Innovation Pathway Study:
U.S. Commercial Nuclear Power

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Executive Summary

The nuclear energy sector has one of the most idiosyncratic histories of research, development, demonstration, and deployment among widely-used energy technologies in the U.S. The unique attributes of nuclear energy and fissile materials, the historical context in which nuclear technologies were introduced, and institutional attributes of the post-war U.S. economy all contributed to the unprecedented growth and then sudden cessation of nuclear power investment and deployment in the 1960s, 70s, and 80s. This study identifies four distinct eras of nuclear power deployment, evaluates the primary factors motivating the trends in each era, and identifies key takeaways in order to distill a better understanding of energy technology innovation processes.

Key Takeaways for Energy Innovation

The federal government played an instrumental role in enabling the development and deployment of commercial nuclear power technologies. In addition to owning a monopoly on fissile materials and exercising strict control over atomic energy research immediately following WWII, the following federal factors enabled nuclear power innovation:

- Federal policy directed the development of commercial nuclear technology and incentivized utilities to invest in nuclear power. The stated purpose of this policy was twofold: to unlock economic benefits of low-cost energy for American industry, and to ensure American technological competitiveness in atomic energy.
- R&D conducted by the Atomic Energy Commission (AEC) was substantial, and comprised approximately 20% of all federal government R&D spending in the immediate post-war era (falling to ~10% by the early 1960s). Power reactor development averaged around 40% of AEC R&D.
- The subsidies afforded by Price-Anderson Act liability indemnification are potentially substantial, although highly uncertain. Through 2005, P-A subsidies are estimated to be at least as valuable as AEC's cumulative R&D budget for civilian power reactors for the period 1954–1972

Nuclear power deployment progressed rapidly from experimental technology to federally-owned and operated experimental projects, federally-subsidized demonstration-scale power plants, and finally full-scale privately-financed commercial deployment. Despite the novel and unknown physics, complex technical challenges, radiation safety concerns, and national security risks, federal investments in atomic energy R&D delivered fully-private investment in commercial power plants 21 years after the Chicago Pile-1 first achieved a critical fission reaction. In the 12 years following the first private order, another 222 GW of nuclear capacity was ordered. The following factors enabled this rapid growth:

- The AEC Power Reactor Demonstration Program (PRDP) was designed to create a market for commercial nuclear power by bringing together successful experimental reactor designs, private-sector NSSS manufacturers, and electric utilities from across the country.
- High rates of growth in demand for electricity in the years prior to and during the deployment of commercial nuclear power created an economic environment in need of continuing capacity expansion and friendly to large baseload power plants.
- Turnkey (i.e., fixed-cost) pricing offered by GE and Westinghouse starting in 1963 reduced uncertainty associated with nuclear power and secured both companies their first full-scale commercial orders. As a result, GE and Westinghouse and their preferred reactor designs

became industry leaders. However, both companies sustained significant losses on the 14 turnkey plants, and the rapid expansion that followed was marked by underestimation of construction risk.
- Optimistic assumptions about economies of scale and the low prices of turnkey plants led many utilities to underestimate the cost of nuclear power plants. The lack of accurate operational and cost information led many utilities to order plants without turnkey contracts.

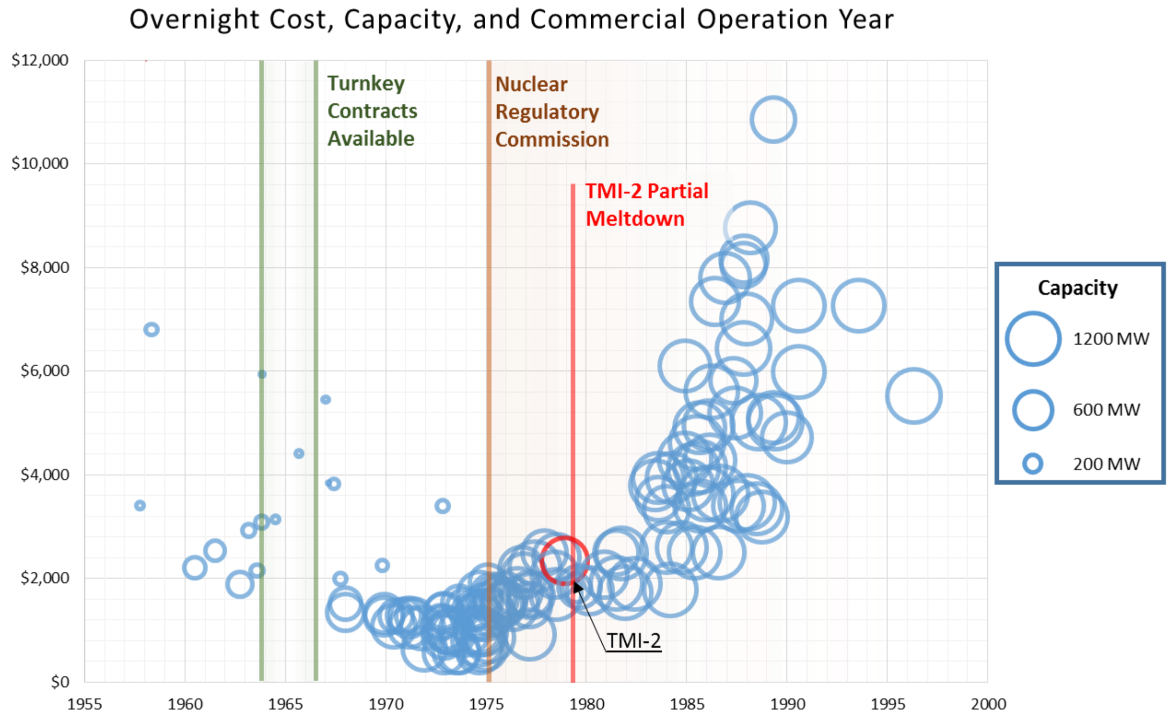
Market competition did not differentiate the designs of NSSS manufacturers, most likely due to the fact that real construction and operating cost information for the earliest commercial plants was not available until after most existing plants had already been ordered. For Light Water Reactors (LWRs), the rate of growth of nuclear power plant orders was sufficiently fast that by the time the first full-scale commercial Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) plants had come online, 70 GW of new nuclear capacity had already been ordered. By 1975, growing construction costs and delays likely informed the end of new nuclear orders, but all four major NSSS manufacturers continued to take new orders up to that point. Although LWR technologies out-performed other reactor technologies in AEC experimental and demonstration reactor rounds, these technologies were downselected by AEC prior to commercial competition. Differences between BWR and PWR designs did not detectably enable or disadvantage any individual company in the marketplace. Potential factors affecting competition include:

- Alternative nuclear reactor technologies (including Heavy-Water Reactors, Fast Breeder Reactors, Sodium-Graphite Reactors, and Organic Moderated Reactors) were not successful in the U.S., primarily because in both AEC experiments and demonstration reactors, LWR technologies established the most economical and reliable operations. After the failure of alternative-technology reactors in the 2nd round of demonstration plants, AEC largely focused its efforts on improving LWR technologies.
- The period during which U.S. utilities purchased nuclear power plants was relatively brief. All commercial U.S. nuclear power plants were purchased in the twelve years from 1963 to 1975. Because the earliest commercial plants were not complete until 1968 and 1969, utilities had very little pricing or operational information with which to select reactor technologies, manufacturers, or engineering or construction firms. EIA analysis shows that utilities consistently underestimated plant costs.
- Real costs of nuclear power plants built by the four major NSSS manufacturers show that prices are substantially similar on a per unit of capacity basis. However, the rapid escalation in reactor costs during the period of reactor construction makes averages over the entire period less reliable.

Construction delays were the direct cause of the "reverse learning curve," but this analysis of existing quantitative data cannot discern to what extent the various potential causes of increases in construction lead times are to blame. The pattern of increasing real construction costs and lead times holds through the entire period of commercial nuclear power deployment. The likely contributors to the "reverse learning curve" include:

- As a new technology, deployment of nuclear power meant that consumers included many new entrants to market, most with no experience planning or operating power plants as capital-intensive or technically complex. Approximately half of utilities investing in nuclear units purchased only one unit (one quarter bought two, the remaining quarter bought three or more). Only 1/10th of utilities with nuclear plants served as own construction manager or architect-engineer. However, the relative experience of construction managers was not

- Regulatory independence and safety concerns required improved designs and increased depth of safety margins. Anecdotal evidence from early PRDP licensing demonstrated that AEC was internally conflicted between its roles of promoting nuclear power deployment while also ensuring the safety of new plants and designs. After 1974, Nuclear Regulatory Commission (NRC) exercised oversight independently, potentially increasing regulatory compliance costs. The partial meltdown of Three Mile Island Unit 2 in 1979 also caused new safety regulations that applied to reactors both under construction and already complete.
- Attempts to benefit from economies of scale produced larger reactors, but required new, more complex designs. EIA analysis of reactor size found that if construction lead times are held constant, larger reactors produce power at a lower price. But the same analysis also found that larger reactors increase construction times sufficiently such that reactor size is positively correlated with higher costs per unit of capacity.



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Glossary

A-C	Allis-Chalmers
ACRS	Advisory Committee on Reactor Safeguards
AEA	Atomic Energy Act (of 1946 or 1954)
AEC	U.S. Atomic Energy Commission
AMF	American Machine & Foundry
ANL	Argonne National Laboratory
B&W	Babcock & Wilcox
BWR	Boiling Water Reactor
CAP	Civilian Application Program
C-E	Combustion Engineering
CVNPA	Carolinas-Virginia Nuclear Power Associates
DoD	U.S. Department of Defense
DOE	U.S. Department of Energy
EBR-1	Experimental Breeder Reactor 1
ECCS	Emergency Core Cooling System
ERDA	Energy Research and Development Administration
ESADA	Empire States Atomic Development Associates
FBR	Fast Breeder Reactor
GA	General Atomics
GE	General Electric
GHG	Greenhouse Gas
GNEC	General Nuclear Engineering Corporation
GNF	Global Nuclear Fuels
HTGR	High-Temperature Gas-Cooled Reactor
HWR	Heavy Water Reactor
INL	Idaho National Laboratory
IPP	Independent Power Producer
LCOE	Levelized Cost of Energy
IPP	Independent Power Producer
JCP&L	Jersey Central Power and Light
LANL	Los Alamos National Laboratory
LWR	Light Water Reactor
MW	Megawatt(s)
NE	Nuclear Energy
NEPA	National Environmental Policy Act
NEPO	Nuclear Energy Plant Optimization Program
NEUP	Nuclear Energy University Program
NG	Natural Gas
NP2010	Nuclear Power 2010
NPP	Nuclear Power Plant
NRC	Nuclear Regulatory Commission
NRTS	National Reactor Testing Station
NSSS	Nuclear Steam Supply System
OMR	Organic-Moderated Reactor
ORNL	Oak Ridge National Laboratory
P-A	Price-Anderson Act
PECO	Philadelphia Electric Company
PG&E	Pacific Gas & Electric Company
PRDC	Power Reactor Development Company
PRDP	Power Reactor Demonstration Program
PWR	Pressurized Water Reactor
R&D	Research and Development
RD&D	Research, Development, and Demonstration
SCE	Southern California Edison
SGR	Sodium Graphite Reactor
SMR	Small Modular Reactor
SRNL	Savannah River National Laboratory
SSFL	Santa Susana Field Laboratory
TMI-2	Three Mile Island Nuclear Generating Station Unit 2
TVA	Tennessee Valley Authority
YAEC	Yankee Atomic Electric Company

Introduction

This paper is part of a larger study that seeks to identify shared attributes and common causal factors among the pathways of technology innovation in the energy sector. The purpose of this study is to contribute useful analysis of historical experience to the Department of Energy's ongoing effort in energy technology innovation. This whitepaper provides data research and preliminary analysis of the development of commercial nuclear power generation, including early-stage R&D, reactor design and development, commercial demonstration plants, and wide-spread technology deployment. The scope covers the nearly 30-year period following passage of the Atomic Energy Act (AEA) of 1946 during which nearly all nuclear reactors in the United States were designed, tested, and deployed. Data presented here have been collected from a wide range of historical and contemporary sources, and complete datasets can be found in the associated data files.

This series of energy technology innovation studies is being conducted in order to distill lessons that can be generalized to other energy technologies, especially those currently in early stages of development or deployment. This paper is not intended to address the challenges and opportunities faced by any technology in particular, including current nuclear power technologies, (including Small Modular Reactors, Generation III+, and Generation IV designs), except by providing synoptic observations about the interactions of government agencies, academia, and the private sector as they relate to the development and deployment of a new energy technology. Additional papers in this series address technologies including smart grid, renewable energy technologies, and a literature review of innovation studies.

Background

Nuclear Energy Technologies in Brief

Nuclear energy technologies that have been successfully deployed in the United States share many common characteristics, and display little technological differentiation relative to the wide variety of reactor designs implemented around the world. For the most part, the reactors in use today were ordered and built in a brief period of time between 1963 and the mid-1980s. But the U.S. nuclear fleet has roots stretching back to the military research and federal policies immediately following WWII. Common characteristics of all operating NPPs in the U.S. include:

- Power plants are large baseload thermoelectric generation stations comprised of between one and three 500–1300 MW units
- All plants use low-enriched uranium fuel assemblies and control rod moderators
- Light water is used as both coolant and working fluid
- As a result of power generation, all plants produce radioactive waste products which must be safely stored, often onsite

The main technology variations among NPPs deployed in the U.S. is between Pressurized Water Reactors (PWRs) and Boiling Water Reactors (BWRs). Both systems are composed of a reactor core, containment vessel, and system for generating steam from the reactor's heat. Together these components are called a Nuclear Steam Supply System (NSSS).

- **Pressurized Water Reactors:** The most common type of reactor in both the U.S. and the world, PWRs use high-pressure water as the reactor coolant, which allows the water to reach a high temperature without boiling. PWRs have a steam generator where the high-temperature, high-pressure water exchanges heat with a low-pressure water loop, generating steam for power generation. In the U.S., Westinghouse, Combustion Engineering (C-E), and Babcock & Wilcox (B&W) were the primary manufacturers of PWR NSSSs

- **Boiling Water Reactors:** BWRs allow the cooling water to boil in the reactor core, directly generating useful steam. The steam produced in the reactor core is used to drive turbines (which must be radiation-shielded). Because BWRs require no steam generator, efficiencies are higher, and the reactor containment operates at a lower pressure than PWRs. General Electric (GE) was the primary supplier of BWR NSSSs in the U.S., and through its joint venture GE-Hitachi, GE continues to market BWR designs worldwide

Inherent characteristics about nuclear power differentiate the sector from all other electricity generating technologies and energy sources.

- Access to technology and materials have always been tightly controlled by federal government due to safety and proliferation concerns
- Nuclear energy research began as government-driven wartime program; transitioned to national laboratories, and gradually to private sector
- Nuclear energy research involved relatively little academic role until DOE-era
- Federal support of nuclear power has continued through all stages of technology development and deployment; the federal government shares the financial risk of accidents and carries the responsibility for resolving waste storage issues

Structure of the Nuclear Energy Industry

Brief descriptions of the different types of actors involved in the development and deployment of commercial nuclear power.

Nuclear Steam Supply System (NSSS) Manufacturers: These are companies with extensive pre-commercialization nuclear experience, often as a result of direct contracting for the Atomic Energy Commission (AEC). In addition to the four primary NSSS manufacturers in the U.S., four additional companies worked on experimental or demonstration reactors, and another six companies proposed or offered unsuccessful NSSS designs.

Table 1. Successful and unsuccessful power reactor manufacturers. Manufacturers in bold sold commercial reactors beyond the AEC demonstration program. Does not include military programs.[1] [2]

U.S. NSSS Manufacturers	Unsuccessful NSSS Manufacturers
Westinghouse	American Machine & Foundry (AMF)
General Electric (GE)	Nuclear Development Corporation of America
Babcock & Wilcox (B&W)	Foster-Wheeler
Combustion Engineering (C-E)	Ford Instrument Company
Allis-Chalmers (A-C)	Alcoa Products
Atomics International/North American Aviation	General Dynamics
General Nuclear Engineering Corp (GNEC)	
General Atomics (GA)	

Utilities (and other owners): Some of the first demonstration reactors involved split ownership by AEC and operating utilities, however during the period of largest nuclear deployment, utilities were the primary purchasers of NPPs. Because electric power monopolies had not yet been deregulated, no independent power producers (IPPs) purchased NPPs, although many reactors are currently owned by IPPs. In one case, the New York Power Authority, a state agency, purchased a reactor (James A. FitzPatrick).

Architect-Engineers: While NSSS vendors supplied reactor and steam-handling components, NPPs required engineers to select and prepare the site, design the balance of the plant, and integrate the NSSS. Engineering NPPs was substantially more complex than traditional thermoelectric power plants, and despite efforts to standardize designs, differences between individual plants and added complexity of larger plants are identified as likely sources of construction delays that increased NPP costs. In a small number of cases, utilities served as their own architect-engineer.

Construction Firms: Construction firms managed plant construction. As with engineering, some utilities such as Duke and the TVA managed their own construction exclusively. However, most utilities relied on construction management firms such as Bechtel, Daniel International, Ebasco, or Stone & Webster.

Fuel Suppliers: Today, fuel for U.S. is provided by one of two companies: Global Nuclear Fuels (GNF), and Westinghouse. GNF is owned by GE-Hitachi and supplies fuel assemblies for U.S. and global BWRs, as well as for the Canadian fleet of CANDU Heavy Water Reactors (HWRs). Westinghouse manufactures fuel assemblies for U.S. PWRs.

Regulators: Since before any research or power reactors had been constructed, the federal government tightly controlled the regulatory environment for nuclear energy R&D. Starting with the AEA of 1946, AEC served as both promoter and regulator of nuclear power. Through the Advisory Committee on Reactor Safeguards (ACRS), AEC oversaw the safety of NPP designs. In the early 1970s, as nuclear power was rapidly expanding, pressure to separate the research/promotional and regulatory roles of AEC resulted in the Energy Reorganization Act of 1974, which created the Nuclear Regulatory Commission (NRC) as the nuclear power regulator, and the Energy Research and Development Administration (ERDA) to carry on AEC's R&D roles. ERDA was later combined with the Federal Energy Administration to form the Department of Energy (DOE).

Other Actors: Other actors traditionally relevant to research and development of energy technologies (including academic researchers, private research labs, and state policymakers) did not play a substantial role in the development of commercial nuclear power.

History of Nuclear Energy Innovation in the United States

The history of commercial nuclear power in the U.S. can be divided into four "Eras," each encompassing large-scale trends, policies, and other 'primary factors' in the development and deployment of nuclear technologies. Although a data-driven approach was taken when investigating the factors that influenced Eras I and II, an investigation of Eras III and IV was not considered within the scope of this study. This study addresses the primary factors affecting Eras I and II, but Eras III and IV are also described below for context.

Era I: 1947–1963

Era I covers the basic scientific research to support controlled fission reactions, research and development of reactor concepts, designs, operation, and materials, and deployment of research reactors. The Era begins with the implementation of the AEA of 1946, which established the AEC, set civilian nuclear energy as a federal policy goal, and enabled early power reactor research. The period includes federal support (via AEC) for research, testing, development and demonstration of nuclear power reactors, and ends with the first order for a privately-financed full-scale commercial power reactor (Oyster Creek). Era I also includes AEC's contracting with companies that would go on to be the primary suppliers of commercial NSSSs, and selection of some of the utilities that would become major purchasers of NPPs. **Error! Not a valid bookmark self-reference.** presents a timeline of Eras I and II, including the major demonstration milestones and legislative interventions.

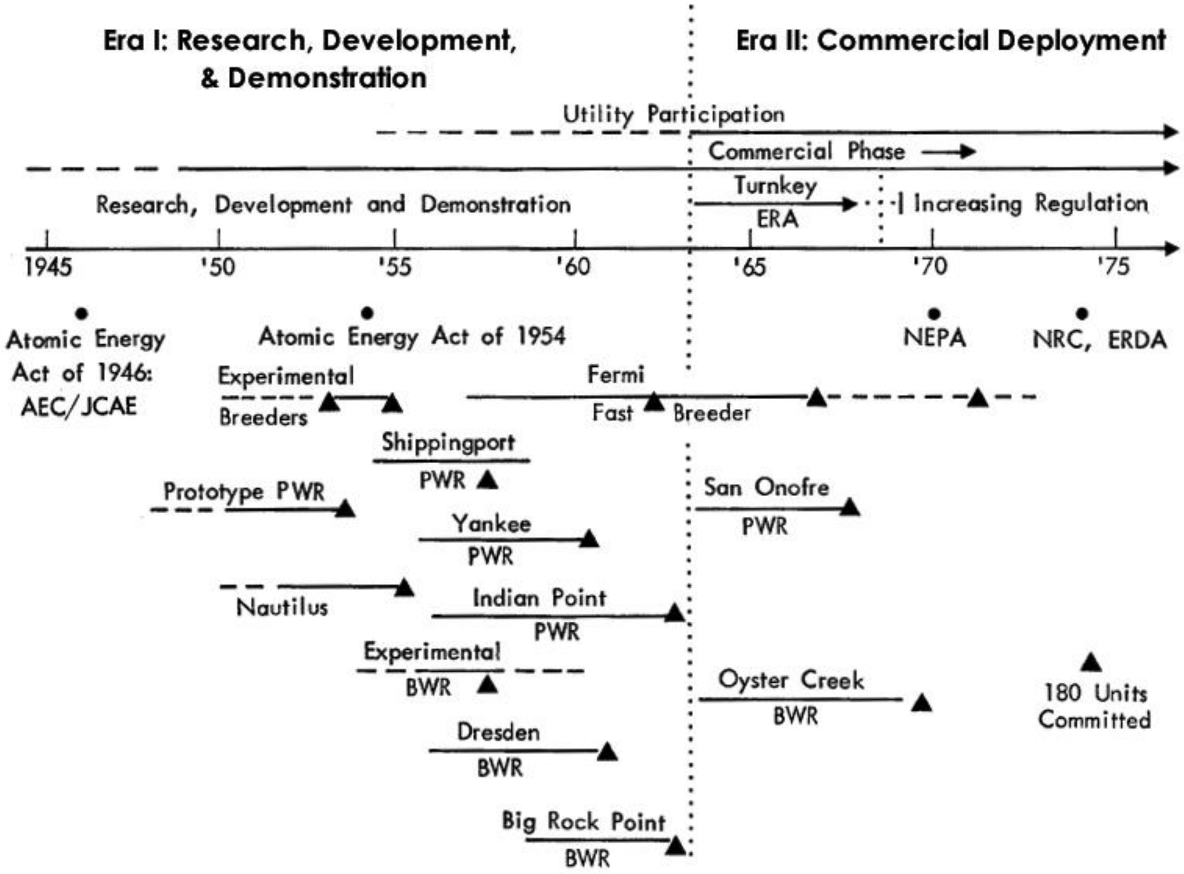

Figure 1. Timeline of nuclear energy power reactor research, development, and deployment in Eras I & II.[3]

Primary factors identified in Era I include:

- **Atomic Energy Acts of 1946 and 1954:** The AEA of 1946 established the AEC and set federal policy for civilian use of nuclear energy, including the explicit use of nuclear power for commercial reactors, however retained significant federal control over access to fissile materials, research data, and intellectual property. The AEA amendments of 1954 loosened these restrictions and directed AEC to begin licensing privately-owned power plants.

- **AEC R&D:** AEC R&D policies, programs, and funding created the basic scientific understanding of how to build a uranium-fueled fission reactor, control the reaction, and extract usable heat that could be used to generate electricity. After the 1954 AEA amendments, the Civilian Application Program (CAP) enabled the transfer of AEC and DoD research to private sector companies for use in commercial development of reactors.
- **AEC Demonstration Programs:** Following the AEA amendments of 1954, AEC implemented the Power Reactor Demonstration Program (PRDP)[a] to encourage utilities to partner with prospective NSSS manufacturers and AEC in order to gain crucial construction and operational experience.[4] [5] [6] The PRDP played a significant role in identifying the commercial readiness of various reactor technologies and provided GE and Westinghouse with sufficient confidence to offer commercial reactors.
- **Price-Anderson Act:** The 1957 law was intended to reduce liability risks associated with commercial nuclear power plants by setting a maximum liability for plant owners in case of accidents, above which the federal government would pay damages. The act was intended to temporarily address the inability of utilities to obtain insurance, however it has been continually extended and updated.

Era II: 1963–1975

Era II covers the period during which all operating NPPs were ordered.[b] Era II begins with Jersey Central Power and Light's (JCP&L) order for the Oyster Creek Nuclear Generating Station under GE's fixed-cost, "turnkey" pricing program. GE's turnkey pricing was emulated by Westinghouse, and inaugurated the first set of commercial NPP orders without any AEC role. The end of Era II is designated as 1975, after which almost no new orders were placed, and many standing orders were cancelled.

Primary factors identified in Era II include:

- **LWR Design Consolidation**: Successful PRDP NSSS manufacturers were anxious to promote successful LWR designs demonstrated by the PRDP, and the commercial readiness of GE's BWR and Westinghouse's PWR accelerated adoption of LWR designs and ensured the two companies' market leader positions.
- **Turnkey Pricing and Evolution of Costs:** Turnkey pricing — offered first by GE, and then by Westinghouse — significantly reduced the largest uncertainties in calculating financial risk of new investments in NPPs. Although both manufacturers took sizeable losses on turnkey plants, the 14 turnkey plants increased confidence in the technology sufficiently that new orders continued to increase after turnkey contracts were no longer offered.
- **Regulatory Factors:** Although federal control of nuclear power technology remained tightly-held, during Era II, rapid deployment of NPPs was in line with AEC and federal policy. Early regulatory costs were substantially lower than during later eras, especially costs associated with construction delays. By 1974, the NRC began to implement an independent regulatory program focused on increasing safety and reducing accidents.

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[a] This program is confusingly referred to as both the PRDP and the "Power Demonstration Reactor Program," or PDRP. Both histories and contemporary sources refer to the program using either name, but PRDP is used here.

[b] Watts Bar 2 started in October 2015, the first new NPP startup since Watts Bar 1 in 1996. Although the partially-completed plant was mothballed for decades, construction on the reactor was originally begun in 1973.

- **External Economic & Political Factors:** Era II spans a period of rapid growth in demand for electric power; over Era II, aggregate demand increased an average of 6.9% per year. However by 1975, demand growth dropped substantially, and has never reached the same rate since. Similarly, trends in environmental politics that would eventually impair nuclear power deployment began in Era II that were not fully felt until after 1975, including passage of the National Environmental Policy Act (NEPA), and formation of the NRC in 1974.

Era III: 1975–2000

Era III includes the completion of all remaining reactors ordered in Era II, as well as large numbers of cancellations of standing orders and of some plants already under-construction. After 1975, the escalation of real construction costs and growth of construction lead times (trends which began in Era II) combined with a decline in growth of electricity demand made many of the plants on order uneconomical. Era III also includes the dawn of the newly-independent NRC, the partial meltdown accident at Three Mile Island Unit 2 (TMI-2), and the subsequent introduction of additional safety regulations. The nuclear sector may have recovered as growth in demand for power recovered in 1977 and 1978, but external factors such as increasing financing costs, public opposition to nuclear power, and a second collapse in electricity demand growth in the early 1980s all worked against new investments in nuclear power. All nine plants ordered in Era III were cancelled.

Primary factors in Era III include:

- **Reverse learning curve:** The most significant reason for the abrupt end to new nuclear power was the realization of much higher construction costs and much longer lead times than plants completed in Era II. Plants completed after 1975 took an average of more than twice as long to complete as plants completed prior to 1975. And plants completed after 1985 had average costs more than three times those completed prior.[7]
- **Reductions in energy demand growth:** In Era II, annual growth of electricity demand averaged 7.4% per year, prior to the 1973 oil embargo. Era III growth never reached this rate, averaging 2.9% per year.[8]
- **Regulatory impacts on costs and lead time:** NRC responded to the TMI-2 accident by requiring changes to plant designs, including plants already under construction. The costs of these and other NRC regulations are an often-cited cause of the growth in costs and lead times.
- **Changing public opinions:** While expansion of nuclear power was a clear federal policy goal in Eras I and II, changing public opinion about the safety of reactors, the responsibility of radioactive waste disposal, and the risks of proliferation likely influenced Era III nuclear power policy.

Era IV: 2000–2016

Era IV covers the most recent history of nuclear power in the U.S. This period includes the revival of nuclear power with new, Generation III+ NSSS designs, regulatory reform, loan guarantees, and market improvements, as well as the ultimate failure of an anticipated 'nuclear renaissance' to flourish. Era IV federal involvement was driven by DOE's Nuclear Power 2010 program (NP2010), DOE loan guarantees for new plants, and NRC's efforts to streamline new reactor licensing by offering combined construction and operating licenses for new plants. Additionally, growing concerns about Greenhouse Gas (GHG) emissions and other air pollutants have increased interest in emissions-free nuclear power in order to help replace the retiring coal fleet. Market forces in Era IV were increasingly favorable until 2009, when the global recession and falling Natural Gas prices made new nuclear power less competitive.

Primary factors in Era IV include:

- **License extensions for existing reactors:** NRC has begun extending NPP operating licenses for 20-year increments, and many existing plants are expected to continue operating for a total of 60 years. NRC is currently considering a process for extensions beyond 60 years.
- **DOE/NRC incentives to reinvest in nuclear power:** Through the NP2010 program, DOE provided R&D and first-of-a-kind engineering for new GE and Westinghouse Gen III+ designs, and financed design certification with the NRC. Other supporting DOE programs include the Nuclear Energy Universities Program (NEUP) and the Nuclear Energy Plant Optimization Program (NEPO). DOE also provided loan guarantees worth $8.3 billion for the construction of two new Gen III+ units at Alvin W. Vogtle Electric Generating Plant. NRC also comprehensively reformed and streamlined a new reactor licensing process, and at its peak, was reviewing applications for 28 new units (although many have since been suspended or withdrawn).
- **Climate change risks:** Policies directed at reducing GHG emissions in the power sector (such as EPA’s Clean Power Plan) have increased interest in new nuclear plants, as well as helped to incentivize keeping legacy plants online.
- **Natural gas revolution:** New drilling and hydrofracking technologies have enabled economic extraction of large amounts of shale gas, causing dramatic decreases in near-term and long-term NG price projections. These changes have enabled utilities to replace retiring coal generation with NG-fired Combined Cycle (NGCC) plants at much lower costs and lead times than new nuclear plants, and with substantially less uncertainty; 2015 estimates of the Levelized Cost of Energy (LCOE) place NGCC at half the cost of nuclear power.[9]

Analysis & Discussion

Having reviewed the historical literature and identified primary factors driving the development and deployment of commercial nuclear power technologies, this analysis is focused on using quantitative and qualitative data to search for evidence of the effect and magnitude of these factors, and to distill key principles regarding energy technology innovation. This section is organized according to the development of nuclear energy through time (rather than according to importance).

Role of Atomic Energy Commission and other federal interventions

Due in part to the unique attributes of nuclear energy, and due in part to government policy, commercial nuclear energy could not have succeeded in the U.S. without the actions of AEC during Era I. This section will demonstrate the scale and importance of AEC RD&D in Era I for preparing the technology for rapid deployment in Era II.

Federal policy allowed commercial nuclear R&D, and provided for executive oversight and direction

Prior to the AEA of 1946, private-sector nuclear energy research was restricted, and government research efforts were centered in the Manhattan Project, and primarily focused on weapons. The AEA of 1946 created the AEC and shifted research goals to expand potential peaceful uses while also preserving strict government control over all atomic energy R&D and over all fissile materials. The AEA of 1946 was a product of compromise between interest in opening nuclear research to the private sector, and (primarily military) interest in keeping nuclear secrets secure. As a result the final version of the act declared among its purposes to create "A program assisting and fostering private research and development to encourage maximum scientific progress." However the act also created "A program for the control of scientific and technical information…" and "A program for Government control of the production, ownership, and use of fissionable material."[10]

Despite controls placed on access to information, the AEA of 1946 put in place the infrastructure to perform the fundamental physical, materials, and systems research necessary for nuclear power. The AEA directed the AEC to conduct research activities relating to "the theory and production of atomic energy" and the "utilization of fissionable and radioactive materials and processes … for all other purposes including industrial uses."

The AEA of 1954 reacted to the restrictions present in the 1946 act by loosening federal restrictions on access to fissile materials, federally-conducted research, and patent protections. The 1954 amendments also enabled the licensing of commercial nuclear power plants necessary to allow NSSS manufacturers, allow utility ownership of NPPs, and launch the PRDP. Table 2 explains some of the differences between the 1946 and 1954 acts.

Table 2. Comparison of AEA of 1946 and 1954 Amendments.[11] [12]

	Governance	Information/Patents	Fissile materials	Demonstration Program
AEA of 1946	**Civilian control:** independent commission (five members; civilians and military), AEC with four advisory boards (including one for industrial uses)	**Born Secret:** all information about NE tech (incl. weapons, materials, power) classified unless specifically declassified; disallowed all NE patents	**Federal Monopoly:** only AEC facilities may produce or possess fissile materials	**R&D only:** demonstration activities allowed under R&D activities
AEA Amendments of 1954	**Regulation & Licensing:** provided AEC powers to regulate private use of NE technologies and license commercial NE facilities	**Private Sector Access:** Allowed private access to restricted data, allowed patents of nuclear energy technologies (no weapons)	**Licensed Use:** AEC may license users of and distribute fissile materials; only AEC may produce fissile materials	**Demonstration Program:** Licensing structure created specifically for Power Reactor Demonstration Program

Federal policy enabled, encouraged, and incentivized the development, demonstration, and deployment of civilian commercial power reactors through several programs. Federal support produced initial proof-of-concept experimental reactors for power generation. The first nuclear reactor to generate electricity was the Experimental Breeder Reactor-1 (EBR-1), which began operating in August, 1951, less than 10 years after the first criticality experiment conducted by the Manhattan Project. Table 3 shows the wide range of power reactor technologies explored by AEC during Era I. Both leading LWR technologies are among the earliest experimental power reactors constructed by AEC (BORAX and S1W).

Table 3. Experimental Power Reactors through 1970.[13]

Designation	Owner	Location	Technology/Type	Start-Up
EBR-1	AEC	NRTS (INL), Arco, ID	Sodium-cooled, fast	1951
HRE-1	AEC	ORNL, Oak Ridge, TN	Aqueous homogenous solution (UO_2SO_4)	1952
BORAX-1	AEC	NRTS (INL), Arco, ID	Boiling Water Reactor (BWR)	1953
S1W	AEC	NRTS (INL), Arco, ID	Pressurized Water Reactor (PWR)	1953
BORAX-2, 3, 4	AEC	NRTS (INL), Arco, ID	BWR	1954
EBWR	AEC	ANL, Argonne, IL	BWR	1956
LAPRE-1	AEC	LANL, Los Alamos, NM	Aqueous homogenous (phosphoric acid)	1956
HRE-2	AEC	ORNL, Oak Ridge, TN	Aqueous homogenous solution (UO_2SO_4)	1957
VBWR	GE & PG&E	Pleasanton, CA	BWR	1957
SRE-PEP	AEC & SCE	SSFL, Santa Susana, CA	Sodium graphite	1957
MORE	AEC	NRTS (INL), Arco, ID	Organic cooled and moderated	1957
LAPRE-1	AEC	LANL, Los Alamos, NM	Aqueous homogenous (phosphoric acid)	1959
PRTR	AEC	Hanford Site, Richland, WA	Pressure tube, heavy-water moderated and cooled	1960
LAMPRE-1	AEC	LANL, Los Alamos, NM	Fast molten plutonium fueled, sodium cooled	1961
BORAX-5	AEC	NRTS (INL), Arco, ID	BWR, integral nuclear superheat	1962
Saxton	Saxton Nuclear Exp. Corp.	Saxton, PA	PWR	1962
HWCTR	AEC	SRNL, Aiken, SC	Pressurized heavy water	1962
EBR-2	AEC	NRTS (INL), Arco, ID	Sodium-cooled, fast	1963
EVESR	ESADA & GE	Pleasanton, CA	Light-water moderated, superheater	1963
MSRE	AEC	ORNL, Oak Ridge, TN	Single region, graphite moderated	1965
SEFOR	Southwest Atomic Energy Associates	Cove Creek Township, AR	Mixed-oxide fueled, sodium-cooled, fast	1969
UHTREX	AEC	LANL, Los Alamos, NM	Helium cooled	1969

Shortly after passage of the AEA or 1954, AEC announced the Power Reactor Demonstration Program, a three-round program designed to test the level of commercial readiness of various reactor designs, stimulate interest and experience in nuclear power among utilities, reduce uncertainty for reactor designs, and enable the creation of plant designs that could be replicated commercially. The three rounds of the program specified different goals and eligible participants, and offered different incentives. Critical to each round, however, was AEC's commitment to provide R&D at AEC laboratories for design and development of the demonstration reactors. Table 4 summarizes the three rounds of the PRDP.

Table 4. Power Reactor Demonstration Program rounds, applicants, and plants.[14]

	Round I	Round II	Round III	Modified Round III
Opened	January, 1955	September, 1955	January, 1957	August, 1962
Purpose and Goals	Stimulate construction of prototype commercial reactors, leverage private financing and engineering resources, and accelerate NE competitiveness in power sector	Engage public utilities in construction of small, experimental reactors (<40 MW) suitable for rural areas with high power costs or for export	Provide continuing assistance for development of power reactors; focused on large-scale commercial reactors, including BWRs, PWRs, FBRs, SGRs, HWRs, or homogenous reactors	Support the construction of large baseload plants using proven technologies to demonstrate NPPs as reliable sources of electric power
Incentives	AEC-funded R&D for plant design; AEC supply fissile materials for 7 years; guaranteed R&D contracts with awardees	AEC fund and own NSSS; AEC provide R&D at cost; AEC fund first fuel assembly; AEC manage R&D; Utility owns Balance of Plant	Similar to Round I	AEC provide up to 10% of plant cost in form of pre-construction R&D
Applicants	**Successful:** • Yankee Atomic Electric Company: Yankee Rowe • Nuclear Power Group: Dresden[c] • Consumers' Public Power Group: Hallam • Power Reactor Development Corp. (Detroit Ed., et al.): Fermi	**Successful:** • City of Piqua, Ohio: Piqua • Rural Cooperative Power Assn.: Elk River • Dairyland Power Cooperative: LaCrosse[d] **Unsuccessful:** • Chugach Electric Assn.[e] • Wolverine Electric Cooperative • Holyoke Gas and Electric Co.	**Successful:** • CVNPA: Carolinas-Virginia Tube Reactor • Consumer's Power Company: Big Rock Point • Northern States Power Company: Pathfinder • Philadelphia Electric Co. (PECO): Peach Bottom[f] • Southern California Edison (SCE): San Onofre[g]	**Successful:** • Connecticut Yankee Atomic Power Company: Haddam Neck **Unsuccessful:** • City of Los Angeles Department of Water and Power: Corral Canyon[i]

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[c] The Nuclear Power Group withdrew its PRDP application during contract negotiations, and the Dresden BWR was completed with private financing (Allen 1977).

[d] Dairyland and Allis-Chalmers (A-C) submitted an unsolicited proposal to AEC in 1961, six years after Round II of the PRDP had been announced. AEC approved the project under terms similar to other Round II contracts. (Allen 1977).

[e] AEC signed a contract with Chugach Electric and the Nuclear Development Corporation of America initially in order to study the proposed sodium-heavy water reactor. However, after two years, the contract was reevaluated and terminated (Allen 1977)

[f] PECO was the operator and major owner, however Peach Bottom was supported by a large consortium of more than 50 utilities (Allen 1977).

[g] Initially an unsolicited proposal, San Onofre was included in the Round III.

[i] AEC signed a contract with DWP, however it was contingent upon a suitable site being found. Public opposition prevented the Corral Canyon site from being used and the contract was terminated in 1970 (Allen 1977).

		• Orlando Utilities Commission • University of Florida	**Unsuccessful:** • East Central Nuclear Group/Florida-West Coast Nuclear Group[h]	
Approved and Completed Plants	• Yankee Rowe PWR (1961) • Dresden BWR (1959) • Hallam SGR (1962)[j] • Fermi FBR (1963)[k]	• Piqua OMR (1963) • Elk River BWR (1962) • LaCrosse BWR (1967)	• Carolinas-Virginia Tube Reactor HWR (1963) • Big Rock Point BWR (1963) • Pathfinder BWR w/integrated nuclear superheat (N/A)[l] • Peach Bottom HTGR (1967) • San Onofre PWR (1967)	• Haddam Neck PWR (1968)

AEC funds substantially supported early-stage R&D

Budget data for AEC is only available through 1972, after which accounting changes and the transition to ERDA and DOE break the trend line. However, through 1972, AEC's total research expenditures on power reactors increased steadily through Era I. Research on power reactors includes both civilian and military reactors, as well as "other" reactor development. The trend of AEC investments in reactor development R&D is shown in Figure 2, alongside the total AEC budget.

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[h] AEC and participating utilities initially signed a contract to build a gas-cooled HWR, but due to delays the contract was terminated in 1961 (Allen 1977).

[j] Hallam was completed with contract modifications that resembled Round II PRDP contracts: AEC was owner of the NSSS and responsible for R&D conducted on-site (Allen 1977).

[k] Fermi Unit 1 was completed in 1963 but never entered commercial operation due to continuing safety and technical problems (Allen 1977).

[l] Although Pathfinder was fully constructed, it never entered commercial operation as the complications produced by the nuclear superheater proved too difficult (Allen 1977).

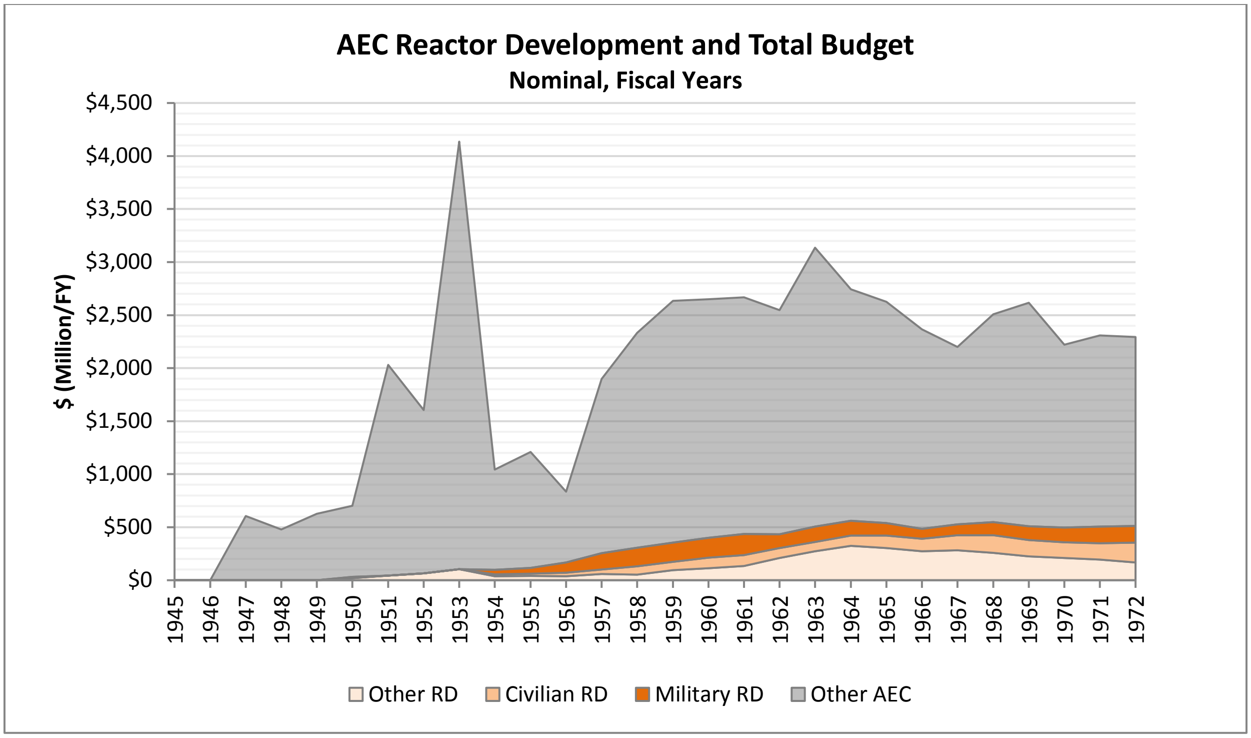

Figure 2. AEC power reactor R&D spending relative to total budget.[15] Source includes Statistical Abstracts of the United States for 1957–1976.

AEC's reactor development budget represented a substantial share of all federal and total national R&D. Total AEC R&D (including non-reactor R&D) ranged between 10% and 20% nbof total federal R&D in the post-war era, and averaged 8.6% during Era II. During this same period, reactor development R&D was approximately 40–50% of AEC R&D. Figure 3 shows the trend of AEC R&D.

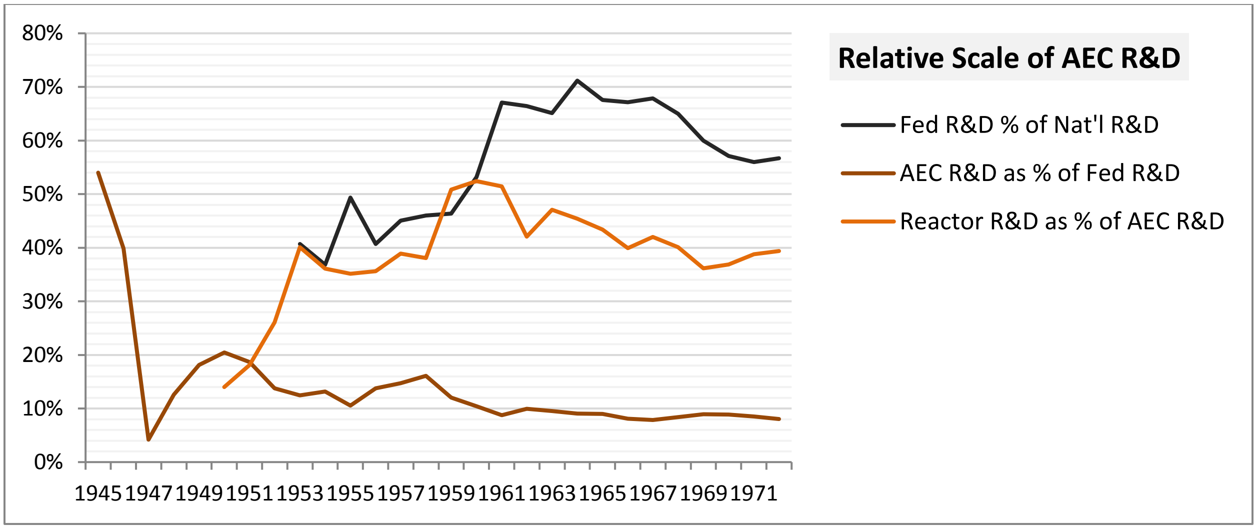

Figure 3. Size of AEC R&D investments relative to total federal and total national R&D investments.[16] Source includes Statistical Abstracts of the United States for 1957–1976.

AEC's funding of reactor R&D and the PRDP was a critical step in development of a commercial nuclear power sector. AEC's experimental and demonstration reactors paved the way for commercial plants. Figure 4 illustrates the delay between R&D investments and large-scale capacity deployment, and Figure 5 shows the development of total generating capacity by type of reactor.

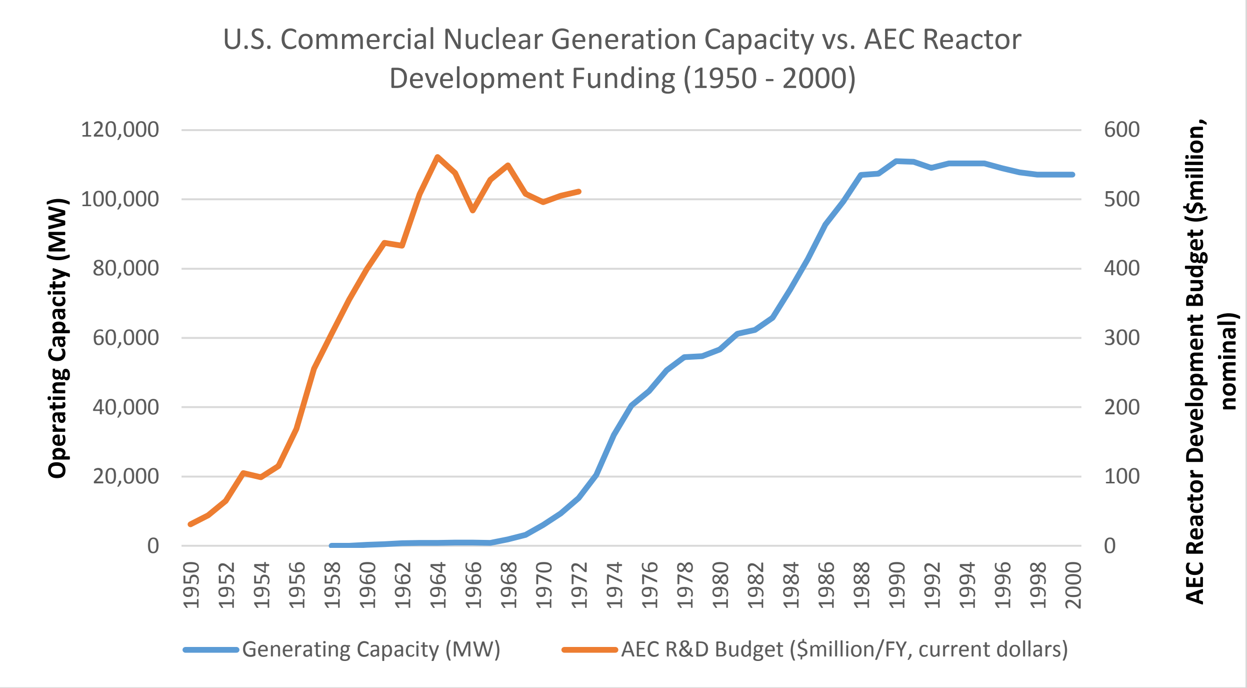

Figure 4. Rapid deployment of commercial nuclear power occurred approximately 20 years after initial R&D funding[17] [18] [19] [20] [21] Sources include Statistical Abstracts of the United States for 1957–1976.

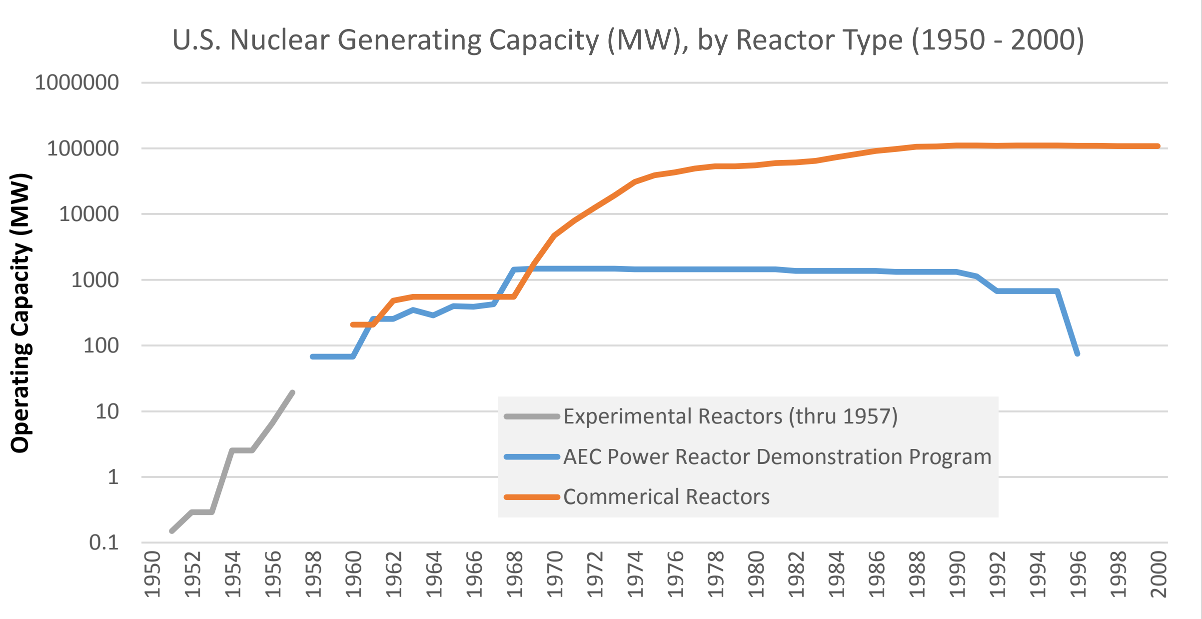

Figure 5. AEC-funded experimental reactors proved and refined the technologies to be deployed in demonstration and commercial reactors.[22] [23] [24] [25]

Private-sector nuclear energy R&D

The value of private sector R&D for nuclear energy generally, and for development of successful NSSS designs specifically, is unknown. One potential measure of the scale of this investment is the value of NSSS sales and NSSS orders, as reported in the Census Bureau's *Statistical Abstract of the United States.* These trends are reported in nominal dollars and displayed alongside AEC's spending on power reactors in Figure 6.

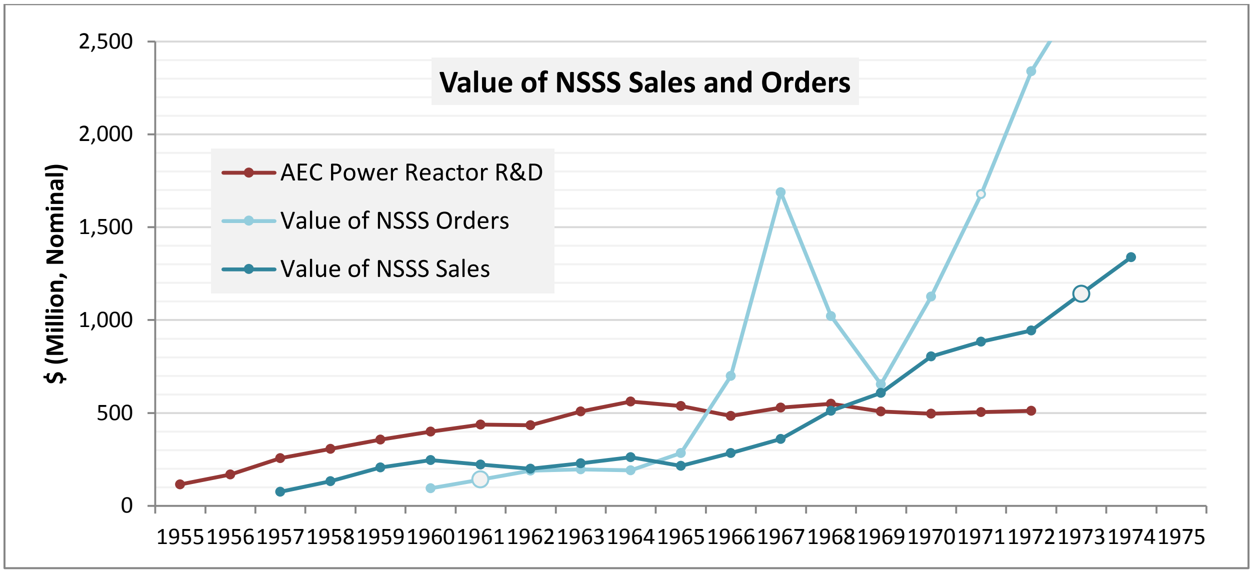

Figure 6. Value of NSSS sales (i.e., value of products and services delivered) and new orders by U.S. firms, relative to power reactor R&D spending by AEC. Although no data is available for private-sector R&D, design, and engineering costs, sectoral sales provide an order-of-magnitutde estimate. For value of orders in 1960–1966, total value is an underestimate, since complete reporting is not available. Open circles indicate missing data.[26] Source includes Statistical Abstracts of the United States for 1957–1976.

Another high-level estimate is the total value of all expenditures on NPPs by utilities. This measure uses reported overnight construction costs applied to the capacity and amortized over the construction duration of each NPP. These estimates do not include financing costs, but they do include the costs incurred by engineering and construction firms, in addition to the cost of the NSSS. Figure 7 presents this data, alongside the AEC power reactor R&D spending adjusted for inflation.

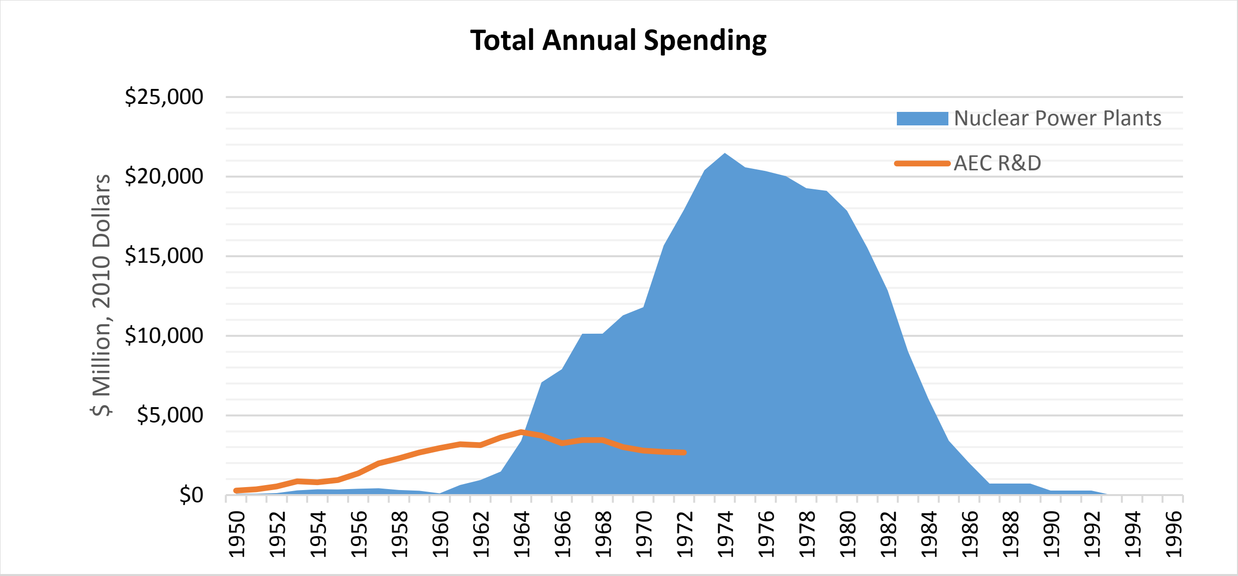

Figure 7. Annual spending on reactors calculated using amortized overnight construction costs and construction duration of 132 reactors; does not include financing costs for any reactors. AEC R&D annual budget for reactor development (includes military).[27] [28] [29] [30] Source includes Statistical Abstracts of the United States for 1957–1976.

Price-Anderson Act subsidies

The Price-Anderson Act of 1957 (P-A) was a legislative effort to stimulate private-sector investment in NPPs by capping the liability of NPP owners in case of an accident. The act provided a claims ceiling above which any individual NPP owner could not be held responsible, regardless of cause. The act was designed as a means to reduce financial risks for cautious utilities interested in investing in NPPs. Historical evidence suggests that the P-A liability caps were both essential to and effective in enabling the development of civilian nuclear power. In congressional testimony prior to passage of the Act in 1956-57, both GE and Westinghouse expressed unwillingness to sell commercial nuclear reactors without liability protection in place: Westinghouse Vice President Charles Weaver testified “Obviously we cannot risk the financial stability of our company for a relatively small project no matter how important it is to the country’s reactor development effort, if it could result in a major liability in relation to our assets.”[31]

Establishing a dollar value for the subsidy afforded by P-A is a challenging task, but the most rigorous past analyses have estimated this value by approximating the rate and cost of nuclear accidents, and estimating how much a private insurance replacement to P-A would cost. These efforts are limited by a lack of historical examples of highly unlikely but very costly (so-called “long-tail”) accidents such as full-scale meltdowns with containment breeches. Additionally, studies that estimate the cost of a private-sector replacement for P-A may not fully account for all of the savings available to the federal government, such as virtually unlimited borrowing capacity and historically low borrowing costs. Table 5 shows some estimated values of the P-A liability caps. Importantly, all of these estimates pre-date the reductions in federal subsidies and inflation-pegged industry contributions found in the Energy Policy Act of 2005.

Table 5. Estimates of implied economic value of Price-Anderson Act liability caps for Nuclear Power Plants.[32] [33] [34] Values adjusted to $2010 using CPI deflator.

Study	Annual Value	Cumulative Value

Dubin and Rothwell 1990	$122 million per reactor per year through 1988; $45 m/reactor-year after	$233 billion (1959–1990); discounted
Heyes and Liston-Heyes 1998	$26 m/reactor-year through 1988; $4.7 m/reactor-year after	
Goldberg 2000		$39.7 billion (1959–1999)

The value of P-A subsides potentially exceeds the total value of AEC civilian power reactor R&D in Eras I and II. Using the lowest estimate from Heyes and Liston-Heyes, the total cumulative value of P-A subsidies through 2005 is approximately $14 billion ($2010). This estimate compares to the total inflation-adjusted value of known AEC civilian power reactor R&D for 1954–1972 of $12.7 billion.[35] [36]

Technology Adoption Rate

The rapid rate of nuclear power adoption was spurred by federal policy and incentives intended to reduce technology and financial uncertainty, and enabled by manufacturers who offered fixed-cost contracts for NSSSs or complete power plants. The combined effect of these factors, alongside high rates of electricity demand growth ushered in wide-spread adoption of nuclear power, and brought many more actors (including utilities, construction, architecture, and engineering firms) into the nuclear power market.

Turnkey pricing was critical for initial deployments and rapid expansion

GE began offering BWR NPPs to utilities on a turnkey, fixed-cost basis in 1963. These contracts reduced perceptions of risk and encouraged first round of commercial orders, signaling the beginning of Era II. Westinghouse soon followed GE's lead, and offered its PWR technology on similar terms. In all, 13 plants were ordered on a turnkey basis before GE and Westinghouse stopped offering such contracts in mid-1966.[37] [38] [m] Turnkey contracts solidified GE and Westinghouse as industry leaders, and ensured their market positions through Era II. Moreover, the desired effect of offering turnkey contracts on perceived technology maturity and risk was sufficiently compelling for many utilities, as an additional 44 non-turnkey (cost-plus) plants were ordered in the year-and-a-half following the turnkey era.[39] [40] [41] Figure 8 shows the deployment of 14 turnkey plants from GE and Westinghouse during Era II.

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[m] Some sources list 13 turnkey plants, as one contract was modified-turnkey with a capped-, rather than fixed-cost. The 14 units considered turnkey in this study appear in Figure 8.

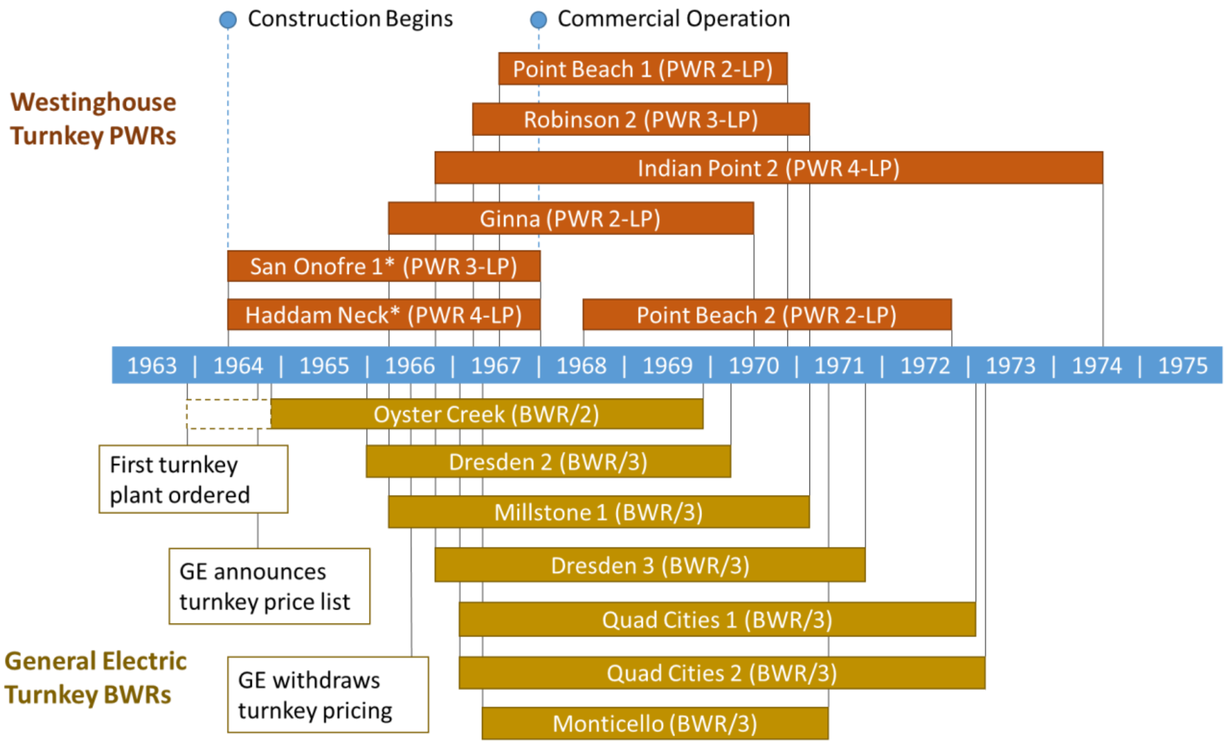

Figure 8. Timeline of turnkey plant orders and completions in Era II. *San Onofre Unit 1 and Haddam Neck are considered turnkey plants due to the financing arrangements, although they also fell under the third and modified-third rounds of the PRDP, respectively.[42] [43] [44] [45] [46]

The brief turnkey era established GE and Westinghouse as the primary NSSS manufacturers in the U.S. for the next five decades. GE and Westinghouse were able to out-price other potential manufacturers and sustain losses on turnkey projects that other companies interested in the sector could not. Today, GE and Westinghouse reactors together supply approximately 80% of operating nuclear capacity in the U.S. AEC also took note of the success of LWR technologies following the large escalation for turnkey orders and began to phase out future LWR R&D, as well as future demonstration programs.[47]

The rapid sales of turnkey PWR and BWR contracts also solidified the market success of LWR technologies over other NSS systems during the critical early years of Era II. In 1963, when GE first offered turnkey contracts for reactors based on BWR technology used in the Dresden and Big Rock Point plants, demonstration plants based on other technologies were incomplete, experiencing technical problems, or had already been abandoned. The Piqua Organic-Moderated Reactor (OMR) had only just achieved criticality despite having been completed two years earlier. These delays contributed to AEC's determination to end support for the organic reactor concept in the same year.[48]

Heavy Water Reactor (HWR) technologies suffered a similar fate as two PRDP Round III projects suffered delays and operating problems which prevented timely competition with LWR reactors in Era II.[49] The Hallam Sodium-Graphite Reactor (SGR) attempted to commercialize the success of the Sodium Reactor Experiment, but utilized significant design differences which resulted in equipment failures, construction delays, and other engineering problems that ultimately led AEC to abandon further development of the concept in 1964.[50]

The Fermi Fast Breeder Reactor (FBR) was also hampered by AEC's interest in building a demonstration-scale power reactor based on a technology that still suffered fundamental design problems. In 1955, the year before AEC signed a contract with Detroit Edison to build the Fermi FBR, the first Experimental Breeder Reactor (EBR-1) had suffered a core meltdown, and the AEC's Advisory Committee on Reactor Safeguards (ACRS) advised that additional research be completed on EBR-2 to ensure safety. AEC's contract with Detroit Edison took effect before licensing hearings on the proposed plant were complete, signaling AEC's confidence in the project. However, design and engineering problems delayed operation at the Fermi Plant. Fermi Unit 1 began operation in 1963 and suffered a core meltdown in 1966.[51]

In addition to the successes of GE and Westinghouse, two additional manufacturers saw smaller-scale success: C-E and B&W both secured orders in the years immediately following the turnkey era for PWR plants based on the original Westinghouse design.[n] Figure 9 shows the development of market share for these four manufacturers and BWR vs. PWR technology.

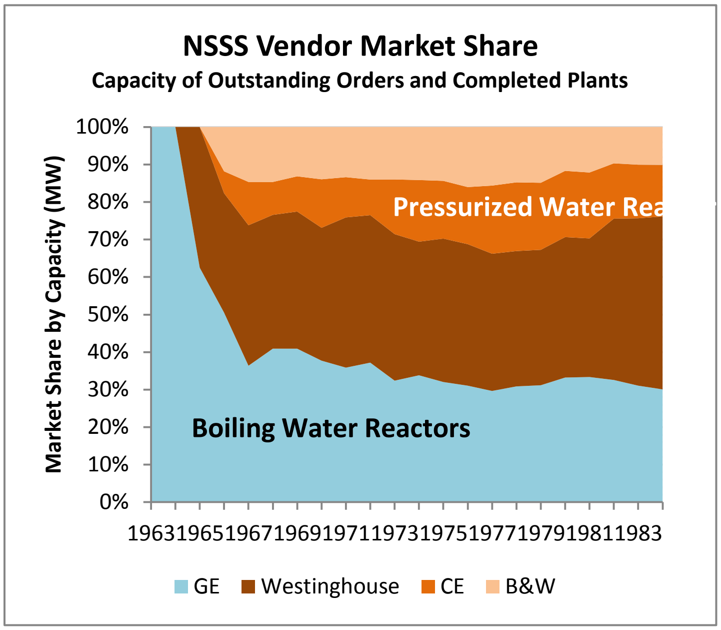

Figure 9. Market share as measured by each vendors' outstanding orders and finished plants. Source: EIA 2016, Thomas 1990.

Many new actors entered sector with little experience

Rapid proliferation of new orders involved many new utilities, construction firms, and architect-engineers with little or no nuclear experience. The majority of new actors in the sector entered prior to the completion of Oyster Creek in late 1969.

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[n] Combustion Engineering independently designed an evolutionary PWR named "System-80," three of which are installed at APS's Palo Verde Nuclear Generating Station.

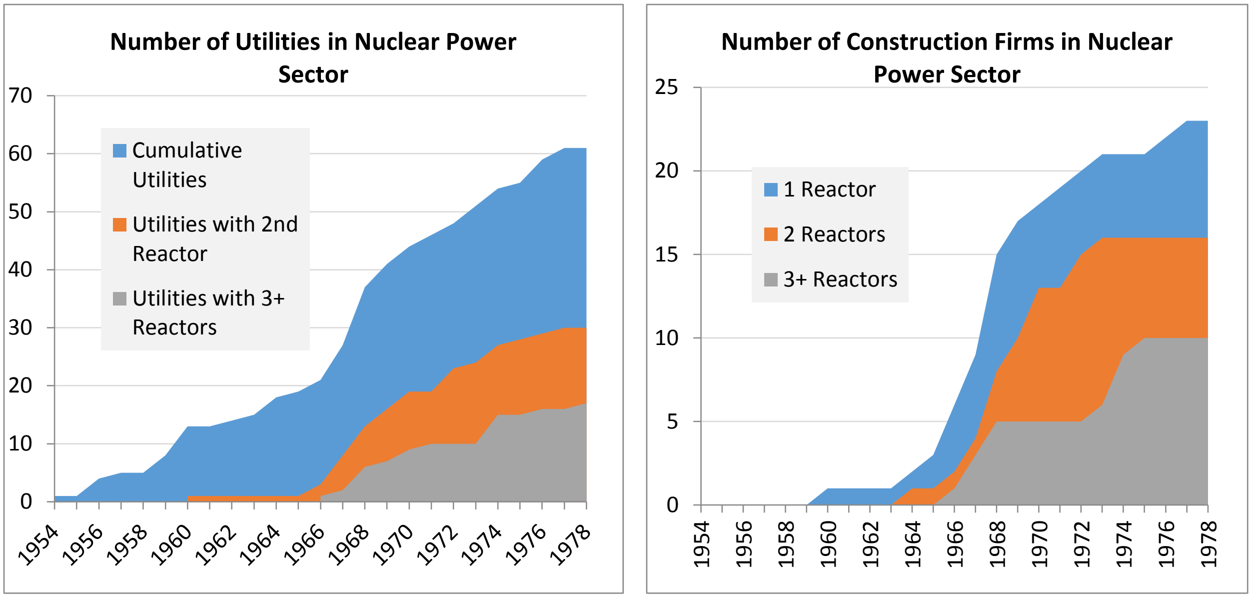

Figure 10. Number of actors in nuclear power sector over time. Actors are considered to "enter the market" when a construction license is granted. Left: cumulative number of utilities with power plants complete or under construction. For plants owned by multiple utilities, only the majority owner is included. Right: cumulative number of construction firms involved in nuclear power sector, by number of reactors built or under construction. Utilities acting as their own construction manager are included. Excludes most demonstration reactors. Source: NRC 2016a.

Only about one out of ten utilities with nuclear power plants were involved in engineering or construction management. The Tennessee Valley Authority (TVA) and Duke Companies were most heavily involved with design and construction of nuclear power plants.

Table 6. Utility involvement in engineering and construction of nuclear power plants. For plants owned by multiple utilities, only the majority owner is counted.[52]

	Utilities with NPPs	*Utilities as own Architect/Engineer*	*Utilities as own Construction*
One Reactor	31	1	0
Two	13	3	3
Three or more	17	2	4
Total	**61**	**6**	**7**

Nuclear energy capacity expansion occurred very quickly

In Era II, nuclear capacity grew very quickly once the first orders for NPPs were committed. The pace of commercial nuclear power deployment in Era II was remarkable for a new and complex technology. Starting in 1969 (the year Oyster Creek started commercial operation) through the end of Era II, nuclear capacity grew by an average of 34% per year, peaking at 48% in 1970.[53] [54] Although new technologies often experience rapid growth early in their deployment, NPPs were being built at such high rates that nuclear power achieved multiple key deployment milestones earlier than many other energy technologies.[o] For example, after small commercial deployment in the early 1980s, wind power did not

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[o] Deployment milestones are based on EIA Form-860 data. Due to incomplete data for early years, hydropower and coal sources are not included in this analysis. The first NG source is reported in 1925, however historical uses of NG prior to 1925 suggest it is likely earlier power generators existed.

see rapid expansion until the early-2000s, more than 25 years after first commercial availability, and 2012 the first year that wind capacity additions contributed more than 1% of total capacity. Table 7 compares the time between first use and several deployment milestones for energy technologies in the U.S., and Figure 11 shows nuclear power's rapid progress from less than 1 GW installed capacity to greater than 10 GW is uncharacteristic of any other technology.

Table 7. Delay between first commercial deployment and deployment milestones for five energy technologies in the U.S.[55] [56]

	Natural Gas	Nuclear	Wind	Solar	Storage
First commercial deployment	1925	1957	1975	1984	2003
Years until annual capacity additions...					
… >1GW (nameplate, net)	23	12	26	28	—
… >1% total installed capacity	20	13	37	—	—
… >10GW	49	17	37	—	—

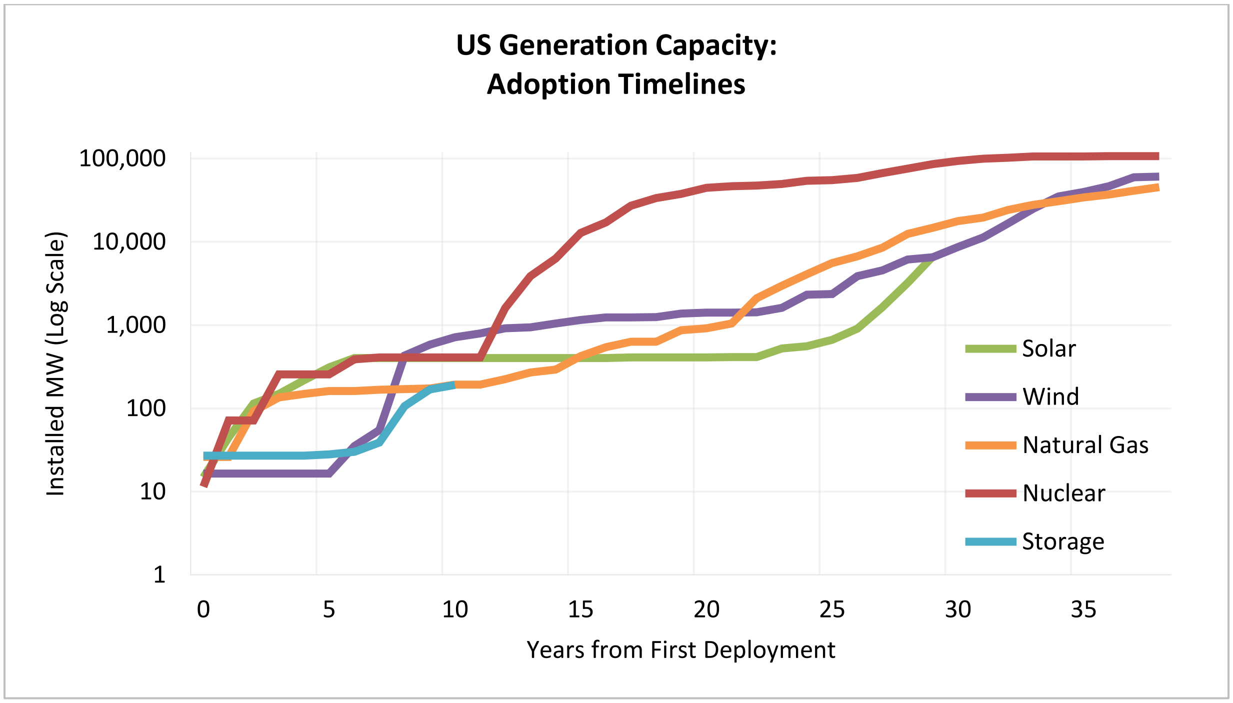

Figure 11. Adoption rates of multiple energy technologies. Adapted from original in presentation.[57]

By the end of Era II, nuclear power capacity was being installed at the same absolute rate as coal and natural gas. Despite being a new technology, approximately 45 utilities had already ordered or built nuclear plants before the first fully-privately-financed order had ever come online (Oyster Creek in late 1969).[58] [59] [60] By 1974, annual capacity growth of Nuclear Power peaked at 10.8 GW. In the same year, natural gas (NG) installations also peaked at 10.9 GW,[p] and coal installations were 11.9 GW.[61] Both coal- and NG-fired generation were mature technologies with decades of commercial availability; during Era

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[p] NG installations would later exceed this annual total in the early 2000s, with over 64 GW installed in 2002 (EIA 2016).

II, each year averaged 10.0 GW of new coal capacity and 7.1 GW of new NG capacity[62] [63] Figure 12 shows the deployment of nuclear capacity alongside fossil and hydropower technologies.

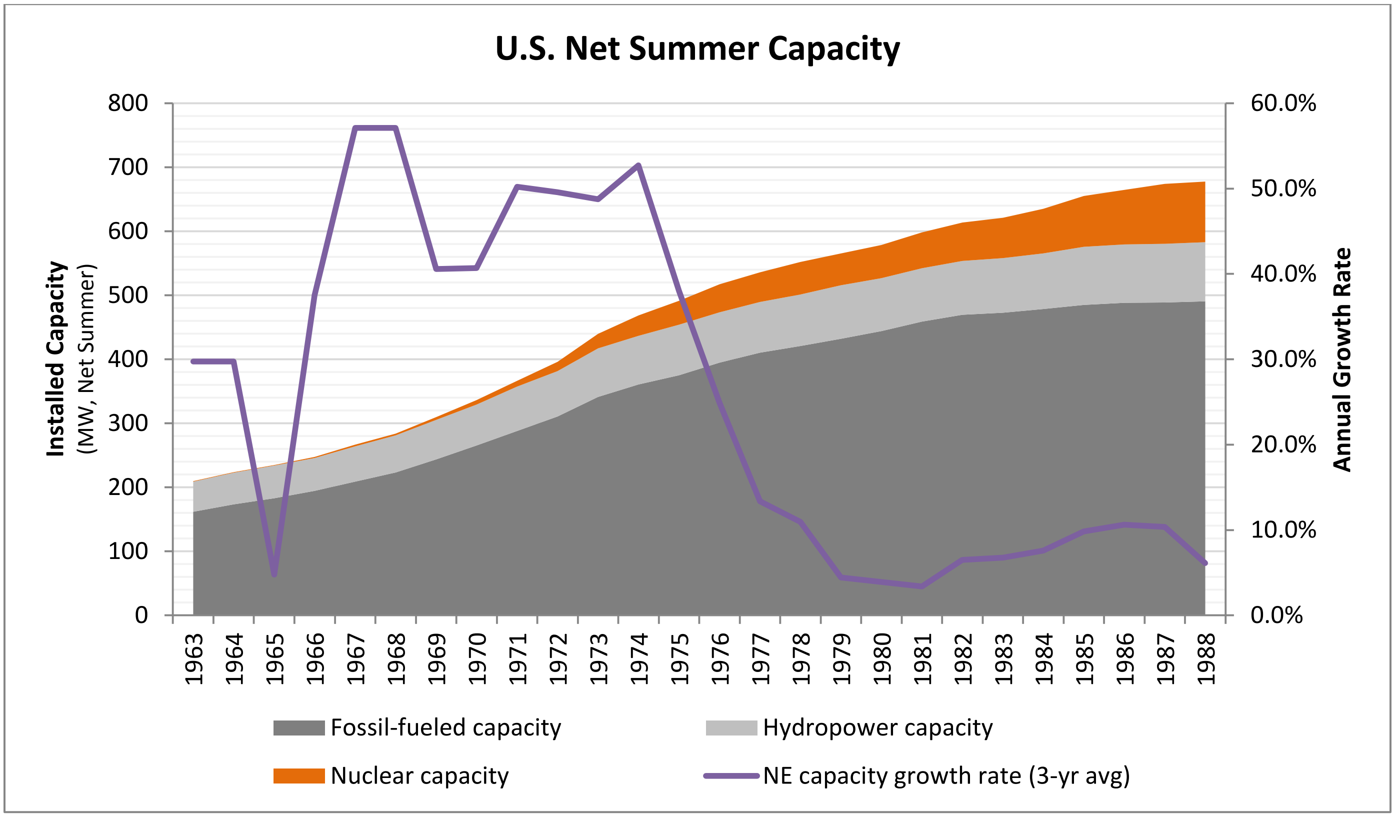

Figure 12. Nuclear energy's role in U.S. generation fleet, and 3-year rolling average of annual nuclear capacity growth rate.[64] [65] [66]

Evolution of NPP financing

No data is available to categorically analyze financing methods for all nuclear power plants. Evidence shows that early plants were financed a variety of methods, including debt, equity, and hybrid versions of the same. In order to build Oyster Creek, the first privately-financed reactor, Jersey Central Power and Light (JCP&L) issued bonds at 10%, whereas TVA's reactors were funded by bonds issued at 5.7%.[67] [68] An example of hybrid financing, the Yankee Atomic Electric Co. (YAEC) was formed as a joint venture of 10 New England utilities in order to build the Yankee Rowe Nuclear Power Station. YAEC sold equity but also took on debt in order to finance the plant.[69] A similar hybrid structure was used to finance other Yankee power stations, including Vermont and Maine.

Except for some of the demonstration plants, public financing of NPPs has rarely been used in the U.S. For Shippingport and a few PRDP reactors, AEC financed and took ownership of NSSSs. However following the 2nd round of the PRDP, AEC limited its financial commitment for new demonstration plants, and starting with Oyster Creek, all subsequent reactors in Eras I and II were built without AEC financing.[70] Another exception to private financing, the James A. FitzPatrick Nuclear Power Plant was financed by the New York Power Authority (NYPA), a state agency.[71] Although NYPA funded construction, the plant was operated by Niagara Mohawk Power Company, until it was sold to Entergy in 2000.

Competition among NSSS manufacturers

In Era I, the 14 potential NSSS providers narrowed to four successful companies. In Era II, two of these four (GE and Westinghouse) provided the majority of reactors. Despite the differences between BWRs and PWRs, no technology or manufacturer ever appeared to display a clear advantage (other than GE's and Westinghouse's head start due to the turnkey program). Throughout Era II, reactor designs were constantly being improved (e.g., reduction of cooling loops, improved containment, etc.). However, it is not apparent from either prospective orders or from retrospective overnight costs that any manufacturer ever appreciated a significant design advantage. Figure 13 demonstrates that although the smaller manufactures obtained fewer orders overall, all manufacturers suffered similar rates of cancelled orders after 1975.

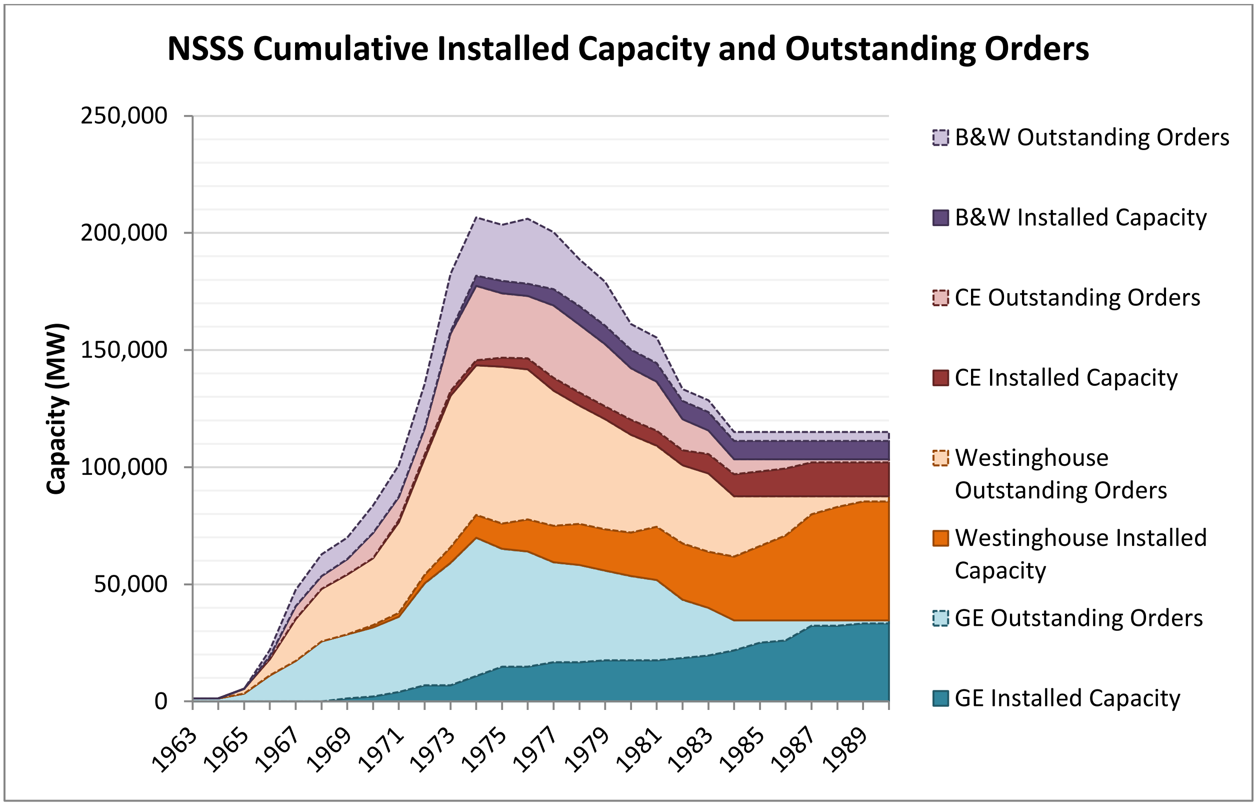

Figure 13. Cumulative installed capacity and outstanding orders for NSSSs by manufacturer. After 1975, no new orders were recieved. Note: cumulative installed capacity does not include subsequent shutdowns.[72] [73] [74] [75] [76]

Although utilities would not have known the actual cost of construction at the time, the relative costs of plants based on reactors from the four major manufactures are remarkably similar. Considering the rapid escalation in costs for all reactors, there is some difficulty averaging all NPP costs together (for example, plants completed after the partial meltdown of TMI-2 have much higher real overnight construction costs), however Table 8 shows that for GE and Westinghouse, average costs are very similar.

Table 8. Average NPP overnight cost by NSSS manufacturer.[77]

Overnight Costs by NSSS Manufacturer					
Manufacturer	All Plants	Post-TMI	Pre-TMI	Demonstration	Turnkey
GE	$3,214	$5,971	$1,363	$3,103	$1,133
Westinghouse	$2,980	$4,094	$1,454	$4,928	$1,233

B&W	$1,420		$1,369	$1,884
C-E	$2,612	$3,870	$1,511	

Reverse Learning Curve

The rapid escalation of costs and construction delays for NPPs ordered in Era II has been described as a "reverse learning curve," because the trend is the opposite of what would be expected for a new energy technology. The reverse learning curve was the primary cause of the end of new nuclear orders in the U.S. for more than three decades. While all of these plants were ordered in Era II, escalation in costs occurred through both Eras II and III. The average real overnight cost (including financing) for new nuclear power plants increased by 440% for plants beginning construction early in Era II (1966–1967) compared to plants beginning construction at the end of Era II (1974–1975).[78] During this period, the average increase in real overnight costs was 14% per year (based on construction start year).[79] Figure 14 shows the trend in reactor overnight costs relative to the construction starting year and the plant capacity, and Figure 15 shows the reactor commercial operation start date.

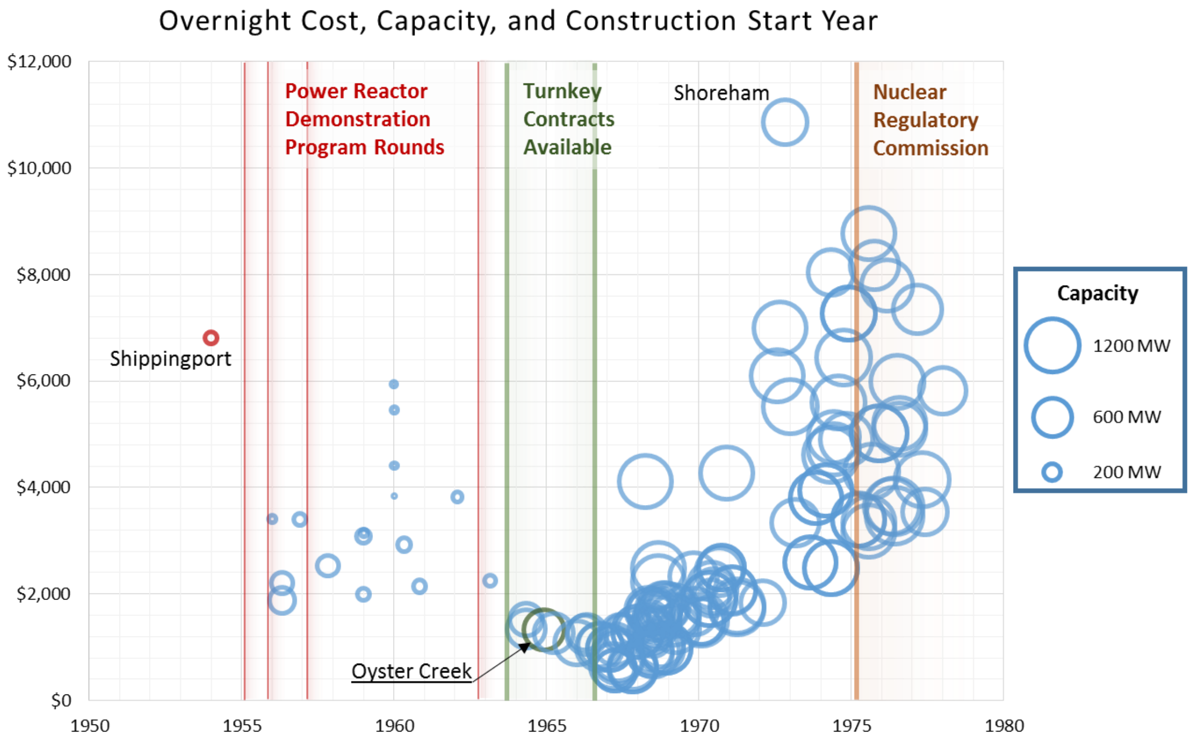

Figure 14. Reactor construction start year, real overnight cost ($2010/kW), and capacity.[80] [81] [82]

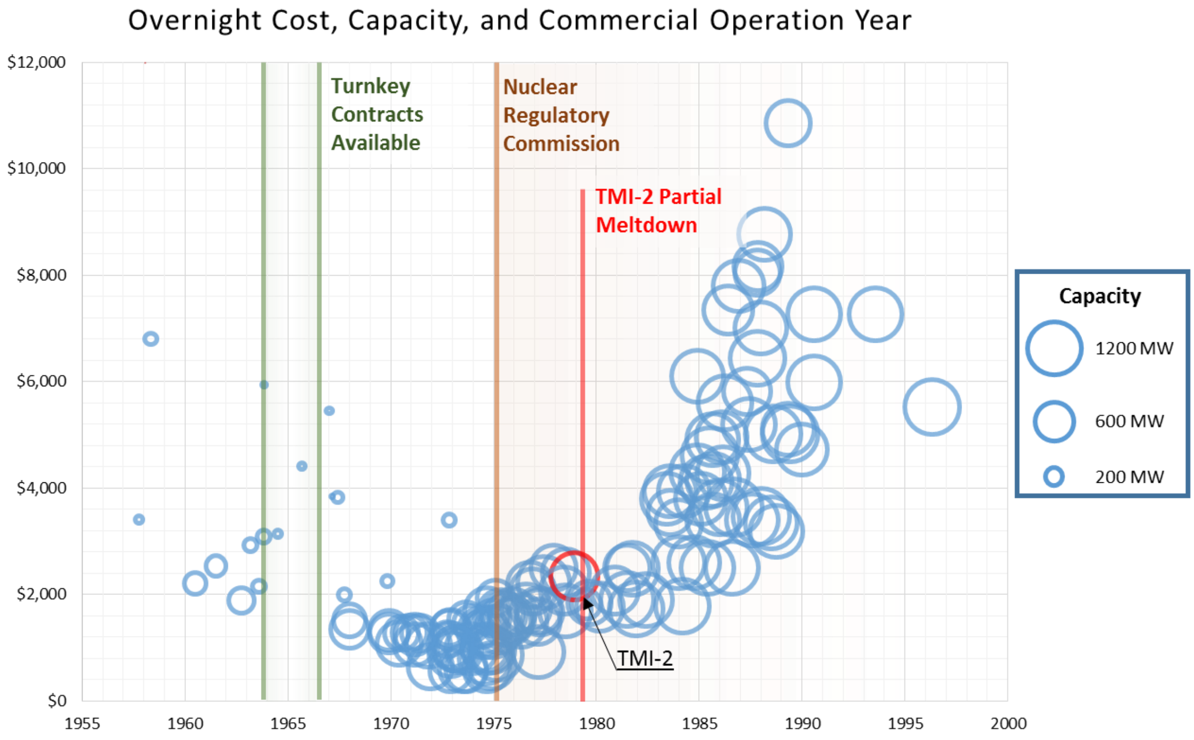

Figure 15. Reactor commercial operation start year, real overnight cost ($2010/kW), and capacity.[83] [84] [85]

Evidence of Reverse Learning Curve

In an extensive study of NPP cost growth, EIA evaluated the inflation-adjusted (real) overnight costs and rate-base costs of all completed nuclear power plants. EIA's primary finding was that three quarters of cost increases could be attributed to increased quantity of inputs to production (including land, labor, materials, and equipment), while the remaining quarter of cost increases could be attributed to increases in real financing charges,[q] increases in the relative inflation of inputs to production, and increases in the construction lead times (i.e., the duration between the beginning of construction and the start of commercial operation).[86] However, among the factors examined in the study, construction lead times were the most strongly correlated with real cost increases, indicating that the direct causes of construction delays (including design changes, retrofits due to changes in safety and environmental regulations, and labor productivity problems) also influence the increased costs associated with increases in quantity of inputs to production.[87] Figure 16 shows the upward-trending relationship between construction start year and construction lead time. It is important to note that EIA's analysis was conducted before at least 26 units were operating, and EIA's analysis excludes plants with some of the longest construction lead times in the U.S. nuclear fleet.[88]

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[q] Although the EIA analysis accounts for financing costs, the study notes that the relatively small share of time-related costs is likely affected by the real interest rate used to calculate financing charges in the analysis, which was negative for five of the years between 1971 and 1981 (EIA 1986). Because many of the construction delays realized by the highest-cost plants occurred after the EIA study was completed, it is likely that direct time-related costs contributed a larger share of real overnight cost increases for these plants.

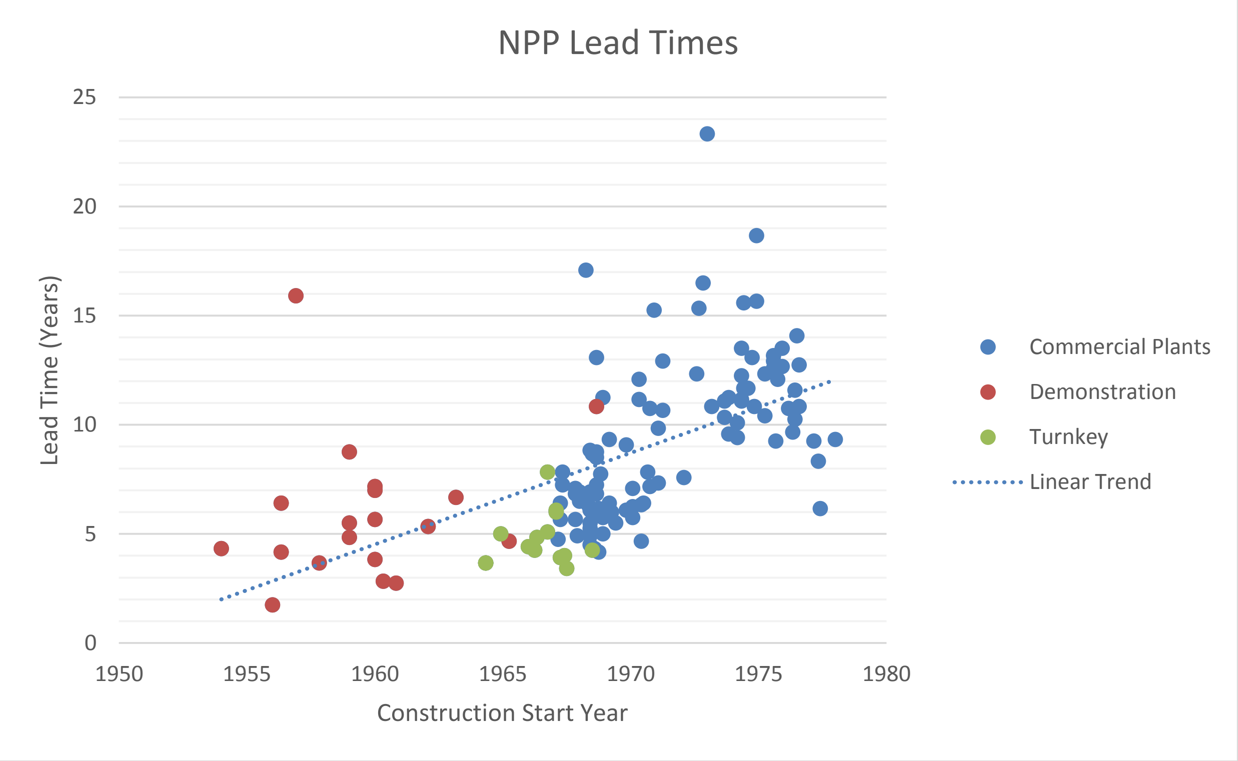

Figure 16. Positive trend in NPP Lead Times. At time of EIA analysis, at least 26 NPPs were incomplete.[89]

EIA conducted regression analyses to measure the relationship between multiple factors and the real overnight costs and construction durations of NPPs. EIA examined factors such as the size of a reactor unit, the NPP's region, when construction was started, the cooling system, the experience of the construction firm, whether or not a utility acted as its own construction manager, and whether or not the unit is the first to be built at an NPP site. These regressions are specified in equations 1 and 2 below.

(1) ln(costs/kW) = ln(size) + RWNW + RS + COOL + FIRST + ln(lead-time) + CONSTRT + BUILD + CST1 + INTER + e
(2) ln(lead-time) = ln(size) + RNEMW + RS + COOL + FIRST + CONSTRT + BUILD + CST1 + INTER + e

- ln(costs/kW) is the natural logarithm of the overnight construction costs in 1982 dollars per unit of net capacity of the plant;
- In(size) is the natural logarithm of the net capacity of the unit
- In(lead-time) is the natural logarithm of the actual construction lead-time
- RWNW is a binary variable indicating if the unit is located in the West or Northwest region
- RS is a binary variable indicating if the plant is located in the South or Southwest region
- RNEMW is a binary variable indicating if the plant is located in the Northeast and Midwest regions
- COOL is a binary variable indicating if a natural cooling system is used
- FIRST is a binary variable indicating if the unit is a single unit or first of multiple units
- CONSTRT is the day construction started
- BUILD is a binary variable indicating if the utility is the constructor
- CST1 is the constructor's experience variable
- INTER is the interactive term between BUILD and CST1

- e is an error term

The results of these regressions are presented below. Table 9 shows the important roles of construction lead time and a utility's management of its own construction in affecting the real costs of a plant. Table 10 shows that the size of a power plant is a significant factor affecting the construction lead time, but no other factors show statistical significance at the 95% level. EIA's analysis identifies four unobservable factors which could contribute to the effects of increased lead time on overnight cost, including the material and labor costs associated with design changes (due to safety and environmental regulatory retrofits), non-linearities in the labor market (i.e., additional labor may only be available at higher wages), inefficiencies in labor allocation due to interruptions in construction schedules, and labor productivity reductions due to lowered morale.[90]

Table 9. Raw results of EIA regression analysis of real overnight construction costs.[91]

Variable	Regression Coefficient	Standard Error
Intercept	0.065	1.27
Log of Capacity	-0.569	0.19*
Location (South or Southwest) [a]	-0.106	0.05*
Location (West) [a]	0.115	0.09
Use of Cooling Towers [a]	0.094	0.07
Single Unit or First of Multi-Unit [a]	0.346	0.06*
Date of Construction Start	2.4e-4	3e-5*
Log of Construction Lead Time	1.210	0.12*
Experience of Utility (Acting as own Contractor)[b]	8.155	3.16*
Experience of External Contractor [c]	-1.776	1.22
Constructed by Utility [a]	0.422	0.11*
Adjusted R-Squared	0.831	—

* Significant ($p<0.05$, two-tailed)
a) Binary variable
b) This is the coefficient associated with the interaction term between the binary variable for utilities that act as their own construction managers and the experience variable. This coefficient would measure the difference in the regression coefficients associated with experience for those utilities that act as their own construction managers and those that employ outside contractors.
c) This is the coefficient associated with the contractor's experience variable, and can be interpreted as the regression coefficient associated with the experience variable for those utilities that employ outside contractors.

Table 10. Raw regression results of EIA regression analysis of construction lead times.[92]

Variable	Regression Coefficient	Standard Error
Intercept	2.887	1.32*
Log of Capacity	0.732	0.19*
Location (East or Midwest) [a]	0.019	0.10
Location (South or Southwest) [a]	0.015	0.10
Use of Cooling Towers [a]	0.013	0.07
Single Unit or First of Multi-Unit [a]	-0.040	0.06
Constructed by Utility [a]	0.132	0.15
Date of Construction Start	4.1e-5	3e-5
Experience of External Contractor [b]	0.106	0.28
Experience of Utility (Acting as own Contractor)[c]	-0.381	0.65
Adjusted R-Squared	0.298	—
Sum of Squared Error	3.622	—

* Significant ($p<0.05$, two-tailed)
a) Binary variable
b) This is the coefficient associated with the contractor's experience variable, and can be interpreted as the regression coefficient associated with the experience variable for those utilities that employ outside contractors
c) This is the coefficient associated with the interaction term between the binary variable for utilities that act as their own construction managers and the experience variable. This coefficient would measure the difference in the regression coefficients associated with experience for those utilities that act as their own construction managers and those that employ outside contractors.

One important finding of EIA's analysis regards the apparent lack of economies of scale for larger-capacity plants. In theory, and in the expectations of both NSSS manufacturers and utilities, larger NPPs should have provided lower overnight construction costs, since much of the cost of the plant is fixed. In practice, EIA finds that there is a positive relationship between size and cost, indicating an inverse economy of scale. EIA's regression analysis found that *when controlling for lead time,* a 25% increase in capacity would be associated with a 12% reduction in cost per unit of capacity. However, EIA finds that a 25% increase in capacity is also expected to produce an 18% increase in lead time, which due to the added costs of construction delays, produces a 22% increase in the cost of land, labor, and materials. On net, this produces a positive relationship between capacity and cost.

EIA's analysis also examines the difference between expected costs and realized costs. Expected costs are derived from those reported by utilities at the start of construction. EIA's analysis finds that utilities expected costs did not correlate with their expectations for construction lead times, indicating that utilities did not anticipate the cost increases associated with factors contributing to construction delays (including design changes, regulatory retrofits, and labor productivity changes).[93] Table 11 shows the data collected by EIA.

Table 11. Relationship between construction progress and estimated costs. Note: EIA analysis did not include all plants, when later plants are included, there is no downward trend for 1976-77.[94]

		Estimated Cost at Stage of Completion					
Construction Start	Number of Plants	0%	25%	50%	75%	90%	Realized Costs
1966-67	11	$298	$378	$414	$558	$583	$623
1968-69	26	$361	$484	$552	$778	$877	$1,062
1970-71	12	$404	$554	$683	$982	$1,105	$1,407
1972-73	7	$594	$631	$824	$1,496	$1,773	$1,891
1974-75	14	$615	$958	$1,132	$1,731	$2,160	$2,346
1976-77	5	$794	$914	$1,065	$1,748	$1,937	$2,132

Another important finding from EIA's analysis is the relationship between cost and a utility's involvement in construction. EIA finds a negative correlation between utilities acting as construction manager and NPP real overnight cost, and notes that utilities acting as their own construction manager reduces real costs by approximately 35%.[95]

Regulatory factors

Following the construction of the first few commercial NPPs in the late 1960s, AEC regulations on the siting, operations, and other safety characteristics of NPPs steadily grew. Additionally, the passage of NEPA in 1969 added costs to NPP siting and construction. Criticism of the AEC's combined promotional and regulatory role of nuclear energy led to the formation of NRC in January, 1975.

Quantifying the role of additional regulations in increasing NPP costs is very difficult, and comprehensive databases of all AEC and NRC regulations do not exist. Additional analysis could be completed with detailed case studies of siting and construction delays, retrofits, and other costs for individual NPPs.

Economic factors

A number of economic factors occurred simultaneous to the reverse learning curve, and although their causal relationship with increasing costs and construction delays is not definitive, these factors affected the decisions of utilities with NPPs under construction:

- 1973-74 OPEC embargo. In connection with the increase of oil prices, coal prices also doubled in the early 1970s, together increasing the attractiveness of nuclear power, even as construction costs grew.
- Stagflation & interest rate spikes: by the end of Era II, annualized inflation rates had increased beyond 10% while GDP growth lagged behind, leading to falling forecasts for future growth, and reduced demand for new capacity, as well as worse economics for new plants.
- Expected demand growth: during the 1960s and first several years of the 1970s, national annual growth in electricity demand ranged between 6–7%, necessitating steady and substantial annual increases in generating capacity. By the end of Era II, however, annual growth dropped precipitously, reaching a low of 3% in 1975-76. Since Era II, annual electricity demand growth has never been as high. Figure 17 shows the demand trend, and Table 12 shows how Census Bureau projections of future demand evolved through the energy crisis.

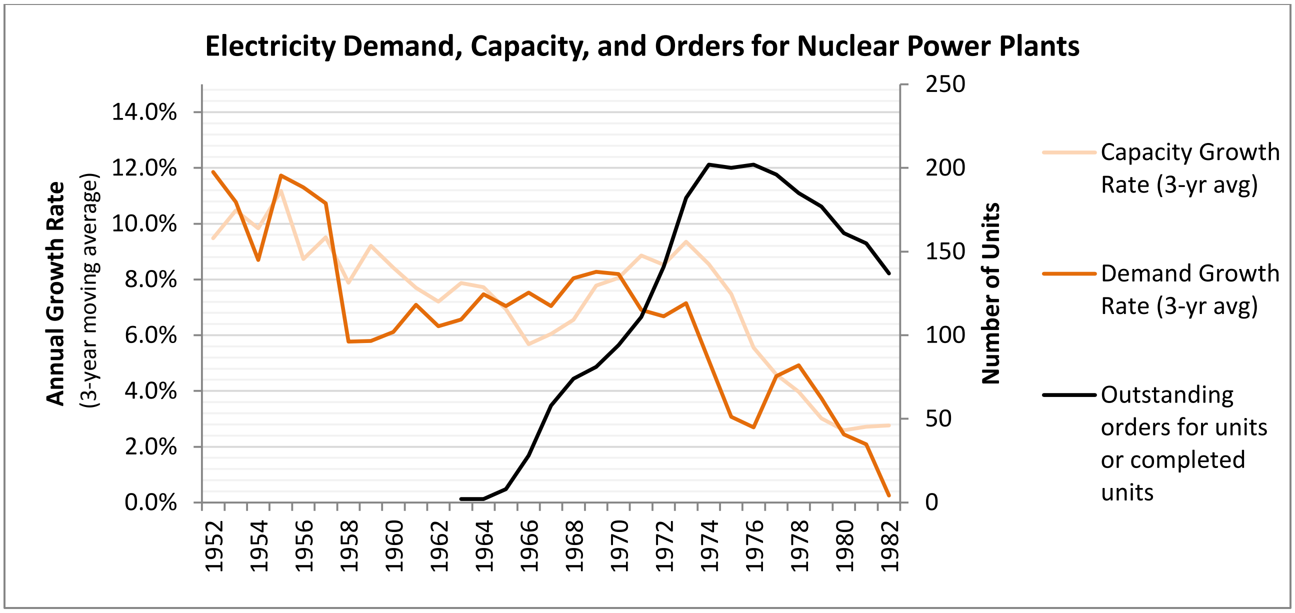

Figure 17. Total U.S. electricity demand steadily declined through Eras I and II, coinciding with a decline the annual growth rate of total U.S. generating capacity, and with a reversal in the number of NPPs on order.[96] [97] [98]

Table 12. Projections of future total and peak electricity demand at different points during Eras II and III.[99]

Statistical	Total Demand (Billion kWh)		Peak Load (GW)	
Abstract Year	1980	1990	1980	1990
1967	2,693	—	494	—
1972	3,086	5,852	556	1,056
1977	2,618	4,552	492	866

Political factors

Local opposition to siting of NPPs occurred almost as early as the first NPPs themselves, with fledgling organization around opposition to the Bodega Bay NPP in 1963. Local opposition groups, fledgling environmental groups with anti-nuclear positions, and public media such as *The China Syndrome* cemented a growing public opposition to new nuclear investments. While this factor began during Era II, it was most important in Eras III and IV, and is not discussed in great detail here, beyond the effects of local opposition to power plant siting.

Next Steps

Data Gaps

Additional data could be researched on the following subjects:

- **Private-Sector R&D:** Corporate annual reports for the four major NSSS vendors are available at the Library of Congress, however these records are not digital
- **Reactor Financing:** Additional research may provide better data on reactor financing methods, however a comprehensive database for all reactors would likely require extensive effort
- **Regulatory Inflation:** EIA attempted to measure the number of new regulations promulgated by NRC and regress this trend against reactor cost, however the EIA analysis was conducted in 1986 and does not address the most costly reactors, which had yet to be completed

Key Analytical Questions

Several key analytical questions are raised by this analysis, however resolving these questions would require additional research that is outside the scope of this effort:

- **"Regulatory Ratcheting" vs. Costly Complexity:** The 1986 EIA analysis is the most comprehensive effort to identify the root causes of NPP cost escalation, however the analysis leaves the key question uncertain, partly because an effort is not made to quantify the impacts of individual NRC rules, and partly because the analysis was completed before all existing NPPs had come online. Lovering et al. attempt to address this question though comparisons with other countries' nuclear overnight costs. However, more detailed case studies of individual nuclear power plant construction costs may provide additional information about the primary cause of construction delays and cost overruns.
- **Economies of scale vs. design standardization:** One of the driving assumptions throughout Eras I and II was that larger NPPs would produce economies of scale. This assumption was central to GE's decision in 1963 to offer turnkey pricing for NSSSs larger than any it had yet produced. In practice, larger plants are correlated with higher overnight costs, and EIA's analysis indicates that this is potentially due to increases in complexity causing design and construction delays for large plants. Standardized Small Modular Reactors (SMRs) have been proposed as a potential means of reducing the cost and complexity of new nuclear power. Additional analysis — including detailed case studies of large plants — could address the key questions of whether economies of scale exist for large plants, and why these signals are not seen in the aggregate.
- **International Lessons**: As is emphasized in Lovering et al. 2016, the international experience with nuclear power mirrors the U.S. experience in some cases, while in others it diverges significantly, with lower and predictable overnight construction costs in countries like South Korea. An approach to these analytical questions using international data could improve the usefulness of key messages for energy innovation.

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