NUCLEAR ECONOMICS
CONSULTING GROUP

NECG

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Edward Kee

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Topics

- Future of U.S. nuclear power
- Nuclear power economics
- U.S. situation and unique conditions
- U.S. policy options
- Nuclear power hacks

Future of U.S. nuclear power

- Favorable conditions for new nuclear build
  - Need for new capacity
  - Proven nuclear safety regulator, plus long positive experience with nuclear power
  - Nuclear power provides significant public goods
- But U.S. market approach to nuclear power
  - Does not value nuclear power public goods
  - Places large risks on private companies and uses financial metrics ill-suited for nuclear power
- This is market failure

What does market failure look like?

Future of U.S. nuclear power

- U.S. nuclear power declining
  - Market failure is primary reason
  - Electricity industry reform and market approach
- My three scenarios for U.S. nuclear power
  1. Business as usual
  2. Selected nuclear incentives
  3. New U.S. nuclear power strategy

1 – Business as usual

- No major changes in U.S. federal policy or role
- U.S. nuclear capacity declines as existing nuclear power plants close; decline shaped by
  - State ZEC programs + Federal PTC programs
  - NRC License Renewals (80 to 100 project life)
  - Potential restart of now-closed nuclear units
- Little or no new nuclear power capacity built
- Electricity is mostly natural gas and renewables

2 – New and larger nuclear incentives

- May see some new nuclear build
  - IOUs & state regulators with COL in hand may be first
  - Merchant nuclear is much more difficult
- What incentives may help
  - Long-term power contracts (e.g., like HPC CfD)
  - Government role in equity funding / ownership
  - Government help with completion risk (i.e., cost overruns and delays)
- UK RAB model for Sizewell C may be a model

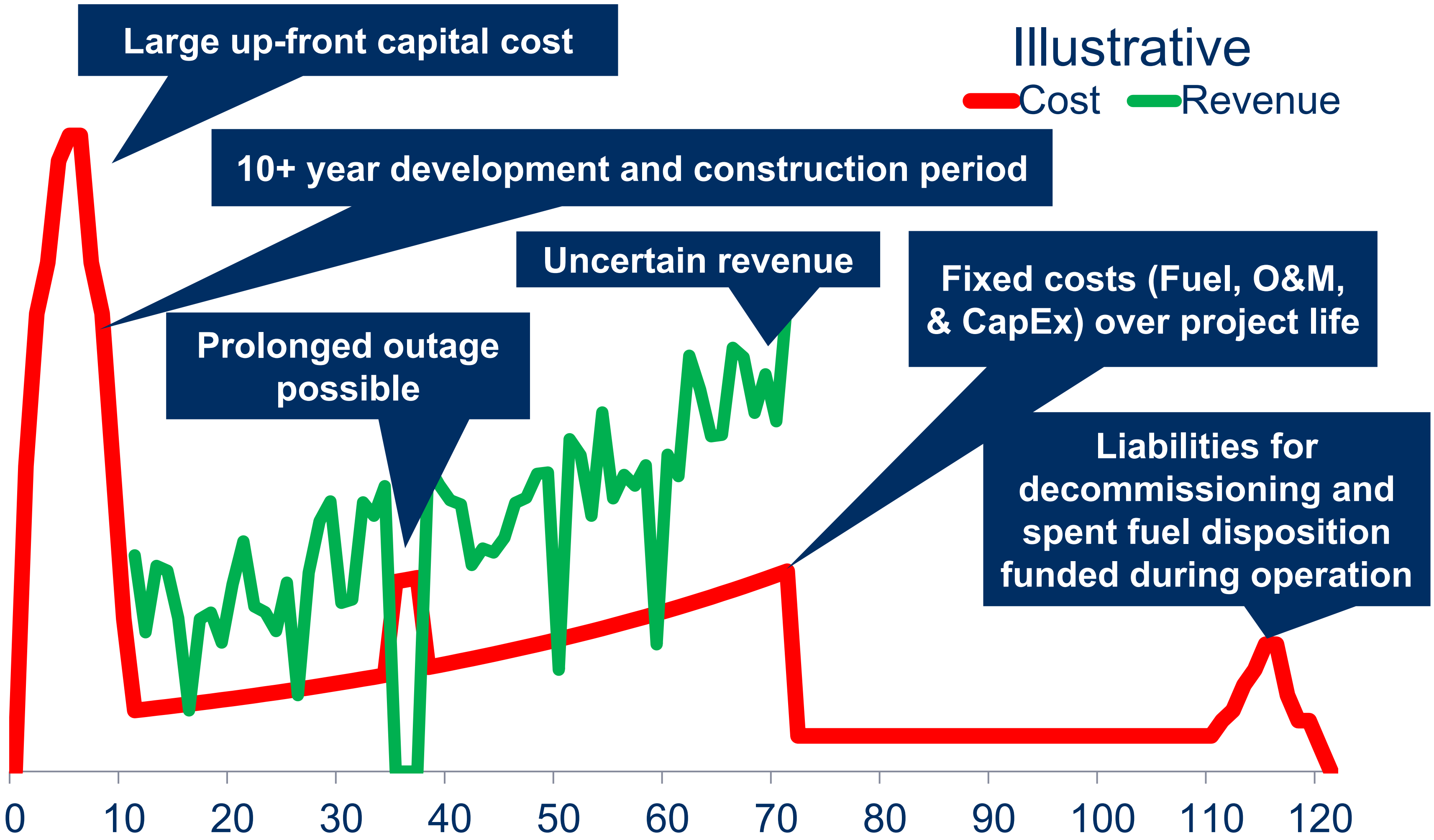
3 – New U.S. nuclear power strategy

- Potential for significant new nuclear build
- Move away from private / market approach
- Nuclear defined as critical national infrastructure
  - Federal government builds and owns nuclear power
  - One or more federal nuclear utility companies created
- Will require strong political support
  - Create new government nuclear companies
  - Pass new laws changing the U.S. system
  - Approve budgets for government nuclear build

Nuclear power project economics

- High initial capital cost
- Fixed operating cost
- Zero marginal cost
- High reliability/availability
- Very long operating life
- Compact size and minimal land use

New nuclear project cash flow



Nuclear fixed and marginal costs

- Nuclear generating costs are fixed
  - Batch-refueling LWRs, but also other designs
  - Nuclear short-run marginal cost (SRMC) = zero
  - Nuclear units bid in electricity markets as "price takers"
- In contrast, combustion-based power plant costs vary with output and thermal efficiency
  - SRMC generally equals fuel costs/MWh
  - But involve multi-attribute bids
  - Units dispatched, may be on the margin
  - Sets market-clearing prices in most trading periods

2022 NEI Costs in Context*

Nuclear Power Economics

Generating Cost Summary ***in $/MWh***

Category	Plants / Sites	Fuel	Capital	Operating	Total Generating
All U.S.	54	$5.37	$6.88	$18.68	$30.92
Merchant	23	$4.93	$3.06	$17.39	$25.38
Regulated	31	$5.72	$9.92	$19.71	$35.35
BWR	20	$5.23	$5.69	$20.01	$31.04
PWR	34	$5.44	$7.51	$17.92	$30.87

* https://www.nei.org/resources/reports-briefs/nuclear-costs-in-context

Nuclear power operating mode

- Utility dispatch and electricity market algorithms
  - Dispatch lowest-marginal-cost generators, including nuclear power, before higher-marginal-cost options
- This is referred to as economic system dispatch
  - Means that nuclear plants are dispatched whenever these nuclear plants are available
  - Baseload operation mode for economic reasons
- Does this mean that nuclear plants cannot operate flexibly (e.g., follow load)?

Nuclear can operate flexibly

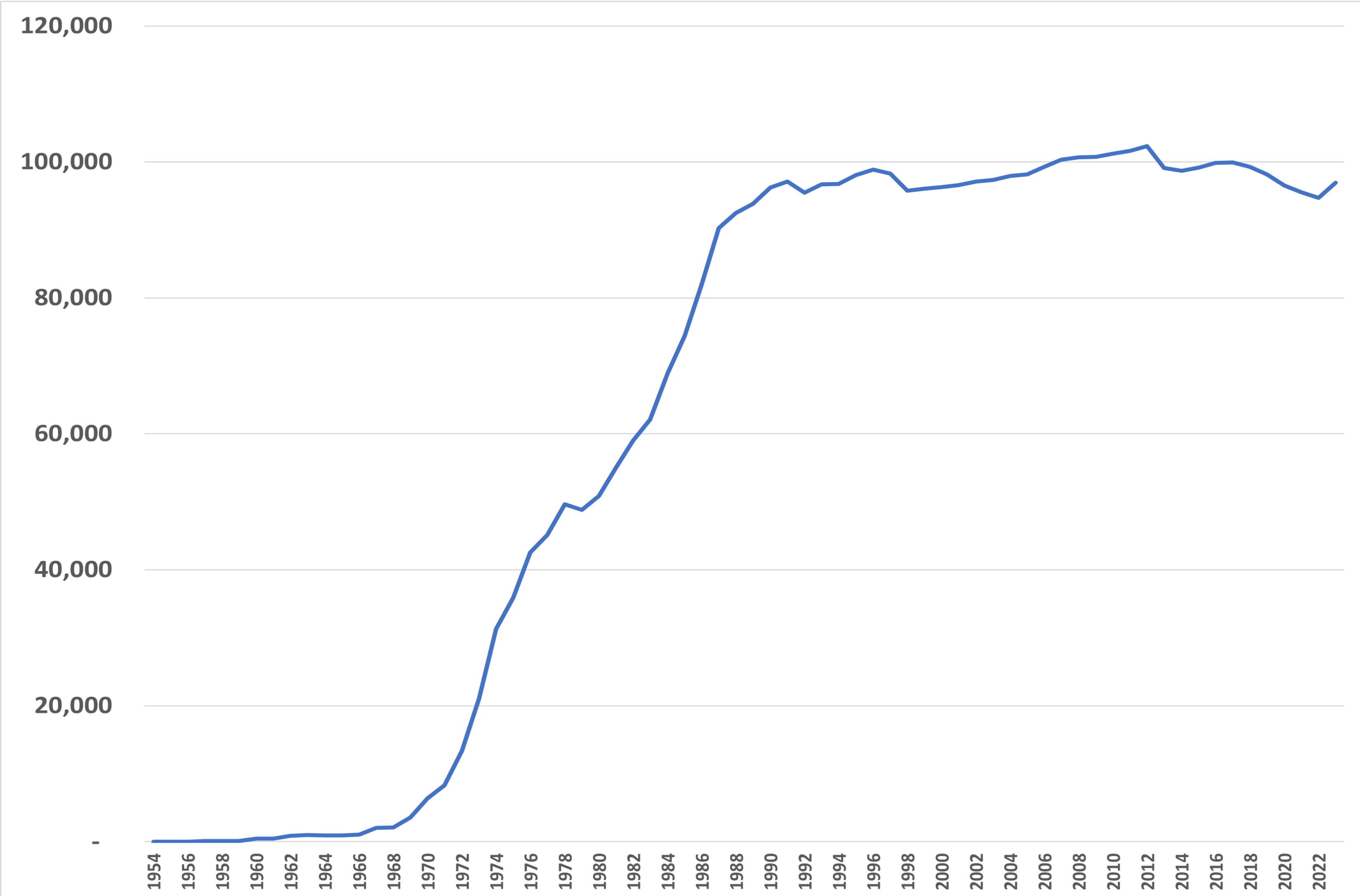
- Base-load mode due to economic dispatch
  - Operating regimes have been fine-tuned to
    - Increase operating performance
    - Decrease operating/fuel costs
  - Supports the conclusion that nuclear is base-load only
- Nuclear units ***can*** operate flexibly, but with
  - Lower electricity output, lower revenue, lower profits
  - Higher generating costs
  - Different operating regimes
  - Increased risk of unplanned outages/downtime

Nuclear flexible operation examples

- Bruce Power fast-response output change
- French nuclear power fleet load following
- Columbia seasonal operation in Pacific Northwest
- EDF Energy's UK Sizewell B plant operated at 50% for 4 months in 2020 due to COVID-19
- Constellation (formerly Exelon) nuclear plants in Illinois reduce output when negative electricity market prices expected

U.S. nuclear capacity

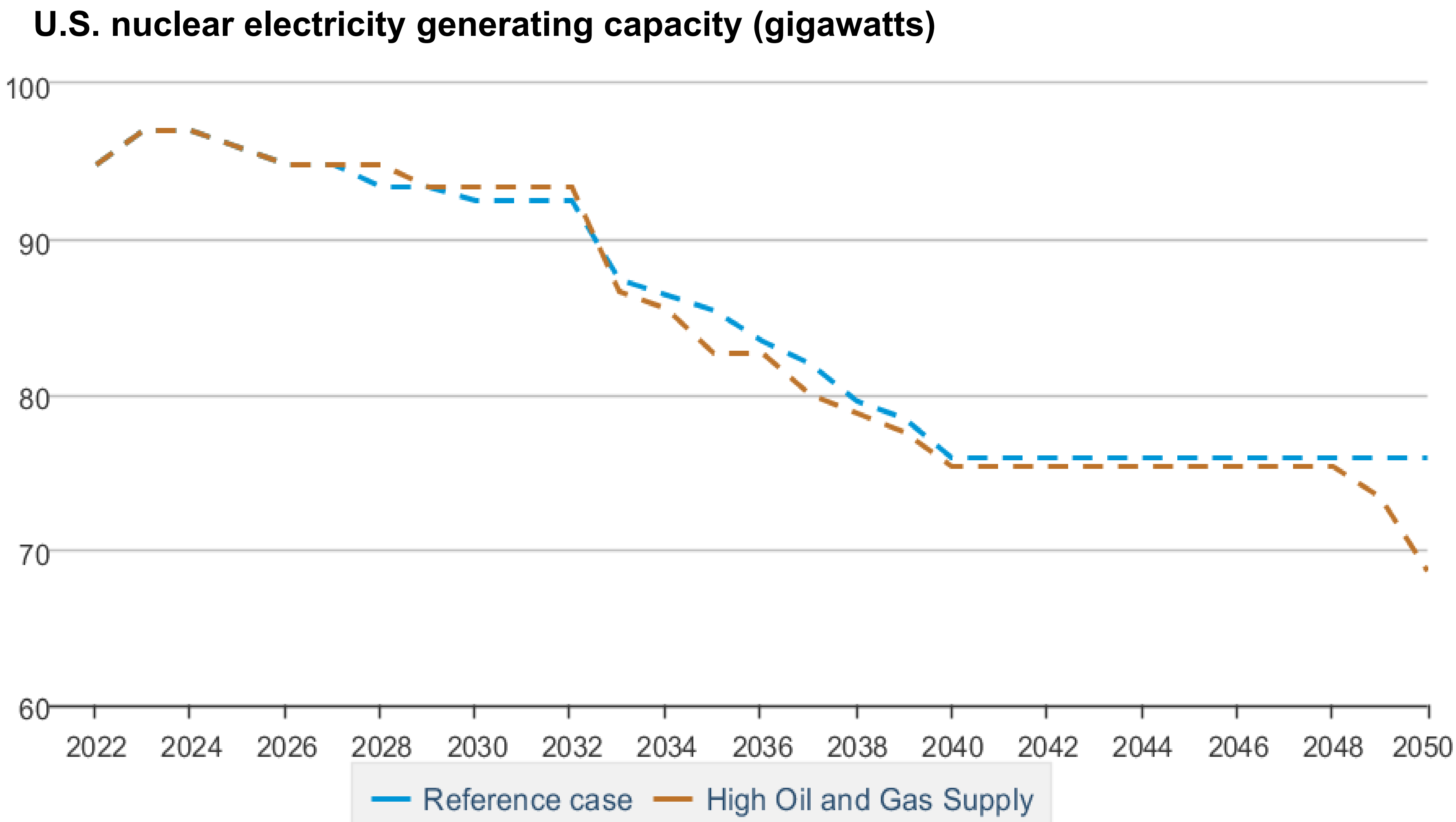
U.S. Situation



Source: International Atomic Energy Agency Power Reactor Information System data, with NECG analysis.

Projected decline of nuclear capacity

U.S. Situation



Source: U.S. EIA, Annual Energy Outlook (AEO) 2023; ***assumes many U.S. nuclear plants operate longer than 60 years***.

NRC license applications

U.S. Situation

- COL Applications for 29 reactors (only 1 after 2009)
  - COL issued
    - 2 - Operating units (Vogtle 3&4)
    - 6 - **Utility build plans on hold***
    - 6 - Terminated
  - COL Suspended (4), Withdrawn (10), or Denied (1)
- 12 (13?) Design Certification applications
  - 8 approved, including NuScale 50 MWe
  - 3 suspended or withdrawn; 1 in process
  - NuScale 77 MWe (not listed on NRC website?)

* **AP1000**: Turkey Point 6&7, W. S. Lee 1&2; **ESBWR**: Fermi 3 and North Anna 3

Factors influencing U.S. nuclear

U.S. Situation

1: Federalist form of government

2: Investor owned utilities

3: Market nuclear power

4: Electricity industry reform

5: Market Conditions

1: Federalism

U.S. Situation

1: Federalist form of government → 2: Investor owned utilities → 3: Market nuclear power → 4: Electricity industry reform → 5: Market Conditions

Sharing of power between national and state governments

National energy policy applies to
- Interstate electricity transactions
- Wholesale electricity markets that cover more than one state

States retain control of
- Regulated electricity companies and retail electricity sales;
- Approval of electric generation facilities (noting NRC authority over nuclear); and
- Mandates to generate or purchase power from renewable (or nuclear power).

Federalism and nuclear power in the courts
- PG&E v. State Energy Resources Comm'n – 1983 (no nuclear without SNF approach)
- Entergy Nuclear Vermont Yankee v. Shumlin – 2013 (state can't require below-market PPA)
- Coalition for Competitive Electricity v. Zibelman – 2018 (ZEC program not prohibited)

Different from unitary form of government in other countries

2: Investor-Owned Utilities (IOUs)

U.S. Situation

1: Federalist form of government | **2: Investor owned utilities** | 3: Market nuclear power | 4: Electricity industry reform | 5: Market Conditions

Entrepreneurial beginnings – electric lighting companies in cities

- Natural monopoly concept led to city franchises
- City franchises grow into state utility regulation of monopoly utilities

By 1920, most states had regulated electric utility laws

- Investor-owned regulated utilities (IOUs) under traditional model (i.e., obligation to serve, cost recovery, monopoly service area, and vertical integration)
- Debate continues about IOU approach vs public power

Today, the U.S. has a well-developed electricity industry

- Traditional approach resulted in large capital deployment and national grid
- IOUs under state regulation + public and federal power + electricity markets

Other countries did this with government-owned electricity sector (France, UK, Russia, China, UAE, etc.)

3: Market-based private nuclear power

U.S. Situation

1: Federalist form of government	2: Investor owned utilities	3: Market nuclear power	4: Electricity industry reform	5: Market Conditions

Manhattan Project (under U.S. Army) - 1942

Atomic Energy Act of 1946

- Government control of nuclear power under the Atomic Energy Commission

Atomic Energy Act of 1954

- Created a leading role for private utilities and private vendors

Result: The U.S. has mostly private *owners* and *builders* of nuclear power plants

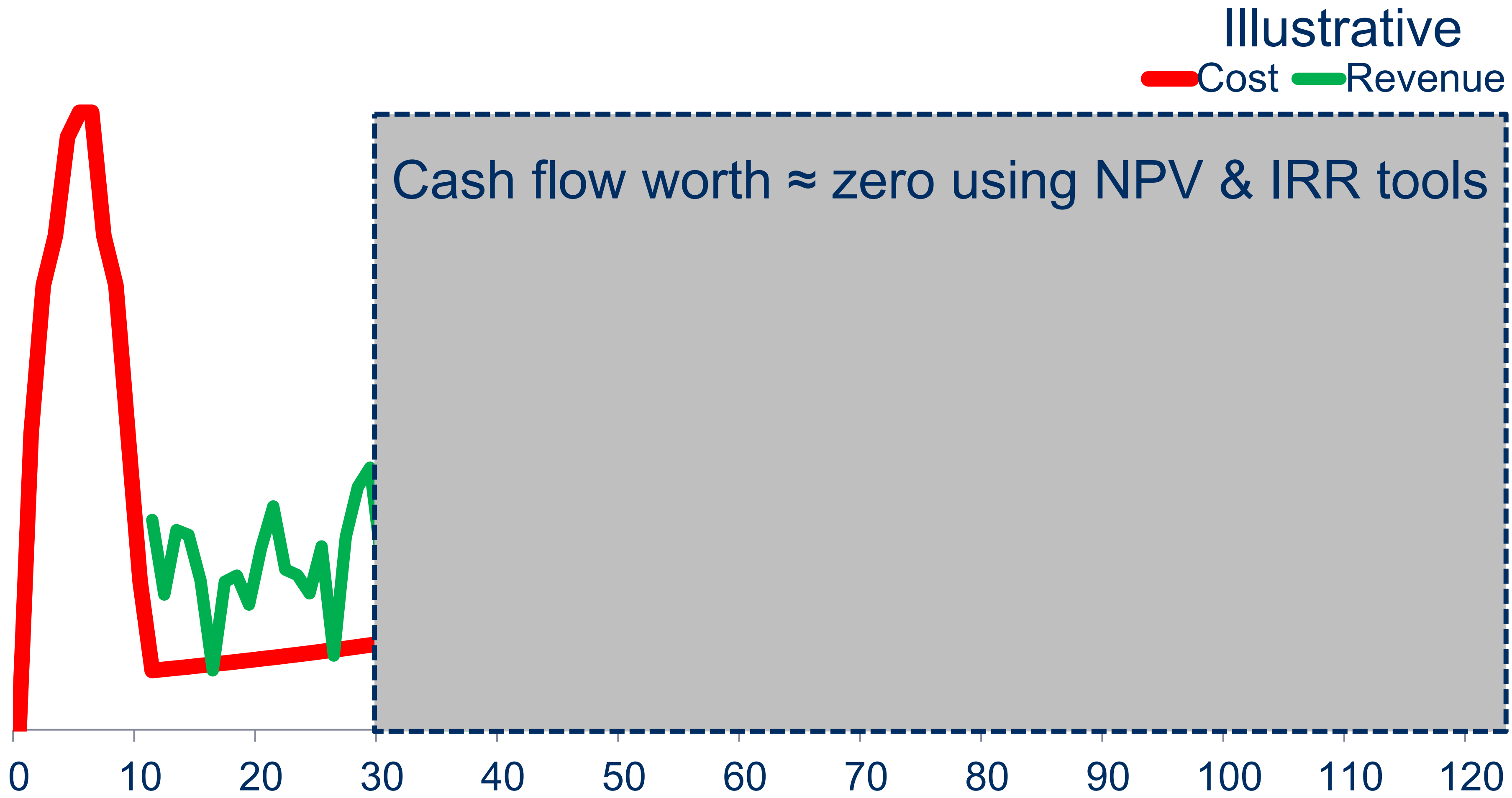
Massive U.S. nuclear build, but with some issues

- Only about 1/3 of planned/started nuclear projects were placed into commercial operation
- Cost overruns, delays, projects canceled or abandoned, with shareholder disallowances
- One-off plants & multiple vendors (i.e., no standard design or fleet build)

U.S. has a market-based nuclear industry, different from the government-owned nuclear industry in other countries

Market nuclear projects hard to finance

U.S. Situation



Private vendors

U.S. Situation

- Each supply chain level adds contingency + profits
  - Higher total cost
  - Longer schedules
  - Increased contractual complications
- Completion risk = cost overruns + schedule delays
  - Completion risk is key issue for nuclear power plants
  - Private / shareholder-owned vendors
    - cannot take completion risk
    - may not be able to pass this on to EPC contactor or buyer
  - Only state entities (buyers or sellers) can take this

4: Electricity Industry Reform

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U.S. Situation

1: Federalist form of government	2: Investor owned utilities	3: Market nuclear power	4: Electricity industry reform	5: Market Conditions

Electricity Reform and Restructuring

- New wholesale electricity markets with competition in generation
- FERC led U.S. electricity reform process
- BUT, each state
  - Decided if and when to implement reforms and restructuring
  - Had its own approach to restructuring of utility industry
- Public power was and is largely outside these reforms

U.S. has mix of Traditional & Market States

- U.S. nuclear fleet is mix of regulated, public power, and merchant plants

Private development of new nuclear power plants, either as merchants or as regulated IOU projects, is not likely without changes

U.S. before electricity reform

- Up to 1990 – Traditional Approach
  - Regulated, vertically-integrated, monopoly utilities
  - Prices based on system total average cost
- In some U.S. states - Electricity Restructuring
  - Bid-based wholesale electricity markets were created
  - Unregulated, non-utility generators
  - Unregulated retail service providers
  - System Marginal energy prices

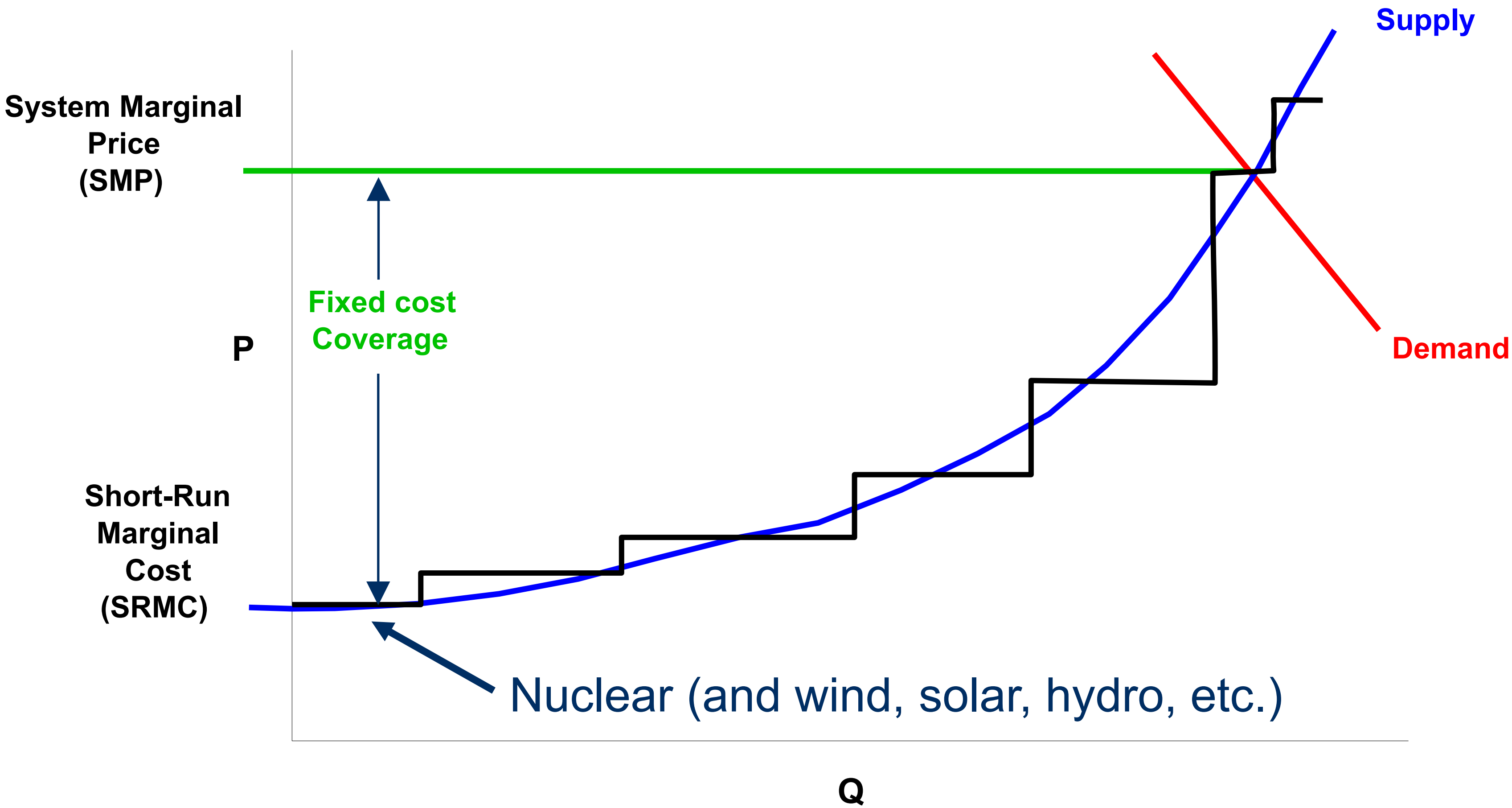
Good background on this topic: "*The U.S. Electricity Industry After 20 Years Of Restructuring*" by Severin Borenstein and James Bushnell, Working Paper 21113, http://www.nber.org/papers/w21113

State-specific industry reform

U.S. Situation

Electricity Markets – SMP & SRMC

One Illustrative trading period



Drivers of electricity reform

U.S. Situation

- **Ideology** – Natural monopolies might be more efficient if some sectors were subject to market forces and competition (failure of Soviet Union)
- **Dissatisfaction** – Regulation or government ownership was seen as delivering higher costs and lower service quality (compared to promises of a reformed electricity industry)
- **Early success** – (1) privatization and deregulation in other industries, and (2) seemingly successful electricity reforms in other countries
- **Shift in institutional power** – Reforms could shift control of the electricity industry from utilities and states to private industry and federal regulators
- **Rent-seeking** – Consumers seek lower costs, companies seek opportunities to earn profits, federal regulators seek greater power

* See: "*Privatization and Deregulation, moving from Monopolies to Markets,*" Edward Kee, 2002, https://nuclear-economics.com/wp-content/uploads/2016/01/2002-01-01-Monopolies-to-Markets-PA-Viewpoint-on-industry-restructuring-EDK.pdf

System Condition at market start matter

- Electricity reform with excess capacity
  - Victoria Australia, for example
  - Starting market prices relatively low
  - Generators respond by closing
- Electricity reform with little excess capacity
  - California, for example
  - Starting market prices relatively high
  - Drives generator new entry

Wholesale electricity markets do not value some important nuclear attributes

- Electricity market prices are set by marginal bid in each trading period

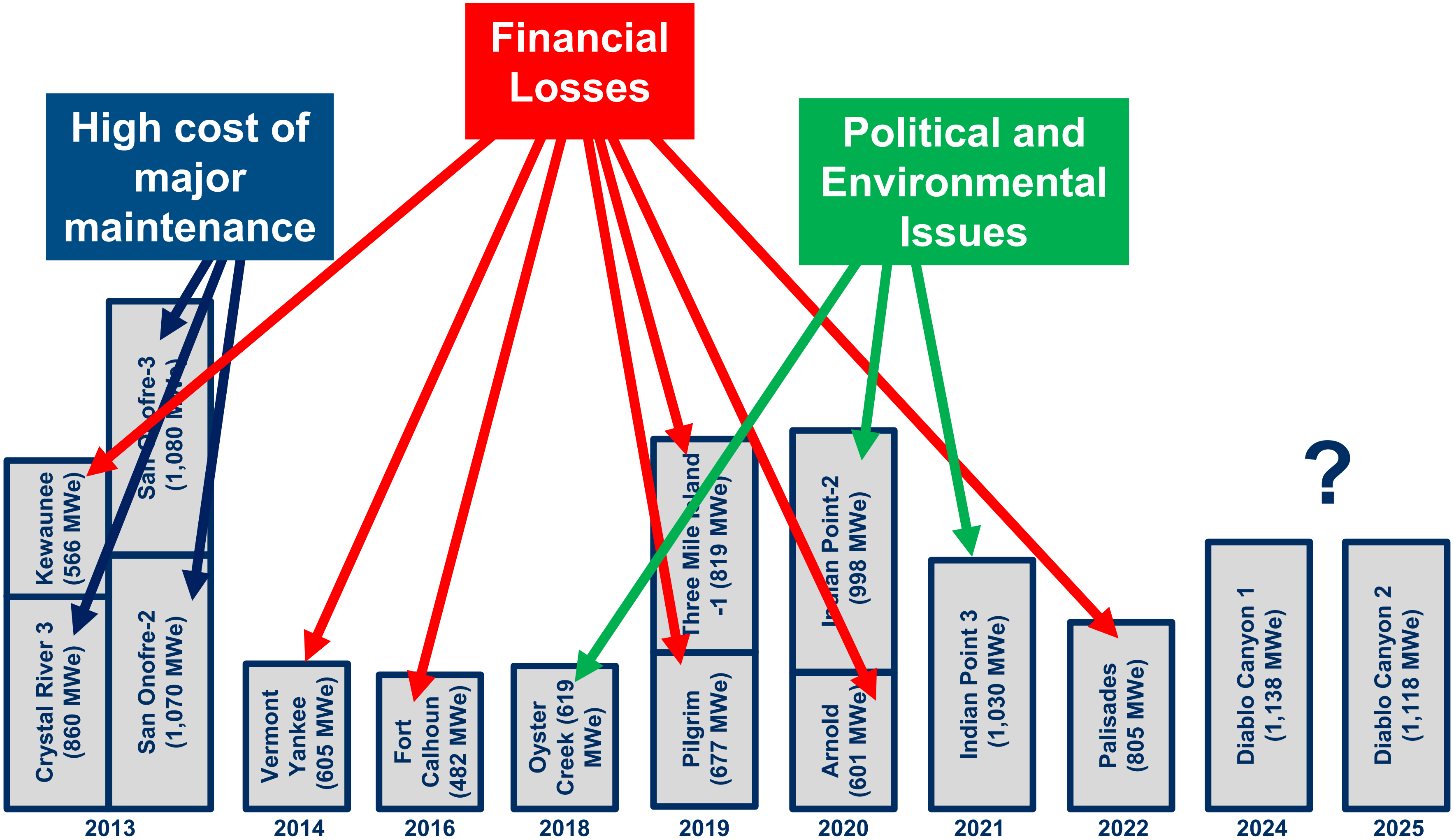
- Nuclear attributes not reflected in market prices
  - Carbon or other emissions (Carbon tax?)
  - Reliable operation (Capacity markets?)
  - Compact size / low land use
  - Low view-shed impact
  - Long-term operation

U.S. Merchant Nuclear - typical deal

- Divestiture or restructuring of nuclear as part of state industry reform approach
- Nuclear plants sold/transferred with a PPA
  - ~10 years (e.g., to end of 40-year operating license)
  - Prices equivalent to costs projected before sale
- New nuclear power plant owner
  - invested in upgrades, uprates, and license renewals
  - Sought financial upside after end of PPA term
  - BUT, when PPAs ended, power prices were low

U.S. nuclear power closures

U.S. Situation



5: Market Conditions

U.S. Situation

1: Federalist form of government

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5: Market Conditions

U.S. has a large existing grid system and generation portfolio

In market states, MCP approach links electricity markets to market conditions

- Close link between electricity market prices and natural gas prices
- Link between local conditions and nodal electricity market prices

Electricity market prices since 2014 not helpful for nuclear power

- Low (and even negative) prices in bid-based wholesale electricity markets due to
  - Low natural gas prices,
  - Overbuild of natural-gas-fired power plants
  - Low demand growth, and
  - High penetration of renewables

Some merchant nuclear power plants retired early due to financial losses and no new merchant nuclear plants built

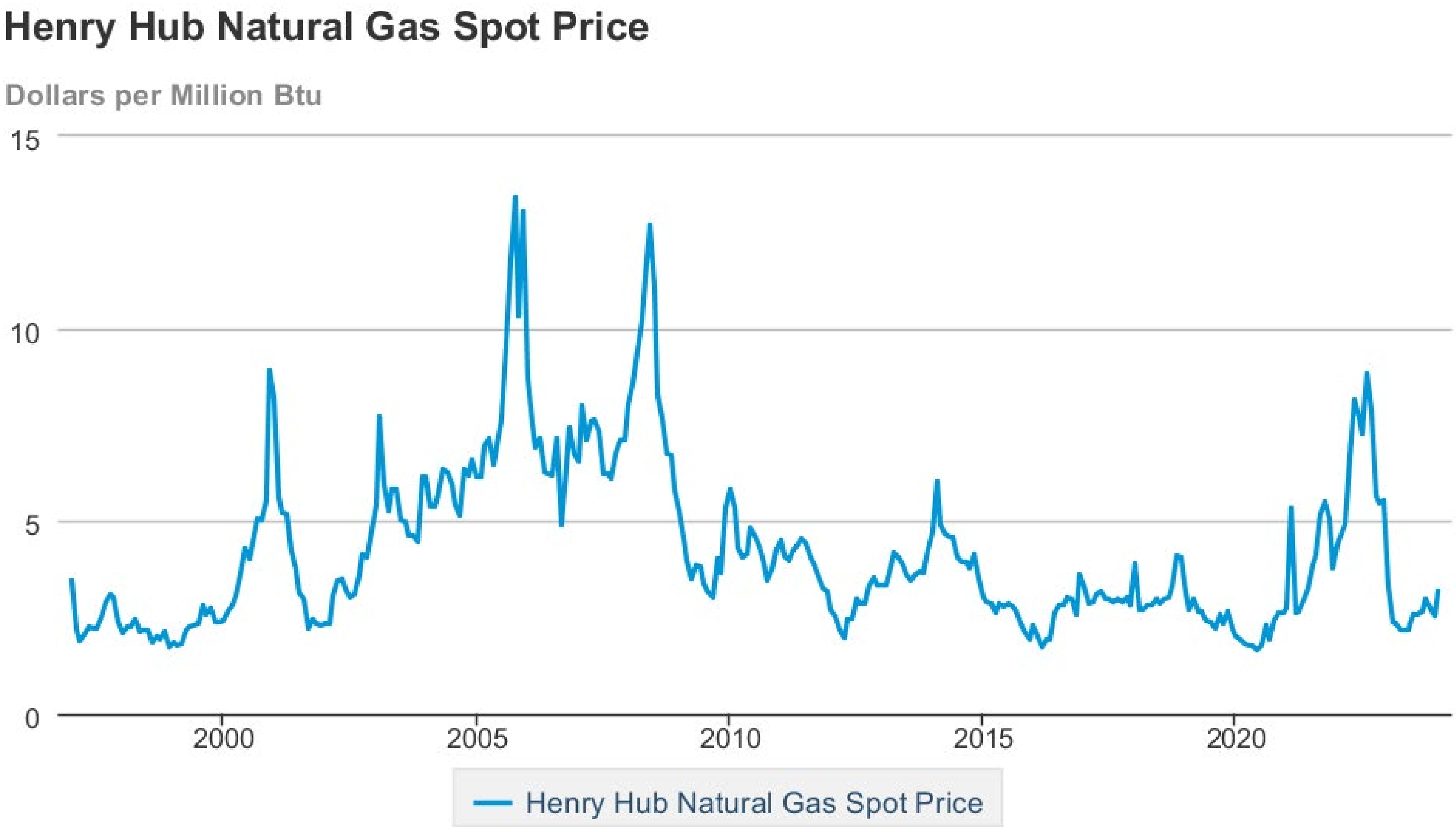
Electricity prices linked to natural gas

U.S. Situation

- Extensive natural gas pipeline network in U.S. and Canada
- High deployment of natural gas generation
  - Simple-cycle peakers + CCGT units
  - IPP companies overinvested, with financial failures
  - Natural gas is the basis for system marginal cost
- Natural gas plant dispatchable operation
  - Technically feasible
  - Economically sensible (i.e., merit order dispatch)

U.S. Natural Gas prices

U.S. Situation



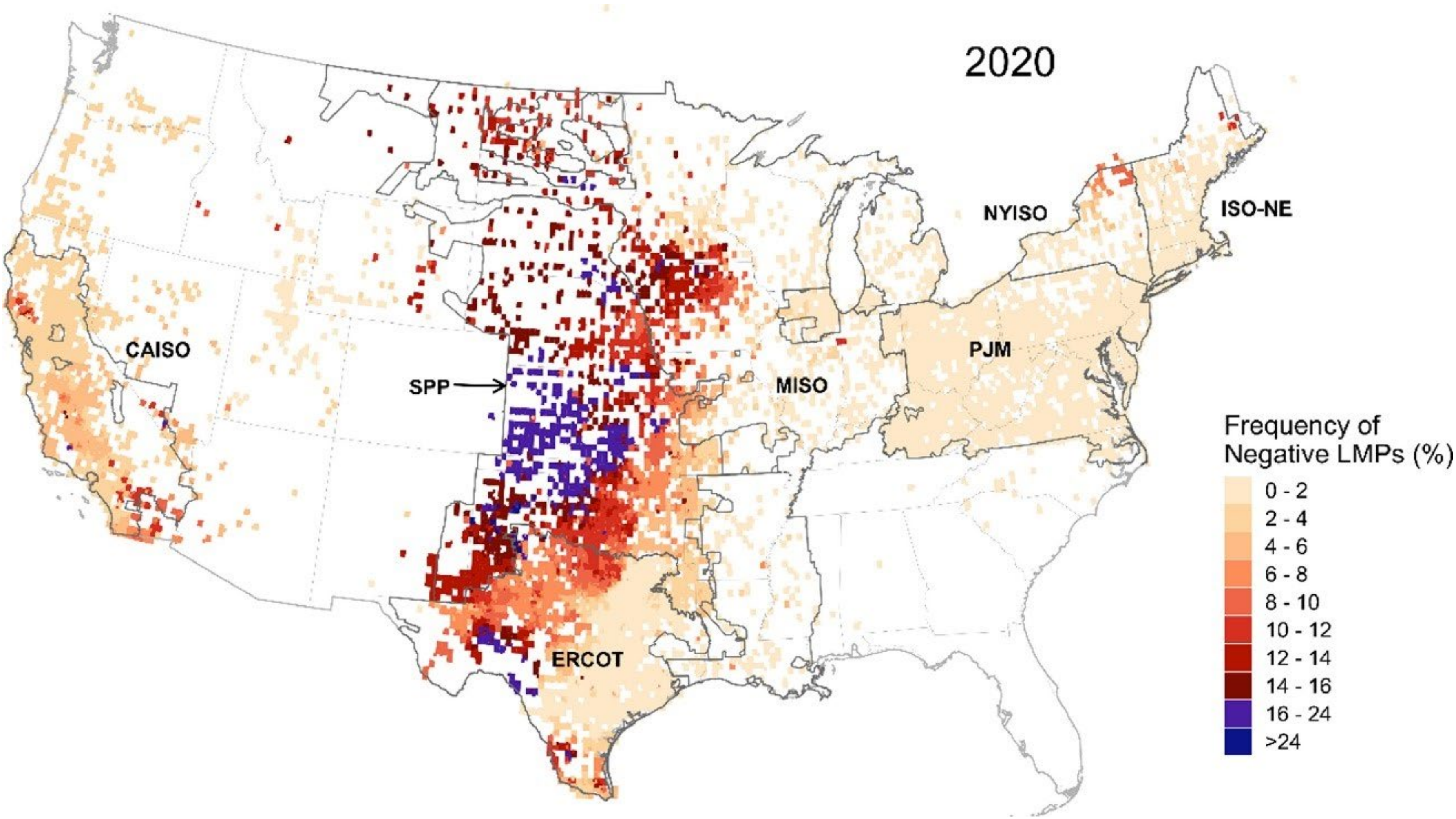
Negative Spot Prices

U.S. Situation

- Allowed in most electricity markets
- Negative prices happen when
  - Inflexible generator bids > demand in a trading period
  - Generators withdraw, if possible, to reduce supply
  - Price-sensitive users increase demand, if possible
- Nuclear power plants
  - Operated at full output between refueling outages
  - Negative spot price means nuclear plants pay to deliver power to the market operator

Negative Spot prices

U.S. Situation



Current U.S. federal policy approaches

- Rely on a market approach to nuclear power, with focused government incentives
- Try to keep existing nuclear in operation
  - Avoid financial early retirement
  - License renewal and uprates
- Restart closed nuclear units (e.g., Palisades and others in SafStor decommissioning)

Federal institutions

U.S. policy options

- Federal Energy Regulatory Commission (FERC)
  - Oversees wholesale electricity markets
  - Electricity market governance = participants
- Federal legislation
  - EPAct of 2005, CNC, Inflation Reduction Act
- DOE programs
  - Grants, cost-share, ARDP, CNC, Loan Program Office
- Export assistance
  - USTDA, EXIM, DFC, State Department

State efforts

- State Zero-Emission Credits (ZECs)
  - New York, New Jersey, Illinois, Ohio
  - Load-serving entities pay for credits to supplement electricity market revenue for nuclear plants
  - Based on clean electricity but politics about jobs
- States classify nuclear power as renewable, so renewable mandates and credits would apply
- State utility laws and regulations to encourage new nuclear (e.g., Georgia and Vogtle 3&4)

Nuclear Power Hacks

- Age of Miracles Podcast (https://ageofmiracles.co/)
- Identifying problems with nuclear power (e.g., high capital cost, long time to build, inflexible operation, etc.)
- Trying to solve these problems by re-thinking / hacking nuclear power
  - Reactor and power plant designs
  - Business models

Hacks I would like to see

- Reduce nuclear capital cost, time to build, and completion risk, while keeping benefits
- Make nuclear fuel a marginal cost
- Allow long-term operating flexibility in U.S.
- Develop a real fleet build approach in the U.S.
- Implement a carbon tax
- Make zero-carbon electricity markets work

Summary

- U.S. nuclear capacity will decline
  - Stalled by project economics and market approach
  - Will not double or triple by 2050
- New reactor designs offer promise, but
  - Market approach and project economics are issues
  - Implementation, licensing, and market entry difficult
- Need fundamental changes in
  - Electricity industry and markets
  - Nuclear business models
  - Role of government

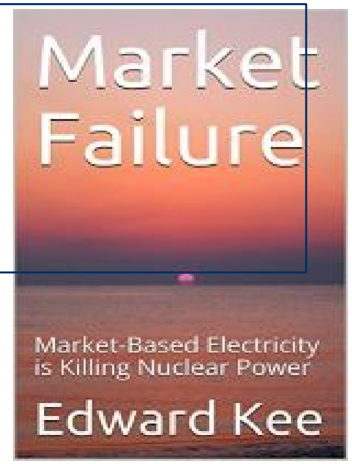
More reading

2014 article: *“**Rescuing U.S. Merchant Nuclear Power: Advancing National Security, Economic, Energy, and Environmental Imperatives**”* **- *https://nuclear-economics.com/wp-content/uploads/2014/08/2014-04-EJ-Merchant-nuclear-rescue-article-Kee-Zoli.pdf***

American Nuclear Society Special Committee ***2016 Toolkit:***
https://thompsondotenergy.files.wordpress.com/2016/12/ans-nis-toolkit-v2.pdf

2021 ***Market Failure*** book

Free PDF version:
https://nuclear-economics.com/market-failure-book-pdf/



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Edward Kee

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