Uranium and Nuclear Power: The Role of Exploration Information in Framing Public Policy

Charles F. Mason

H.A. True Chair in Petroleum and Natural Gas Economics
Department of Economics & Finance
University of Wyoming
Laramie, Wyoming

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The Beginning of the End?

- on 11 March 2011 Fukushima Daiichi in Japan suffers reactor meltdown
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  - Japanese government orders shutdown of all nuclear reactors
  - similar decisions by German and Swiss governments
- “beginning of the end” for Nuclear power?
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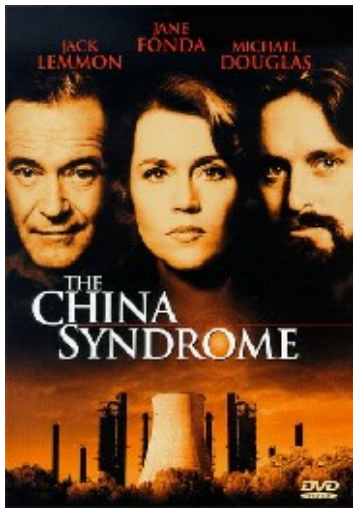
  - strong price incentives
  - extensive road building by AEC
- solid expansion of uranium industry
- transition in mid-1960s, when nuclear power industry took root
- strong growth in uranium market followed
- until March 1979

Two incidents in March 1979



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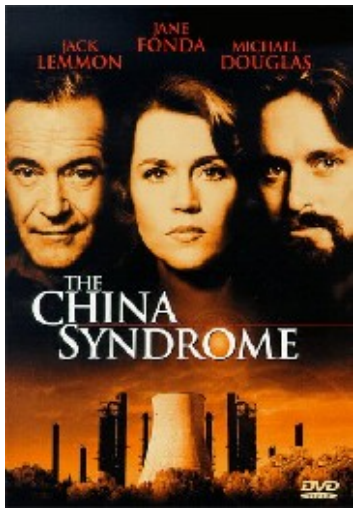

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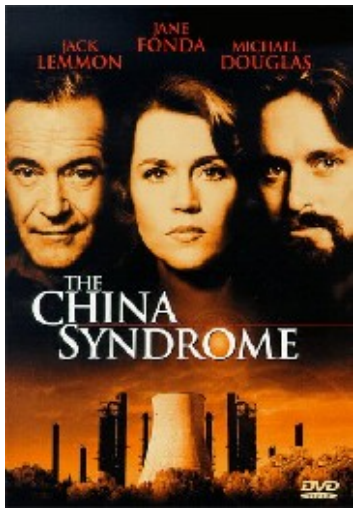

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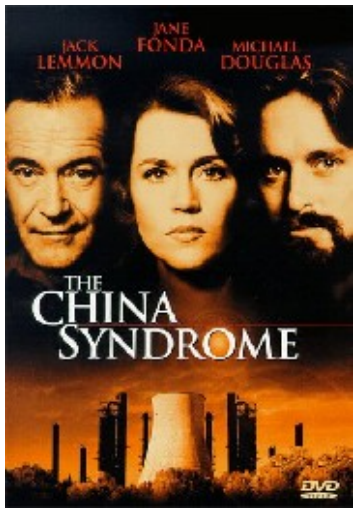

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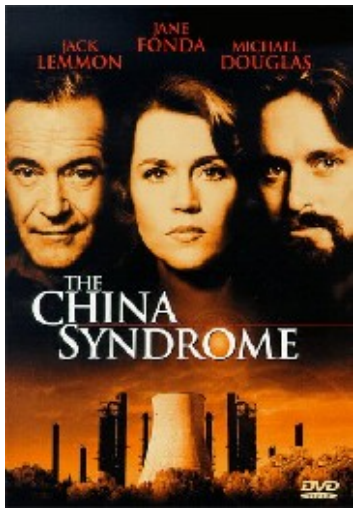

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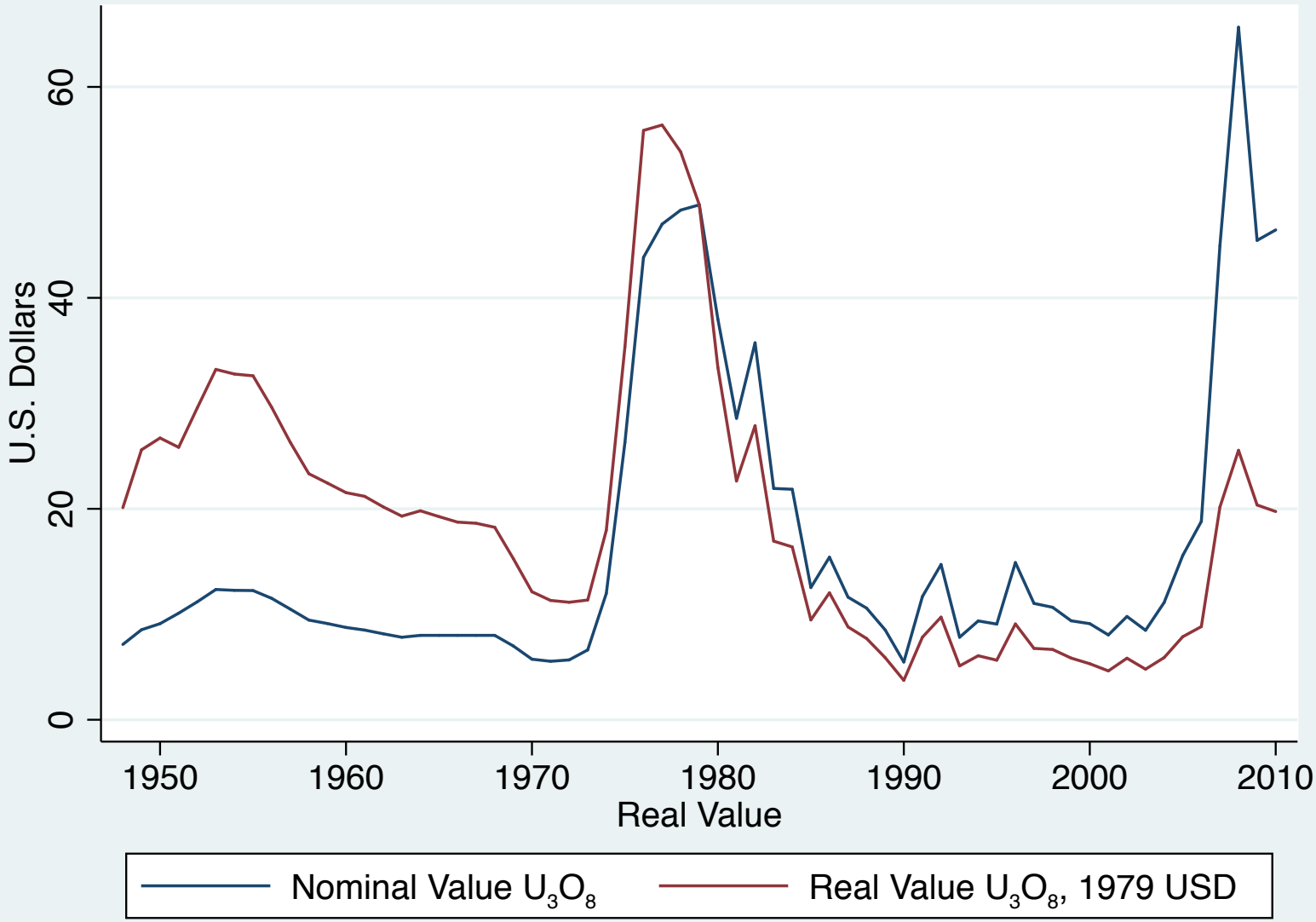
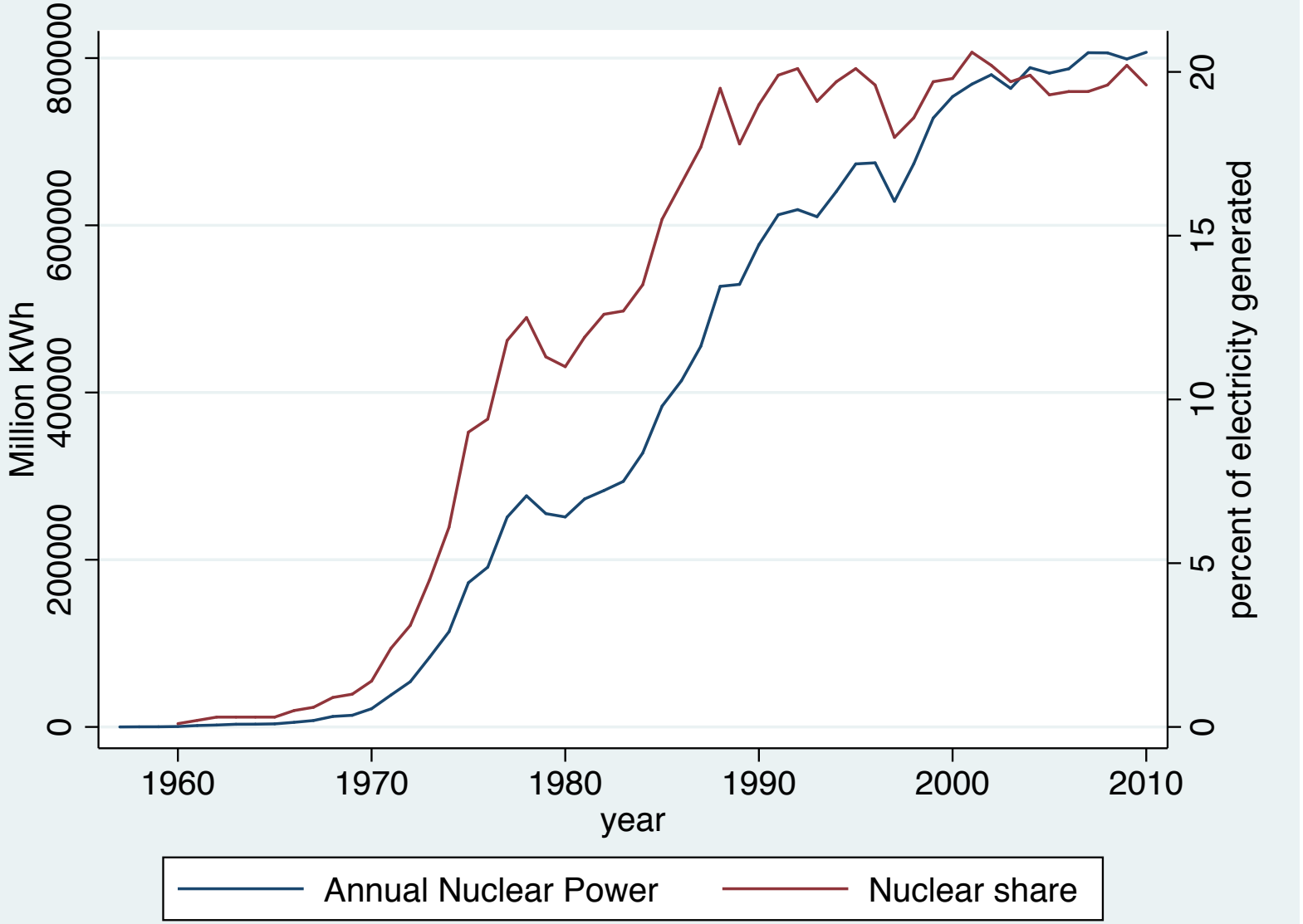
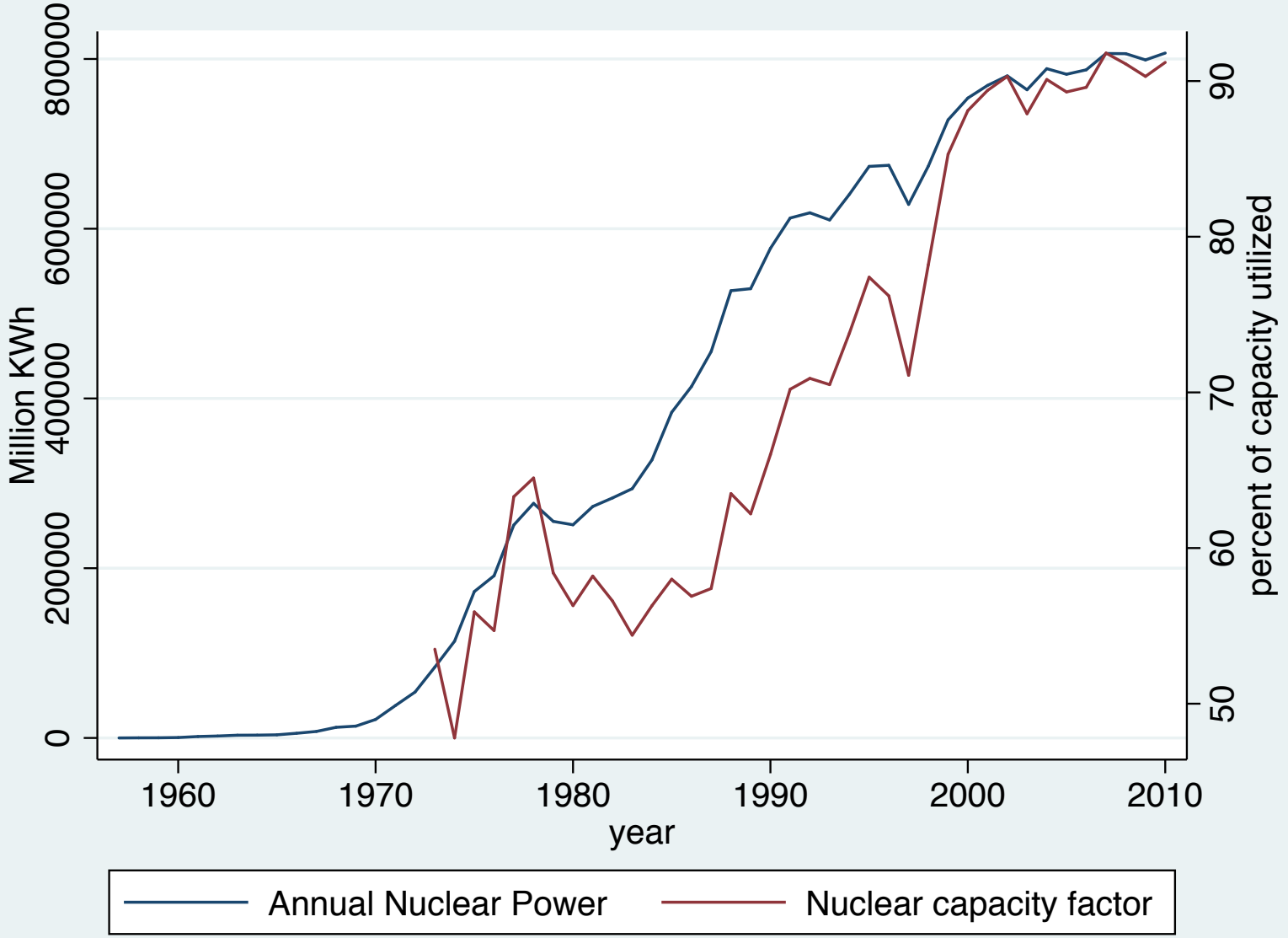
Time path: price of uranium



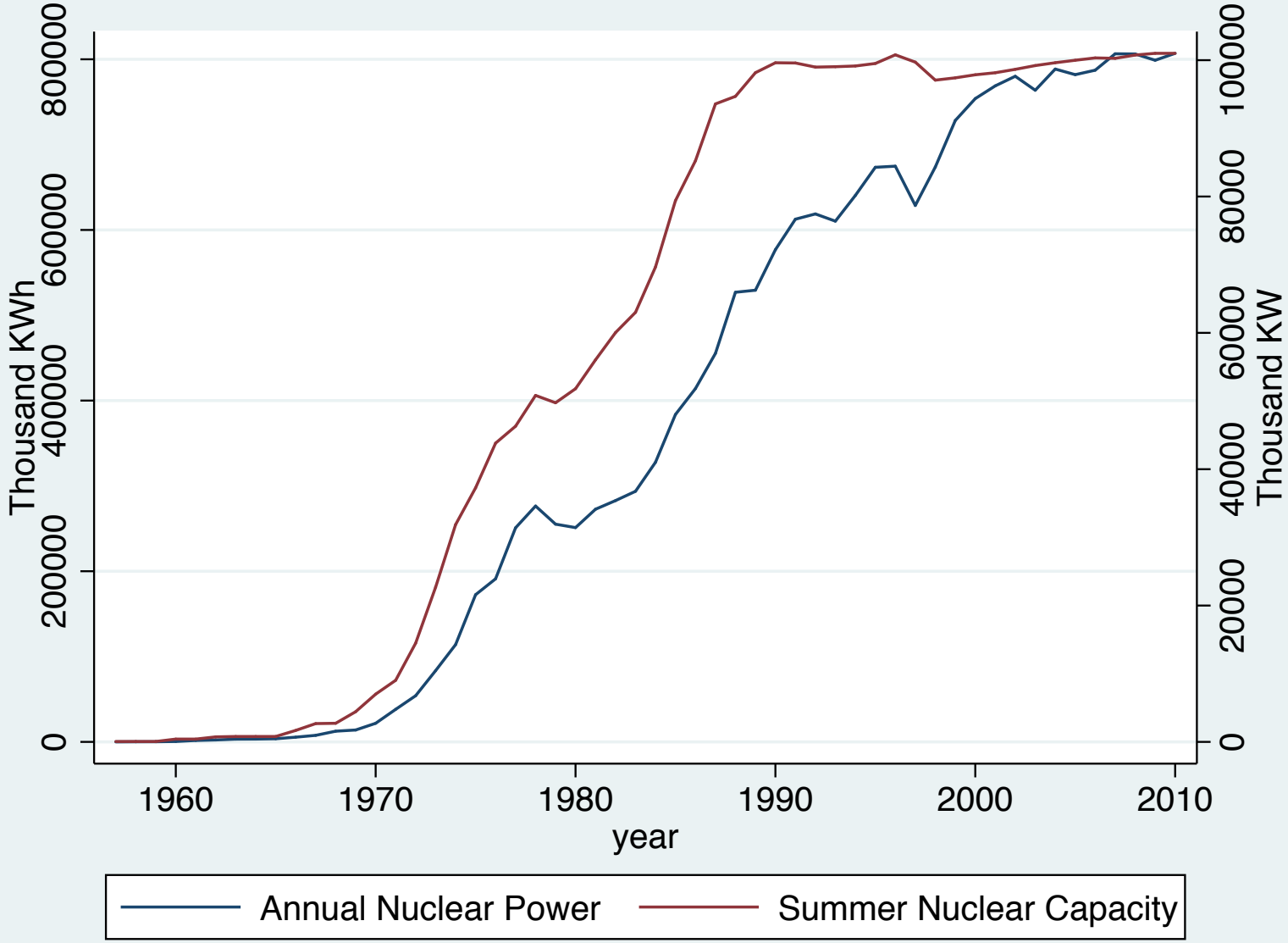
Time path: Nuclear Power



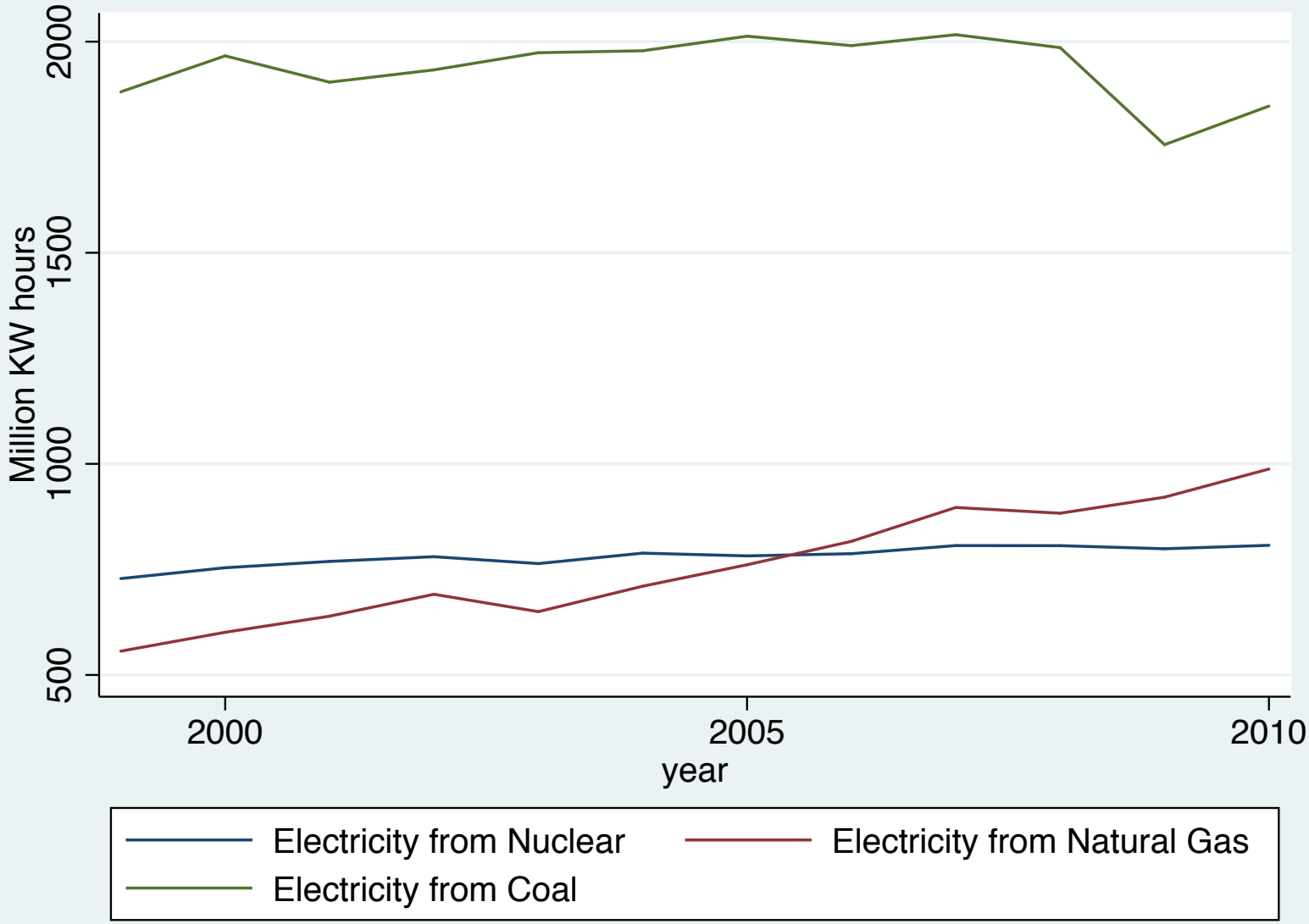
Time path: Nuclear Power, Capacity Utilization



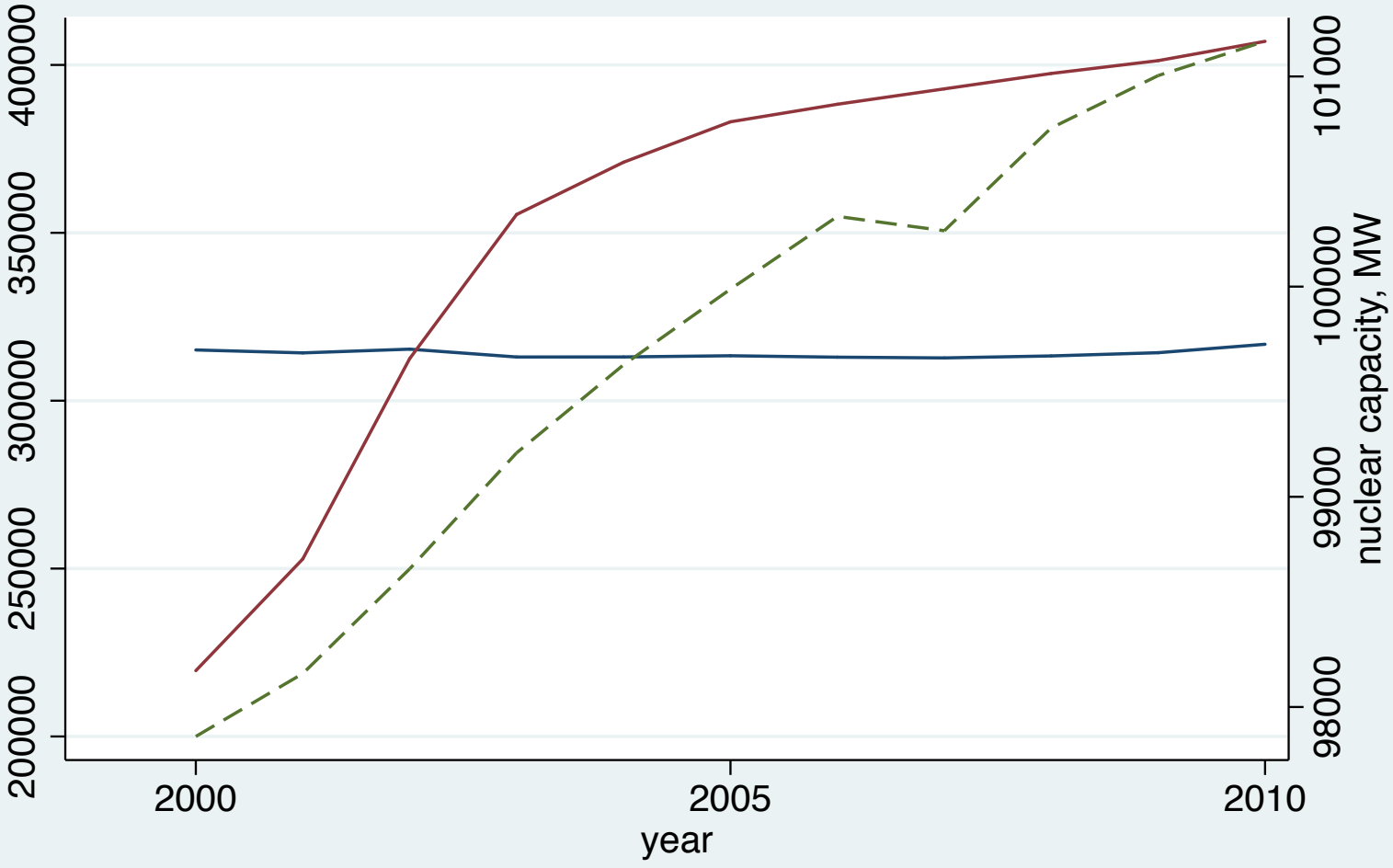
Time path: Nuclear Power, Summer Capacity



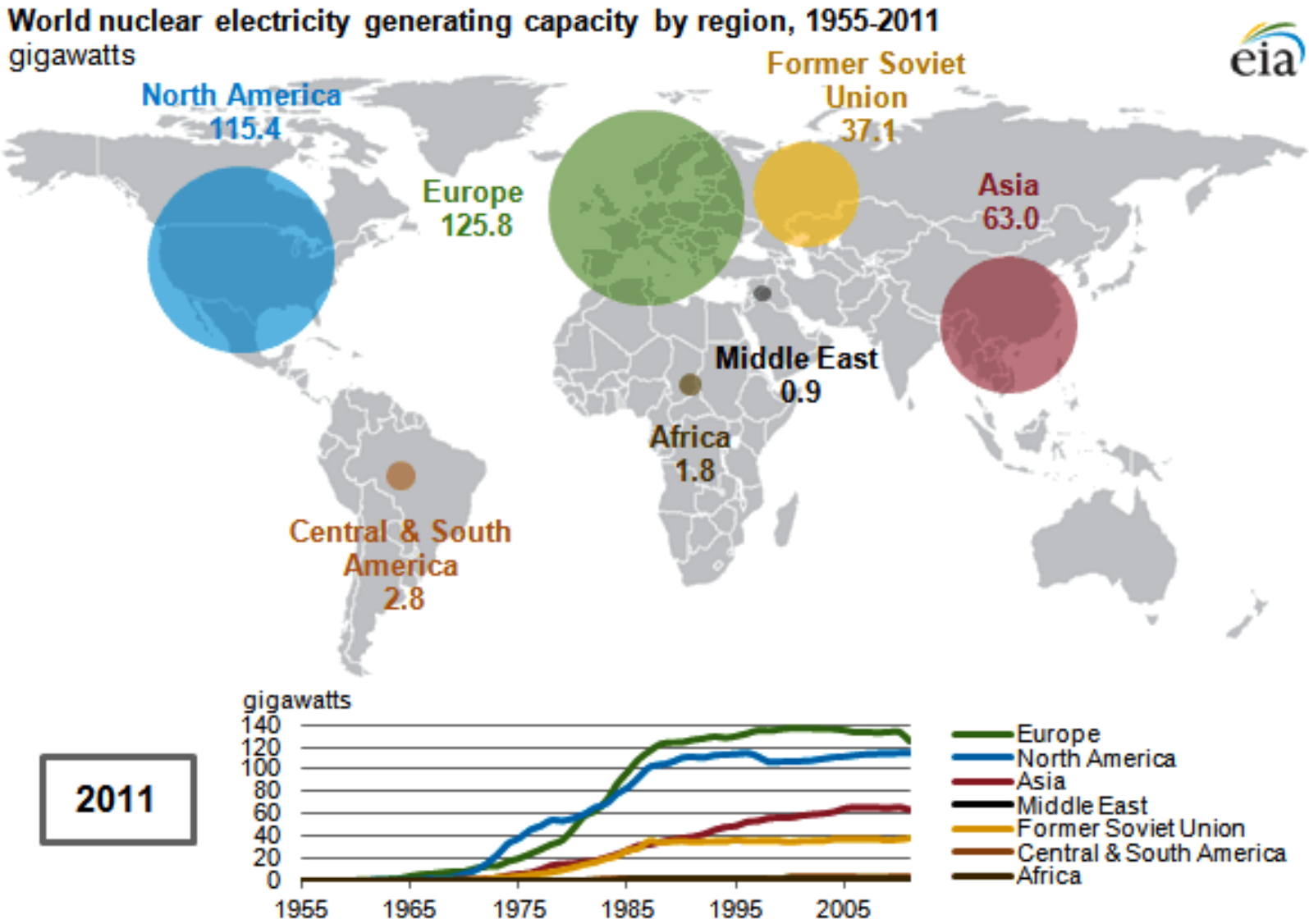
Time path: Electricity Production, Various Fuels



Time path: Various Fuels, Summer Power Capacity



Nuclear Power: Global Role



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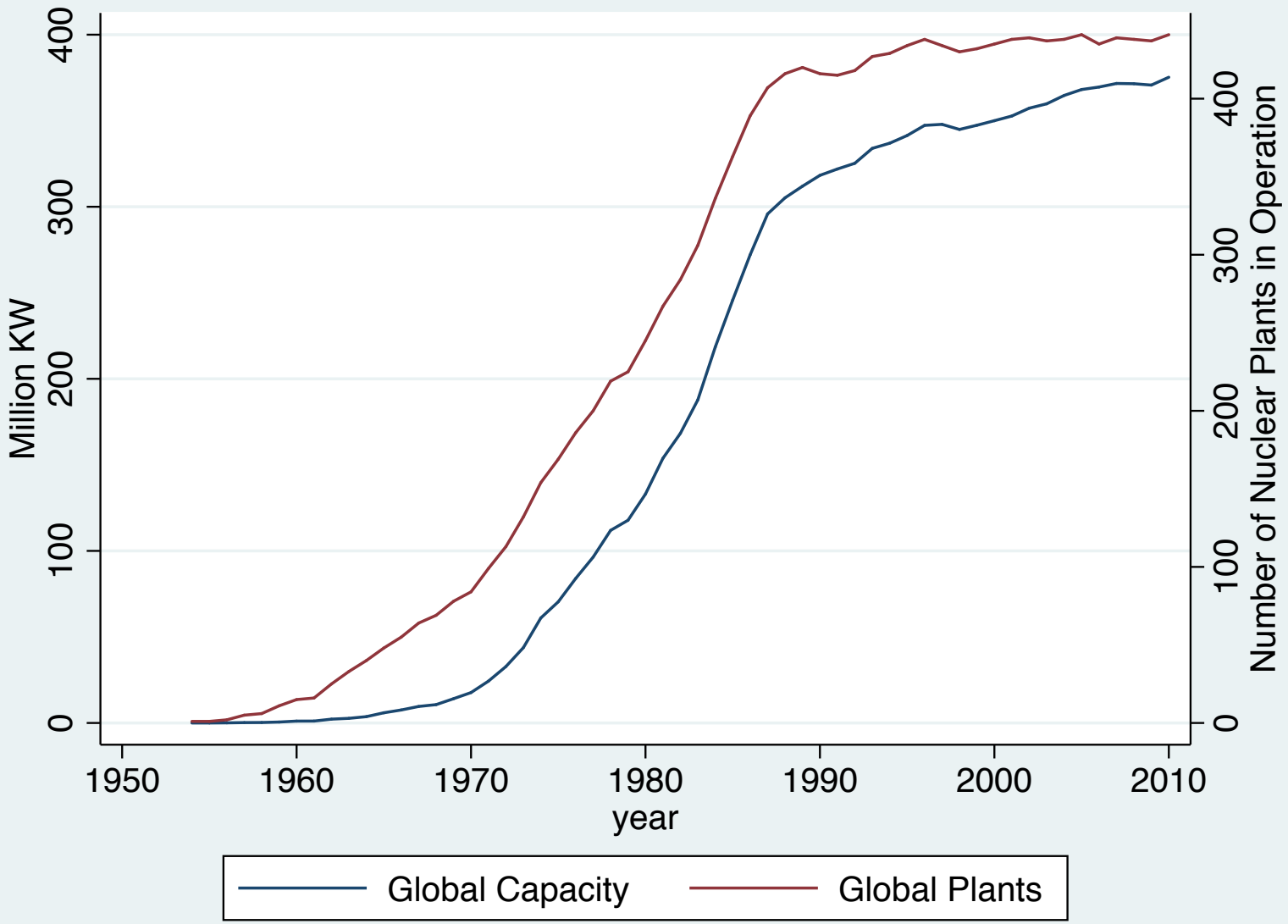
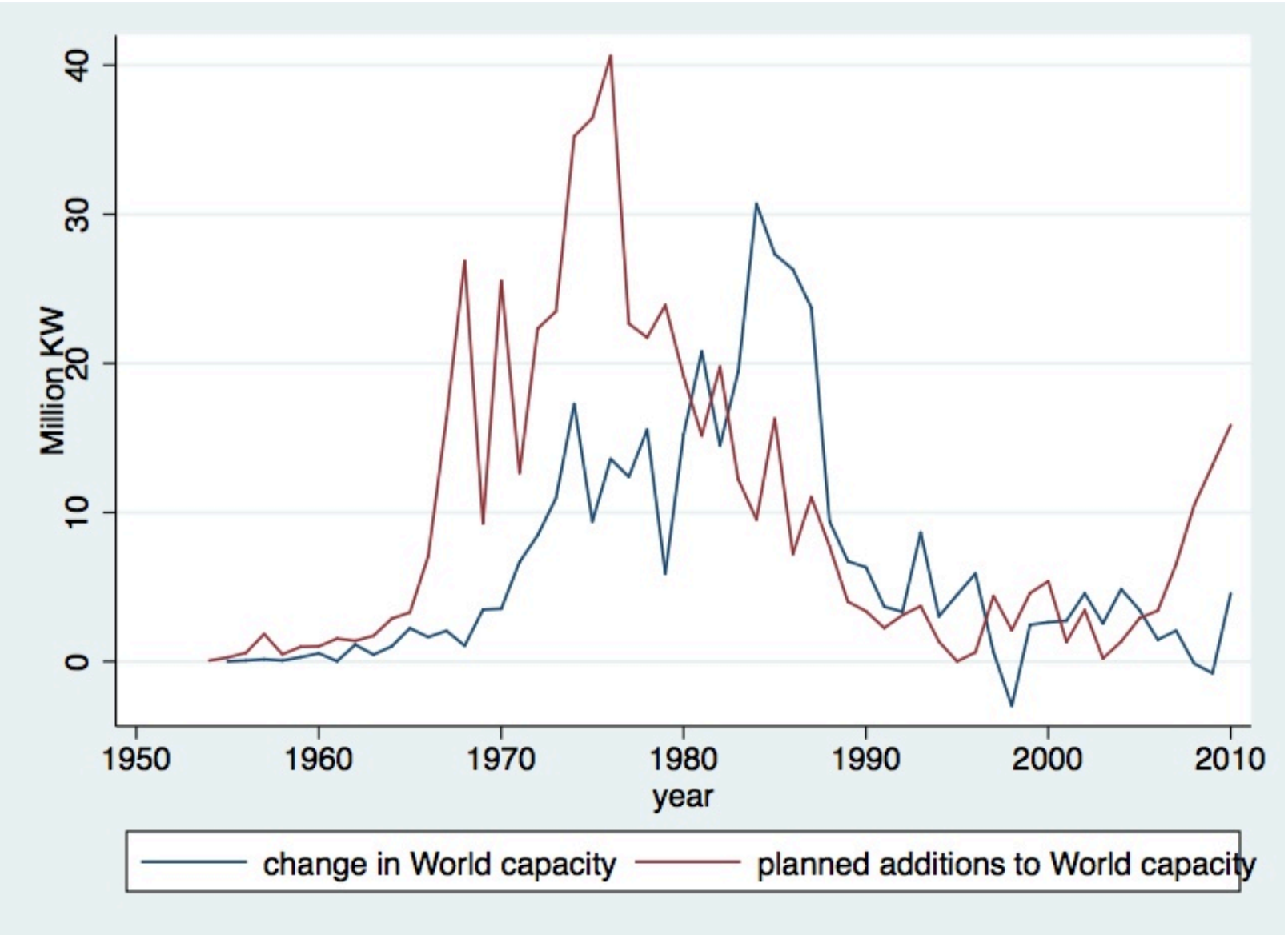
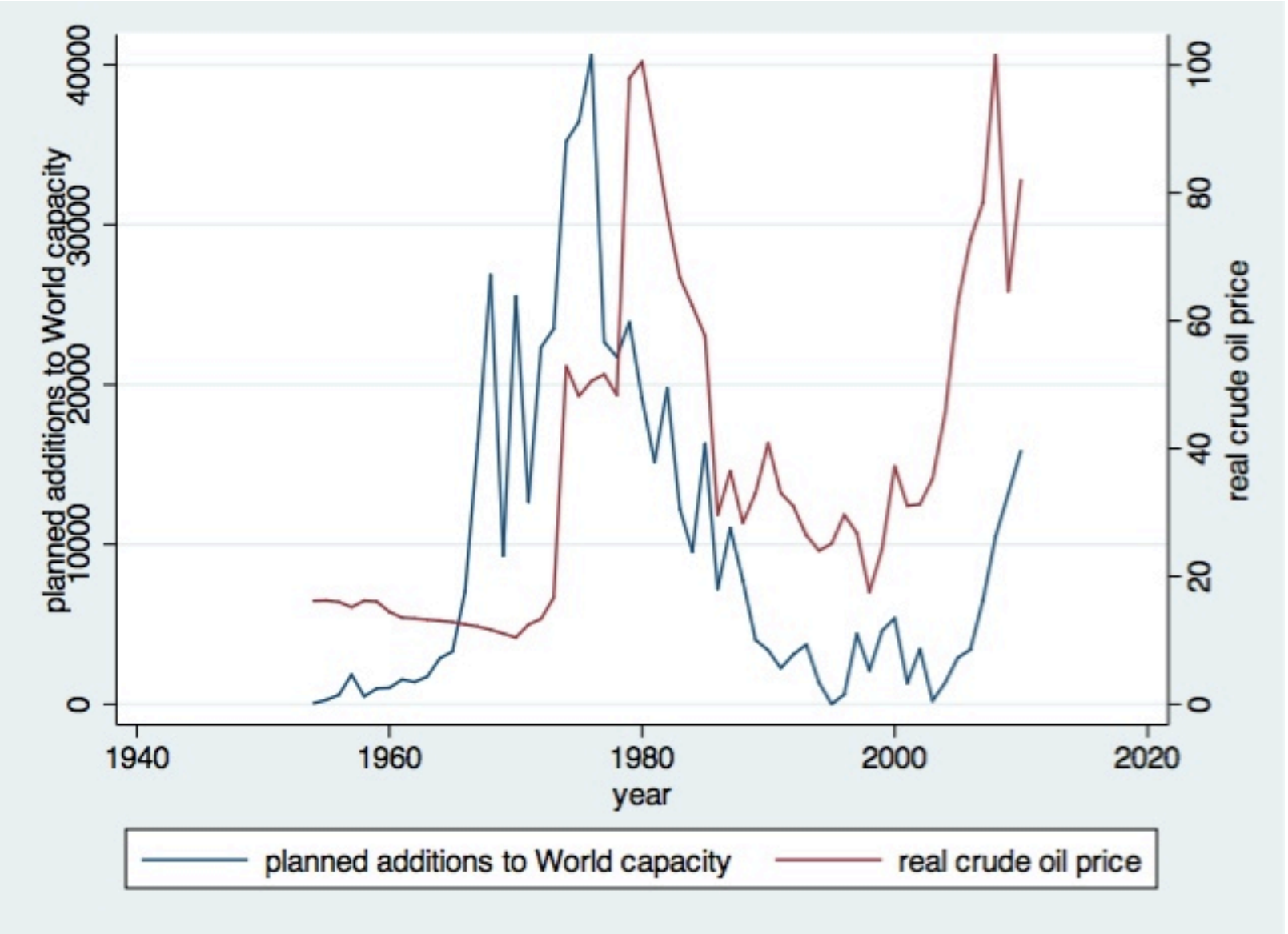


Nuclear Power: Historical Global Expansion



Why Nuclear Expansion?



Assumptions

- several identical resource-extracting firms
- initial stock R_0, which can be added to via exploration
  - $R_{t+1} = R_t - y_t + x_t\theta_t$
  - new finds are $x\theta$
    - x is rate of exploration
    - θ is 'find rate': amount found per unit drilled
  - assume θ is a log-normally distributed, subject to deterministic effect linked to cumulative exploration, X
    - $\theta = f(X)e^{\eta}$
    - η is Normal with *unknown* mean μ, precision ρ
    - beliefs over (μ, ρ) summarized by so-called Normal-Gamma distribution
    - beliefs updated based on exploratory results, posterior distribution also Normal-Gamma
  - integrate out uncertainty over (μ, ρ) to get $g(\eta; I)$
    - generalized student's t-distribution
    - agent effectively uses this distribution over η

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- which induces a change in parameters of $g(\eta; I)$ ...
- which yields a value that depends on the agent's objective function, Ω, $F(\Omega)$:

$$F(\Omega_t) = \int \int \Omega_t g(\eta_t; I_t) \frac{\partial g(\eta_{t+1}; I_{t+1})}{\partial x_t} \mathrm{d}\eta_t \, \mathrm{d}\eta_{t+1}$$

Optimal behavior

- privately optimal rate of extraction sets current rents equal to discounted future expected rents
- expectation depends on current beliefs
- but also manifest anticipated extraction next period
  - if current exploration rises, this increases expected finds, which in turn motivates larger production today
  - so current explor'n influences current prod'n (indirectly)
- privately optimal exploration balances current marginal exploration cost against future expected benefits
  - value of expected finds
  - (negative?) impact of current exploration on future find rate, which will adversely impact payoffs two periods hence
  - expected value of information
    - current exploration yields inform'n, changes future beliefs
    - this is true for other firms as well
    - possibility of public good aspect to information
    - also possibility of using information for speculative purposes

Optimality conditions

private optimality conditions:

$$P_t - C'(y_t^*) = \delta\Big\{P_{t+1} - E_1[C'(y_{t+1}^*)]\Big\};$$

$$C^{e\prime}(x_t^*) = \delta\Big\{E_1\Big[\theta_t\Big(P_{t+1} - C'(y_{t+1}^*)\Big)\Big]\Big\} +$$

$$\delta^2\Big\{E_2\Big[\Big(P_{t+2} - C'(y_{t+2}^*)\Big)x_{t+1}^* f'(X_t)e^{\eta_{t+1}}\Big] + F(\Pi_{t+2})\Big\}$$

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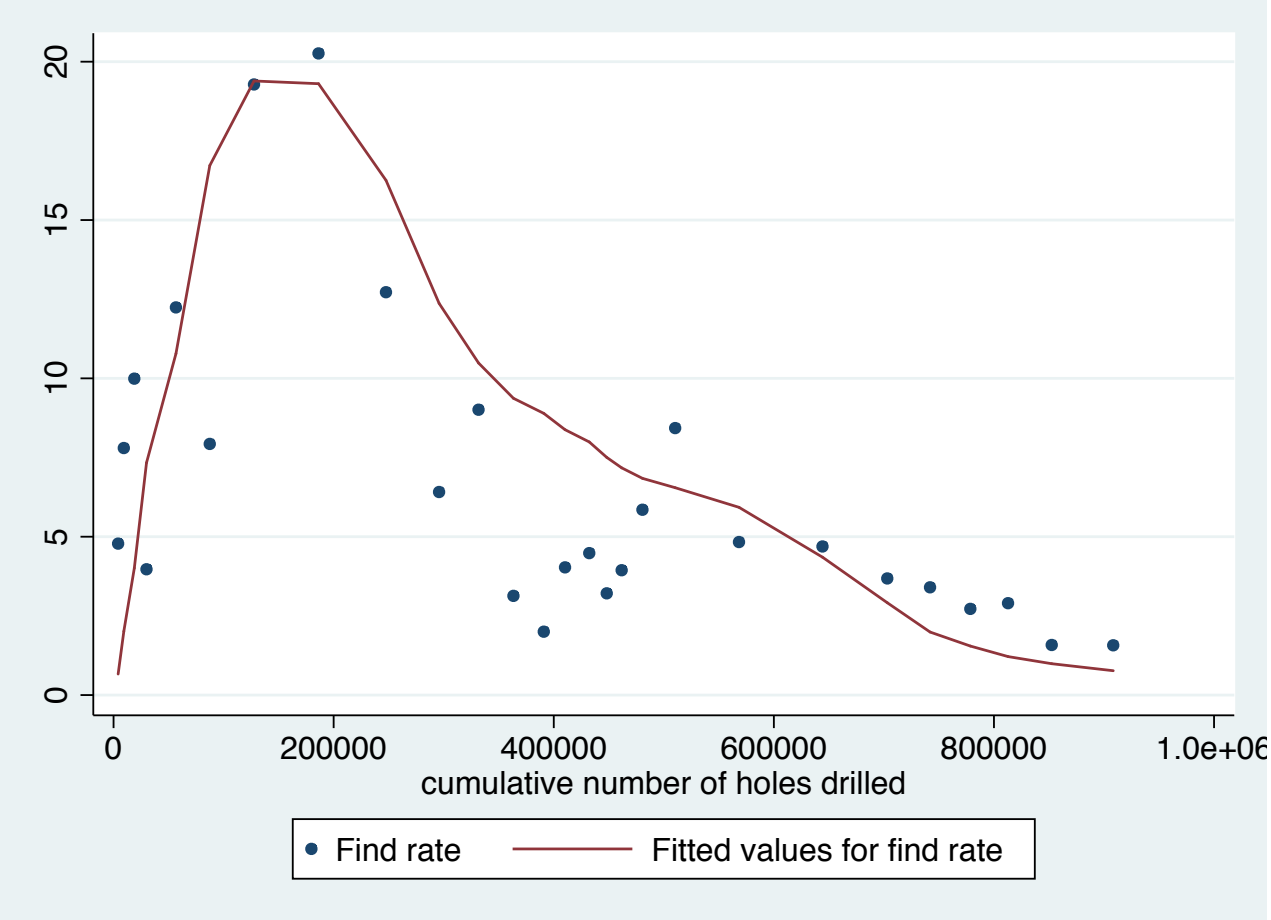
- structure of FOC similar for private, social concerns
- in particular, if industry chooses socially optimal exploration then socially optimal production follows
- but there are reasons exploration is not socially optimal
  - public good vs. speculation
  - fundamental issue: can the firm conceal its exploratory results?
  - nature of mining operations suggests difficulty in spying on other firms
    - contrast to oil exploration
  - $x_t^* \neq x_t^{**}$ if $F(\Pi_{t+2}) \neq F(W_{t+2})$
  - if $W = CS + \Pi$ then inefficient exploration if $F(CS_{t+2}) \neq 0$
  - to evaluate need estimates of production, exploration costs; learning model; demand

Impact of cumulative exploration



$$f(X) = X^{.2651} e^{-.5425-.00000295X}$$

Learning

year	No. Holes	ave. depth	mean	variance
1948	1133	—		
1949	2400	—	-0.6263	5.0000
1950	3800	—	0.4849	0.0033
1951	7200	—	0.0433	0.7155
1952	9080	—	-1.0625	0.3454
1953	24320	—	-0.2025	0.5057
1954	27047	—	-0.7704	0.3523
1955	35113	—	0.1686	0.1817
1956	48580	—	0.2455	0.3003
1957	49013	—	-0.0098	0.2908
1958	25321	148	-0.3928	0.2062
1959	16253	146	0.1138	0.1720
1960	7335	191	-0.8373	0.1591
1961	8256	160	-1.2492	0.1810
1962	6439	230	-0.5098	0.2108
1963	8472	104	-0.3613	0.2079
1964	5972	162	-0.6380	0.2038
1965	6231	187	-0.3942	0.2038
1966	5751	313	0.0435	0.2005
1967	12788	425	0.4482	0.1973
1968	38470	422	-0.0253	0.2011
1969	47850	428	0.2105	0.1936
1970	43980	409	0.3068	0.1857
1971	28416	401	0.5448	0.1820
1972	26909	439	0.5217	0.1973
1973	22557	480	0.7814	0.2023
1974	27400	584	0.3324	0.2220
1975	34285	482	0.5334	0.2159

Demand

Table 2.2: AEC Involvement in the U.S. Uranium Industry

year	price per lb. U_3O_8	AEC purchases, % of output
1948	7.14	100
1949	8.53	100
1950	9.11	100
1951	10.10	100
1952	11.28	100
1953	12.35	100
1954	12.27	100
1955	12.25	100
1956	11.51	100
1957	10.59	100
1958	9.45	100
1959	9.12	100
1960	8.75	100
1961	8.50	100
1962	8.15	100
1963	7.82	100
1964	8.00	100
1965	8.00	100
1966	8.00	99
1967	8.00	83
1968	8.00	66
1969	6.99	60
1970	5.74	32
1971	5.54	20

TABLE 5

DELIVERIES OF U_3O_8 FROM DOMESTIC MILLS

	Tons U_3O_8	
	To AEC	To Commercial Buyers
1950	323	
1951	639	
1952	824	
1953	968	
1954	1,435	
1955	2,125	
1956	4,179	
1957	7,505	
1958	10,708	
1959	15,029	
1960	16,394	
1961	17,646	
1962	17,244	
1963	15,752	
1964	12,607	
1965	11,240	
1966	10,178	
1967	8,902	900
1968	7,937	4,800
1969	7,124	4,200
1970	4,010	9,300
1971	1,295	12,700
1972	—	11,600
1973	—	12,100
1974	—	11,900
1975	—	12,500

Uranium demand during AEC epoch

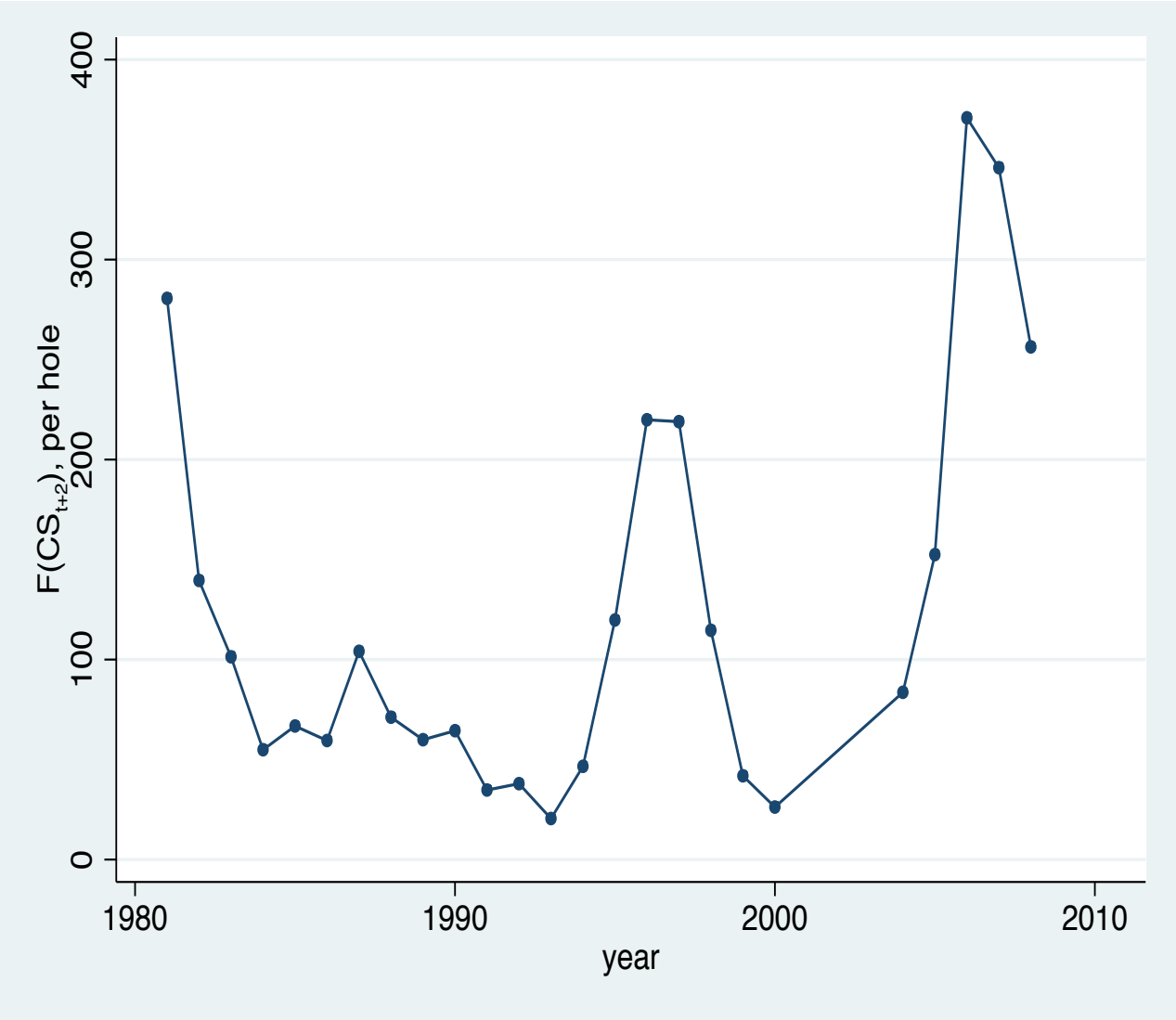
- prior to 1967 AEC only (legal) purchaser of U_3O_8
- primary motive for purchase: defense
- goal: maximize PDV of W (s.t. industry FOC)
- implies maximization of PDV of CS (s.t. industry FOC)
- if so, then observed pattern of prices, production and exploration would be consistent with
  - Industry FOC on exploration
  - industryFOC on production
  - $F(CS) = 0$
- previous results indicate $F(CS) < 0$ during AEC epoch

Uranium demand after AEC

- private market emerges; prices determined by S & D
- different demand function from first epoch?
- primary purchase motive is electricity production
  - important role for competing input resources
  - proxy: crude oil price
- important and growing role for international supplies
  - likely limited market power for domestic producers
  - reserves key in determining production costs

Demand			Supply		
regressor	OLS	IV	regressor	OLS	IV
Q_{all}	-.7575	-.8473	P_{dom}	.0837	.2999
	(.2293)	(.4022)		(.1579)	(.2040)
P_{crude}	.4729	.4878	R_{50}	.0476	.0696
	(.0834)	(.1047)		(. 0251)	(.0290)
constant	31.481	34.168	constant	-822.96	-1091.8
	(6.469)	(10.848)		(278.27)	(327.55)

Uranium demand after AEC, cont.



Peering Into the Future

- Coal is faltering
- Natural Gas is rising rapidly
- huge new deposits of Natural Gas apparently at hand
- what about Uranium?
  - Nuclear continues steady growth, particularly if
    - oil prices continue to rise
    - meaningful carbon policy is enacted
  - likely push towards new exploration, new development

Oil Prices

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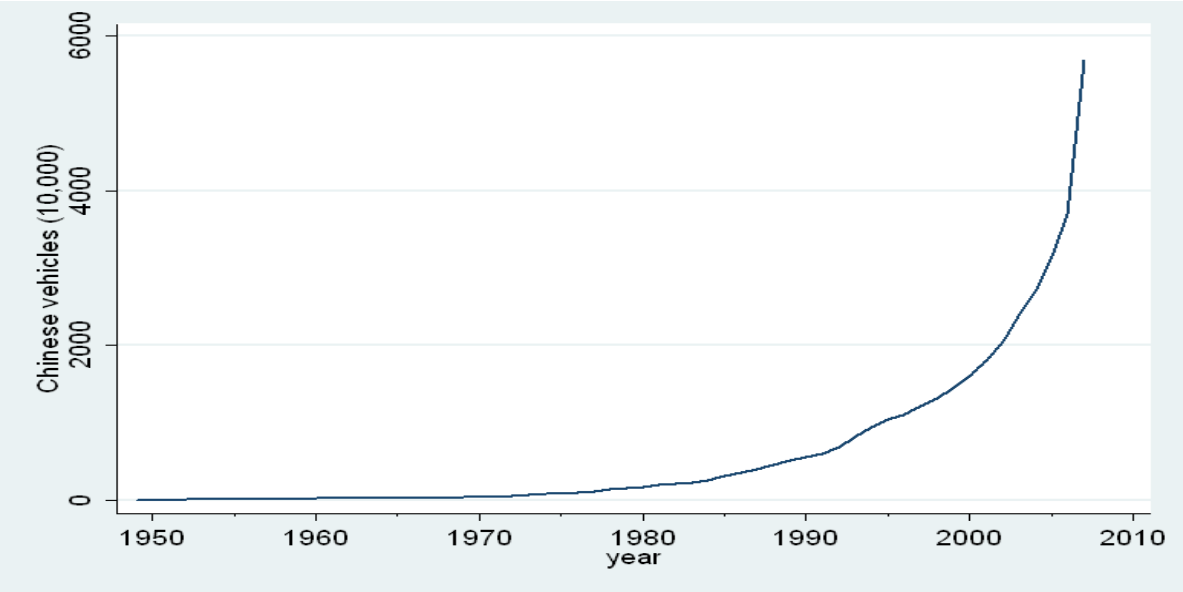
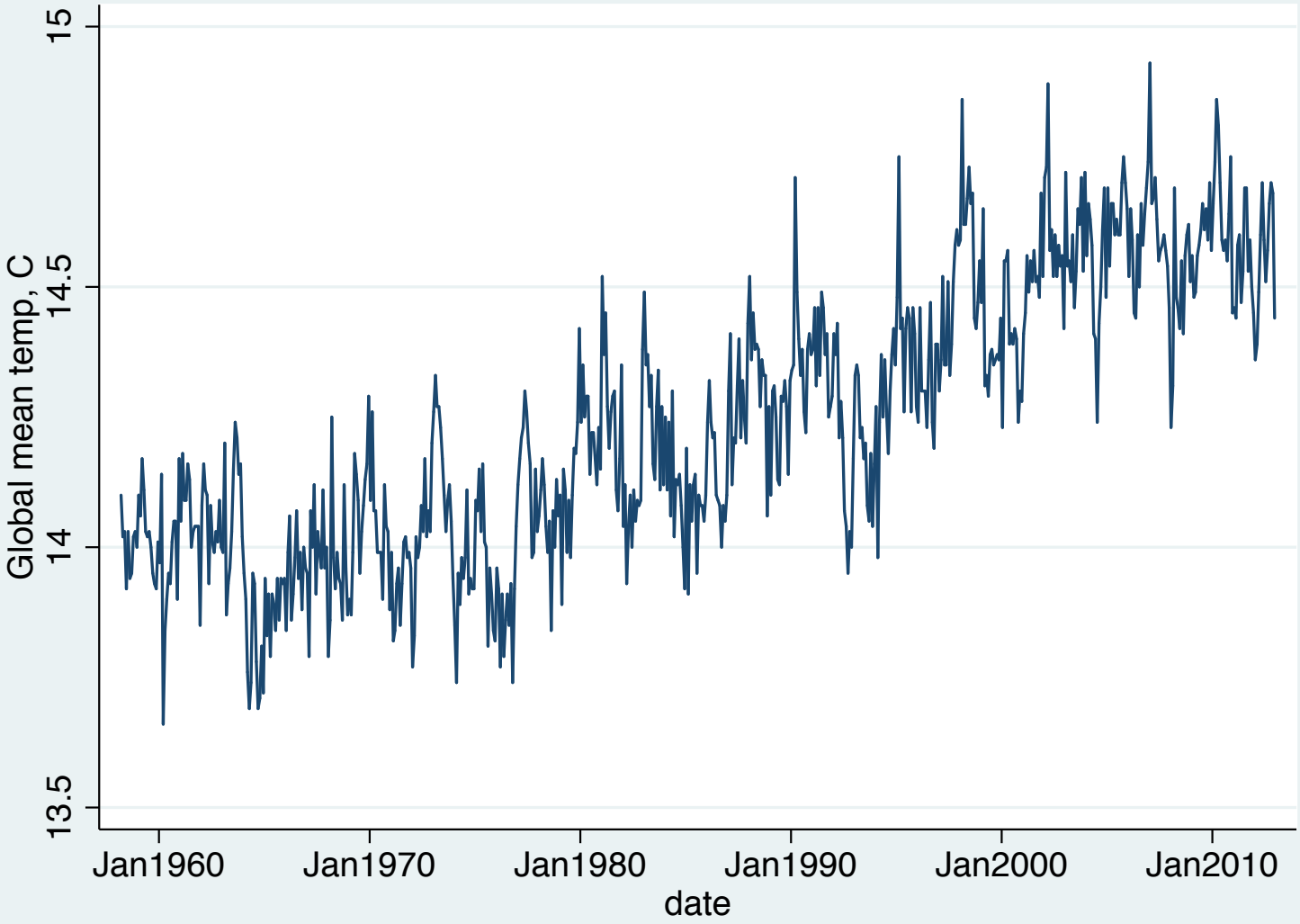
- single best predictor: size of Chinese economy



Climate Change



Carbon Policy and Nuclear Power

- 1.020 kg CO_2 per kWh for coal
- 0.515 kg CO_2 per kWh for natural gas
- plausible impact of carbon policy: pressure towards reduced use of both fuels as inputs into electricity
- then increased pressure for usage of Nuclear energy
  - In North America and Europe
  - also in FSU, BRIC countries
- induces increased demand for Uranium

What can we learn from the past experience?

- AEC epoch
  - strong price signals lead to over-exuberant exploration
  - excess exploration spills over into extraction levels, yielding social over-production
  - attendant welfare losses from over-exploration, over-production
- electricity input demand epoch
  - apparently less persuasive motive for exploration
  - now, socially insufficient exploration levels
  - attendant welfare losses from under-exploration into under-production
    - result: inefficiently large demand for substitute fuels, particularly coal
- is there a role for (international) governmental intervention?
  - will a carbon tax motivate exploration?
  - would a separate incentive do better?
    - analogy to R&D

Rift Widens Over Mining of Uranium in Virginia

New York Times (New York ed'n), 20 January 2013, page A19