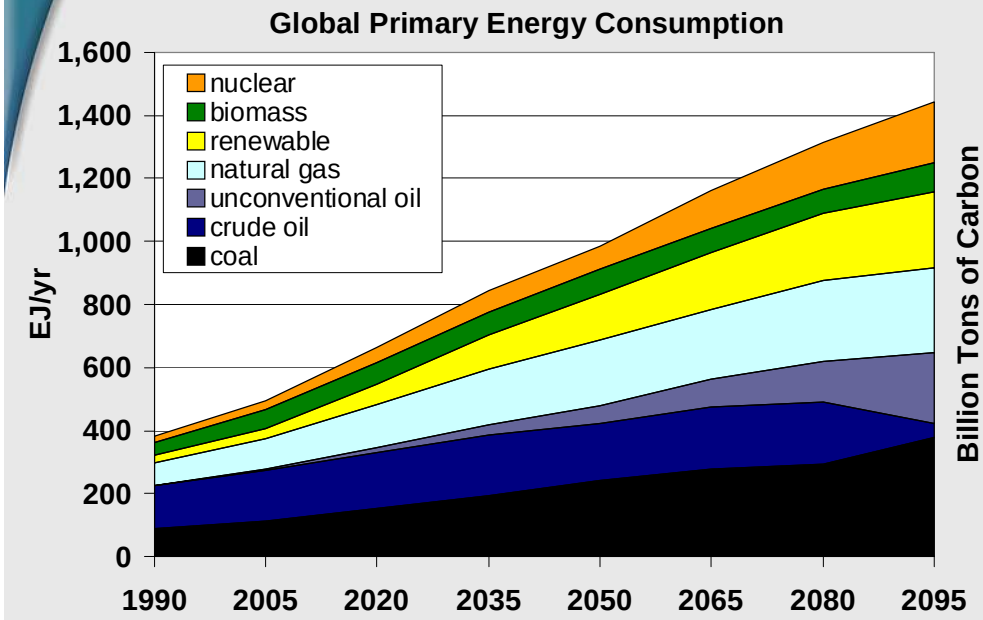
(France,United Kingdom, Germany, Japan, Russia, and others currently reprocess their used fuels.)

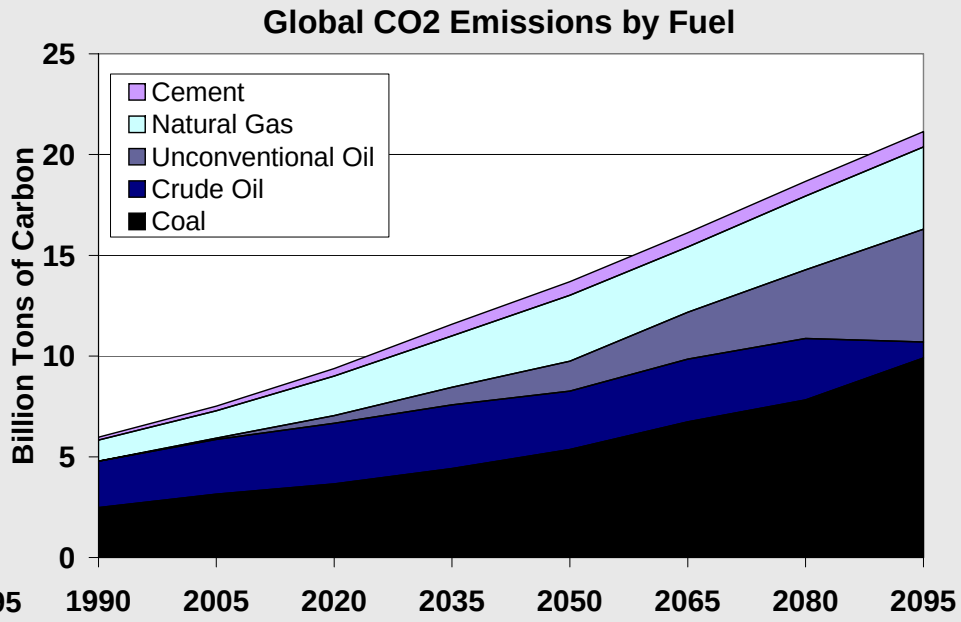
Nuclear Energy Technology Assumptions

	Gen II	Gen III	Gen III	Gen IV	Gen IV
Year	Legacy	2005	2095	2035	2095
Burnup (GWd/MTHM)	45	50	50	175	175
Enrichment (%)	4.08%	4.51%	4.51%	25%	25%
Uranium Ore Cost	Endogenous	Endogenous	Endogenous	Endogenous	Endogenous
Conversion Cost ($/kgU)	10	10	10		
Enrichment Cost ($/SWU)	104	104	104		
Fuel Fabrication Cost ($/kgHM)	240	240	240	1,500	1,500
Blanket Fabrication Cost ($/kgHM)				250	250
Reprocessing Cost ($/kgHM)				1,000	1,000
Interim Storage Cost ($/kgHM)	300	300	300	300	300
Waste Disposal Cost ($/kgHM)	548	548	548	200	200
Capital Overnight ($/kW)	Legacy	2,300	1,750	2,400	2,400
O&M Fixed ($/kW)	Legacy	64	64	64	64
O&M Variable (mills/kWh)	Legacy	1.8	1.8	1.8	1.8
Efficiency (%)	33%	33%	33%	45%	45%
Capacity Factor	0.85	0.85	0.85	0.85	0.85
Lifetime (years)	60	60	60	60	60

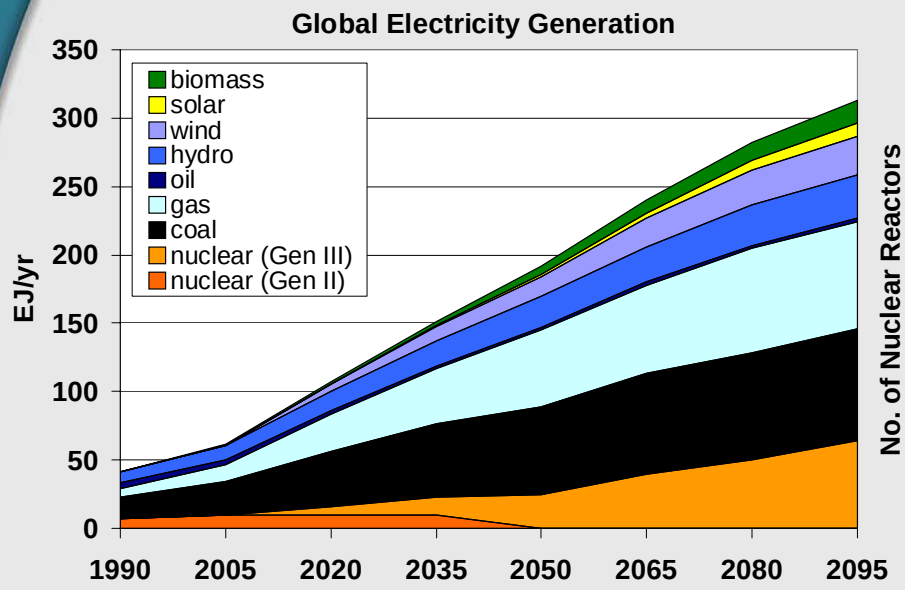
Note: $ year is 2005
Ref: Advanced Fuel Cycle Cost Basis 2007, INL.

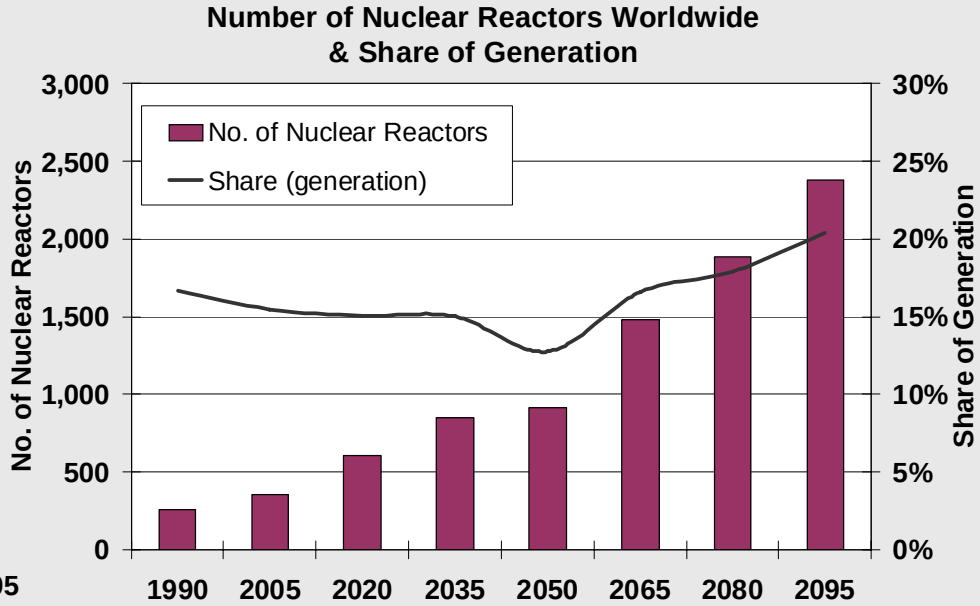
Global Primary Energy Consumption & CO_2 Emissions Reference Scenario





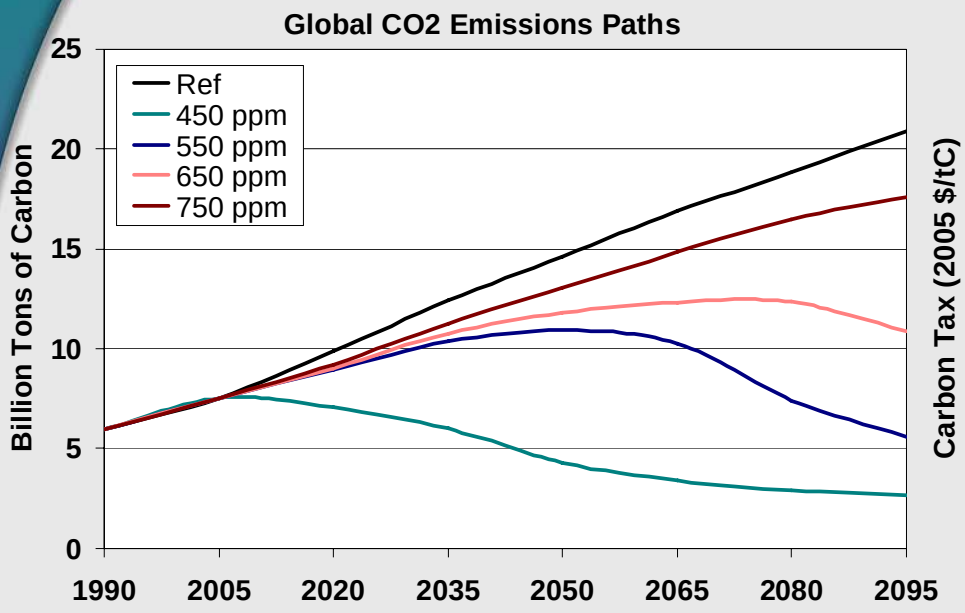
Global Electricity Generation & Nuclear Share Reference Scenario

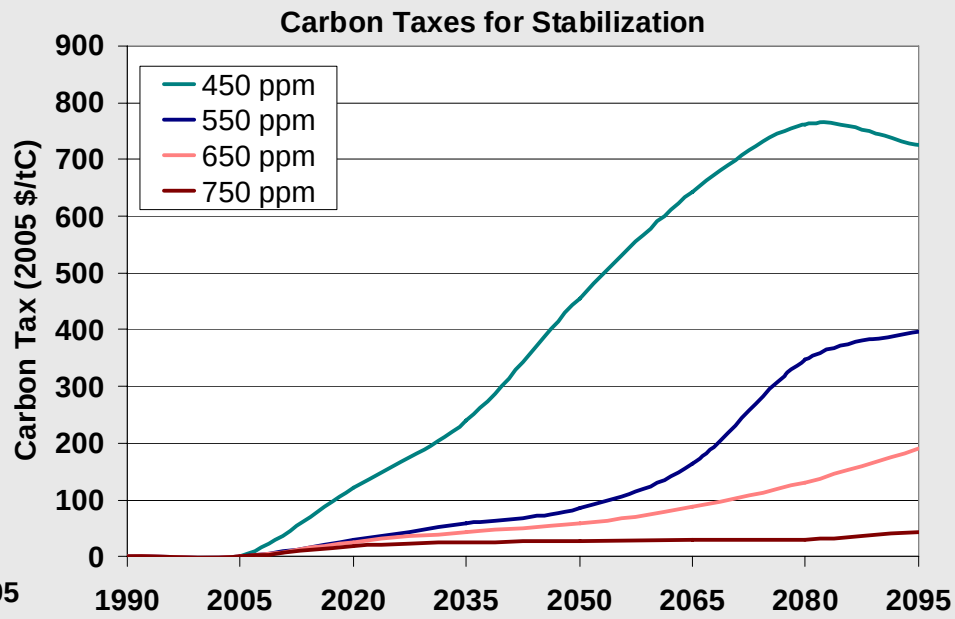




(1000 MWe Reactor @ 0.85 CF)

CO_2 Emissions Path & Resulting Carbon Tax for Stabilizing CO_2 Concentrations

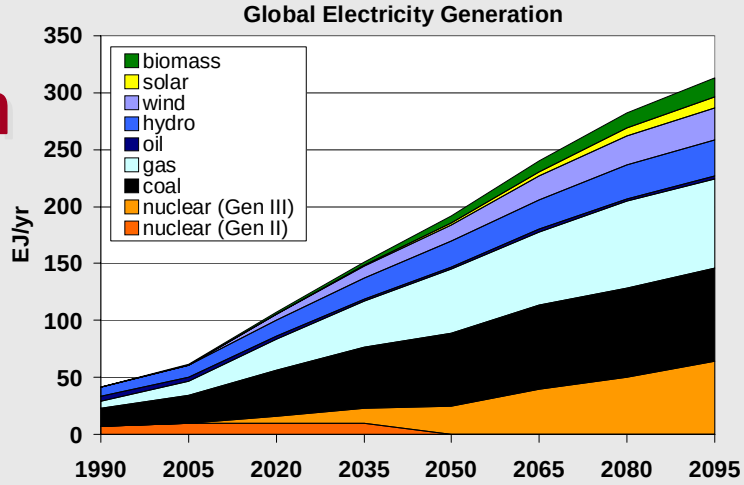




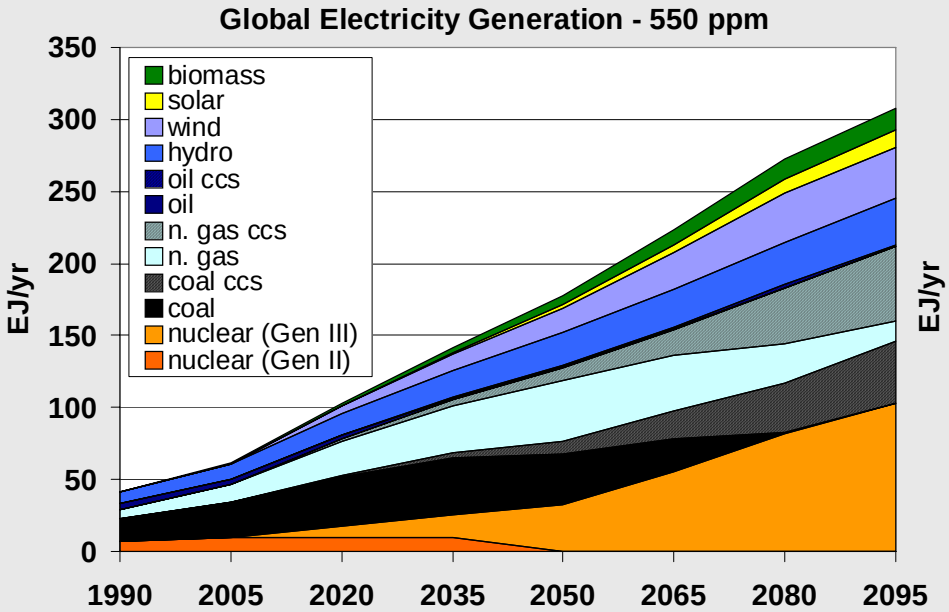
100 $/tC = 1.76 c/kWh
(24 % above base 7.4 c/kWh)

Mix of Global Electricity Generation 550 ppm Scenario with and without CO_2 Capture & Storage

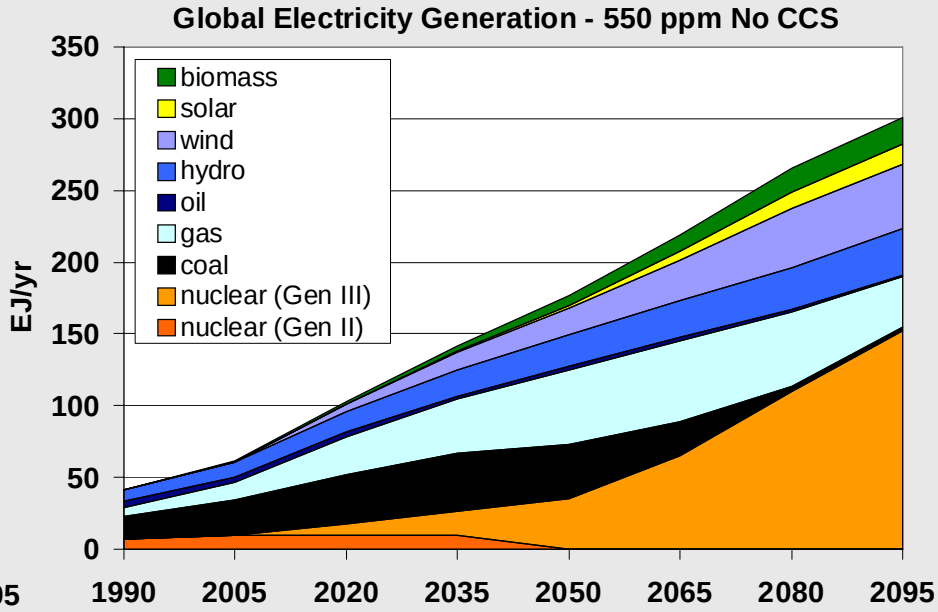
Reference



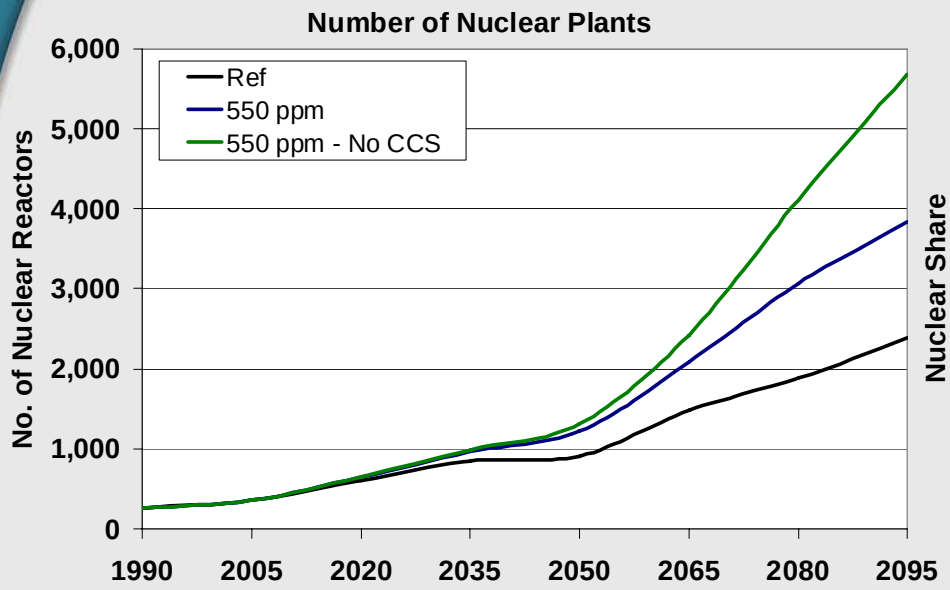
(With CCS)

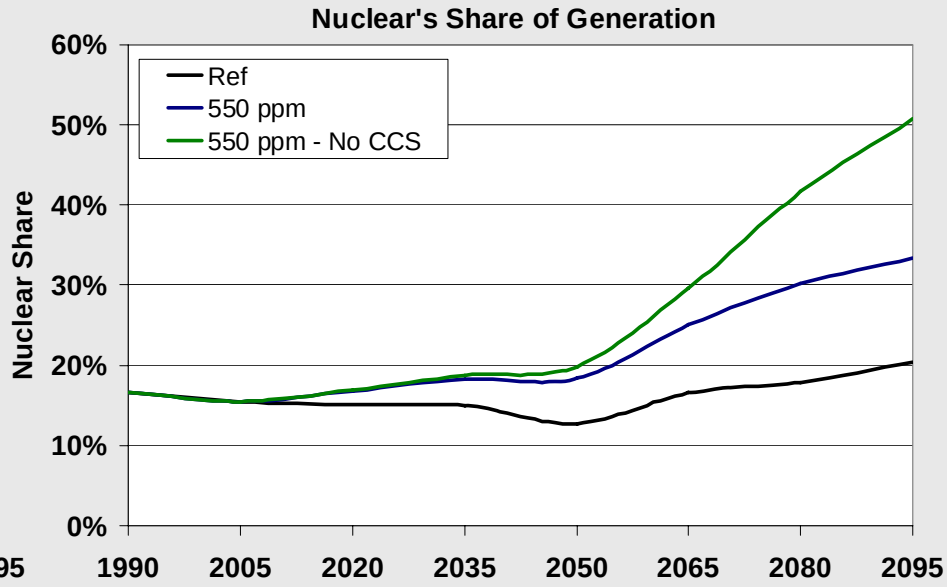


(Without CCS)



Number of Nuclear Power Plants & Nuclear Share of Generation (Global)

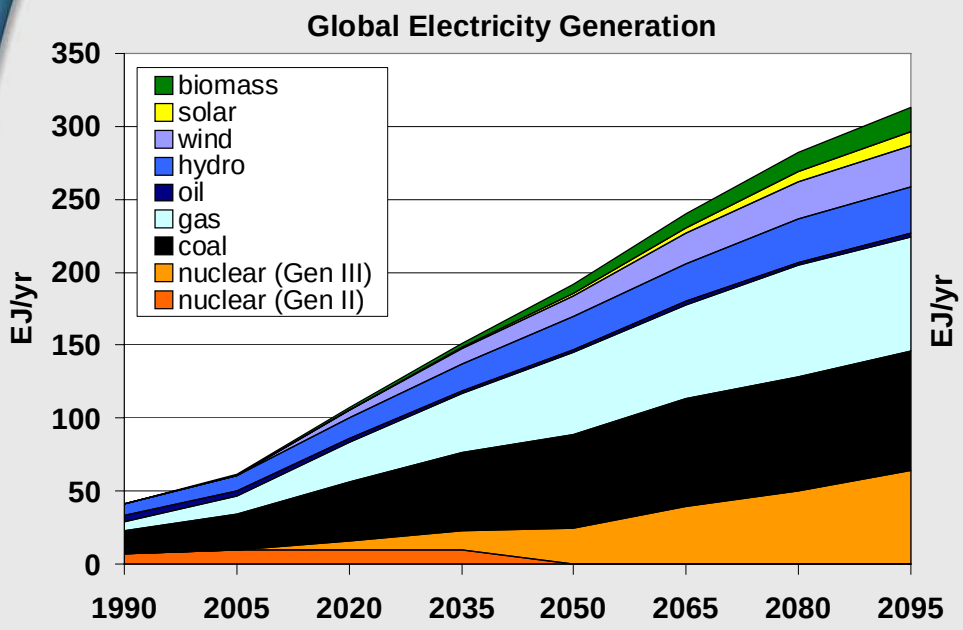




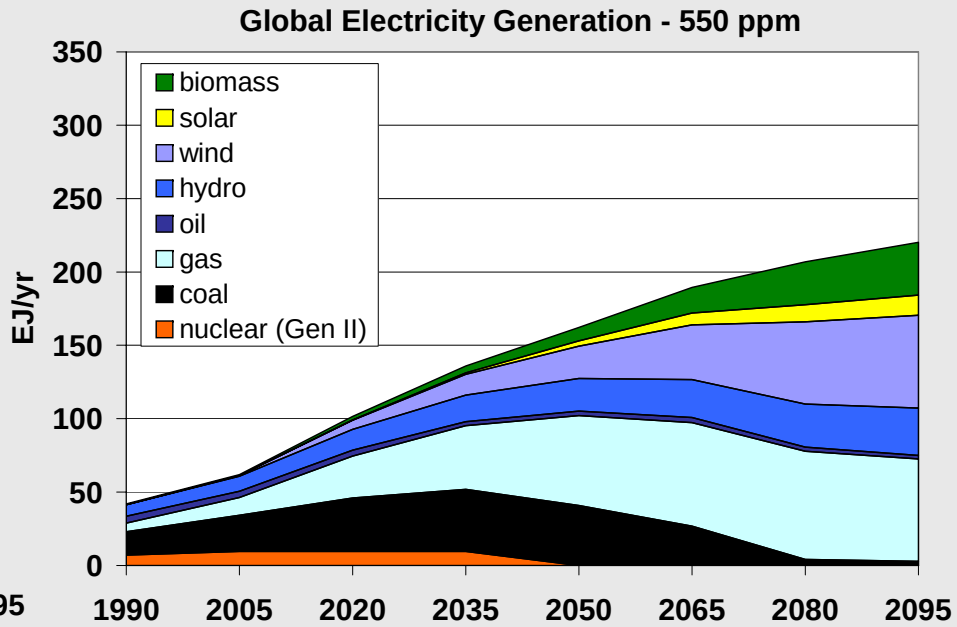
(1000 MWe Reactor @ 0.85 CF)

Comparison of Global Electricity Generation

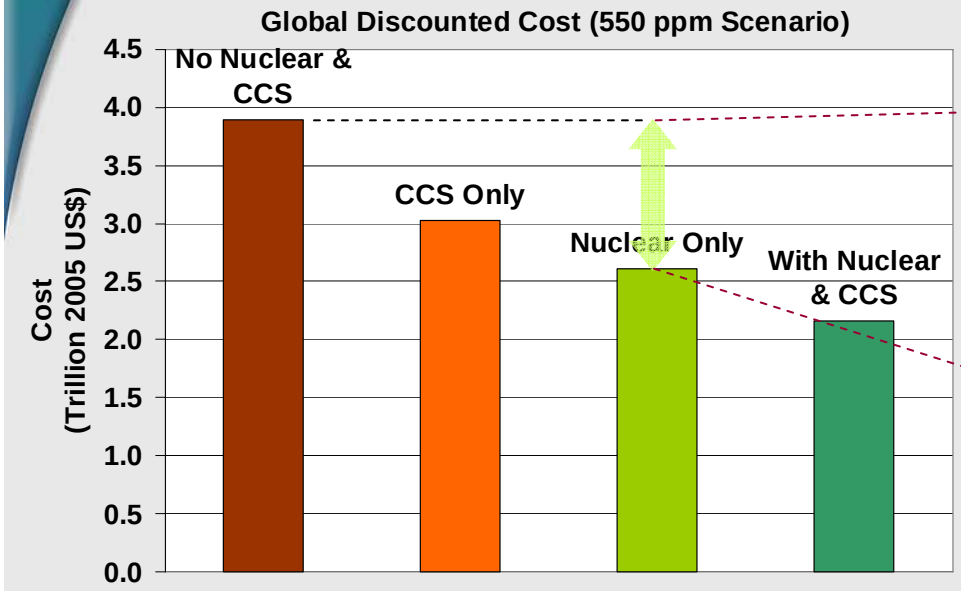
(Reference)

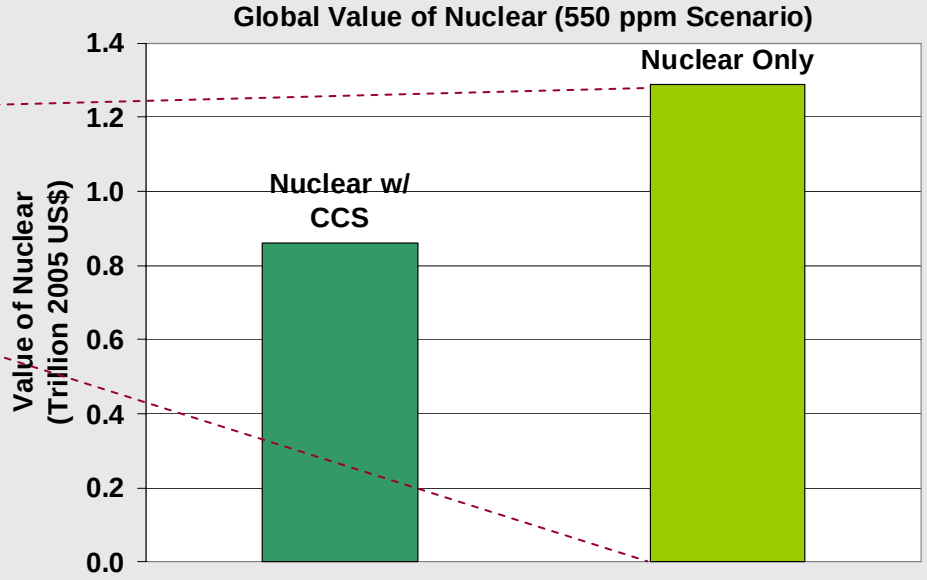


(550 ppm without Nuclear & CCS)



Cost of 550 ppm Scenario & Value of Nuclear Technologies (Global)

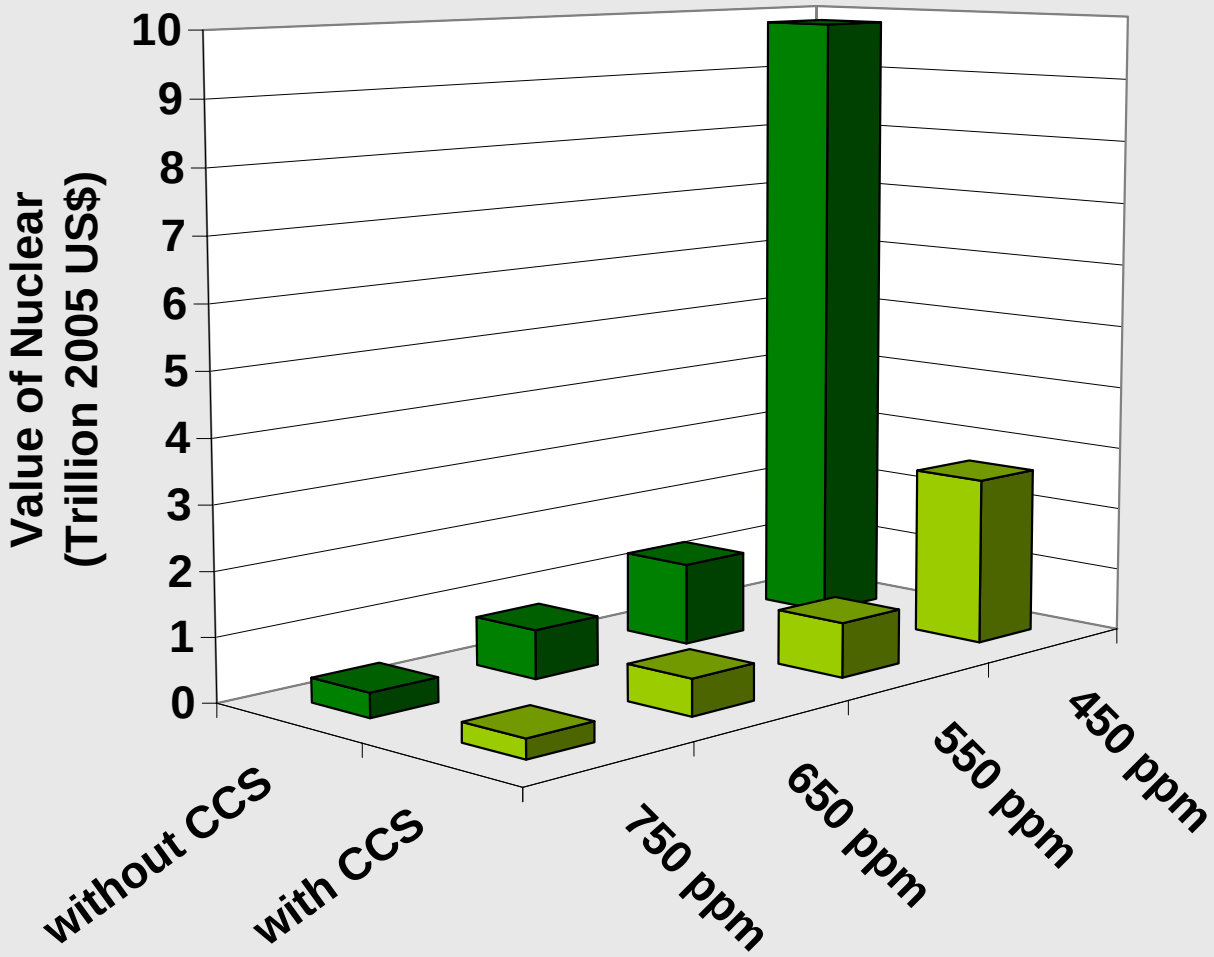




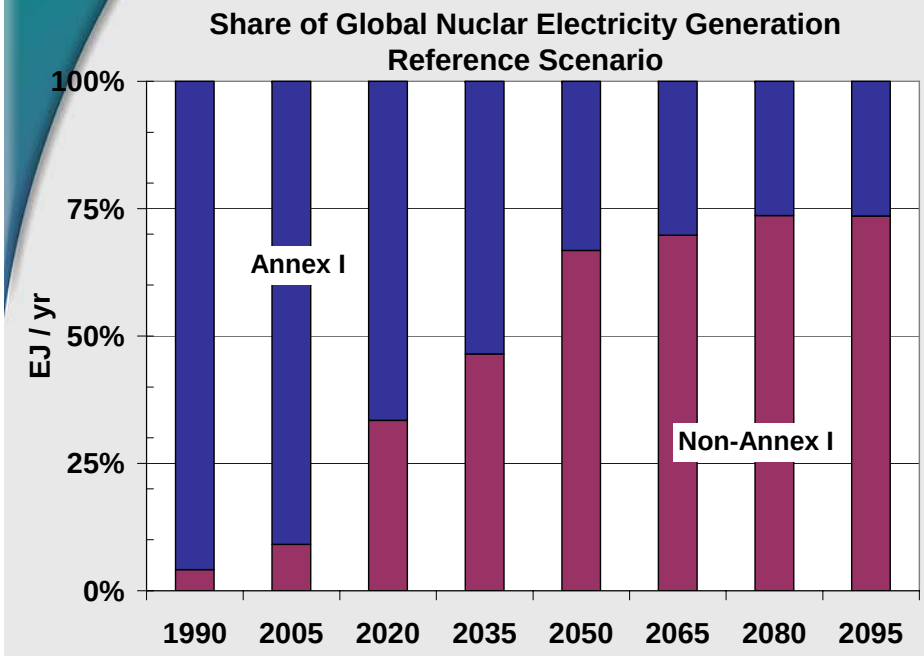
(Discounted @ 5% from 2095 to 2005)

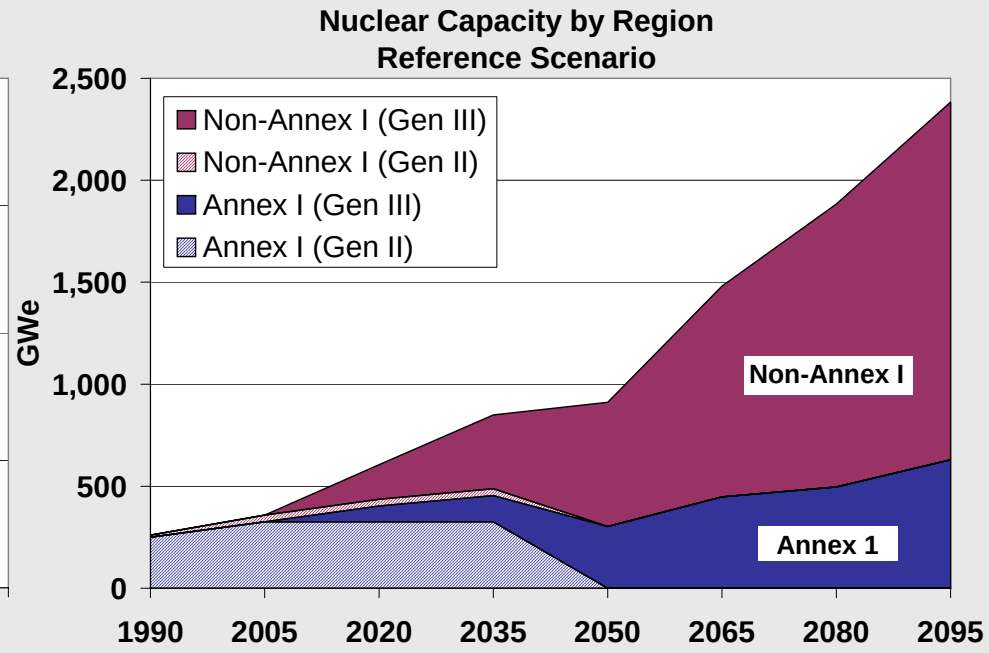
Value of Nuclear =
(Cost without Nuclear)
– (Cost with Nuclear)

Value of Nuclear for a Range of CO_2 Concentration Stabilization Scenarios



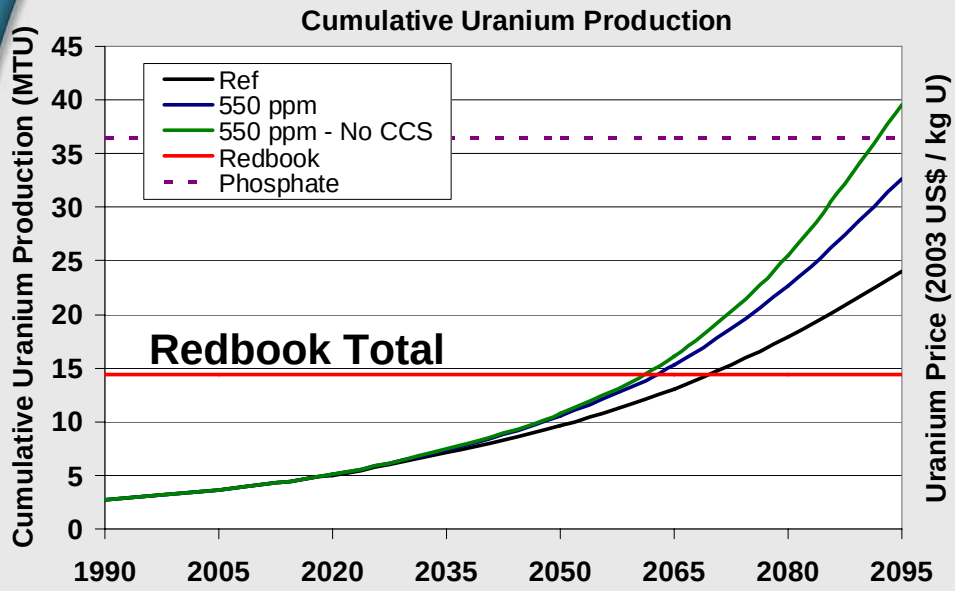
Worldwide Distribution of Nuclear Power

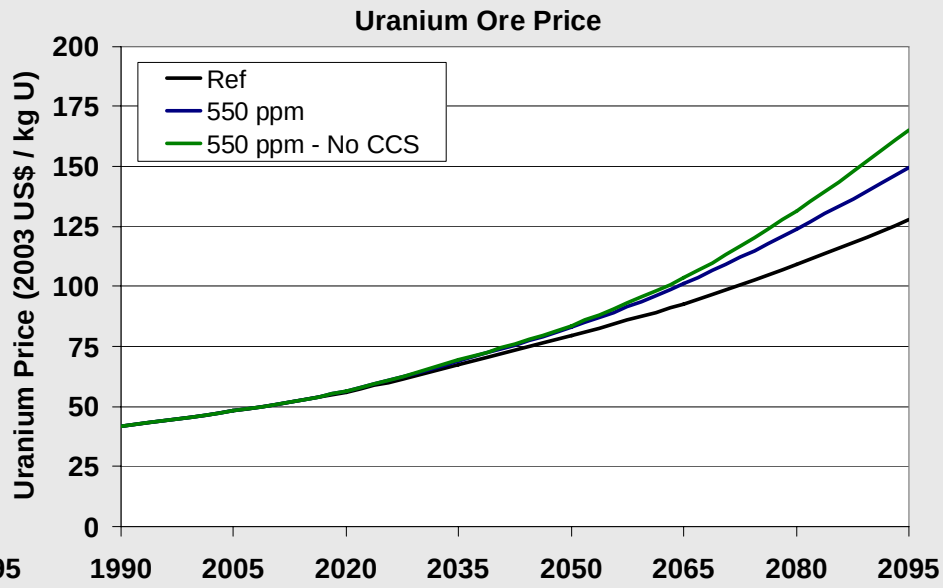




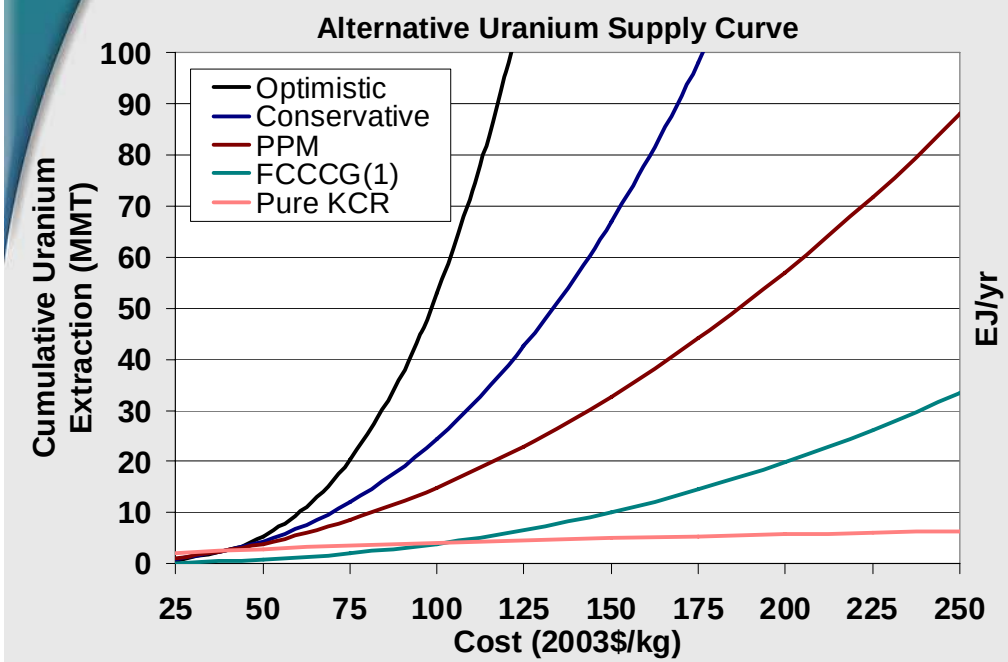
Annex 1: OECD (less Korea & Mexico), Former Soviet Union & Eastern Europe
Non-Annex I: Rest of the World

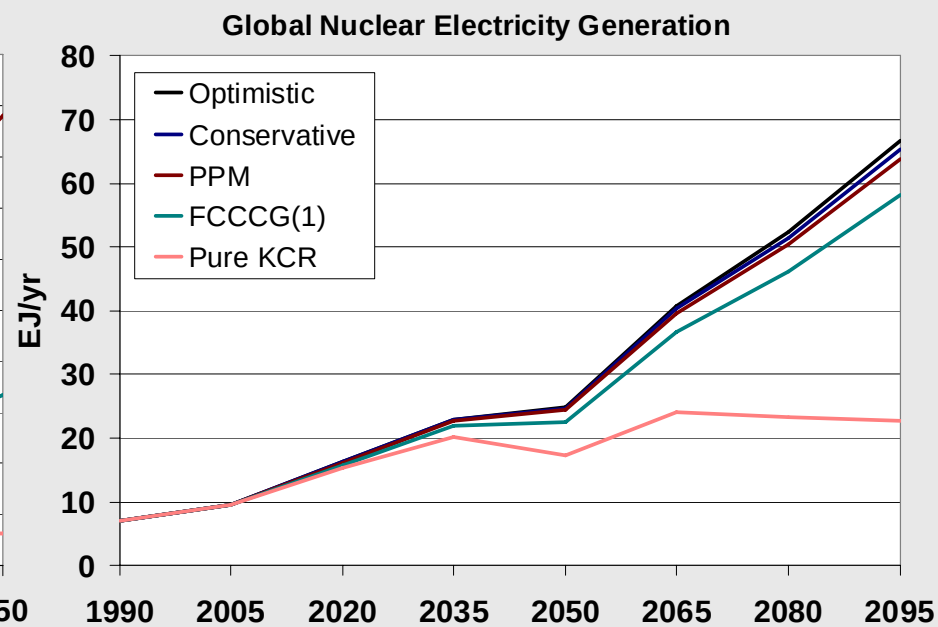
Availability of Natural Uranium Resource





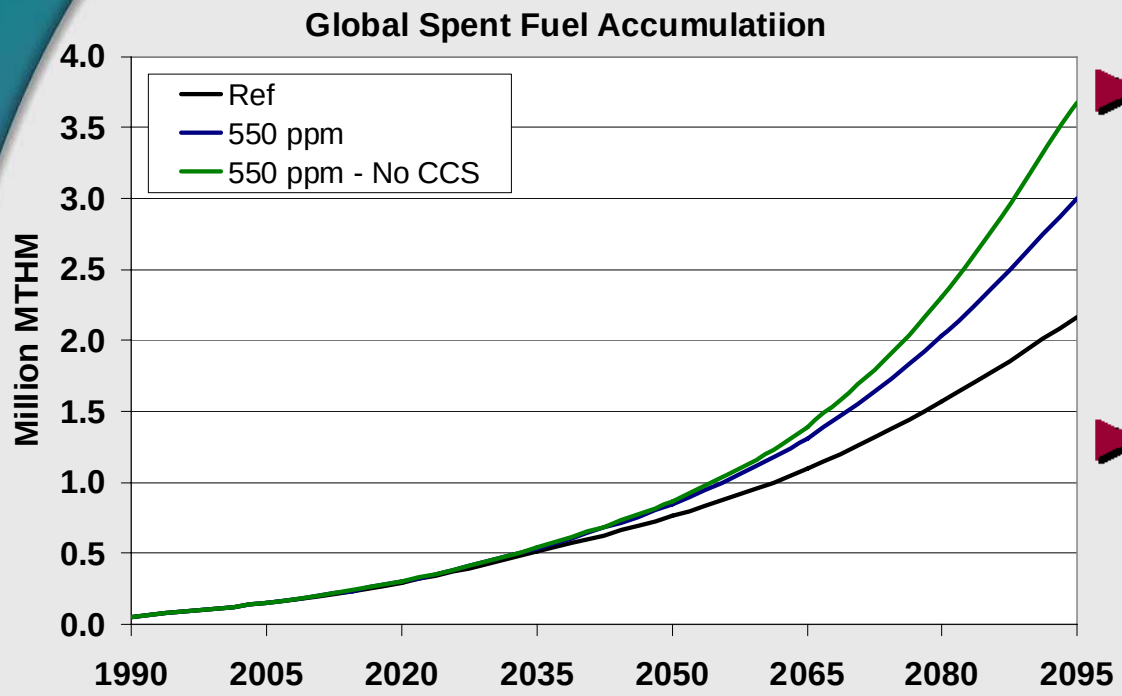
Global Nuclear Electricity Generation Alternative Uranium Supply Curves





(Schneider and Sailor 2008. "Long Term Uranium Supply Estimates.")

Global Spent Fuel Accumulation (Once-thru Fuel Cycle)



- 31 – 53 Yucca Mtns. Globally (each repository at 70,000 tons legislated capacity)
- 4 – 7 Yucca Mtns. Globally (each repository at 570,000* tons maximum physical capacity)

* EPRI 2006

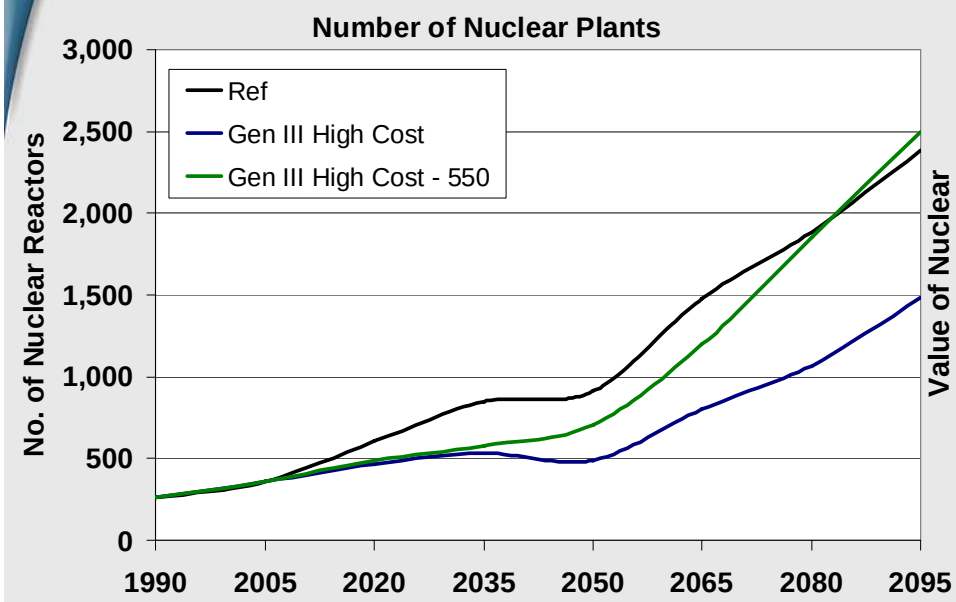
High Nuclear Cost Case

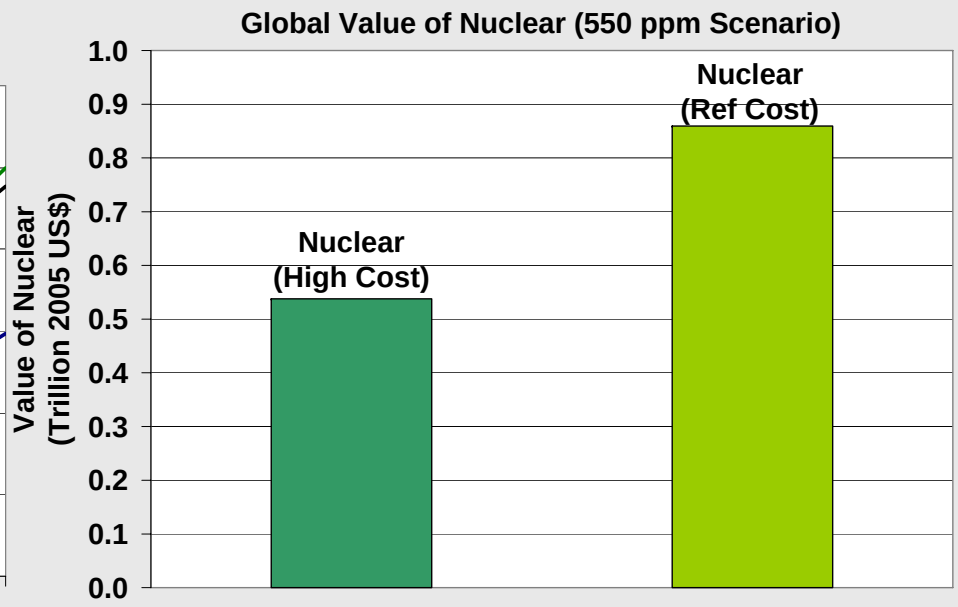
Nuclear Capital Costs

2020: 3,000 $/KWe

2095: 2,300 $/KWe

- Nuclear power continues to have significant value under high cost case.





Conclusions

- **Nuclear energy has the potential to compete aggressively in the power market to provide for a growing worldwide demand while helping to manage the cost of addressing climate change.**
- **The value of maintaining a nuclear option to address climate change is denominated in Trillions of dollars (US).**
  - The tighter the climate constraint, the higher the value of nuclear power (550 ppm: 1.3 tril$, 450 ppm: 9.8 tril$).
  - Nuclear's value is greater with fewer carbon free technology options. CCS is an important competing technology (550 ppm w/ CCS: 0.9 tril$, 550 ppm w/o CCS: 1.3 tril$).
- **The response to climate change could precipitate a rapid and large scale global deployment of nuclear power.**
  - 2,500 to 6,000 reactors could potentially be deployed by the end of the century depending on the climate constraint and technology competition.
  - Nuclear power becomes increasingly a global and ever more widely distributed technology under climate change.
  - Significant increases in the consumption of natural uranium and production of nuclear waste are expected.

GTSP
Global Energy Technology Strategy Program

Comparison of Life-Cycle Emissions

Tons of Carbon Dioxide Equivalent per Gigawatt-Hour

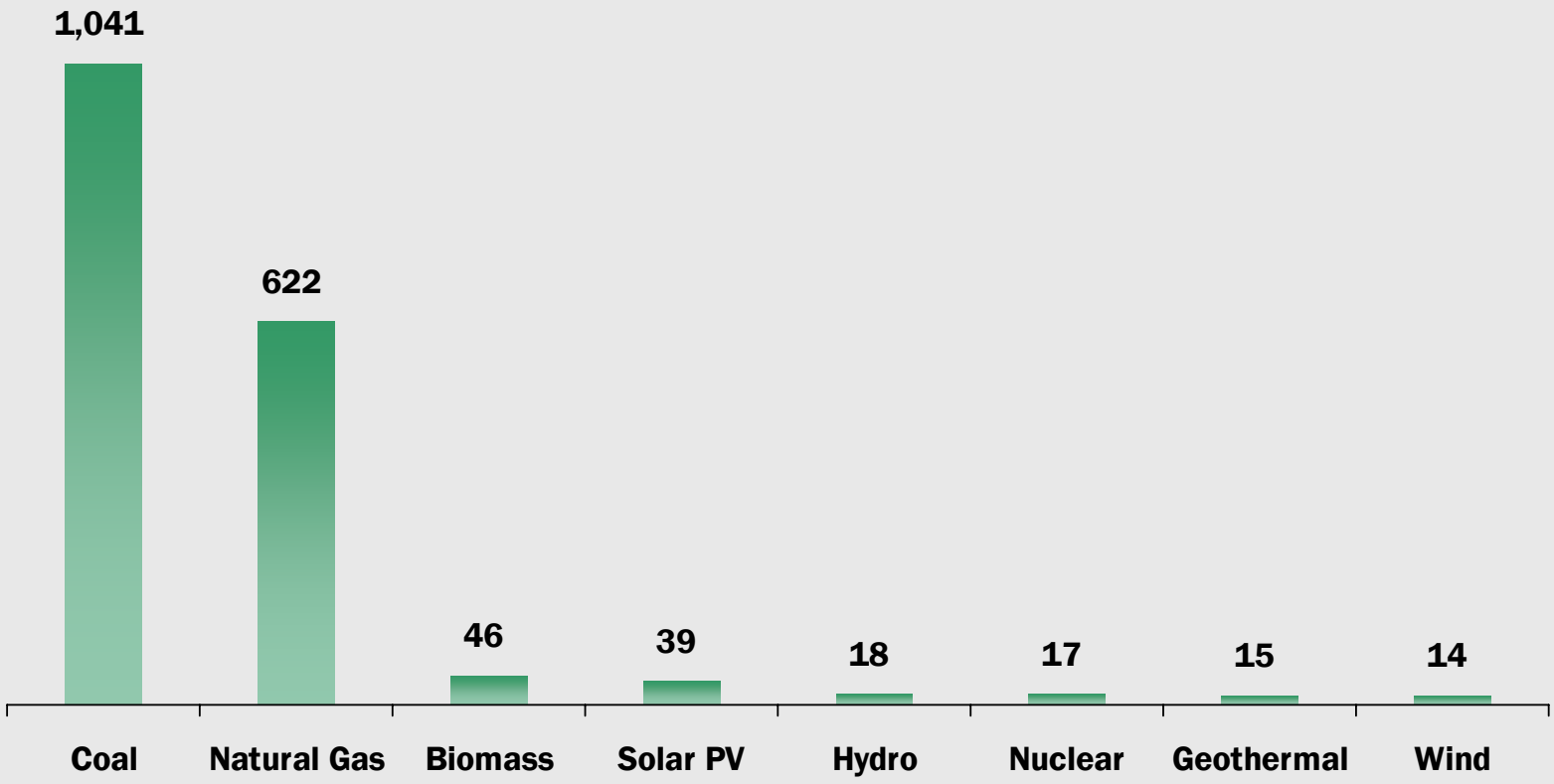


Figure from Nuclear Energy Institute (NEI)
Source: "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis," Paul J. Meier, University of Wisconsin-Madison, August 2002.

Energy Technology Cost Assumptions

Technology	2020	2050	2095
Electricity Cost (2000$/MWhr)			
*Solar	141	97	71
*Wind: Modeled as supply curves of regional on-shore and off-shore resources.			
Capital & O&M Costs (2000$/MWhr)			
Pulverized Coal	31	30	29
Coal (IGCC)	33	31	29
Gas Turbine	18	17	17
Gas (CC)	14	13	12
Oil Turbine	18	17	17
Oil (IGCC)	30	28	26
Biomass	14	14	13
Biomass (IGCC)	15	14	14
Efficiency			
Pulverized Coal	0.41	0.42	0.44
Coal (IGCC)	0.49	0.5	0.5
Gas Turbine	0.4	0.41	0.43
Gas (CC)	0.57	0.65	0.7
Oil Turbine	0.4	0.41	0.43
Oil (IGCC)	0.49	0.5	0.5
Biomass	0.4	0.41	0.43
Biomass (IGCC)	0.48	0.49	0.49

*Reserve capacity and ancillary power are required for intermittent power technologies. Costs for solar electricity do not include these costs.

CO_2 Capture and Storage Technology Cost Assumptions

Technology	2020	2050	2095
Carbon Capture Energy Requirement by Fuel (kWh/kgC)			
Coal	0.63	0.49	0.49
Gas	1.23	1.09	1.09
Oil	0.89	0.79	0.79
Additional Non-energy Cost for Carbon Capture (2000$/kgC)			
Coal	0.03	0.028	0.028
Gas	0.083	0.078	0.078
Oil	0.06	0.056	0.056