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Market and economic assessment of nuclear power – focus on Canada and USA

Edward Kee

The NECG slides that follow are not a complete record of this presentation and discussion. The views expressed in these slides and the discussion of these slides may not be comprehensive and may not reflect the views of NECG's clients or the views of my colleagues.

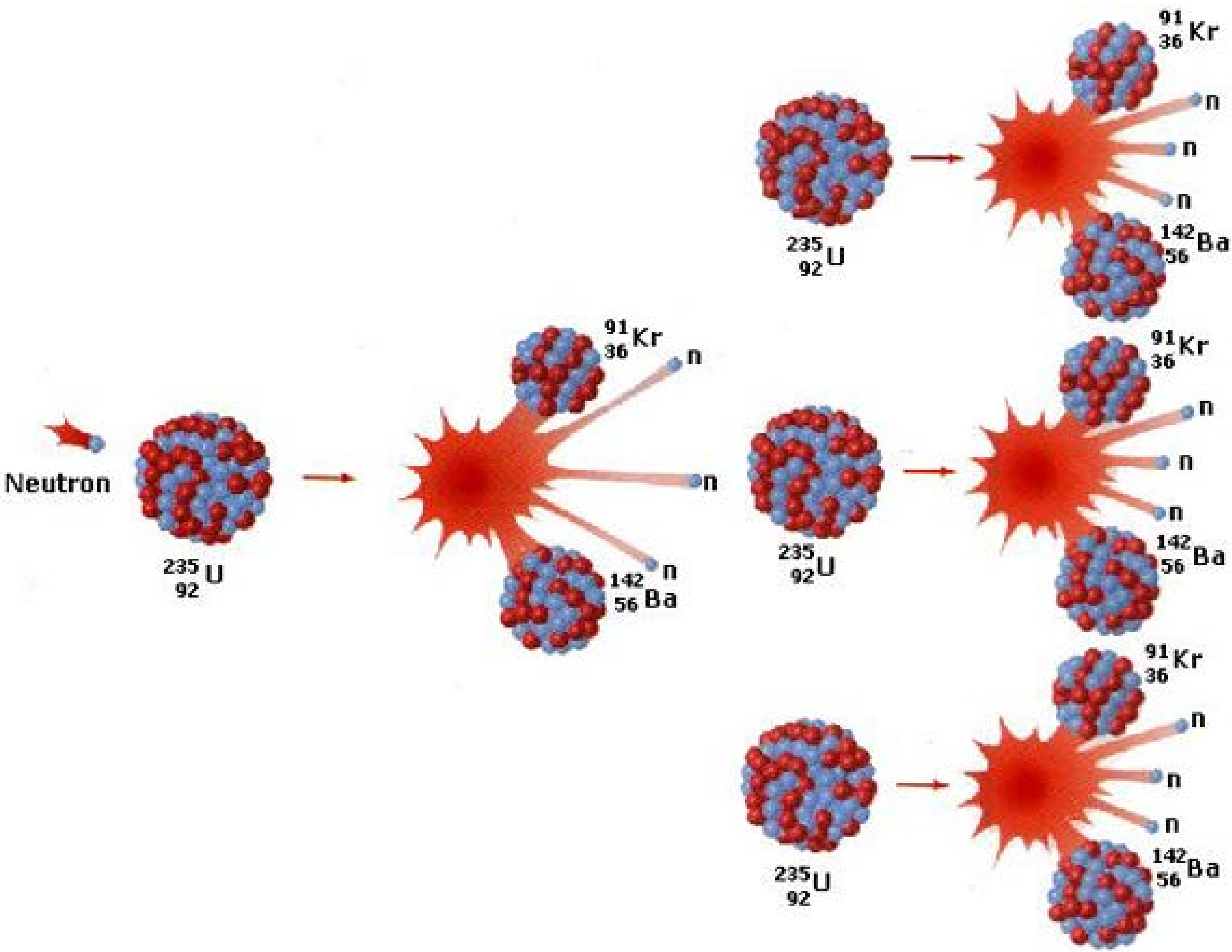
Introduction

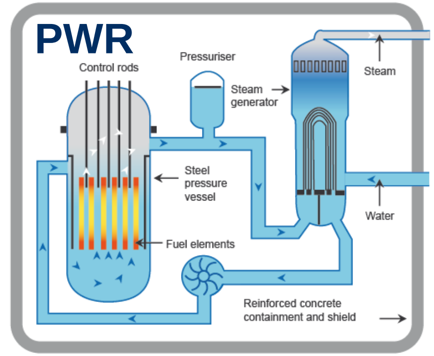
- Edward Kee
  - CEO and Principal Consultant – NECG
  - Affiliated Expert – NERA Economic Consulting
- Market and economic assessment of nuclear power
- Focus on Canada and USA

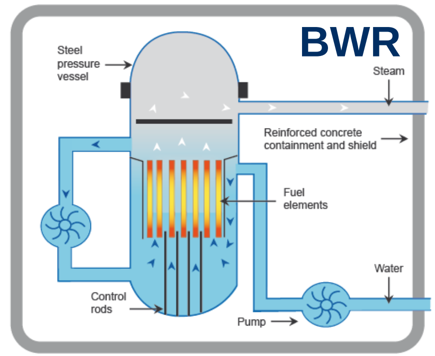
Conclusion/Summary

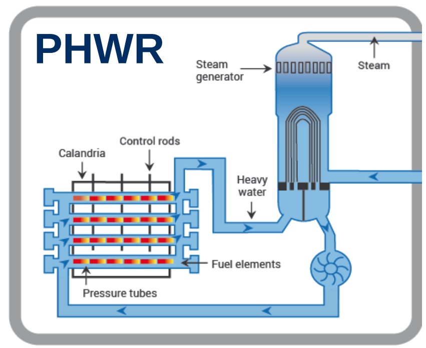
- U.S. existing nuclear power threatened
  - Private ownership and electricity markets
  - Low natural gas prices + subsidized renewables
- No new nuclear in U.S. and Canada
  - Vogtle and Summer approved a decade ago
- Loss of nuclear power will
  - Reduce nuclear industrial capability
  - Lower nonproliferation influence
  - Increase reliance on natural gas generation

How nuclear power works: *power from fission*

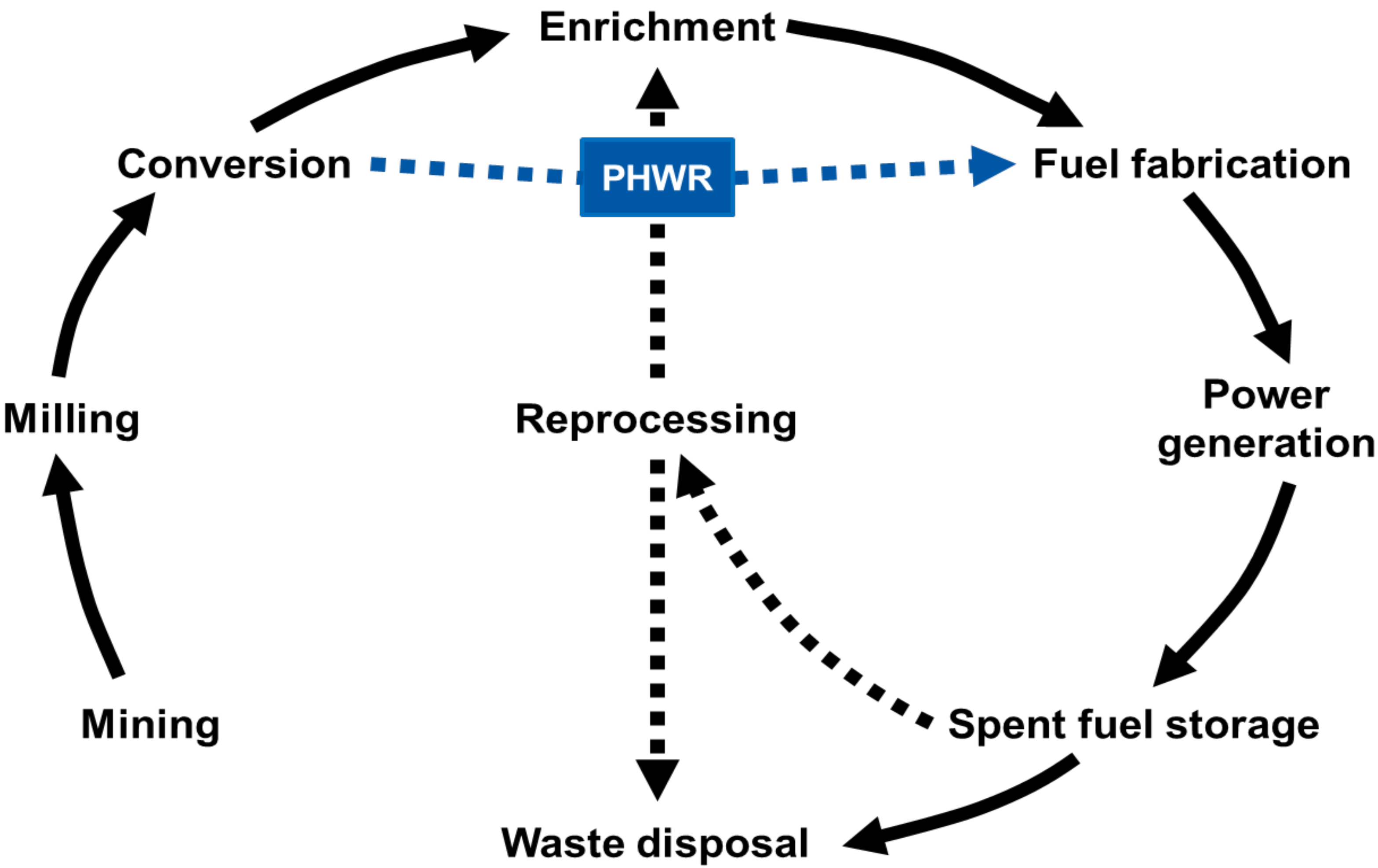




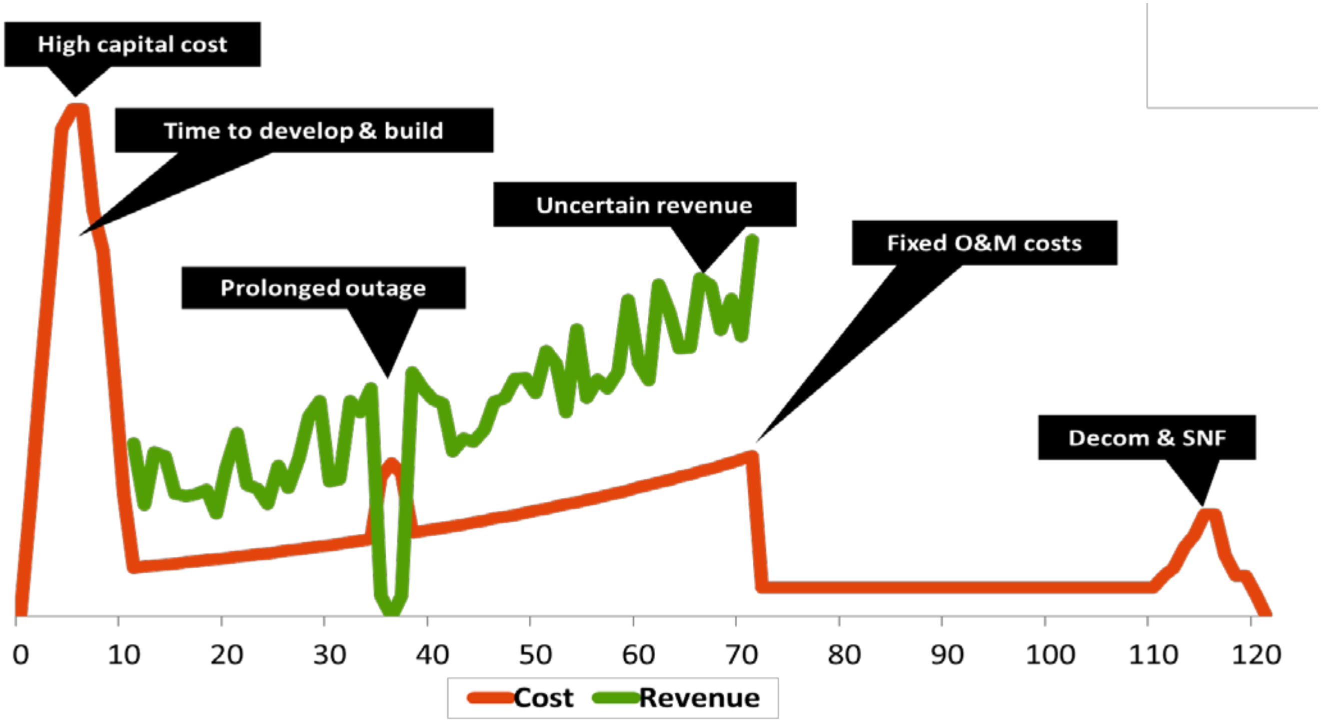




How nuclear power works: *nuclear fuel cycle*



How nuclear power works: *pros and cons*



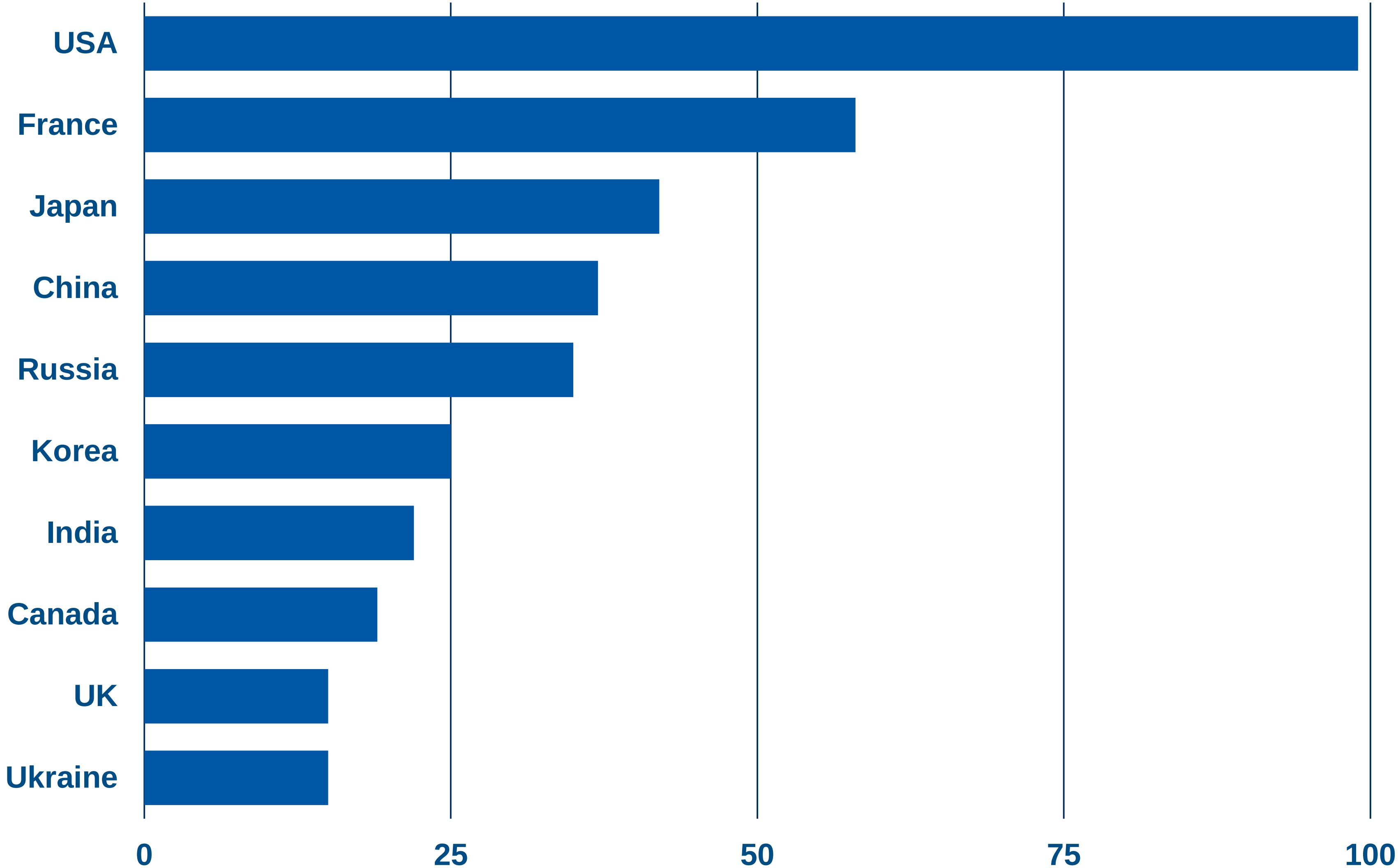
Pros

- High power density
- Long life (60+ years)
- No emissions
- Reliable, dispatchable
- Stable production cost

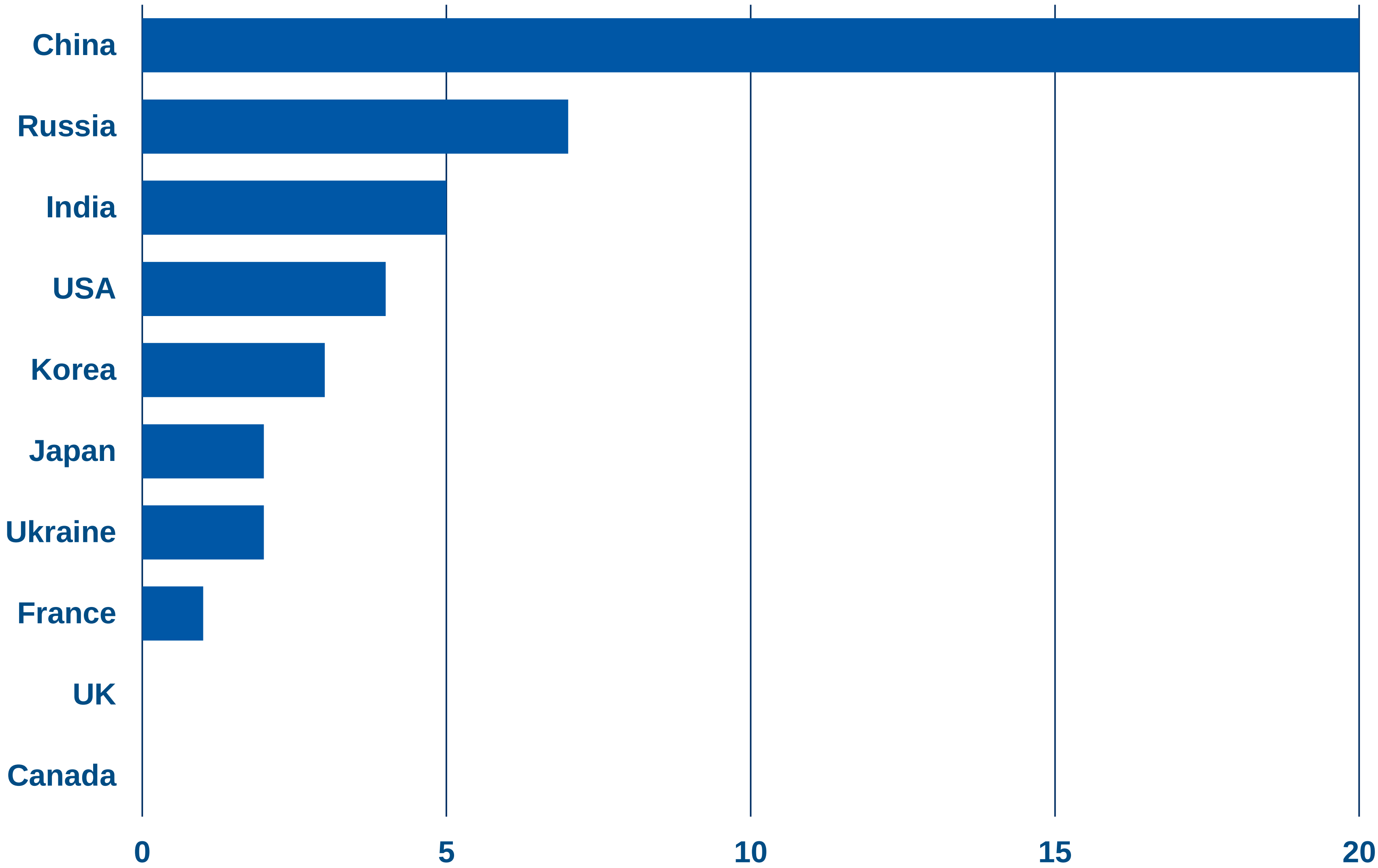
Cons

- High capital cost, long construction period
- Public fear and opposition
- Decommissioning and SNF funded by owner
- Specialized operators and managers
- Nuclear safety regulator oversight

Global nuclear power: *operating reactors*



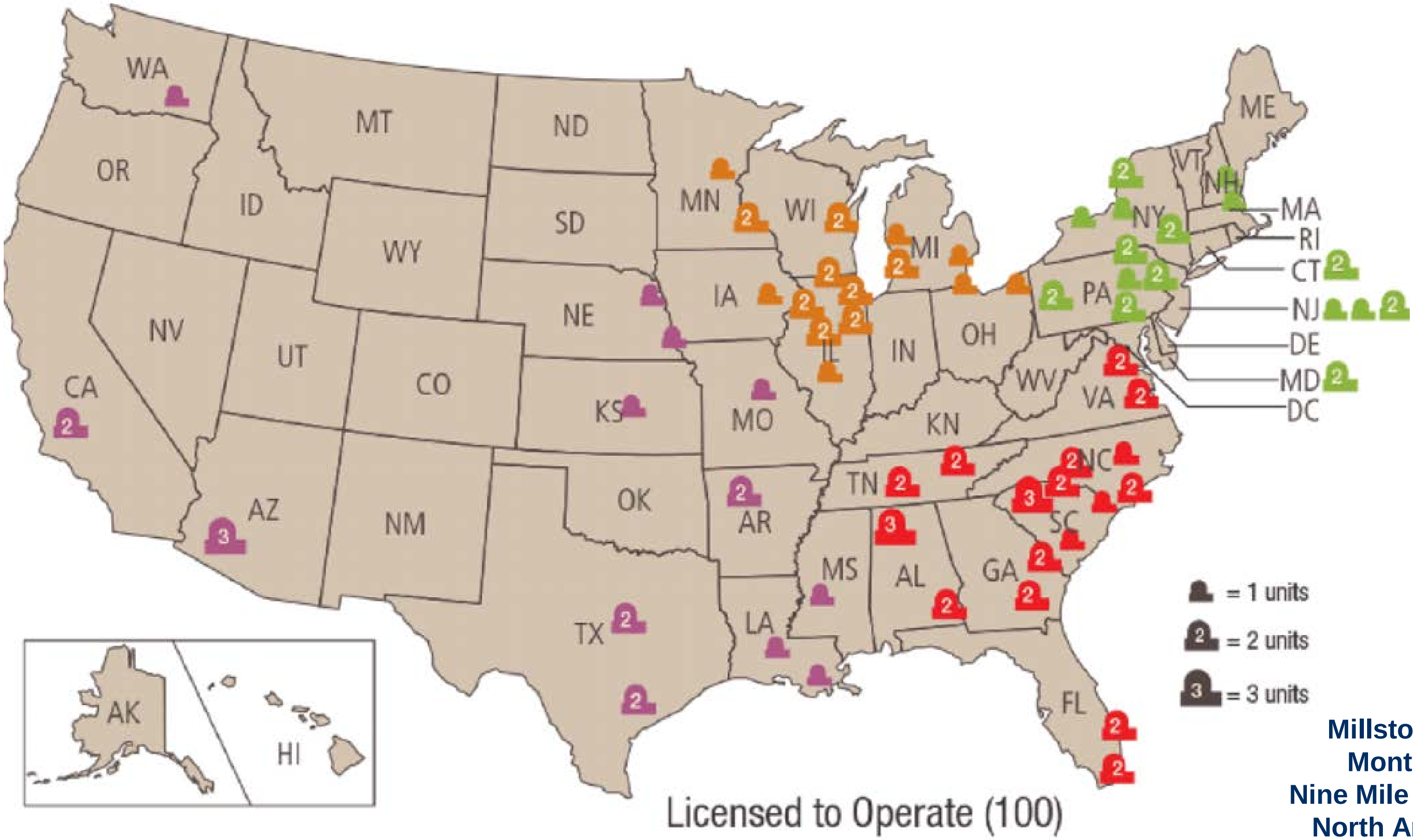
Global nuclear power:
reactors under construction



Canadian nuclear fleet: *operational units*

- Bruce
  - A: 4 reactors; 750 MWe
  - B: 4 reactors; 817 MWe
- Darlington – 4 reactors; 878 MWe
- Pickering – 6 reactors; 515 MWe
  - Units 2 & 3 in permanent shutdown
- Point Lepreau - 1 reactor; 660 MWe

U.S. nuclear fleet: *operational units*



Arkansas Nuclear 1&2
Beaver Valley 1&2
Braidwood 1&2
Browns Ferry 1&2&3
Brunswick 1&2
Byron 1&2

Callaway
Calvert Cliffs 1&2
Catawba 1&2
Clinton
Columbia
Comanche Peak 1&2

Cooper
D.C. Cook 1&2
Davis-Besse
Diablo Canyon 1&2
Dresden 2&3
Duane Arnold

Farley 1&2
Fermi 2
FitzPatrick
Ginna
Grand Gulf 1
Harris 1

Hatch 1&2
Hope Creek 1
Indian Point 2&3
La Salle 1&2
Limerick 1&2
McGuire 1&2

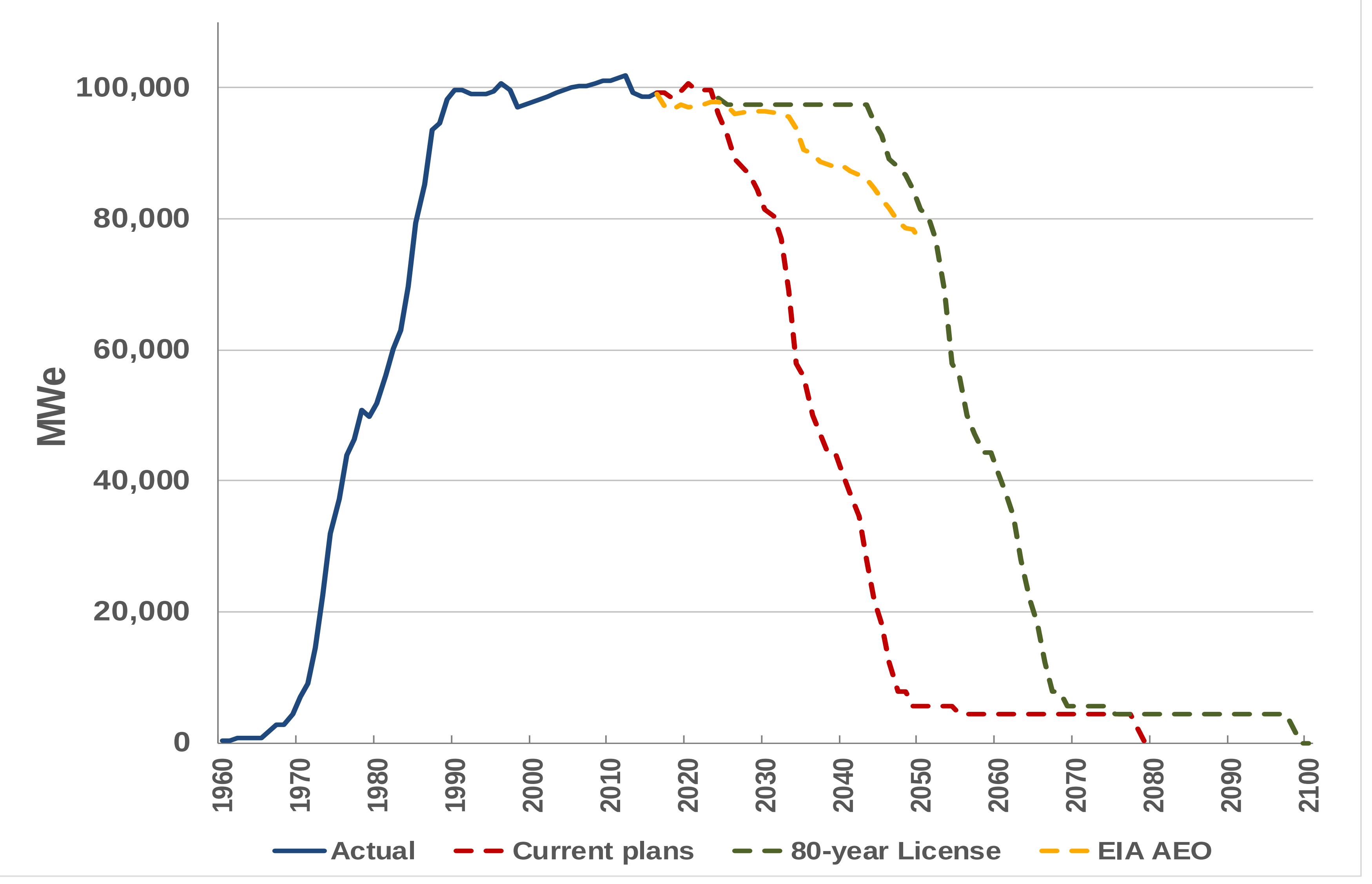
Millstone 2&3
Monticello
Nine Mile Point 1&2
North Anna 1&2
Oconee 1&2&3
Oyster Creek
Palisades
Palo Verde 1&2&3
Peach Bottom 2&3
Perry 1
Pilgrim 1

Point Beach 1&2
Prairie Island 1&2
Quad Cities 1&2
River Bend 1
Robinson 2
Saint Lucie 1&2
Salem 1&2
Seabrook 1
Sequoyah 1&2South Texas 1&2
Summer 1
Surry 1&2
Susquehanna 1&2
Three Mile Island 1
Turkey Point 3&4
Vogtle 1&2
Waterford 3
Watts Bar 1&2
Wolf Creek 1

U.S. nuclear fleet: *companies & status*

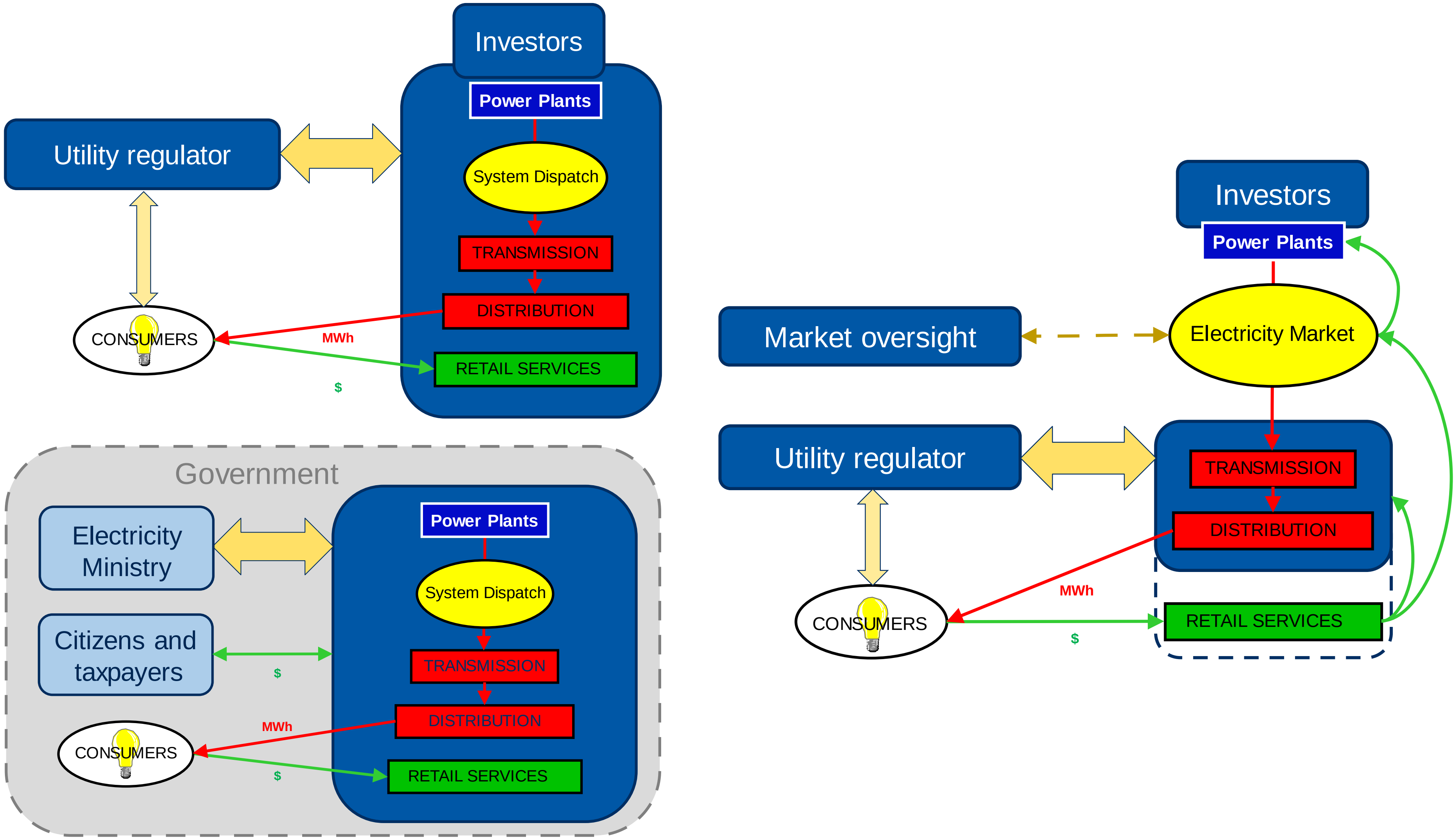
Company/operator	Operating reactors		Under construction		M (merchant) R (regulated) P (public power)
	#	MWe	#	MWe	
Exelon Generation	22	21,529			M
Duke Power Co	11	10,700			R
Entergy	10	9,734			5 M; 5 R
TVA Nuclear	7	7,833			P
FPL Group	8	6,630			4 M; 4 R
Southern Co	6	5,817	2	2,234	R
Dominion	6	5,664			2 M; 4 R
FirstEnergy Nuclear Operating Co	4	3,968			M
Arizona Public Service Co	3	3,936			R
PSEG Nuclear LLC	3	3,500			M
STP Nuclear Operating Co	2	2,581			M
Susquehanna Nuclear ,LLC	2	2,520			M
Luminant	2	2,400			M
Pacific Gas & Electric	2	2,300			R
Indiana Michigan Power Co (AEP)	2	2,069			R
Northern States Power Co. - Minnesota	3	1,594			R
Union Electric Co. (Ameren Missouri)	1	1,193			R
Wolf Creek Nuclear Operating Co.	1	1,175			R
Energy Northwest	1	1,137			P
DTE Electric Co.	1	1,124			R
South Carolina Electric & Gas	1	971	2	2,234	R
Nebraska Public Power District	1	766			P

U.S. nuclear fleet: *total operating capacity*



Source: NECG nuclear database; EIA AEO; NECG analysis

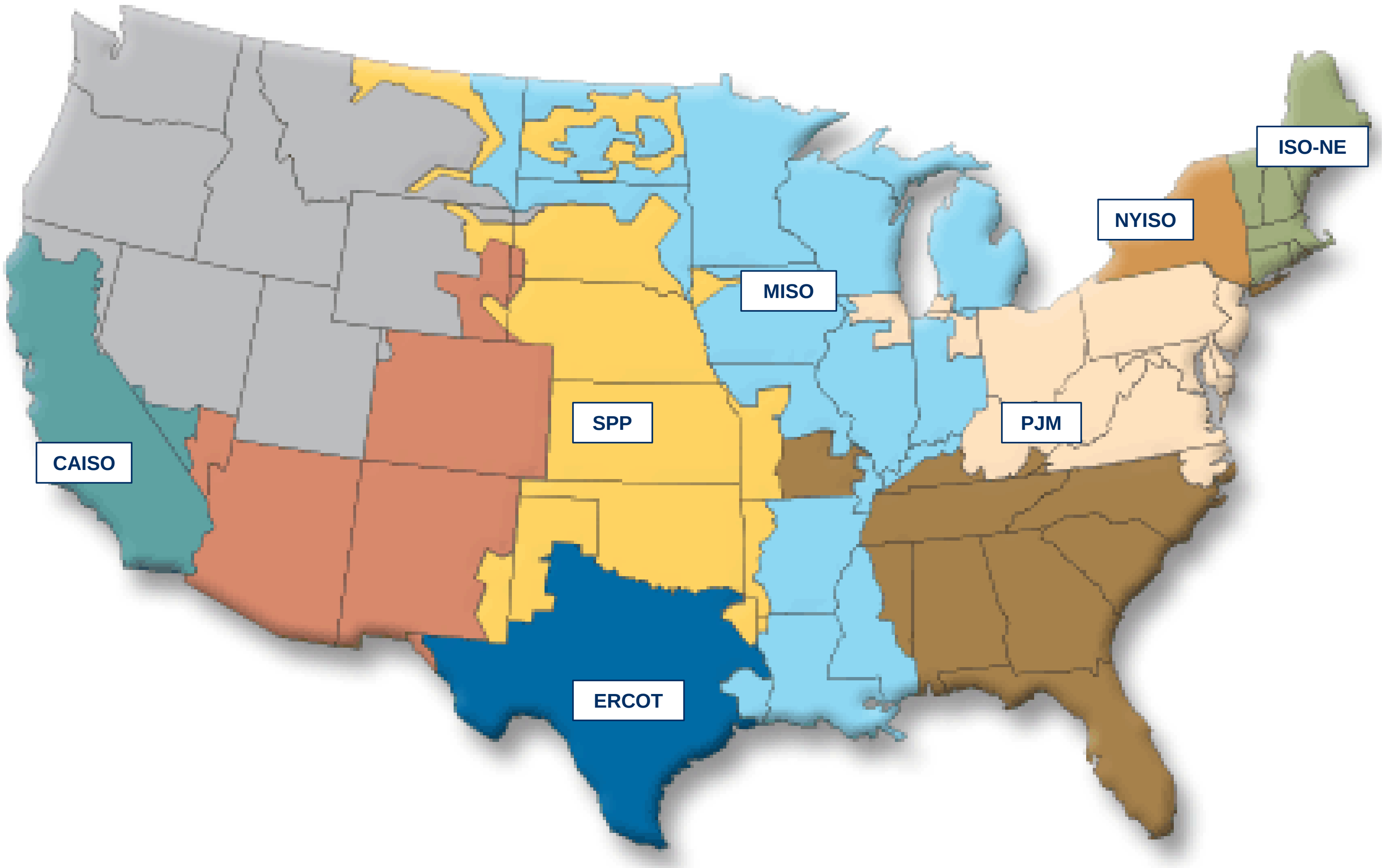
Electricity industry issues: *industry structure*



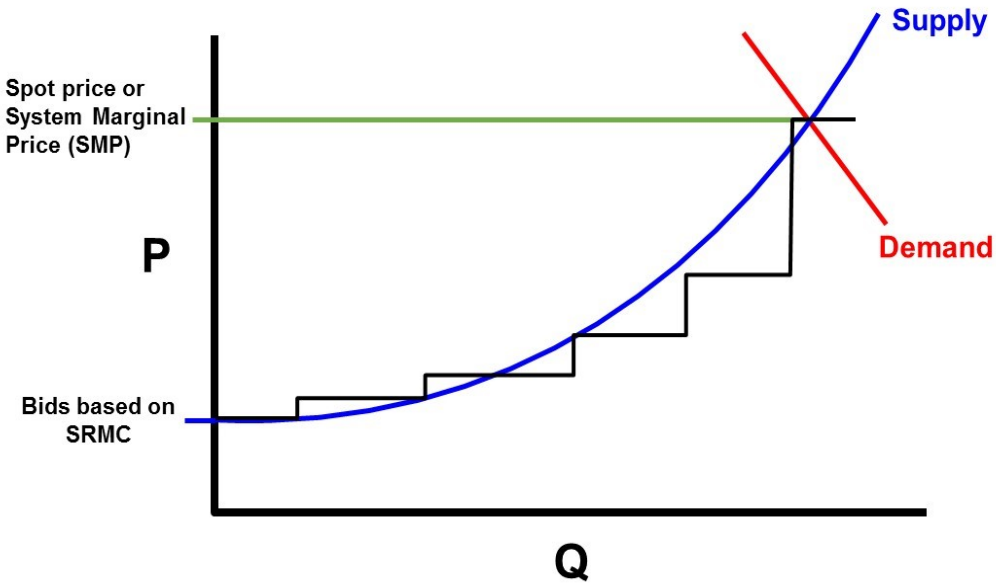
Electricity industry issues:
Canadian industry structure

- Canadian nuclear power plants
  - Mostly owned by government utilities
  - Similar to public power utilities in the US
  - Little or no electricity market risk to revenue
  - Government decision-making is important
- Bruce Power leases the assets at the Bruce nuclear power plant and sells electricity through long-term agreements with Ontario IESO

Electricity industry issues:
U.S. electricity markets / regions



Electricity industry issues: *nuclear in electricity markets*



- No revenue for key nuclear benefits
  - Capacity (except capacity market)
  - Clean (i.e., no CO2) operation
  - Long-term asset operation
  - Stable fuel costs
  - Generation fuel diversity

- Nuclear operating costs fixed; nuclear SRMC = zero
- No benefit from load following
- Overnight shut down difficult
- Bid as price taker – revenue linked to market prices

Electricity industry issues: *negative market prices*

- Negative prices allowed in electricity markets
  - Nuclear at max output between refueling outages, negative prices = payments to market operator
  - Happens when more inflexible generator offers than demand for electricity in a trading period
  - Inflexible (price taker or must run) bids will not be dispatched off by market operator
- Nuclear operating flexibility possible, but only makes economic sense if it stops negative prices

Electricity industry issues:
U.S. state regulation of nuclear

- States that have not restructured
  - Regulatory risk for nuclear plants
  - State disallowances in 1970s and 1980s, due to imprudence, excess capacity, cost overruns
  - Utility reluctance to invest in nuclear (or any large generating plant)
- State role in regulatory approvals
  - Integrated Resource Planning processes
  - Utility self-build option treated like a bid
  - Approval to build comes with high degree of certainty

Nuclear economics:
U.S. nuclear operating cost

Category	# of plants	Fuel cost ($/MWh)	O&M cost ($/MWh)	Ongoing CapEx ($/MWh)	Total ($/MWh)
U.S. average	58*	6.91	20.62	7.97	35.50
Site configuration					
Single unit	23	7.10	27.15	10.26	44.52
Multiple unit	35	6.85	18.74	7.31	32.90
Operator					
Single plant	12	7.49	22.05	9.30	38.84
Fleet operator	46	6.74	20.21	7.58	34.53

* Costs exclude shutdown plants and Fort Calhoun, Fitzpatrick and Pilgrim (that did not submit data to EUCG in 2015)

Source: NEI; Electric Utility Cost Group (EUCG) data; http://www.nei.org/CorporateSite/media/filefolder/Policy/Papers/Nuclear-Costs-in-Context.pdf?ext=.pdf

Nuclear economics:
U.S. nuclear capital cost & LCOE

Plant type	Size	Overnight capital cost ($/kW)	**Overnight capital cost ($)**
Advanced CCGT	2 x 500	$956	$1.0 billion
Advanced nuclear	1 x 1,000	$6,108	$6.1 billion

Source: EIA AEO – Assumptions to Annual Energy Outlook 2016, http://www.eia.gov/forecasts/aeo/assumptions/pdf/0554(2016).pdf

Plant type	CF	Levelized capital cost ($/MWh)	Fixed O&M ($/MWh)	Variable O&M with fuel ($/MWh)	Transmission ($/MWh)	**Total system LCOE ($/MWh)**
Advanced CCGT	87%	15.4	1.3	38.1	1.1	55.8
Advanced nuclear	90%	75.0	12.4	11.3	1.0	99.7

Source: EIA AEO – Table 1b https://www.eia.gov/forecasts/aeo/pdf/electricity_generation.pdf

Nuclear life extension:
CANDU Refurbishment

- Refurbishment
  - Operate 30 yrs., refurbish, operate for 30 yrs.
  - Expensive and difficult
  - Learning from completed refurb projects

- Status:
  - Done – Wolsong-1, Point Lepreau, Bruce 1&2
  - In progress – Embalse
  - Planned – Bruce 3 - 8, Darlington
  - Pickering – extend operation without refurbishment
  - Gentilly – retired without refurbishment

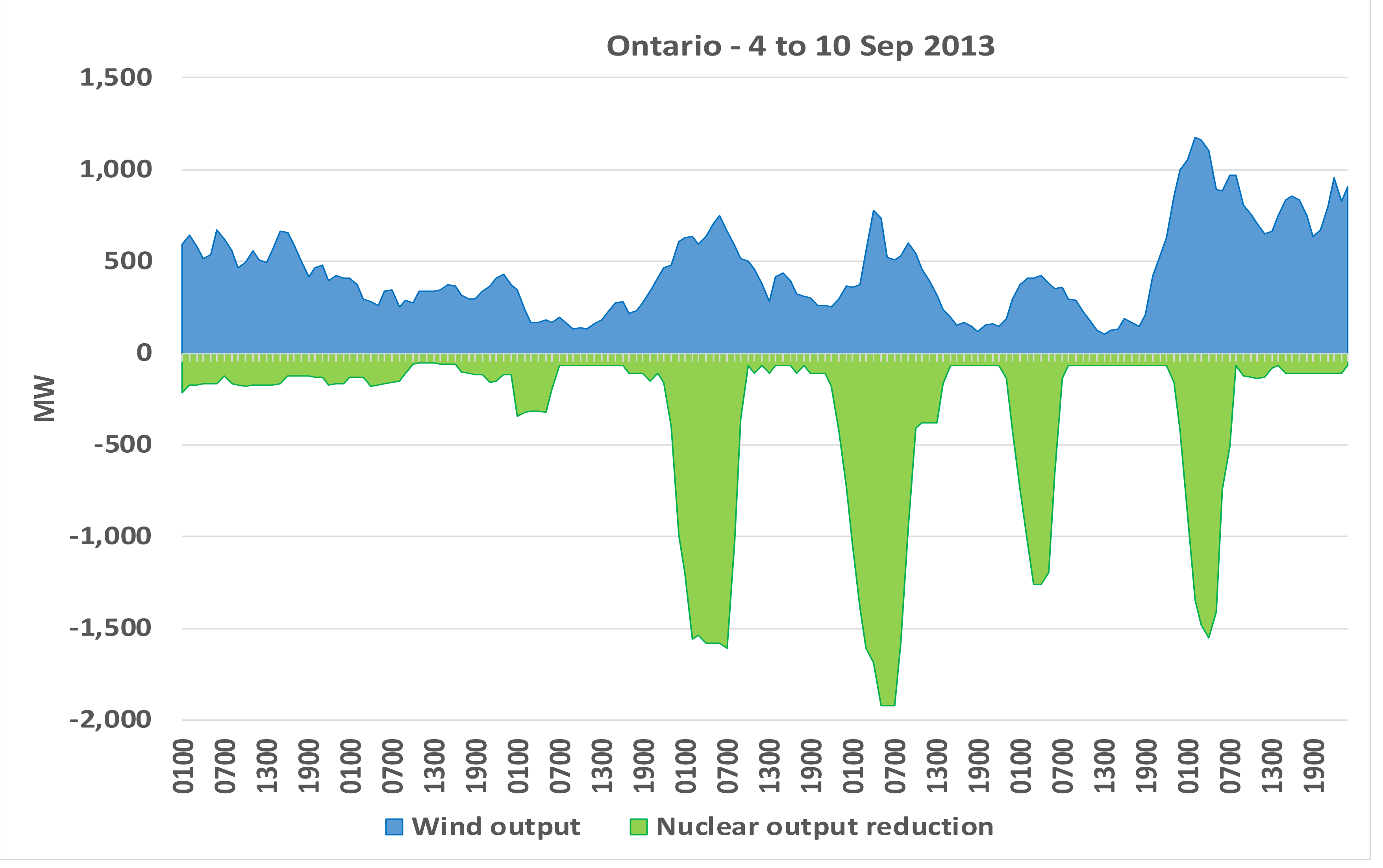
Nuclear life extension:
U.S approach

- U.S. NRC operating licenses had 40 year term
- License renewal (i.e., to 60 years)
  - In 1998, first units (Calvert Cliffs) approved
  - 84 (of 99) units approved
  - Some applications under review
- Subsequent license renewal (i.e., to 80 years)
  - Studies and analyses
  - Applications - Peach Bottom (2018) & Surry (2019)

Nuclear operating flexibility: *Concepts*

- Zero marginal cost ⇨ base load operation
- Several approaches
  - Regulation (i.e., frequency control)
  - Load following (daily)
  - Cycle on/off (weekly, seasonal)
- Technically feasible
  - France & Germany
  - New reactor designs capable
  - Reactor power variation vs steam dump

Nuclear operating flexibility:
Bruce Power (steam dump)



Source: Scott Luft; *Cold Air* blog (http://coldair.luftonline.net/); based on archived data from 201336 Weekly Report (i.e., for 4 to 10 September 2013); NECG analysis

Nuclear operating flexibility:
U.S. experience

- Columbia (Energy Northwest) cycles to facilitate Pacific Northwest hydro system
- 2016 – Exelon Illinois units
  - Done when electricity market negative prices likely
  - Output reduced 10-15% based on steam plant ops
  - NRC discussion and approval
  - FERC and market operator discussion and approval
  - Market power issues?

Nuclear market failure:
U.S. early retirement

- Units retired early
  - Kewaunee, Vermont Yankee, Fort Calhoun, Crystal River, San Onofre, Zion, etc.
- Planned early retirements
  - Palisades (2018)
  - Pilgrim (2019)
  - Oyster Creek (2019)
  - Indian Point 2 & 3 (2020, 2021) - *maybe 2024, 2025*
  - Diablo Canyon 1 & 2 (2024, 2025)
- Other units at risk in Ohio and elsewhere

Nuclear market failure: *concept*

- When the market (defined broadly) does not support activities with net public benefits
- Net public benefits: when total (public + private) benefits greater than total costs
- Activities or investments with private losses will not go forward, despite net public benefits

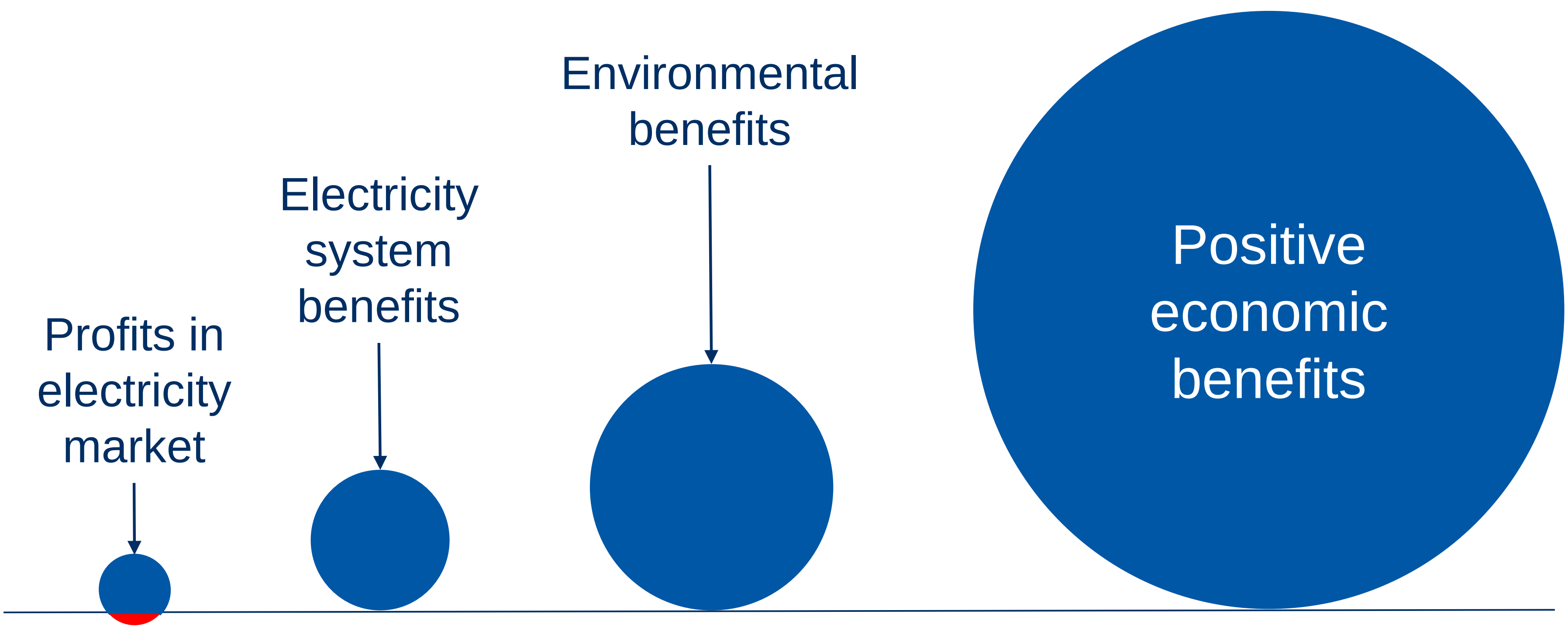
NECG Commentary #14 - ***http://nuclear-economics.com/14-market-failure/***

DOE 2016 - ***https://gain.inl.gov/Shared%20Documents/Economics-Nuclear-Fleet.pdf***

Nuclear market failure: *what is going on?*

- Low electricity market prices
- U.S. practice and policy led to:
  - No compensation for public benefits of nuclear power
  - Separation of generating assets from rest of system
  - Decisions based on market value of commodity power
- When electricity and capacity prices are low:
  - Merchant nuclear plants lose money
  - Regulated & public power nuclear units increase rates
  - New nuclear projects look unprofitable

Nuclear market failure:
no value for public benefits



Nuclear market failure:
ways to stop or fix it

- Role for government due to public benefits:
  - Costs on negative externalities (e.g., carbon pricing)
    - Difficult, too little, uncertain, linked to politics
    - Indirect benefits for nuclear in markets
    - Revenue neutrality in electricity markets (e.g., Finland)
  - Compensation to support positive externalities
    - Tax credits (similar to those for renewables)
    - New York and Illinois ZEC payments
    - UK incentives for new nuclear (e.g., Hinkley Point C)
  - Government ownership (Ontario, China, Russia, UAE, etc.)

ANS Toolkit - http://nuclearconnect.org/wp-content/uploads/2016/02/ANS-NIS-Toolkit-V2.pdf

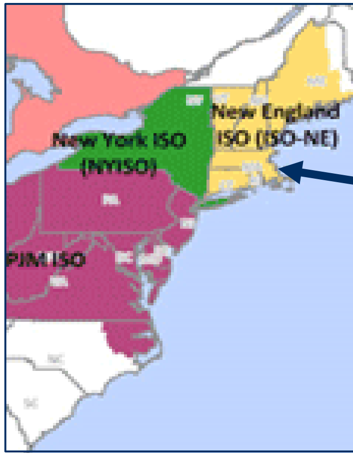
Nuclear market failure:
Pilgrim case study

690 MWe BWR

Original operating license expired in Jun 2012; renewed in 2012; new expiry Jun 2032

Plant is operating; plans to retire on 31 May 2019

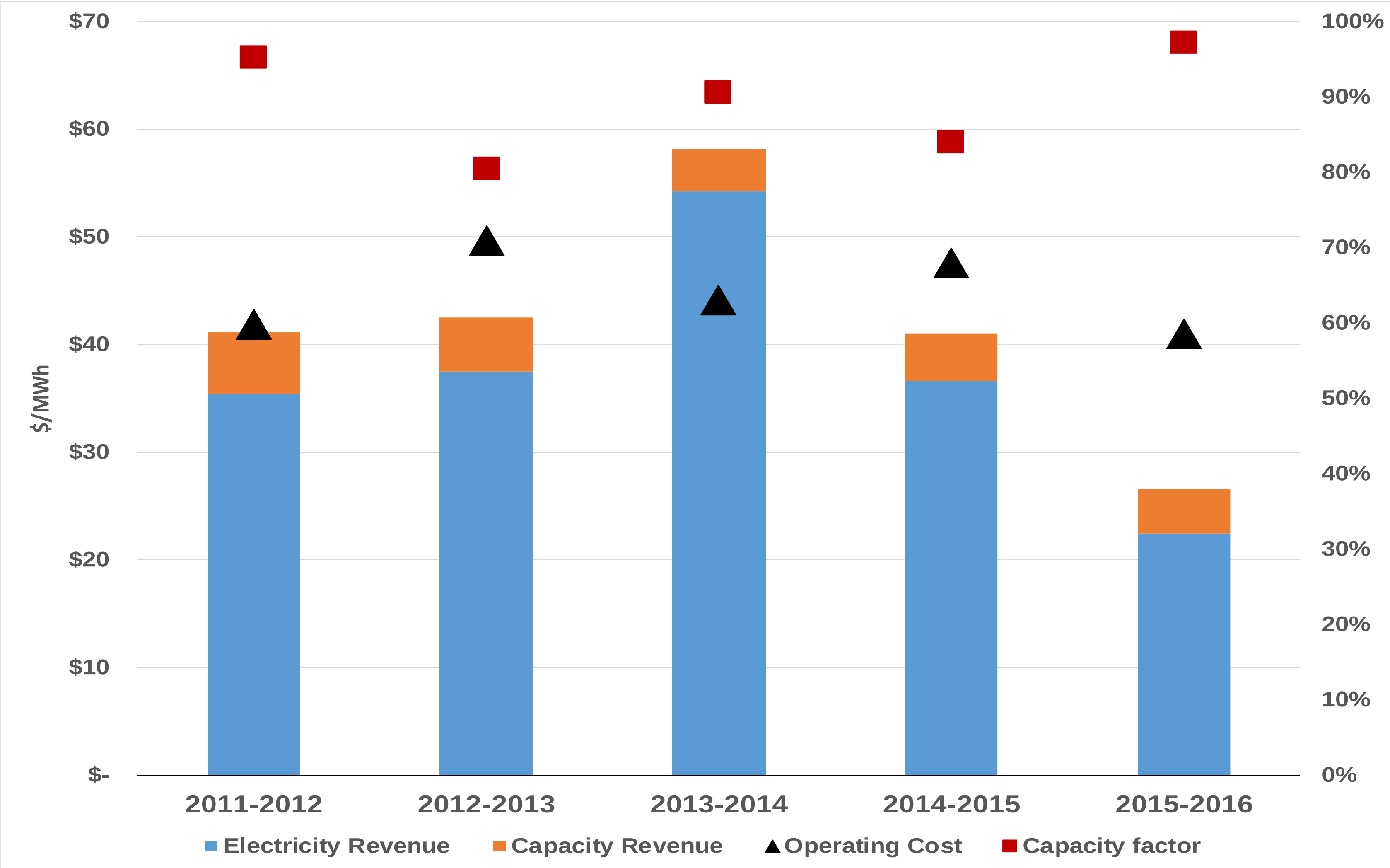
ISO-NE market



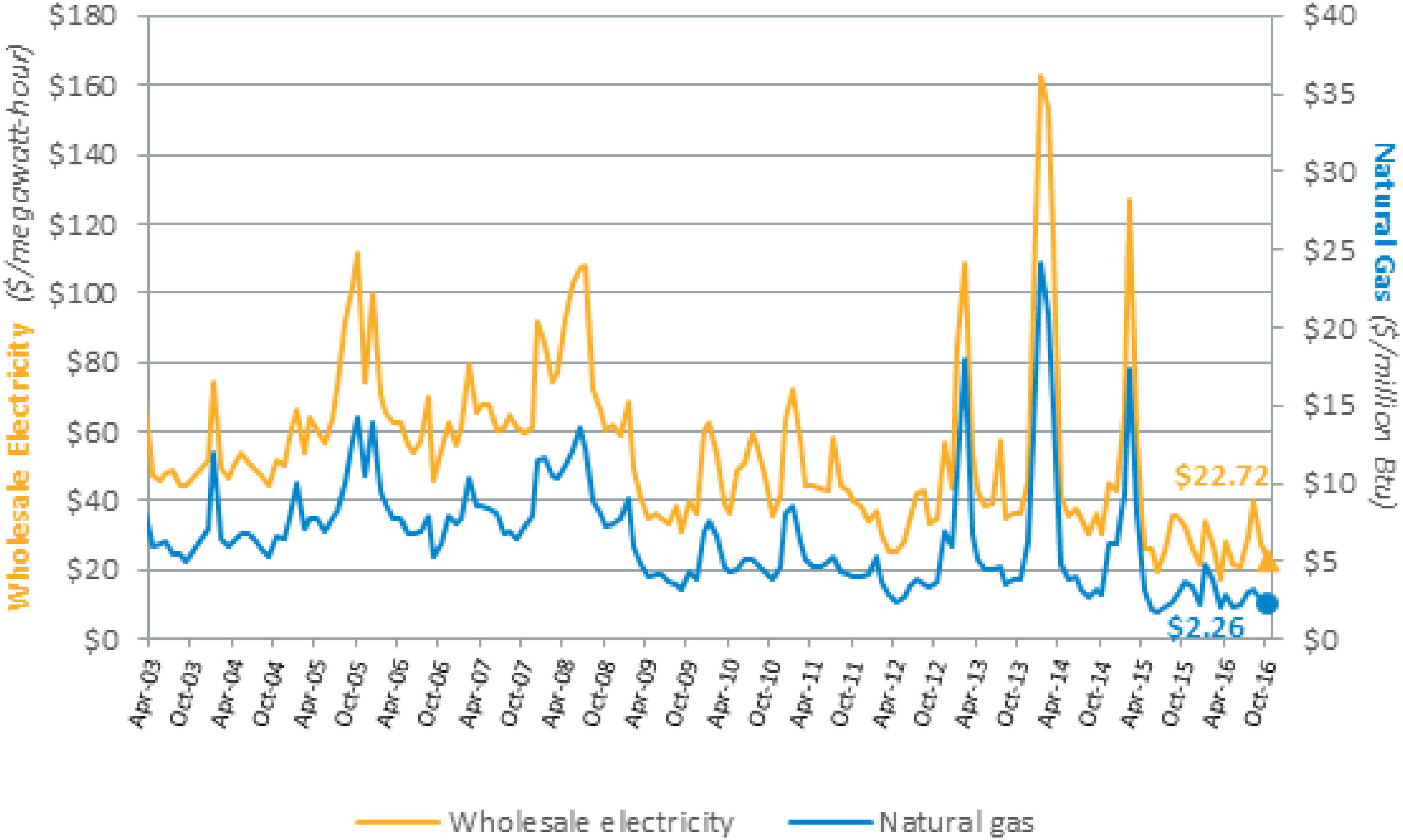
- Estimated operating costs - $44.52/MWh $350,000/MWe/year, or $237 million/year
- Sale of electricity & capacity in ISO-NE market
  - Actual LMP at generator LMP node
  - Actual generator output
  - Actual SEMASS Zonal capacity prices

Nuclear market failure:
Pilgrim financial performance

ESTIMATED



Nuclear market failure:
ISO-NE electricity & gas prices



Source: http://isonewswire.com/updates/2016/11/18/monthly-wholesale-electricity-prices-and-demand-in-new-engla.html

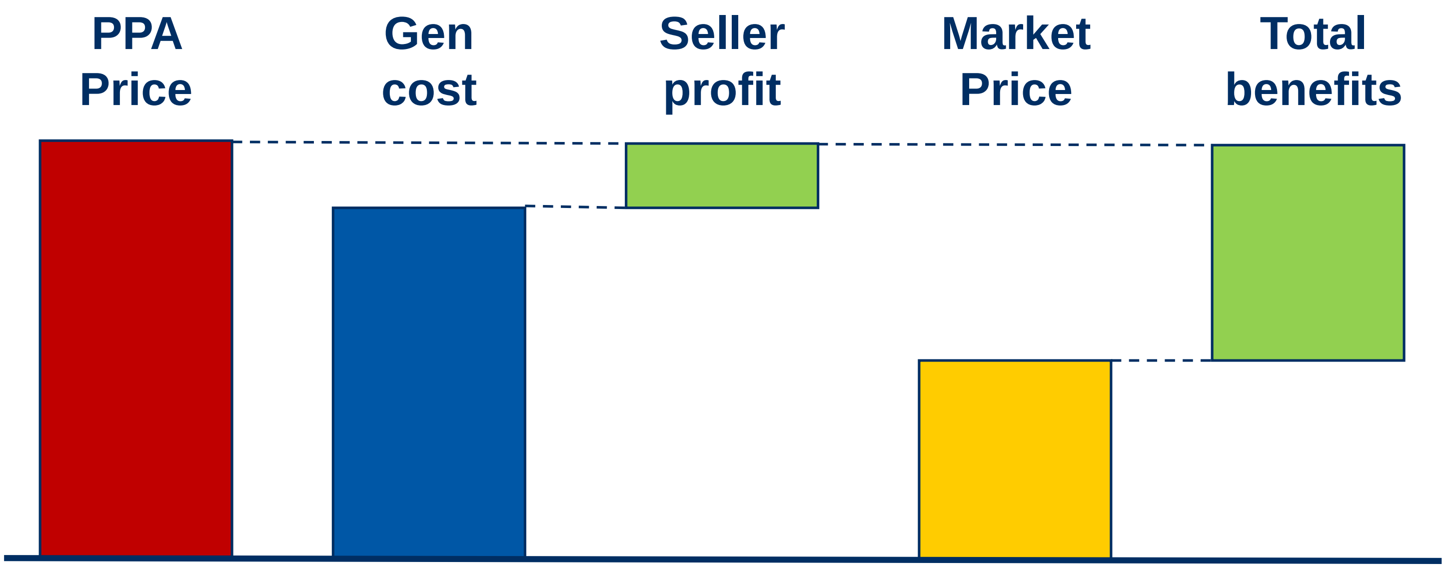
Nuclear market failure:
ISO-NE wholesale electricity prices

- Lower demand, driven by milder weather, and lower natural gas prices led to six lowest monthly LMP in last two years:
  - Mar 2016: $17.20
  - Jun 2015: $19.61
  - Jun 2016: $21.24
  - May 2016: $21.29
  - Dec 2015: $21.35
  - Oct 2016: $22.72

Nuclear market failure:
Palisades early retirement

- Profitable PPA (for Entergy)
- Electricity market price < generation cost
- Termination benefits for seller and buyer

ILLUSTRATIVE



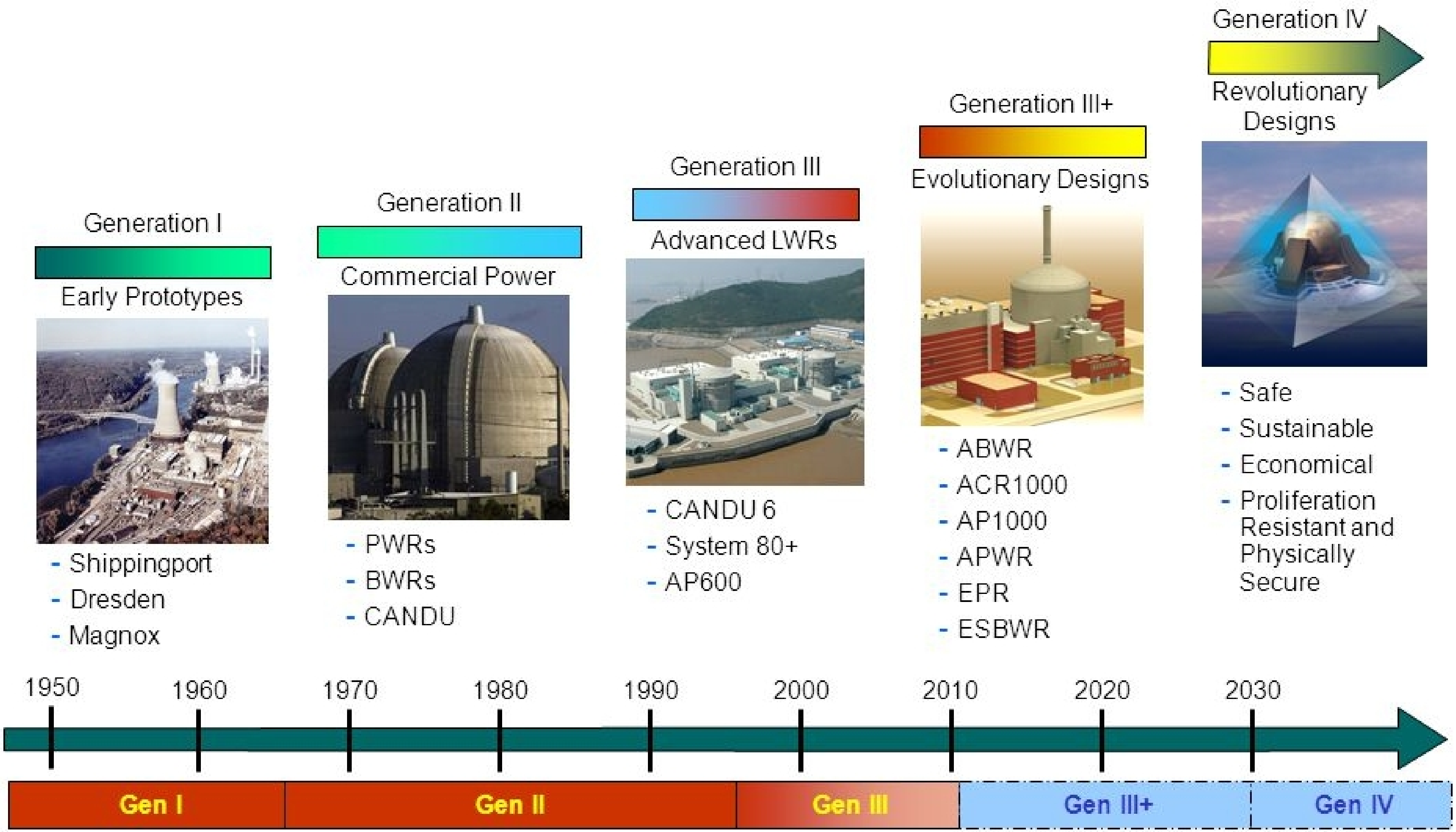
U.S. nuclear fleet: *planned units*

Project	Type	State	Owner	NRC status
Fermi-3	Regulated	Michigan/MISO	DTE	COL issued
Levy County 1 & 2	Regulated	Florida	Duke	COL issued
South Texas Project 3 & 4	Merchant	ERCOT	NRG + CPS	COL issued
W. S. Lee 1&2	Regulated	South Carolina	Duke	COL issued
North Anna-3	Regulated	Virginia/PJM	Dominion	COL under review
Turkey Point 6 & 7	Regulated	Florida	FPL	COL under review
Comanche Peak 3 & 4	Merchant	ERCOT	Luminant	COL suspended
Harris 2 & 3	Regulated	North Carolina	Duke	COL suspended
Bell Bend	Merchant	PJM	UniStar (PPL)	COL withdrawn
Bellefonte 3 & 4	Public Power	Alabama	TVA	COL withdrawn
Callaway-2	Regulated	Missouri	Ameren	COL withdrawn
Calvert Cliffs-3	Merchant	PJM	UniStar (CEG)	COL withdrawn
Grand Gulf-3	Regulated	Mississippi	Entergy	COL withdrawn
Nine Mile Point-3	Merchant	NYISO	UniStar (CEG)	COL withdrawn
River Bend-3	Regulated	Louisiana	Entergy	COL withdrawn
Victoria County	Merchant	Texas	Exelon	COL withdrawn
Clinton	Merchant	Illinois	Exelon	ESP Issued
Grand Gulf	Regulated	Mississippi	Entergy	ESP Issued
North Anna	Regulated	Virginia	Dominion	ESP Issued
Vogtle	Regulated	Georgia	Southern Co.	ESP Issued
Salem-3	Merchant	PJM	PSE&G	ESP Issued
Clinch River (SMR)	Public Power	Tennessee	TVA	ESP under review
Victoria County	Merchant	Texas	Exelon	ESP under review

U.S. nuclear fleet: *reactor designs*

Reactor Design	Vendor/applicant	NRC status
ABWR	GE	DC approved
ABWR (DCR Amendment)	STPNOC/Toshiba	DC approved
AP600	Westinghouse	DC approved
AP1000	Westinghouse	DC approved
ESBWR	GE-Hitachi	DC approved
System 80+	Westinghouse	DC approved
ABWR (DCR renewal)	GE-Hitachi	DC under review
APR1400	KEPCO	DC under review
NuScale Power Module	***NuScale***	***DC under review***
U.S. APWR	Mitsubishi	DC under review
U.S. EPR	AREVA	DC suspended
ABWR (DCR renewal)	Toshiba	DC withdrawn

Nuclear power innovation:
reactor generations and status



Nuclear power innovation: *new reactor designs*

- Technology "lock-in" for light water reactors
  - 60+ years of building and operating
  - 16,000+ reactor-years of experience
  - High costs = response to learning and accidents
- *"New"* reactor concepts
  - Small Modular Reactor (SMR) + Gen IV designs
  - Real vs paper reactors – Rickover 1953 letter
  - Little or no construction/operating experience
  - Same electricity economics as large reactors
- Current drivers are governments, VC, patents

Nuclear power innovation:
SMR concept

- Small light water reactors
  - Expected to be easier to license
  - Higher safety due to integral PWR reactor design, passive safety concepts and sub-grade construction
  - Reactor module removed for refueling/maintenance
  - Modularity and factory build
  - Multiple units on same site
  - Smaller source term (i.e., type and amount of radioactive material released due to an accident)
- Lower requirement for access to cooling water

Nuclear power innovation:
Gen IV reactor concepts

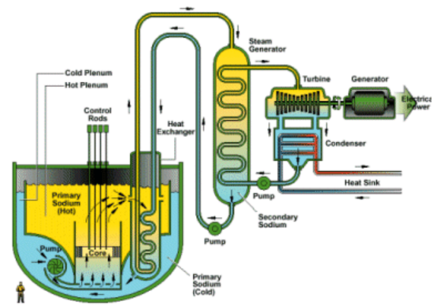
Alternative reactor coolant approaches

- Higher level of intrinsic safety
- Avoid water-cooled reactor accidents
- Avoid many of the safety features required for water-cooled reactors
- May allow simpler, cheaper, safer nuclear power plants

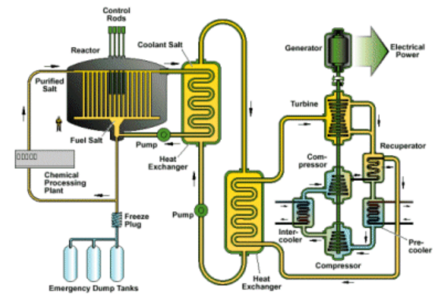
Higher-temperature heat energy

- More efficient electricity generation
- Potential for smaller generator (e.g., helium Brayton cycle or supercritical CO2 cycle)
- May facilitate air cooling
- May allow use in industrial processes

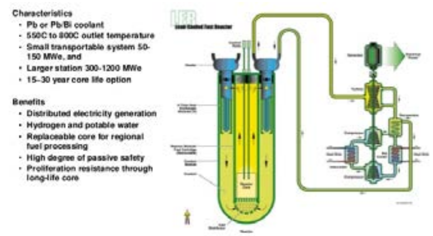
Sodium-cooled fast reactor



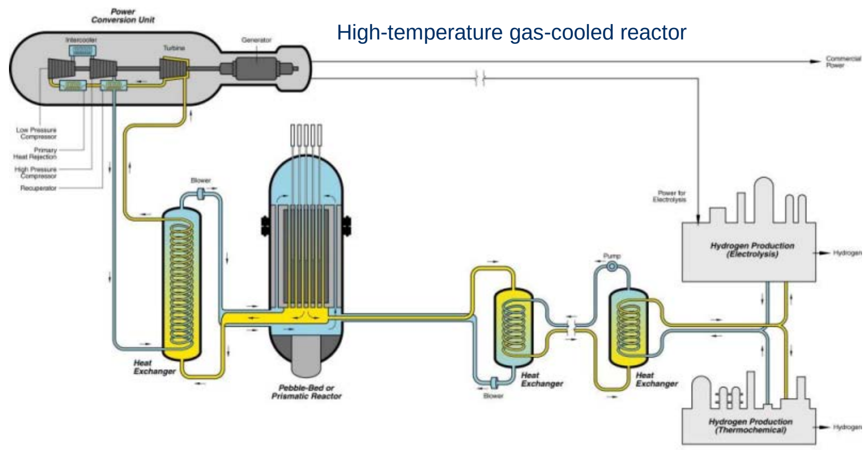
Molten-salt liquid reactor



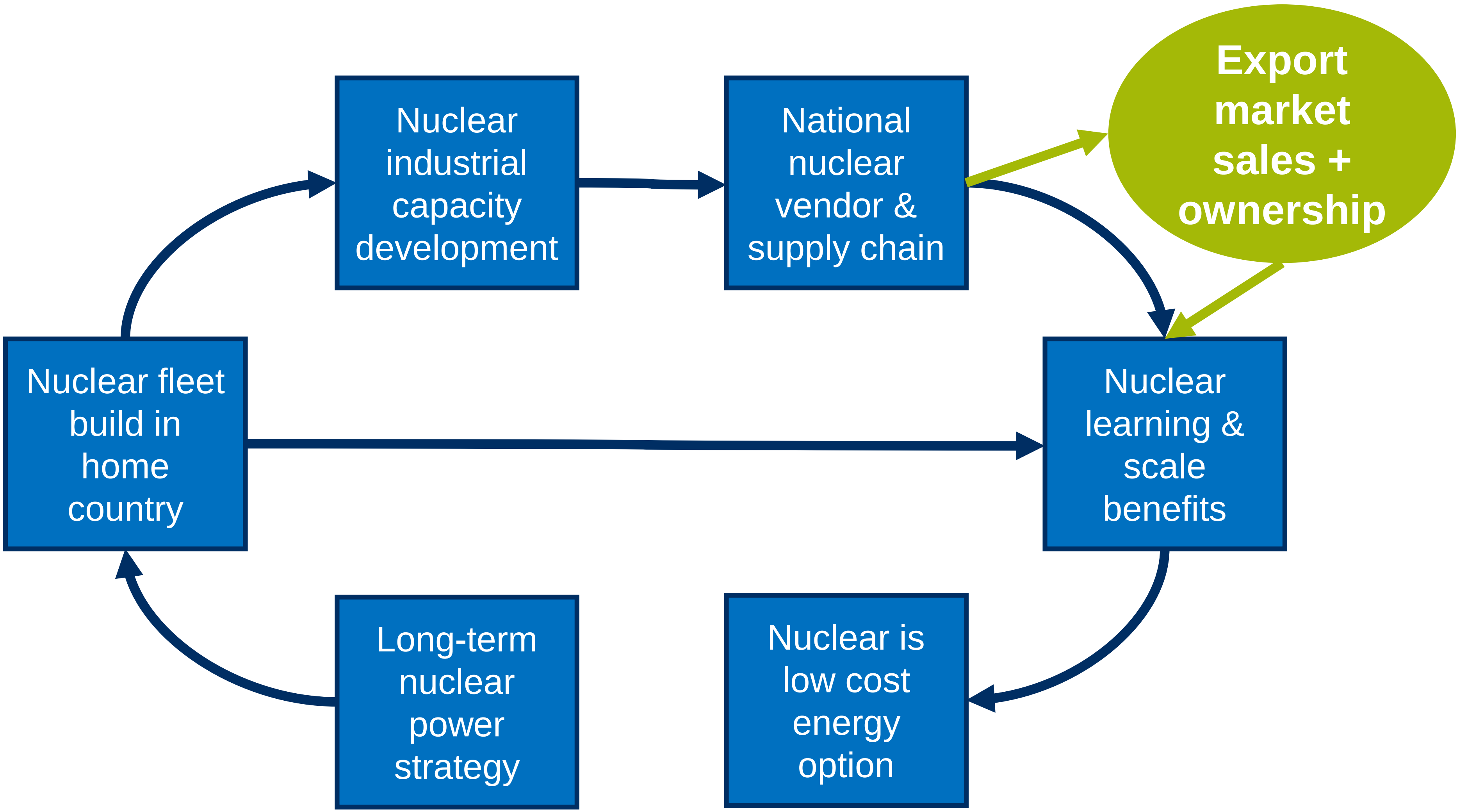
Lead-cooled fast reactor



High-temperature gas-cooled reactor



National nuclear industrial strategy



Summary and conclusions:

- U.S. nuclear market failure caused by
  - Low electricity market prices
  - No compensation for nuclear public benefits
  - Merchant, regulated & public power at risk
  - Only government can fix this problem
- U.S. and Canada losing ground to national nuclear companies

NUCLEAR ECONOMICS CONSULTING GROUP

NECG

Edward Kee

Nuclear Economics Consulting Group
+1 (202) 370-7713
edk@nuclear-economics.com
www.nuclear-economics.com

Attachment/references

- NRC - http://www.nrc.gov/info-finder/reactors/
- NEI - http://www.nei.org/Knowledge-Center/FAQ-About-Nuclear-Energy
- Recent DOE report - https://gain.inl.gov/Shared%20Documents/Economics-Nuclear-Fleet.pdf
- ANS Special Committee on nuclear in the states
  – http://nuclearconnect.org/issues-policy/nuclear-policy-in-the-states & http://nuclearconnect.org/wp-content/uploads/2016/02/ANS-NIS-Toolkit-V2.pdf

Reading:
NECG publications

- http://nuclear-economics.com/resources/publications/
- Papers/Articles/Presentations
  - Market failure and nuclear power (BAS)
  - Carbon pricing not enough to help nuclear power (WNN)
  - Can nuclear succeed in liberalized power markets? (WNN)
  - U.S. nuclear industry in decline (NEI magazine)
  - Role of government in nuclear (KP paper)
  - Rescuing U.S. merchant nuclear power (Electricity Journal)
  - Impact of carbon pricing on nuclear power (IFNEC/NEA)
  - World experience - nuclear and electricity markets (JAIF)
  - IAEA workshop courses 2015

Reading:
NECG Commentaries

- Selected Commentaries
  - #16 – Peak Nuclear Power
  - #15 – Existential Threat [to nuclear power]
  - #14 – Market Failure & Nuclear Power
  - #13 – Davis-Besse
  - #12 – Nuclear [operating] flexibility
  - #10 - Merchant nuclear – role for government
  - #5 – Revenue certainty
  - #4 – Lessons from Vermont Yankee early retirement
  - #3 – Nuclear base load
  - #2 – Short-Run Marginal Cost
  - #1 – Long-term assets in Short-term world

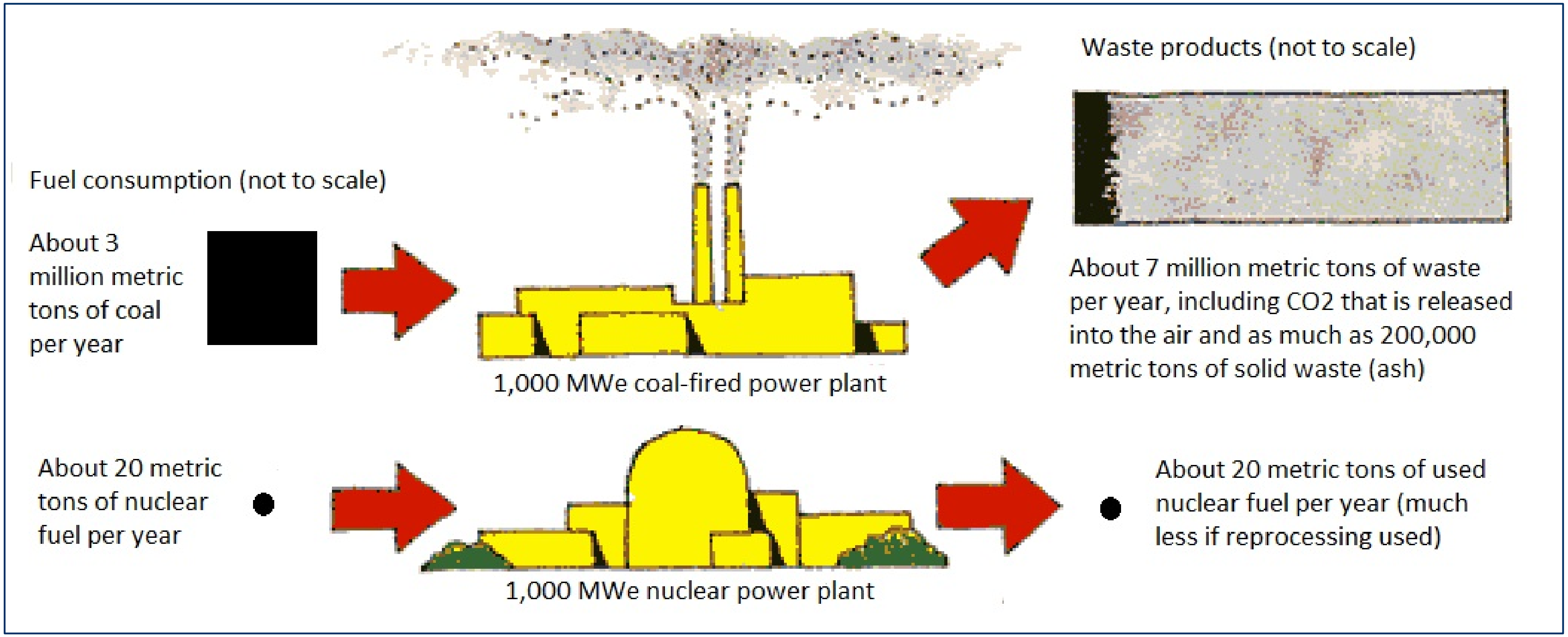
http://nuclear-economics.com/commentary/

Backup slide: *PPAs*

- Ownership equivalents
  - Cooperative arrangements
  - Regulatory participation agreements
  - Pass-through PPA
- Nuclear project finance
  - PPA Guarantees needed
  - Lender / investor requirements
- Hedge Agreement (CfD)

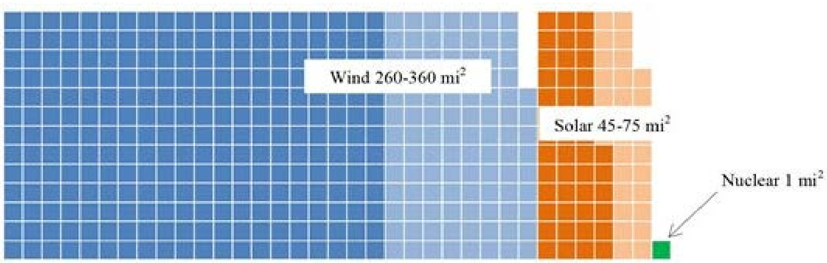
- Nuclear PPAs different
  - Long development period
  - Greater risk in development
  - Longer term/tenor
  - Low-probability, high-impact nuclear events
  - Externalities (Decom, SNF, TPL insurance)
  - Nuclear regulation
  - Nuclear fixed/variable costs imply special pricing terms

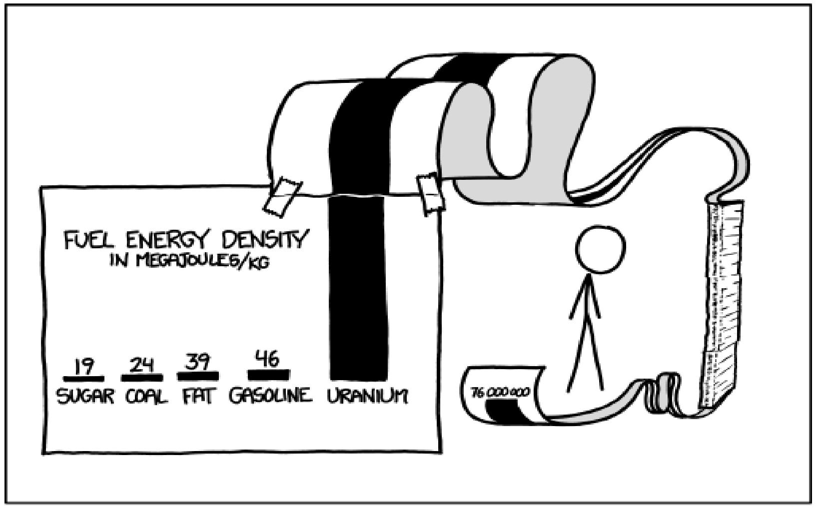
How nuclear power works:
high power density



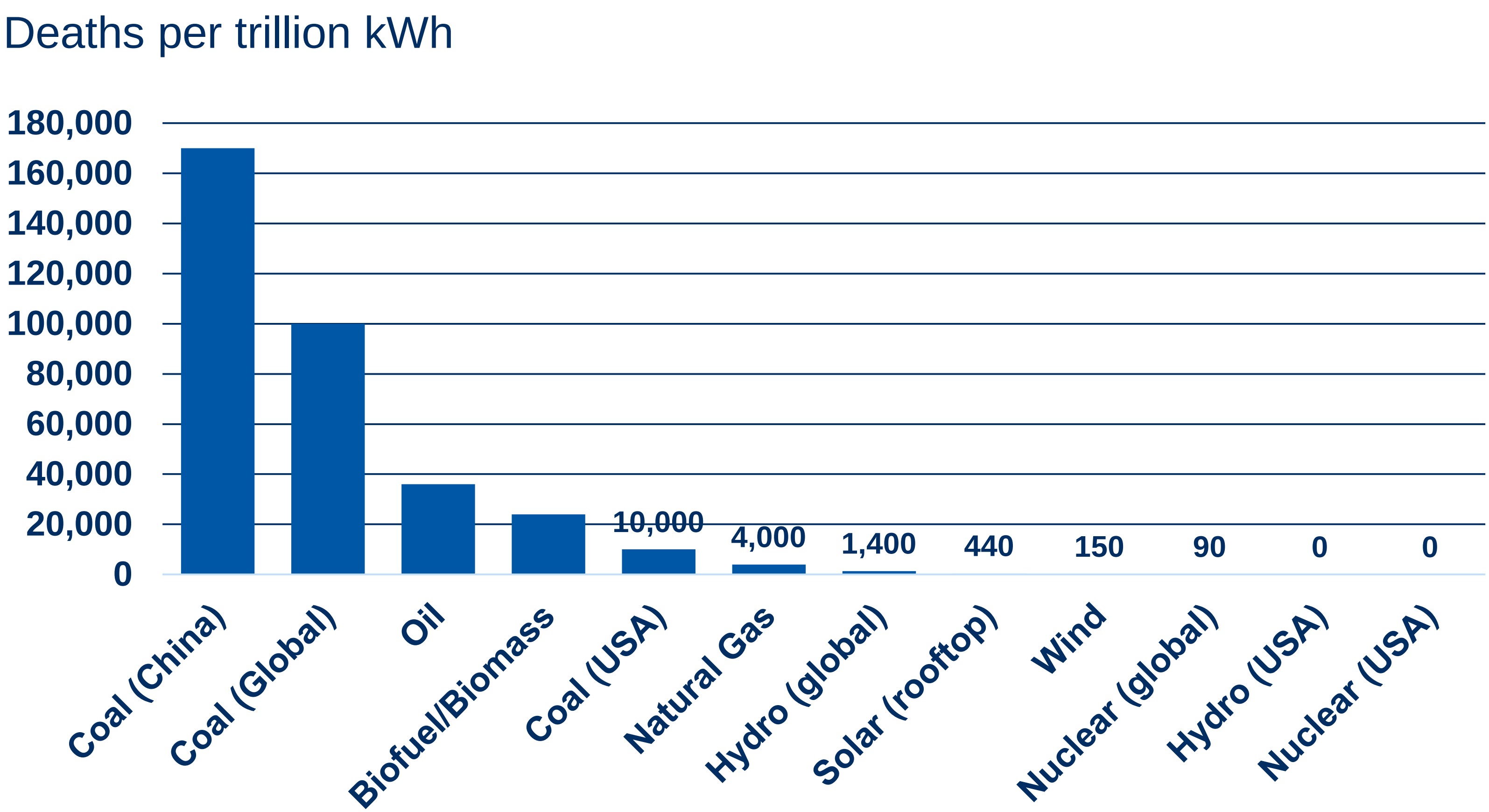
Technology	Capacity Factor, %	Square Miles Needed for 1,000 MW
Wind	32-47	260-360
Solar	17-28	45-75
Nuclear	90	1.3

The table summarizes the approximate land required by wind and solar technologies to match the electricity produced annually by a 1,000-MW nuclear power plant.





How nuclear power works: *high safety*



Nuclear has the lowest death print, even with the worst-case Chernobyl numbers and Fukushima projections, uranium mining deaths, and use of Linear No-Threshold (LNT) hypothesis.

Source: Forbes 10 Jun 2012 (http://www.forbes.com/sites/jamesconca/2012/06/10/energys-deathprint-a-price-always-paid/#46700df49d22); NECG analysis

Bruce Refurbishment Agreement

- Signed at end of 2015
- NERA team did fairness opinion - http://www.ieso.ca/Documents/procurement/bruce/NERA-Fairness-Opinion-Letter-2015-12-02.pdf
- http://www.brucepower.com/bpria-backgrounder/
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