FROM BOMBS TO BUSINESS: THE ECONOMICS OF NUCLEAR TECHNOLOGY DEVELOPMENT

Alexander Ruthe – Columbia University – ELEN 6906 – May 5, 2023 – All Figures and Analysis by Author

I. OVERVIEW

Military pursuits motivate nations to pursue innovative technologies that provide advantages over adversaries. These technologies often have utility beyond the battlefield with an impressive list of innovations including the internet developed under the United States (US) Department of Defense (DoD) Advanced Research Projects Agency (ARPA) in 1969, the Global Positioning System (GPS) developed with NAVSTAR satellites in 1983, and personal voice assistants like Siri which all began under DARPA's Personalized Assistant that Learns (PAL) program [1].

This report will show that this pattern of military innovation driving wider commercial and public use extends to nuclear reactor technology. Specifically, this report will show that nuclear reactor technology development for nuclear weapons and nuclear-powered submarines developed by the world's military superpowers—the United States of America, United Kingdom, Russia, France, and People's Republic of China—has a consistent and significant impact on the development of commercial and public nuclear power plants.

This report proposes three new "learning by doing" [2] metrics to better evaluate the dynamics of the commercial nuclear industry by jointly accounting for labor force productivity, operational efficiency, engineering expertise, and scientific advancements. These metrics are used to compare efficiencies of specific reactor models as well as broader classes of nuclear reactors. This analysis shows specific nuclear policy's impact on the growth and decline of the nuclear industry through learning by doing metrics.

II. INTRODUCTION

Nuclear fission was discovered in 1938 by German chemists Otto Hahn and Fritz Strassmann with the help of Austrian physicist Lise Meitner [3]. The chemists conducted experiments bombarding uranium atoms with neutrons, repeating studies done by Enrico Fermi [4]. However, when the chemists sent their experiment results to Lise Meitner, her calculations using Neil Bohr's droplet nucleus model made stated that the neutron split the uranium nucleus into two roughly equal pieces, contradicting Fermi's conclusions. This was a surprising result because until Meitner's calculations, all other forms of nuclear decay involved only small mass changes to the nucleus.

This rupturing of the nucleus was dubbed fission and quickly captured the attention of scientists like Leo Szilard and Frederic Joliot-Curie who recognized that fission reactions could generate a self-sustaining nuclear chain reaction. On May 4, 1939, Frederic Joliot-Curie filed three patents that would change the course of world history. The first two described nuclear chain reaction power production [5]. The last patent titled *Perfectionnement aux charges explosives* was the first patent for the atomic bomb [6].

Once nuclear chain reactions were experimentally confirmed, scientists began petitioning their governments to support nuclear fission research, including Albert Einstein's 1939 letter to President Franklin D. Roosevelt urging the United States government to pursue nuclear research for "extremely powerful bombs" [7]. Helped by Leo Szilard, albert Einstein proved successful, and the Manhattan Project was born.

The Manhattan Project researched atomic bombs, uranium enrichment, and plutonium production. Pursuit of plutonium production directly led to the development of the world's first nuclear reactor, Chicago Pile-1 at the University of Chicago in 1942 [8]. Plutonium is rate in nature, and the best way to obtain large quantities is in a nuclear reactor where uranium is bombarded by neutrons, leading to plutonium-239 products [9]. Through 1943 and 1944, the Manhattan Project team shifted focus from a gun-type fission bomb to an implosion-type fission bomb [10], and on July 16, 1945, the world's first atomic bomb detonation occurred at the Trinity test in New Mexico. On August 6, 1945, the first atomic bomb was dropped on Hiroshima, Japan. On August 9, 1945, the United States dropped a second atomic bomb on Nagasaki, Japan, ultimately ending the war on August 14, 1945.

The end of World War II was an inflection point in nuclear development. The project employed 129,000 people of which 84,500 were construction workers and 40,500 operating employees [11], providing a labor force trained in nuclear technology development in addition to the US and UK scientists now experts in nuclear technology. In 1946, President Harry S. Truman signed the 1946 Atomic Energy Act that turned over all military nuclear technology to the US Atomic Energy Commission and remained classified [12]. While atomic bomb development continued and hydrogen bomb development began in the United States, the international scientists within the Manhattan Project returned home and transitioned to domestic nuclear programs in the United Kingdom. In the coming decades, Russia, the United Kingdom, France, and China raced to match the US atomic bomb development, followed by a collective pursuit of the thermonuclear hydrogen bomb and tactical nuclear weapons. Growing military expertise in nuclear reactor development for plutonium production was leveraged for nuclear propulsion research and development for submarines and aircraft carriers. Finally, as nuclear technology became declassified and scientists returned to universities following World War II, commercial nuclear power was pursued.

This report studies the relationships of growth between nuclear weapons, nuclear submarines, and commercial nuclear reactors in five nuclear superpowers—the United States, the United Kingdom, China, Russia, and France—following World War II. This report is organized as follows. Section I provides a timeline analysis of nuclear technology growth with key events and uses an economics "learning by doing" metric [2] to show expertise and productivity carries between military nuclear technologies to commercial applications. Section II analyzes learning by doing in commercial nuclear power plant and reactor development using new proposed metrics to capture different learned efficiencies. Section III investigates nuclear policy effects on learning rates.

III. FROM NUCLEAR WEAPONS TO NUCLEAR REACTORS

This section investigates the relationship between military nuclear reactor technology development and adoption in commercial nuclear industries. The data in this study was aggregated from multiple sources. Nuclear power plant data was sourced from the International Atomic Energy Agency (IAEA) Power Reactor Information System (PRIS) [13]. Nuclear reactor information for submarines was sourced from US Navy Fact Files [14], Naval War College Review [15], and the National Museum of American History Archives [16]. Nuclear weapons data was sourced from [17]. All the data aggregated for this report is compiled and shared in the Appendix. Additionally, access to downloading full reports on PRIS is limited, so a custom HTML web scraping script is available in the Appendix that aggregates data from across the website into a coherent dataset.

A. TIMELINE ANALYSIS

HISTORY

The decade following World War II was the beginning of the Cold War with rapidly developing nuclear technology escalating tensions. In 1949, the Soviet Union detonated its first atomic bomb the RDS-1 [18]. In 1952, the United States detonated the world's first thermonuclear hydrogen bomb, Ivy Mike, with a yield approximately 500 times greater than the atomic bomb dropped on Hiroshima [19]. The growing nuclear stockpiles for the United States and Soviet Union are shown in Figure 14 and Figure 2 along with the number of nuclear submarines and power plants from 1940 to 2020.

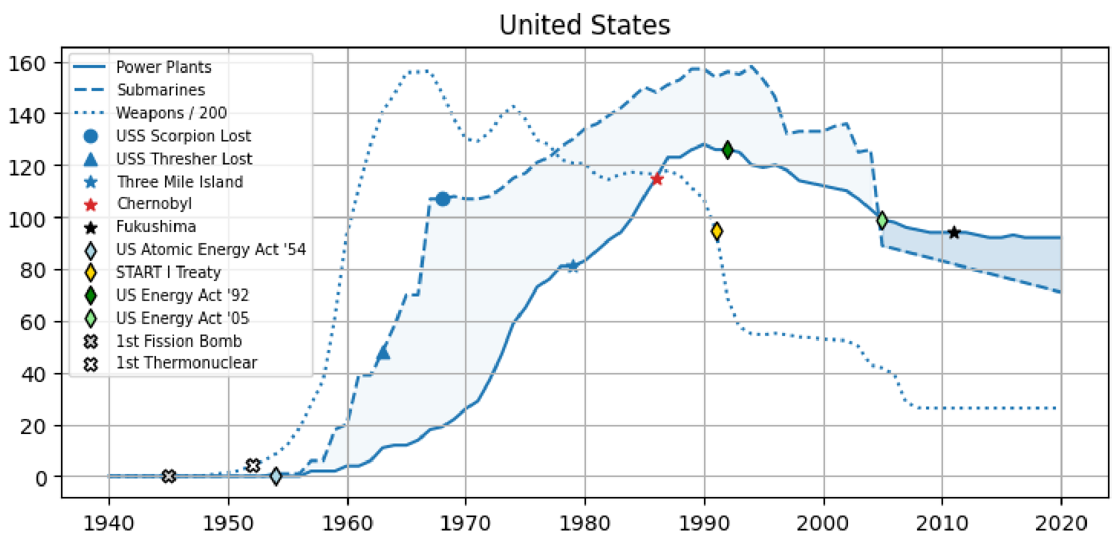


Figure 1: Nuclear history of the United States 1940-2020 by the number of nuclear power plants, nuclear-powered submarines, and nuclear weapons, with the latter being scaled down by a factor of 200. Major events are shown as various markers.

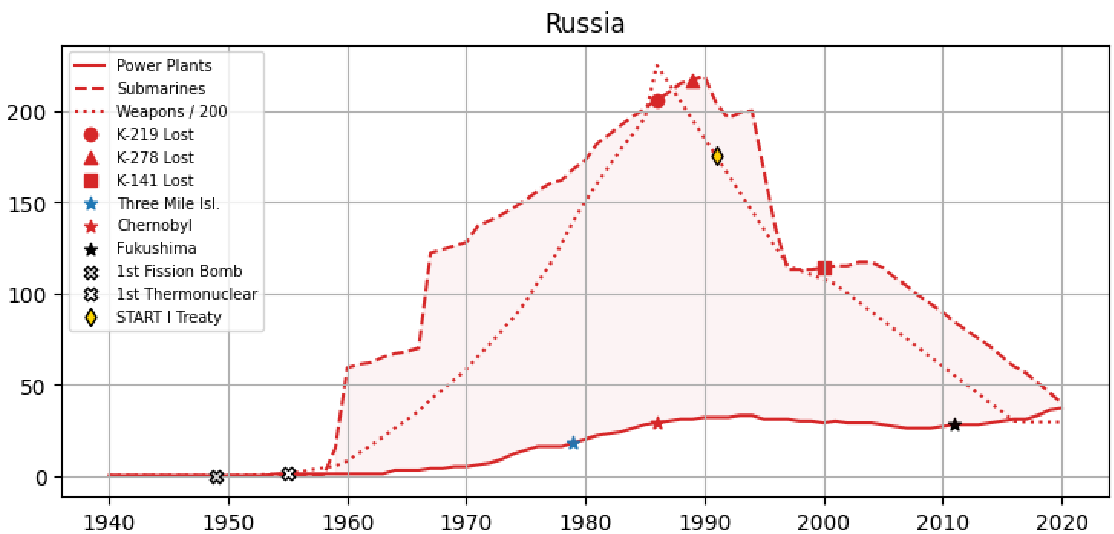


Figure 2: Nuclear history of the Soviet Union then Russia 1940-2020 by the number of nuclear power plants, nuclear-powered submarines, and nuclear weapons, the latter being scaled down by a factor of 200. Major events are shown as various markers.

In 1953, the United States Navy built the first practical nuclear reactor for submarine propulsion, the SW-1 [20], which would subsequently power the world's first nuclear submarine, the US Navy's USS Nautilus in 1954 [21]. Despite US expertise in nuclear reactors from military development, the Obninsk Nuclear Power Plant in the Soviet Union became the world's first nuclear power plant to generate electricity for a power grid in 1954 [22]. The same year, President Dwight D. Eisenhower signed the 1954 Atomic Energy Act which declassified nuclear reactor technology, allowed production of fissile materials e.g., plutonium, and allowed for exchange of nuclear information to foreign nations.

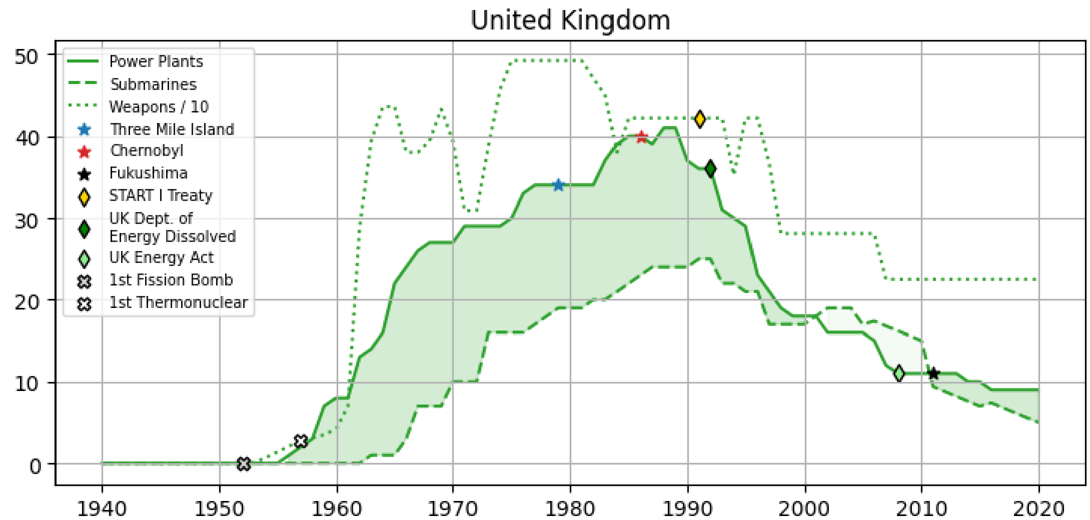


Figure 3: Nuclear history of the United Kingdom 1940-2020 by nuclear weapon, submarine, and power plant count.

In 1955, the Soviet Union tested its first thermonuclear bomb the RDS-37 [23]. The next year, the United Kingdom tested its first thermonuclear bomb at Operation Grapple on Christmas Island [24] as shown in Figure 3. In 1957, the Soviet Union deployed its first nuclear-powered submarine Project 627 [25]. With opposing world superpowers now armed with lethal nuclear weapon stockpiles and tactical delivery vessels, the tension in the Cold War reached its peak. The Berlin Wall was erected in 1961 soon followed by the Cuban Missile Crisis in October. During this time, President John F. Kennedy's foreign policy was dominated by proxy contests and nuclear threats from Soviet Union. Kennedy implemented a strategy to build the US nuclear arsenal, the B-52 bomber fleet, and nuclear submarines [26].

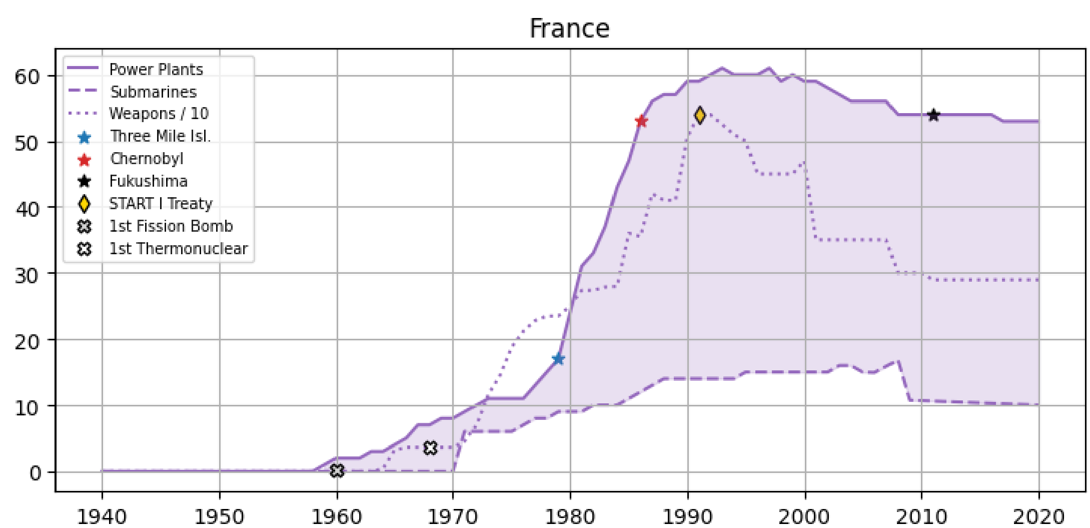


Figure 4: Nuclear history of France 1940-2020 by nuclear weapon, submarine, and power plant count.

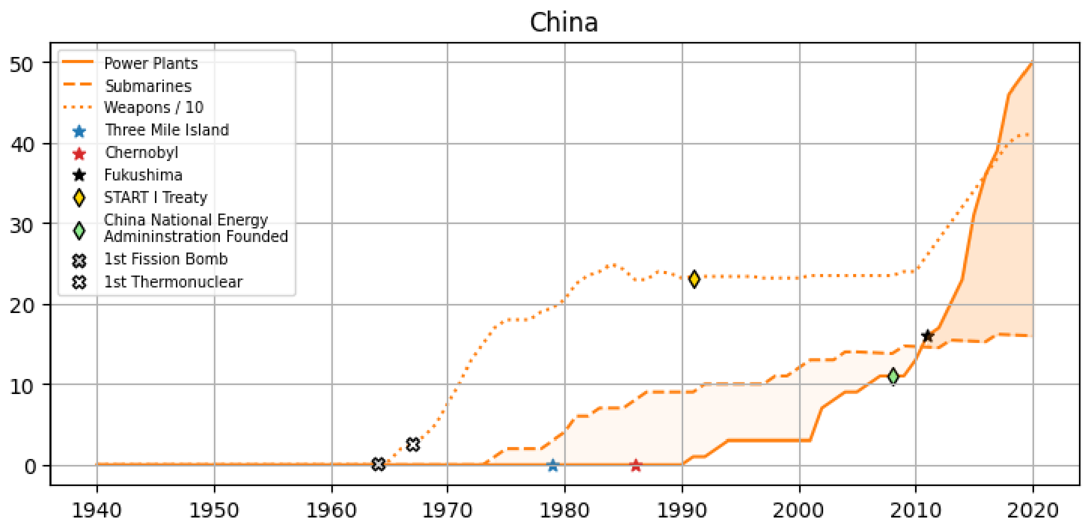


Figure 5: Nuclear history of the China 1940-2020 by nuclear weapon, submarine, and power plant count.

The 1960s were a turning point in the nuclear arms race. In 1961, the Soviet Union tested Tsar Bomba, the largest thermonuclear bomb ever tested, 2,300 times more explosive than the bomb dropped on Hiroshima [27]. The prior year, France tested its first atomic bomb at the Gerboise Bleue test [28], and would go on to test its first thermonuclear bomb in 1968 as shown in Figure 4. China tested its first atomic bomb Project 596 in 1964 and went on to develop its first thermonuclear bomb only three years later in 1967 [29] as shown in Figure 5.

As the number of nuclear-weapon states grew, the nuclear-deterrent strategy became less tenable. The risk of miscalculation, unauthorized use of weapons, and nuclear conflict was multiplied with the introduction of each new nuclear-weapon state. This mutual concern led to the 1968 Treaty on the Non-Proliferation of Nuclear Weapons, which was signed by the United States, Soviet Union, and United Kingdom in 1968, while China and France signed the treaty in 1992 [30]. The United States and Soviet Union agreed to limit nuclear arsenals in the START I Treaty of 1991 and officially ended the cold war [31].

TRENDS

Throughout the second half of the 20th century, nuclear submarines and commercial nuclear power plants were being built despite nuclear disasters and the threat of nuclear war. For all five countries except France, the rise in development of nuclear weapons distinctly precedes the rise in development of nuclear submarines and commercial nuclear power plant development. In the three largest superpowers the United States, Soviet Russia, and China, the rise in development of nuclear submarines also precedes the rise in commercial reactor development. These trends indicate learning by doing across each domain. The transfer of knowledge within the military from nuclear weapons to nuclear submarines is intuitive, given the nuclear reactor expertise required in nuclear weapon fuel production. The transfer of knowledge and expertise from the military to the commercial industry can be better understood through the declassification of nuclear technology and the involvement of university researchers in the Manhattan Project returning to academia and industry following World War II.

The effect of nuclear disasters on submarine and power plant development is challenging to evaluate given the delays in policy impacting development with analyzing reactor metrics across time, which is done in Section I.B. In the United States, growth in nuclear submarine development continued through the loss of USS Scorpion and USS Thresher, neither of which were concluded to have been lost due to failure of the nuclear reactors. Instead, the failures were insufficient welding or accidental torpedo activation which helps explain why nuclear submarine development continued and there was no transition to diesel submarines. In Russia, however, the major losses of K-219 and K-278 may have had an impact on future development of Russian nuclear submarines. K-219 and K-278 were lost to an internal missile explosion and electrical fire respectively, not nuclear reactor issues [32], but the coinciding START I Treaty makes it difficult to evaluate the effect of those submarine disasters on Russian nuclear submarine development.

Three major nuclear disasters impacting the world's perspective on nuclear energy were Three Mile Island in the US (1979), Chernobyl in Russia (1986), and Fukushima in Japan (2011). Each of these is shown along the trend line of nuclear power plant development in each country in Figures 1-5. In the US and UK, the development of nuclear reactors in each country decidedly stagnates in the late 80s before the signing of START I, before the US Energy Act of 1992, and before the dissolution of the UK Department of Energy. By the time each of these events occur, the UK, US, and Russia all see stagnation or decline, meaning there was possibly a public shift away from trust in nuclear power the preceded the energy policies of the early 90s. Once the UK Department of Energy dissolved and the US passed the Energy Act of 1992, both countries saw significant declines in the nuclear reactor development, apparently allowing reactors at the end of their lifespan to be decommissioned without building replacements. The growth of commercial nuclear plants in France doesn't appear to slow following the Three Mile Island disaster, but there is stagnation followed by decline in the decades following the Chernobyl accident. China's nuclear industry was non-existent when Chernobyl occurred, but nonetheless its nuclear growth was seemingly unaffected by the Fukushima disaster.

The most significant indicator of disasters and policies appears to be the Strategic Arms Reduction Treaty (START I) signed in 1991. While only being a bilateral agreement between the United States and then Soviet Union to limit arms, all countries except China appear to experience a downward trend across all nuclear technologies following its signing. While the US and UK energy policies of the early 1990s are certainly confounding variables, the trend is too apparent to be ignored. In the following two decades, nuclear warhead arsenals decreased by % in the US, % in the UK and % in Russia. Nuclear submarine fleets decreased by 56% in the US, 52% in the UK, and 45% in Russia. And despite not being limited in the treaty, the number of nuclear power plants decreased by % in the US, % in the UK and % in Russia.

B. LEARNING BY DOING

This section demonstrates that all global superpower's development of nuclear power plants and adoption of nuclear energy was consistently preceded by military development of nuclear reactors for submarines two decades prior and military development of nuclear weapons two or three decades prior. The only exception is French submarines which lag nuclear power plants. This can be explained in part by learning-by-doing; the commercial industry can extract lessons learned, best practices, labor productivity, supply chains, and innovations from military applications into commercial applications. To show this learning-by-doing realized in nuclear reactor technology's transition from military to commercial applications, the average peak power for nuclear power plants and submarines is plotted in Figure 6. Then, a linear regression is done per decade as a measure of innovation growth. The result in Figure 6 shows steady growth over most decades for each country and technology. However, each country has one decade with a steep rise in average peak power, indicating an innovation breakthrough via learning-by-doing.

What's more, the rate of change for each decade representing the growth of nuclear technology innovation can be plotted as shown in Figure 5 to reveal a significant relationship. Figure 5 shows that the peak in annual innovation growth for nuclear power plants consistently occurs 2 decades after the peak in annual innovation growth for nuclear submarine technology. This shows a clear example of learning- by-doing for each country from the military application of nuclear submarines to the commercial and public application of nuclear power plants.

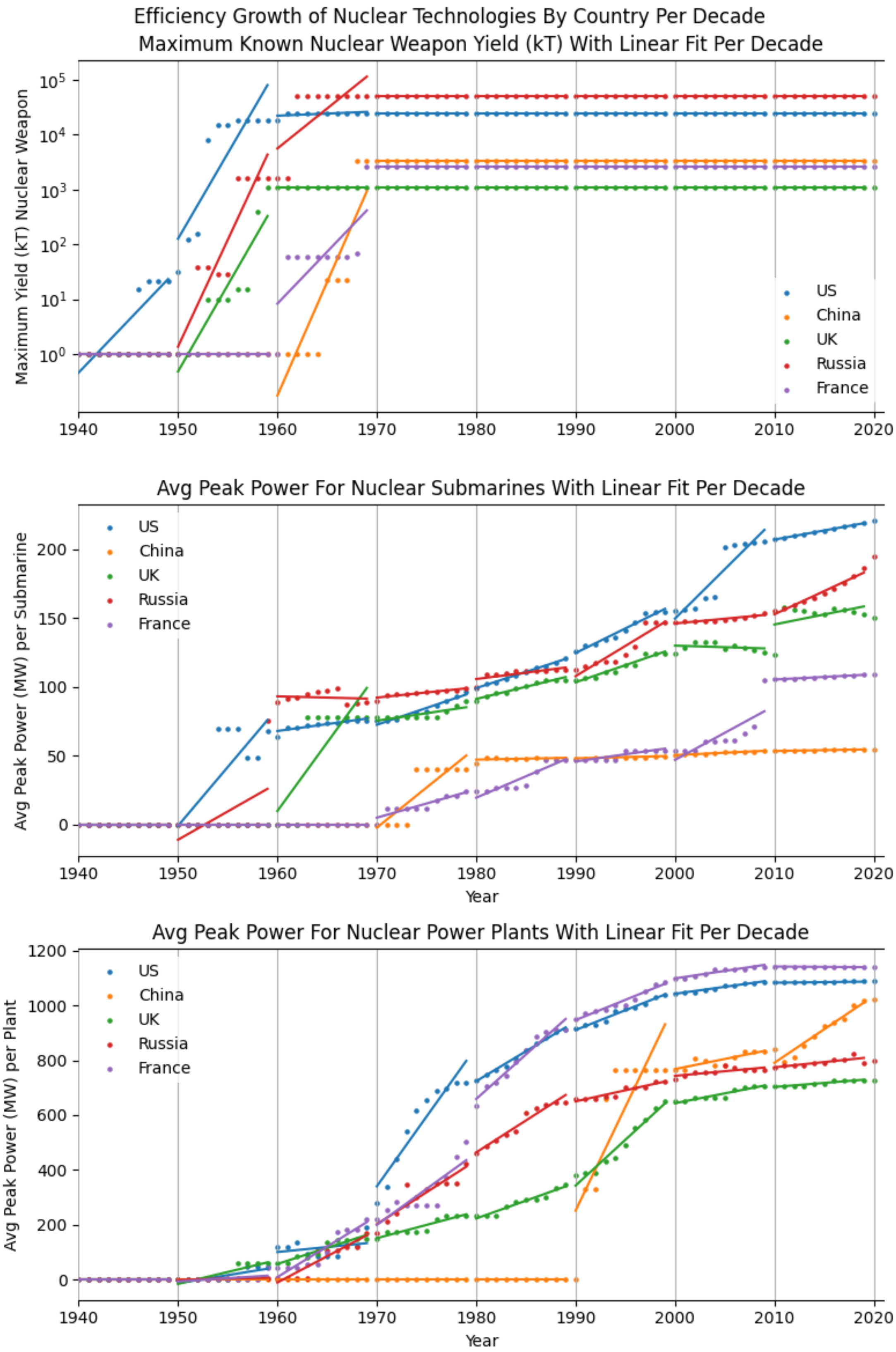


Figure 6: Learning-by-doing as measured by (top) maximum nuclear weapon yield, (middle) submarine peak power averaged by year, and (bottom) power plant peak power averaged by year, with a linear regression fit per decade.

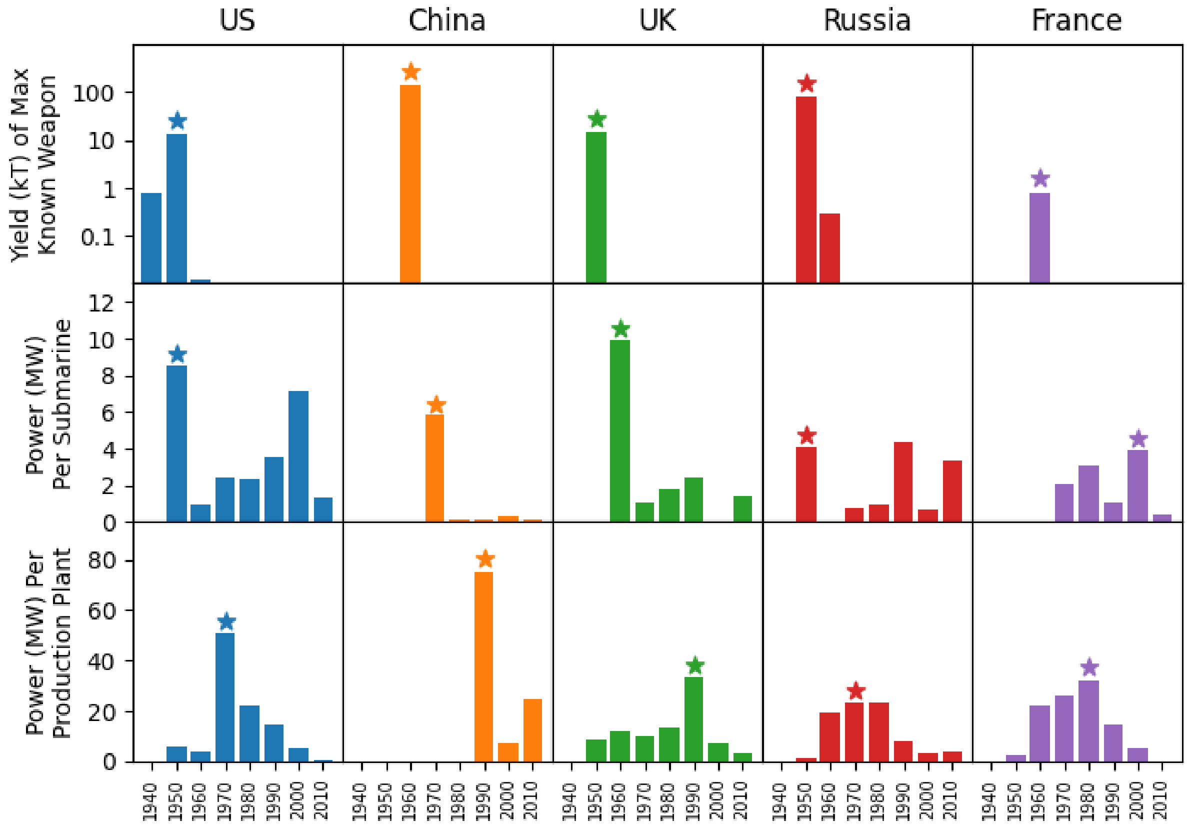


Figure 7: Learning-by-doing as measured by a linear regression per decade of (top row) nuclear weapon yield, (middle row) submarine peak power averaged by year, and (bottom row) power plant peak power averaged by year. Peak nuclear power plant development is consistently preceded by peak military development of nuclear reactors for submarines and nuclear weapons two or three decades prior. This demonstrates learning-by-doing of nuclear technology development transferring from the military to the commercial industry.

IV. CIVILIAN NUCLEAR REACTOR TECHNOLOGY DEVELOPMENT

Once nuclear technology permeated into the commercial industry, companies like Westinghouse and General Electric in the United States began researching, developing, and deploying new reactor models. The United State primarily developed pressurized water reactors (PWR) and boiling water reactors (BWR) following the path of nuclear submarines. The United Kingdom primarily developed gas-cooled reactors (GCR), while France moved away from GCR develop in the 1970s, transitioning focus to PWR development. Russia mainly developed Light Water Graphite Reactors (LWGR) until the Chernobyl disaster, which itself was a LWGR, and switched to PWRs afterwards.

As the capacity of reactors grew, so did the regulation policies and construction durations. The history of reactor construction in the United States is summarized in Figure 8, clearly showing inflating construction periods over time. Construction in the United States, United Kingdom (Figure 9), and France (Figure 10) halted in the 1990s. Development of nuclear reactors in Russia paused for two decade following the Chernobyl disaster, but resumed at a moderate rate in the late 2000s as in Figure 11. China began nuclear power plant development in the 1980s and didn't slow following the nuclear disaster in Fukushima, Japan as seen in Figure 12.

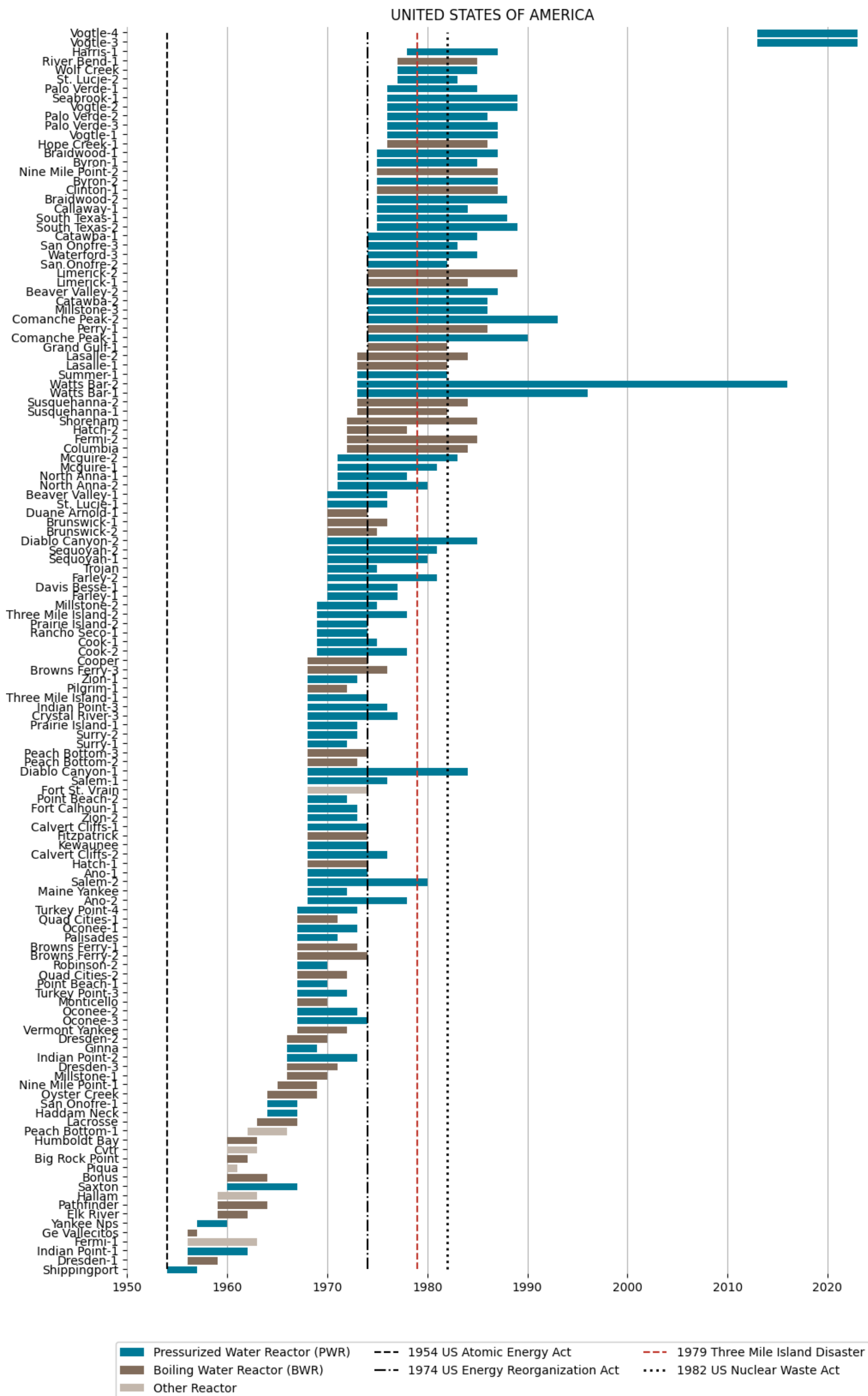


Figure 8: Civilian nuclear reactor construction history in the United States 1950-2020.

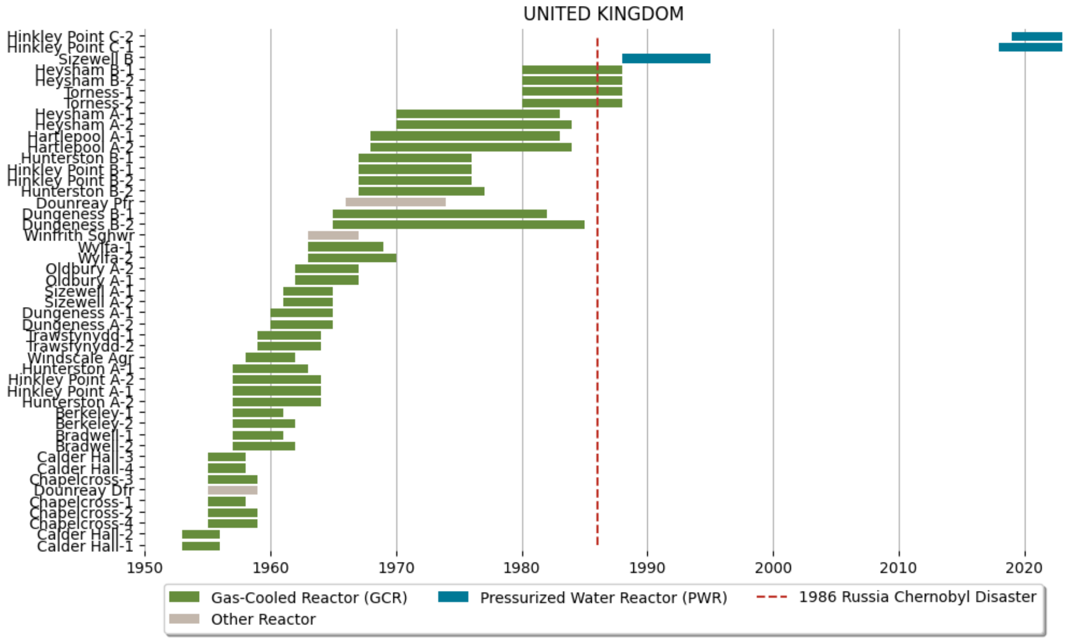


Figure 9: Civilian nuclear reactor construction history in the United Kingdom 1950-2020.

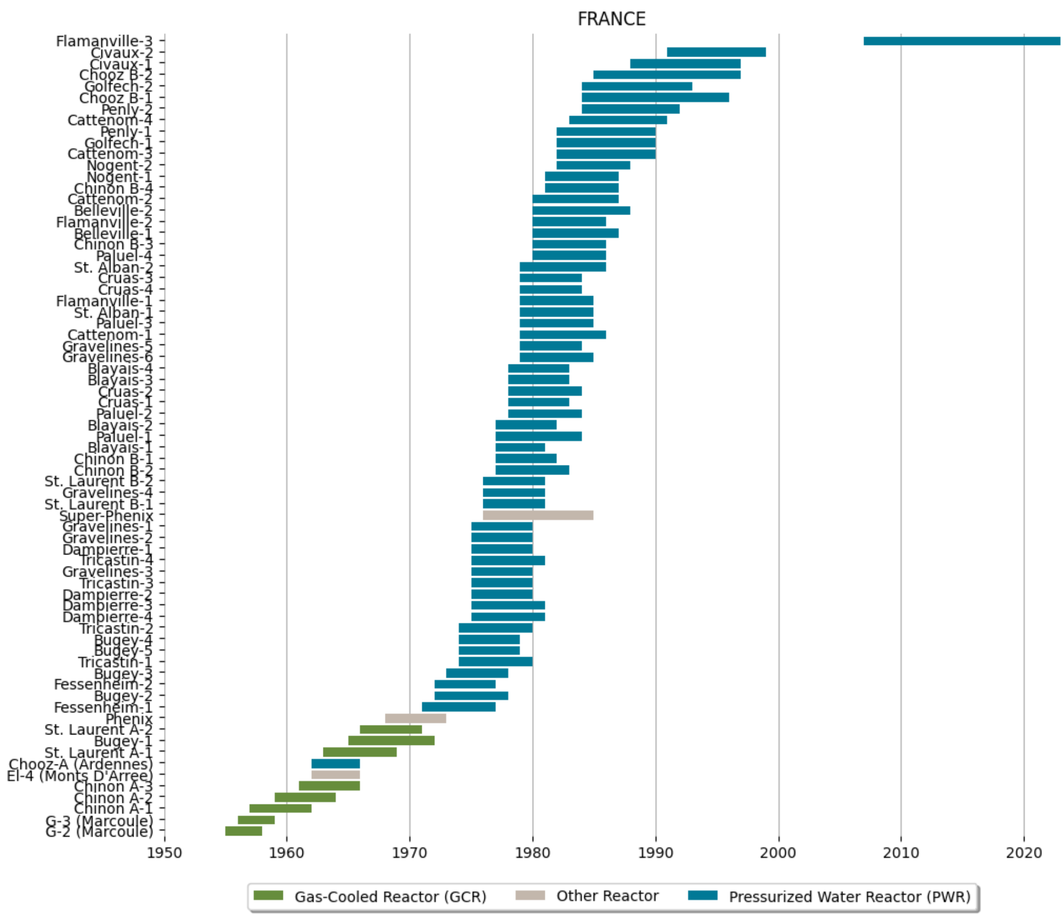


Figure 10: Civilian nuclear reactor construction history in France 1950-2020.

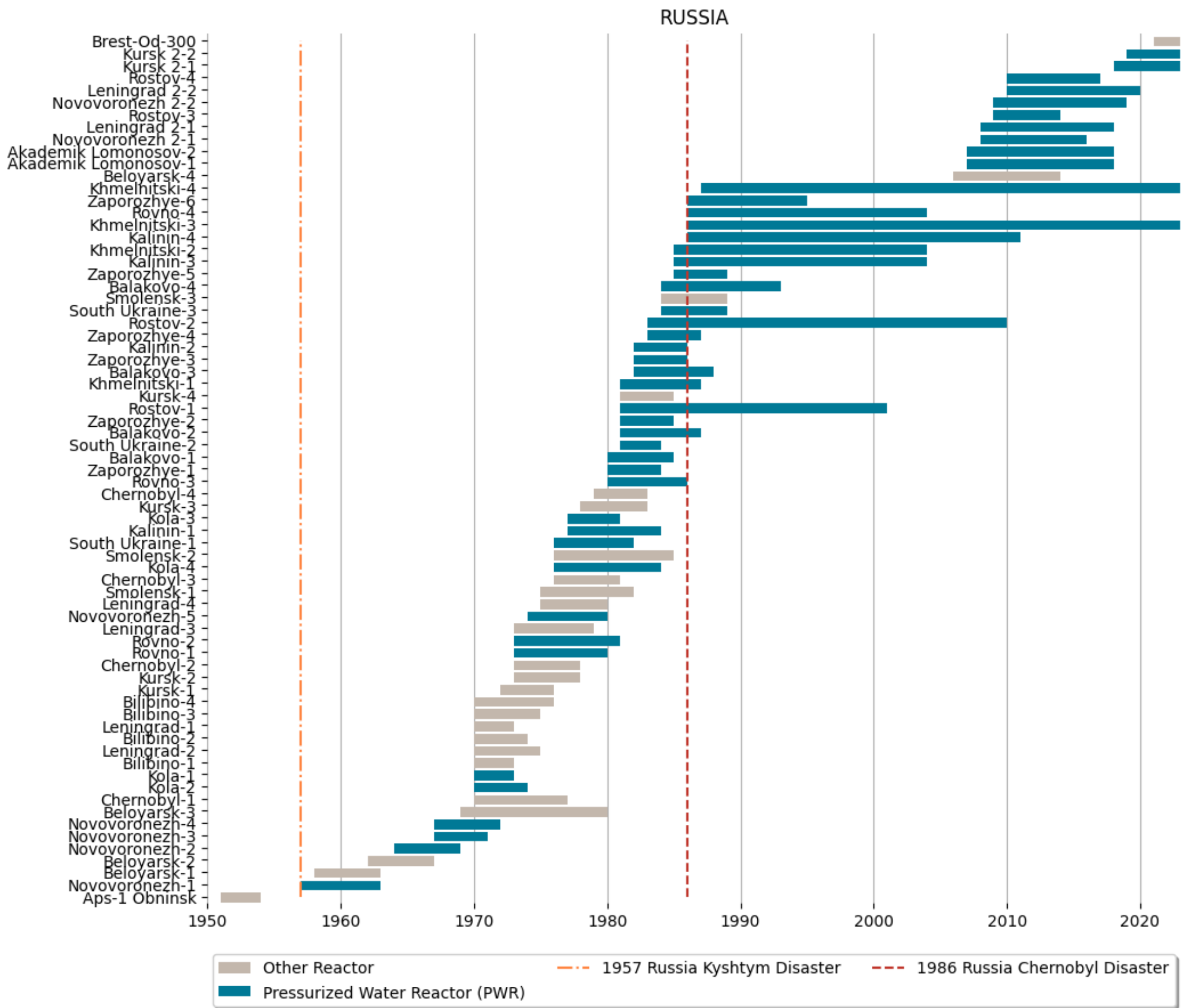


Figure 11: Civilian nuclear reactor construction history in Russia 1950-2020.

Each of these development timelines contain changes in the dominant nuclear reactor technology and iterations of the same reactor model deployed in power plants. This provides grounds for analysis of learning rates across reactor technology types and learning within specific reactor models.

Early learning by doing studies showed that labor productivity increased with cumulative output in airframe manufacturing [33] and wartime shipbuilding [34]. In addition to a labor force learning production processes, learning by doing is derived from improved management, updated engineering designs, refinement of capital equipment, and increased efficiency of suppliers. For nuclear power plants, operator experience can also improve over the life of a plant, leading to growth in plant production efficiency. The effect of cumulative plant experience on annual output was studied in [35]. However, at the time of the study, less than one-third of nuclear power plants active in 2023 had completed construction, using data from only 73 reactors globally limited to BWRs and PWRs. As of 2023, there are 413 operational nuclear power plants and 209 decommissioned power plants, totaling 622 nuclear plants to study.

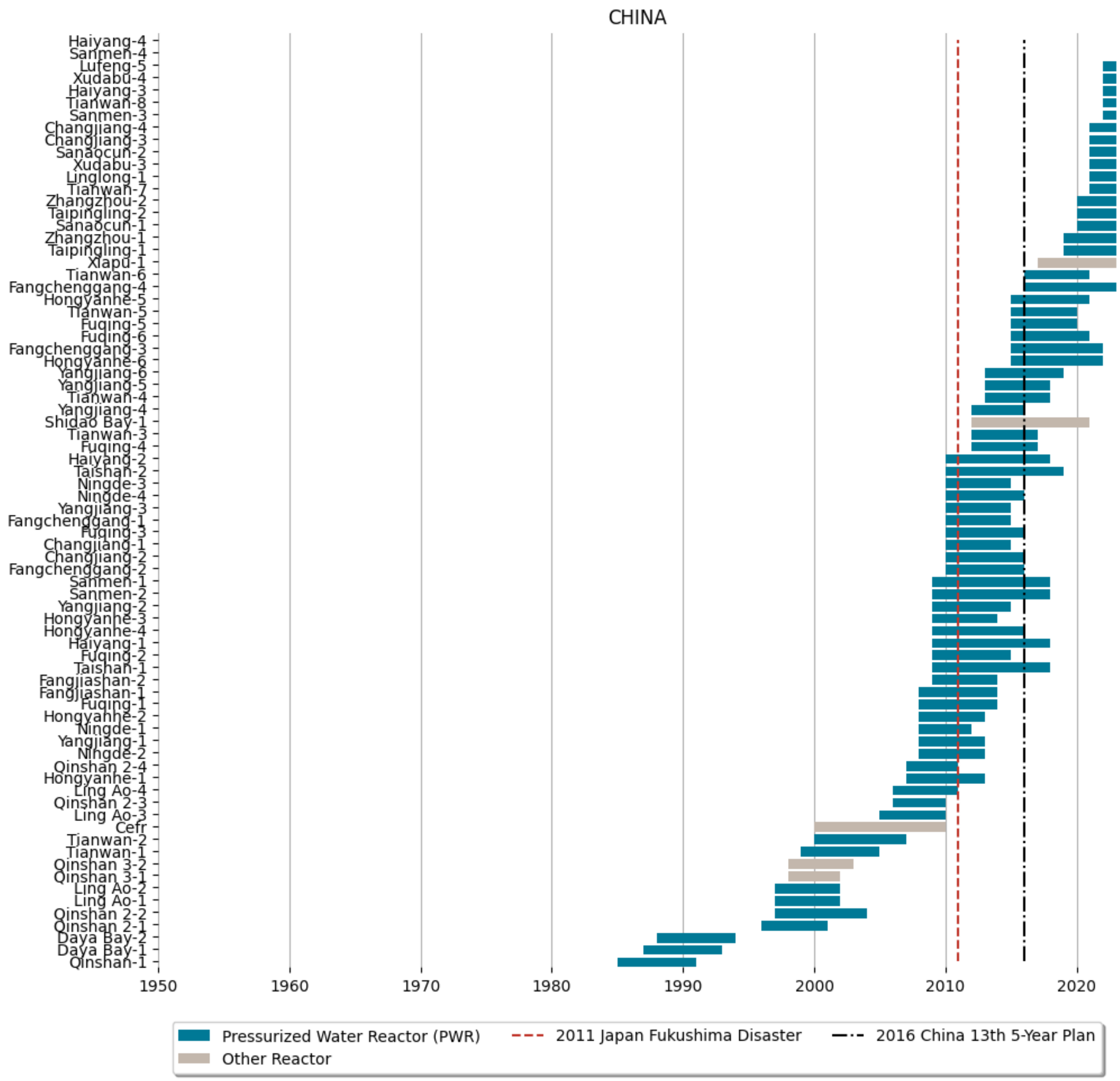


Figure 12: Civilian nuclear reactor construction history in China 1950-2020.

This study focuses on the five leading nuclear countries—United States, China, United Kingdom, Russia, and France—251 active and 101 retired nuclear reactors, totaling 352 which is 57% of the global share.

While capacity factor over the lifetime of individual plants is a sufficient measure of learning by doing operationally, it doesn't capture big picture changes in energy production capacity per plant. With a capacity factor learning by doing metric, a reactor design improvement is only measurable if it allows the nuclear plant to spend more time operating at its capacity. Any improvement in total capacity isn't measured as learning.

A better learning by doing metric for nuclear technology would factor in capacity and development timelines. Capacity build rate is a metric that can be computed by dividing the net capacity of a nuclear plant by the total construction duration as shown in (1).

$$L_{cap} = r_{build} = \frac{\partial C_{net}}{\partial T_{plant}} \qquad (1)$$

This averages the built capacity over the period of the project to give an estimate for how many Megawatts of capacity were built per year for a given reactor model. Capacity build rate serves as a capacity learning metric by capturing improvements in engineering design related to increased nuclear reactor power capacity and infrastructure design related to scaling nuclear power plants.

The capacity learning rate metric in (1) can be estimated for each type of nuclear reactor using a linear regression model to approximate the change in capacity over the active years of each reactor type. Figure 14 shows the build rate estimation for eight combinations of reactor type and country with the most data points. The slope, m, shown is the capacity learning rate metric in units of MW/year. Intuitively, this measures the growth in power capacity for each reactor type. The coefficient of determination is also shown to evaluate the fit the of regression.

The capacity learning rates per reactor type are summarized and compared in Figure 13. All reactor types per country are positive, ranging from 9 MW/year to 64 MW/year.

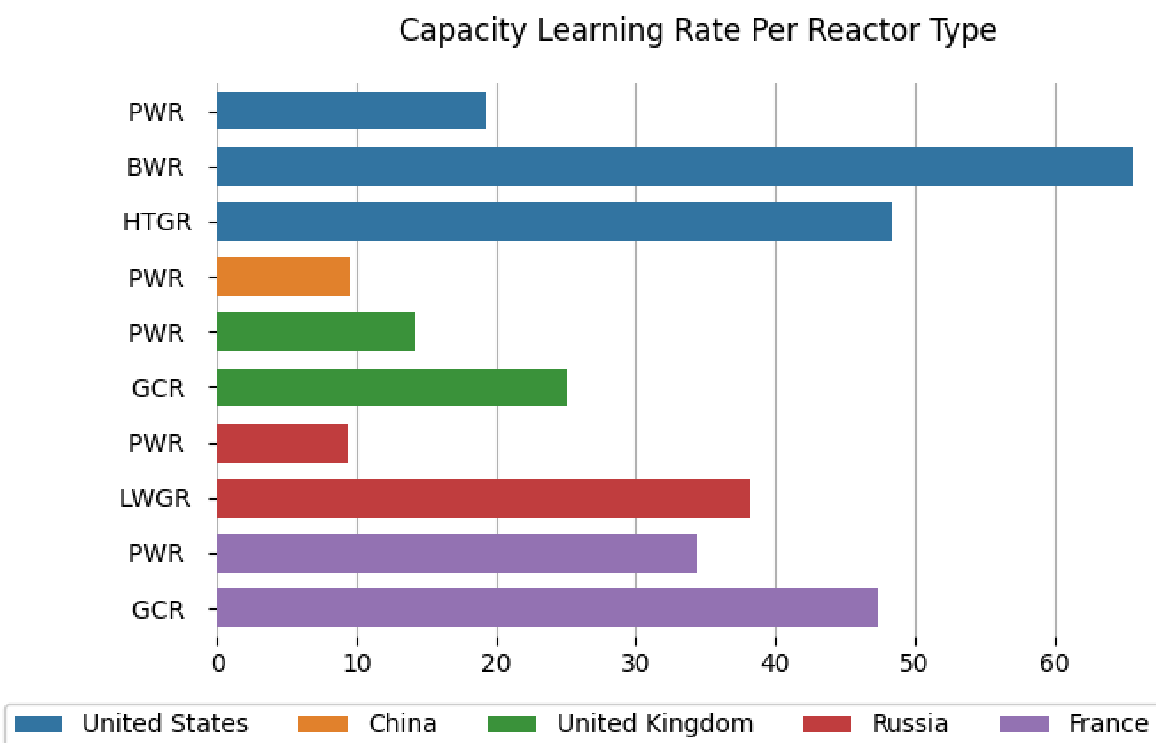


Figure 13: Learning rate comparison with capacity build rate per nuclear reactor type and country in units of MW/year.

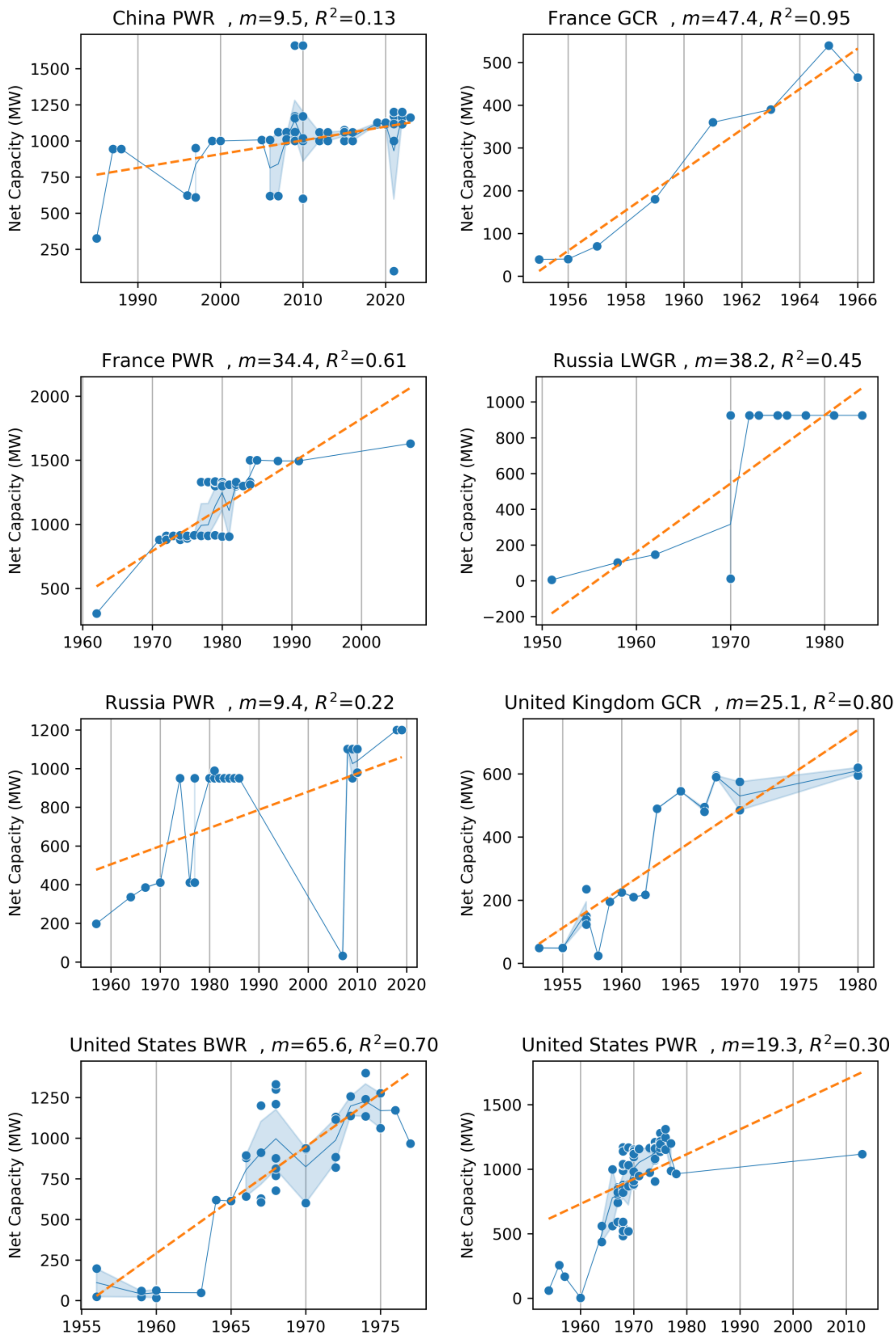


Figure 14: Learning by doing rate estimates by reactor type with linear regression.

While this analysis across nuclear reactor types clearly shows learning by doing, differences in construction duration, reactor models, and contemporary policy, make it challenging to associate learning rate improvements with specific actions of governments and firms. To enable more precise analysis, the learning rates of individual nuclear reactor models will be investigated.

The average build rate for all reactor models with two or more installations is shown in Figure 15. Most reactor models have means between 100 and 200 Megawatts-per-year. Chinese HPR1000 and VVER-1200/V491 models are outliers, with mean build rates of approximately 250 MW/year and 600 MW/year.

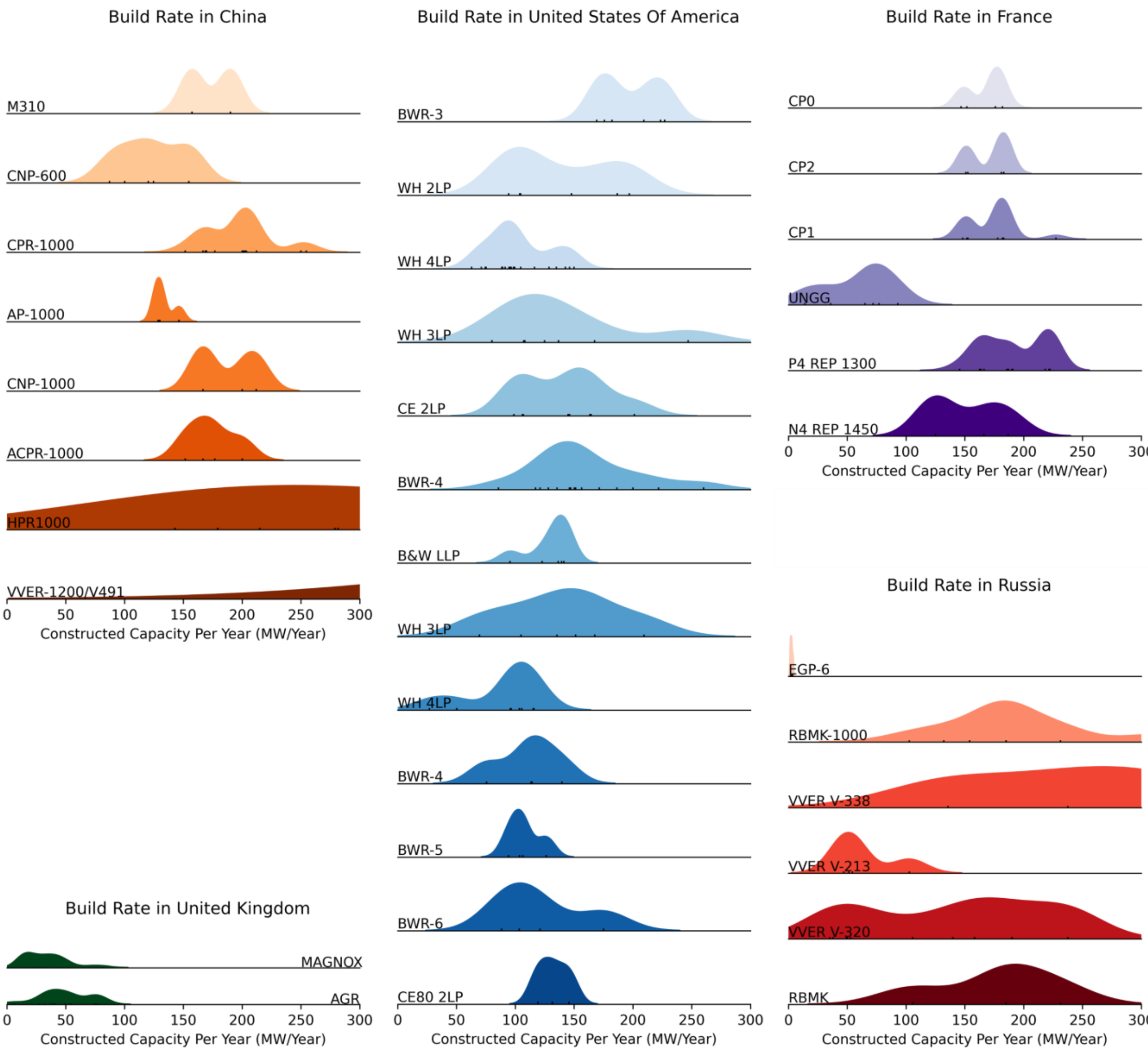


Figure 15: Distribution of rates by reactor model per country.

Build rate, or capacity learning rate, is a design-focused learning rate measure. It measures changes in reactor and infrastructure design, but it doesn't account for construction, supplier, or operations labor force expertise. To include these factors in a learning by doing metric, this study proposes measuring the change in capacity build rate. Measuring the change in build rate effectively accounts for both design factors improving capacity and operations factor improving efficiency. This effective learning metric is given in (2) where C_{net} is the nuclear plant net capacity, T_{plant} is the construction duration of the plant, T_{avg} is the average time between construction of same model reactors, and r_{build} is the capacity build rate.

$$L_{eff} = \frac{\partial \left(\frac{\partial C_{net}}{\partial T_{plant}} \right)}{\partial T_{avg}} = \frac{\partial (r_{build})}{\partial T_{avg}} \qquad (2)$$

This metric has units Watts-per-year-per-year, or W/year^2, a measure of production capacity acceleration. This measure reflects collective changes in the engineering design process, bureaucratic process, and construction process. Using this metric to compare nuclear plants of the same capacity built at the same time and across countries will support investigation into the effects of nuclear policy and investment in energy production. Additionally, comparing different reactor models with this effective learning metric can help identify the best reactor models that are simultaneously improving in construction duration, operability, and capacity.

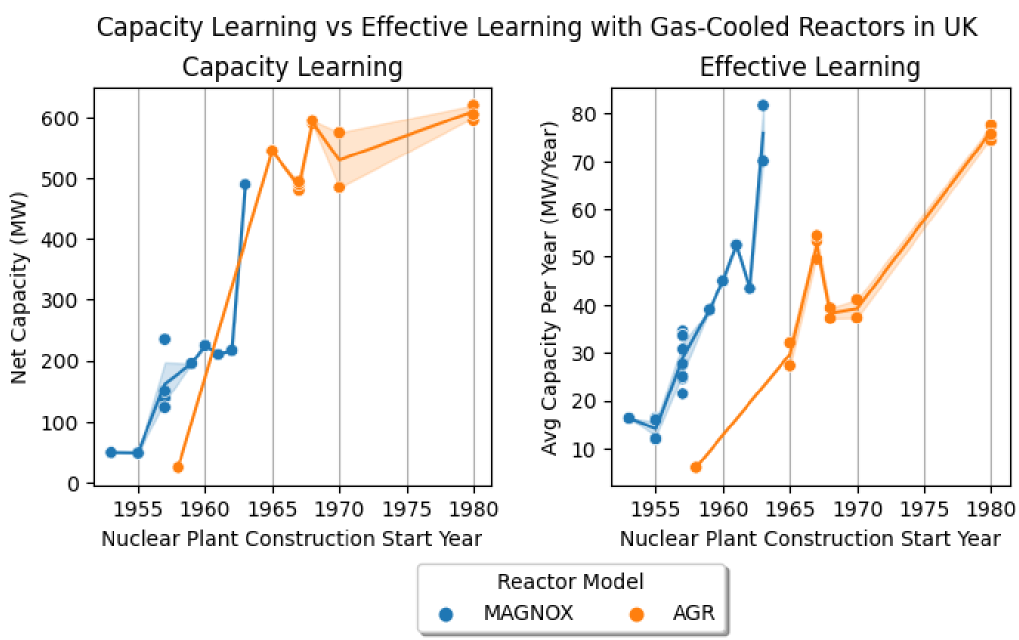


Figure 16: Capacity learning vs effective learning metrics for gas-cooled reactors in the United Kingdom.

While in some cases, both capacity learning and effective learning as defined here capture learning by doing as shown in Figure 16, this is not always the case. An example of three pressurized water reactor models in France shown in Figure 17 emphasizes the utility of effective learning over capacity learning. Each scatter plot data point is one deployed reactor, plotted on the x-axis at the time construction on its associated nuclear power plant began. The y-axis is (left) net capacity and (right) net capacity divided by the construction duration of the power plant. Only evaluating net capacity doesn't capture the improvements to the supply chain, construction process, and labor force productivity, while the effective learning metric does capture these key factors.

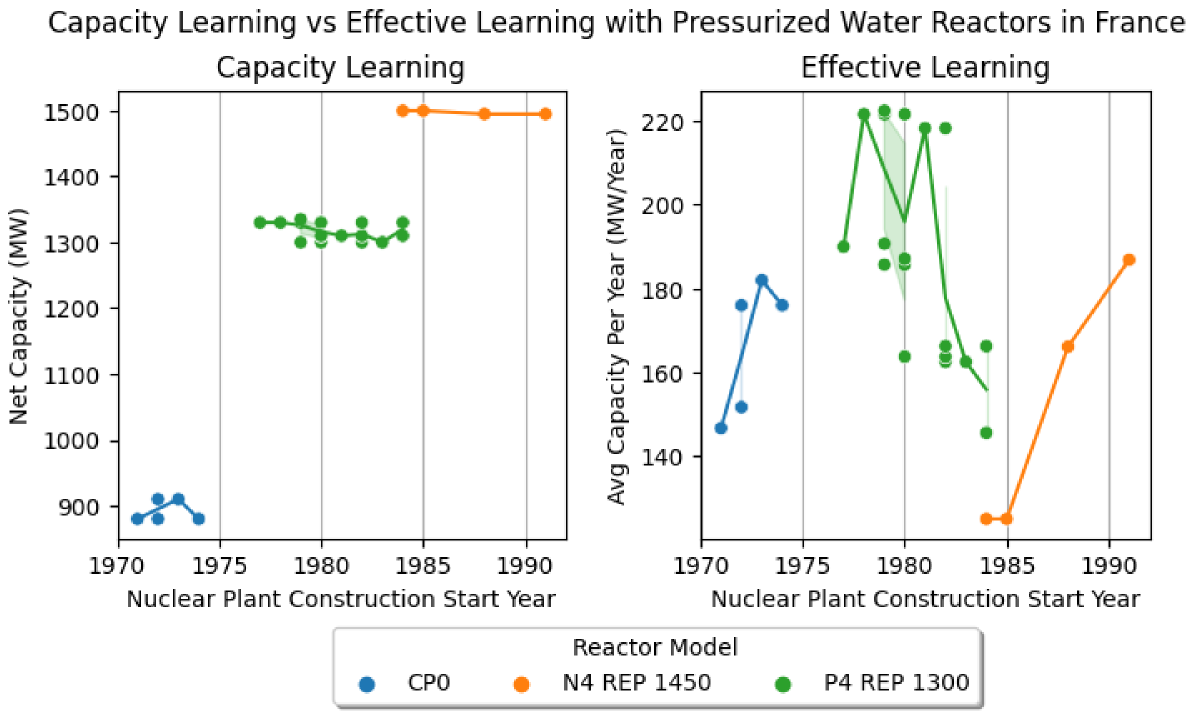


Figure 17: Capacity learning vs effective learning metrics for three French reactor models.

In Figure 17, it's evident that the CP0 and R4 REP 1300 models demonstrate learning by doing measured in MW/year^2 despite the build rate remaining constant. The CP0 reactor model was able to add about 180MW of nuclear capacity per year after three years and a few reactors of experience, up from 145MW per year with the first reactor. This represents a gain of 35MW per year over three years, an effective learning rate of about 11 MW/year^2. This means the CP0 reactor adds 8% more capacity year-over-year due to learning by doing. A similar trend is seen in the N4 REP 1450 reactor model with MW-per-year increasing from 125MW per year to 187MW per year—a 50% increase in 7 years. This is an effective learning rate of about 9 MW/year^2. The P4 REP 1300 reactor MW-per-year decreases over time at an effective learning rate of about 7.5 MW/year^2.

To analyze these metrics for each reactor model, each reactor's effective learning rate and availability learning rate are estimated with a linear regression model. This method is applied to all reactor models with at least three deployments in power plants.

Figure 18 shows the linear regression per country, reactor model, estimated effective learning rate, and coefficient of determination R-squared value. The axes not shown are the same as in Figure 16.

As in Figure 16, the French N4 REP 1450 model shows a strong learning rate of 9.3 MW/year^2 with an 0.97 coefficient of determination. All these learning rate estimates for effective learning based on (2) are aggregated and compared in Figure 19. At first glance, it's apparent that French-made and UK-made nuclear reactors are the most scalable and learnable in terms of (1). Notably, three of these reactor models are gas-cooled reactors (GCR): Magnox, Advanced Gas-Cooled Reactor (AGR), and Uranium Naturel Graphite Gaz (UNGG). The remainder of reactor models with positive learning rates are pressurized water reactors (PWR).

The large inefficiencies in the United States reactor models reflect changes in public opinion, policy, and health of reactor engineering firms. These changes compound to make nuclear development less profitable. The General Electric (GE) built BWR-X models and Westinghouse (WH) XLP models all exhibit negative effective learning rates. In 2017, this manifested Westinghouse Electric Company to file for bankruptcy [36]. The context for the filing was the development of the Vogtle-3 and Vogtle-4 nuclear plants built with Westinghouse AP1000 reactor models, which have never been constructed in the United States and only two have been constructed globally. The Vogtle project cost estimates were running $1 billion higher than expected after in 2017, eight years after the project began in 2009. The Vogtle AP1000 reactor models with projected grid connections in 2023 will have an approximate capacity build rate of 80 MW/year, putting it in the lower third of capacity build rate in the US based on Figure 15. This reflects declines in US nuclear construction experience, design expertise, and supply chain support.

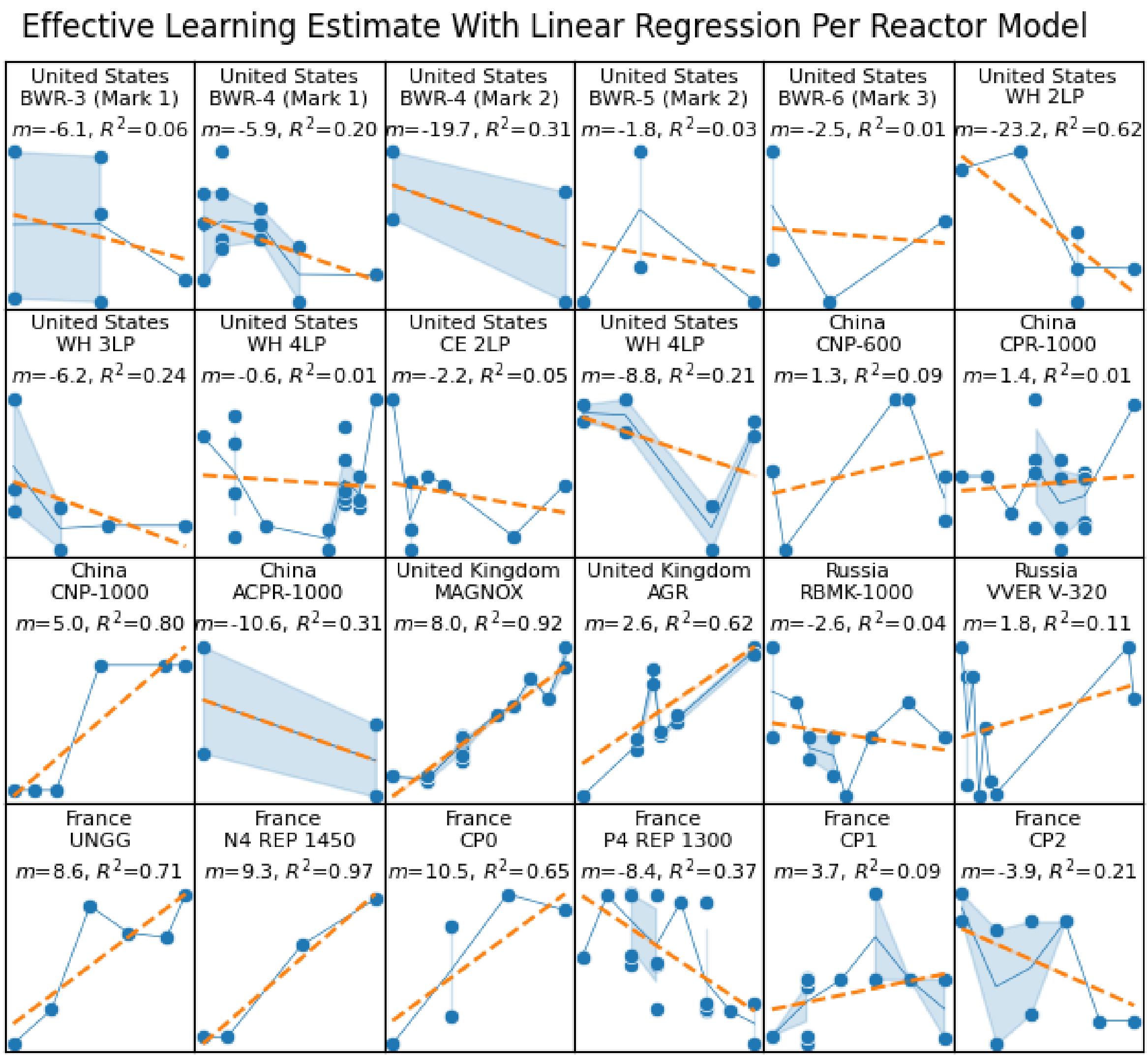


Figure 18: Effective learning rate estimation (MW/year²) with linear regression.

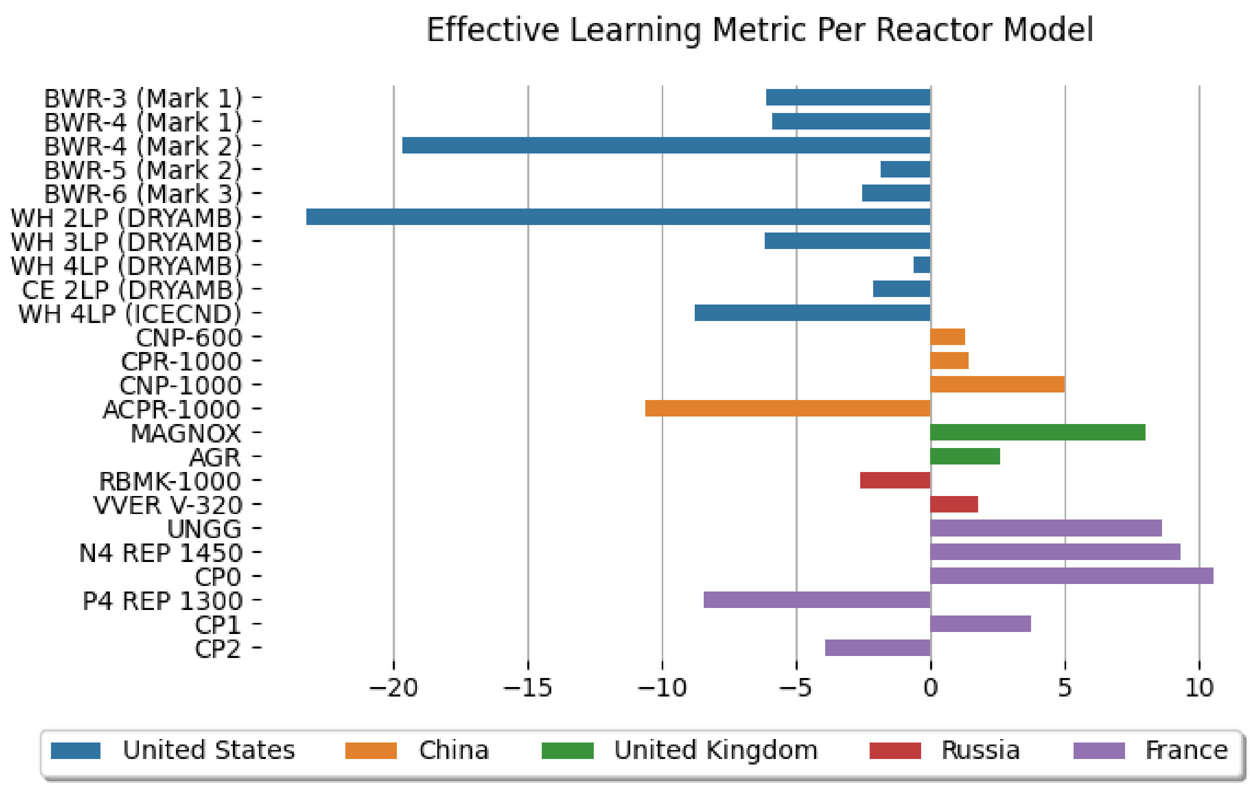


Figure 19: Effective learning rate by reactor model summary in units of MW/year².

In addition to the effective learning metric, an availability learning factor is studied as shown in (3), where A is the average availability of a plant as a percent. This supplemental metric reflects the operational learning by doing at a power plant over time as well as the reliability of reactor designs. This metric is preferred to load factor, which is dependent on the energy market, while being similar to capacity factor with emphasis on reliability.

$$L_{avail} = \frac{A}{T_{avg}} \qquad (3)$$

As shown in

Figure 20, almost all models exhibit a positive availability learning rate. Outlier reactor models include the BWR-4 (Mark 2) of the US and UNNG of France with availability learning rates of 5.5% and 5% respectively. Most other reactors have learning rates under 2%.

Despite having the highest availability learning rate, the BWR-4 (Mark 2) exhibited an effective learning efficiency decline of 19%. Meanwhile the UNGG reactor is among the highest effective learning rate and availability learning rate increases at 8% and 5% respectively. This may indicate that operational factors in plant availability have a less significant relationship to engineering and productivity factors characterizing the effective learning rate.

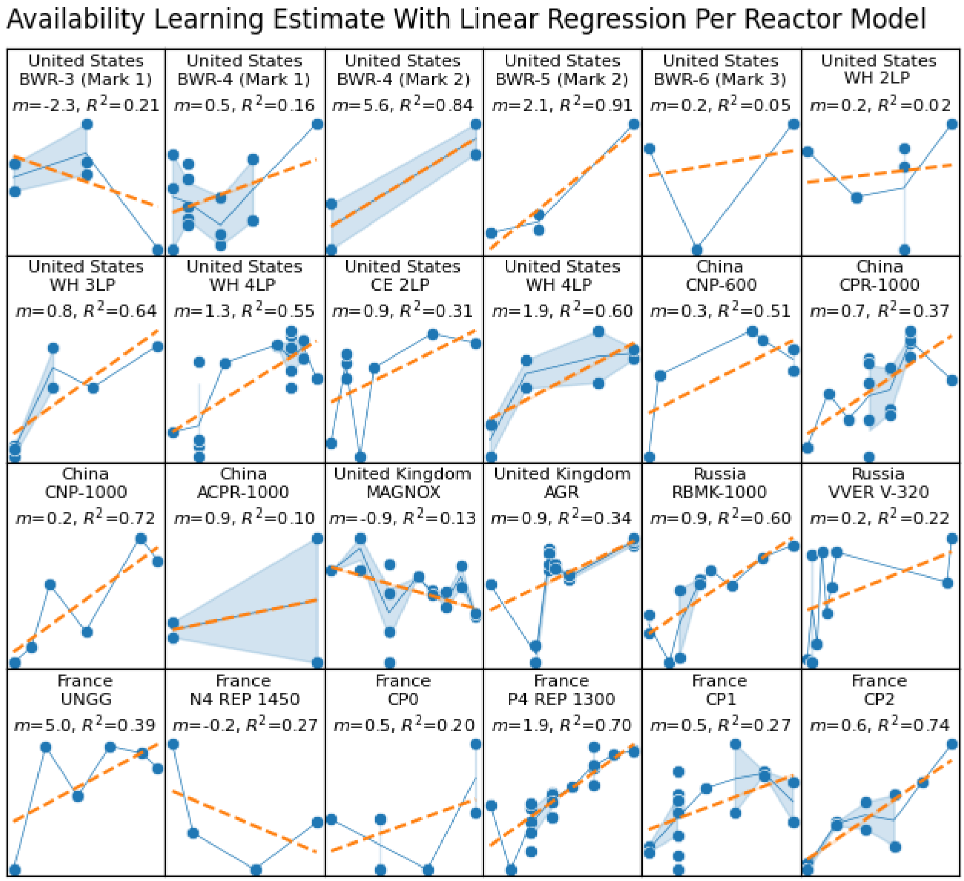


Figure 20: Availability learning rate estimation with linear regression.

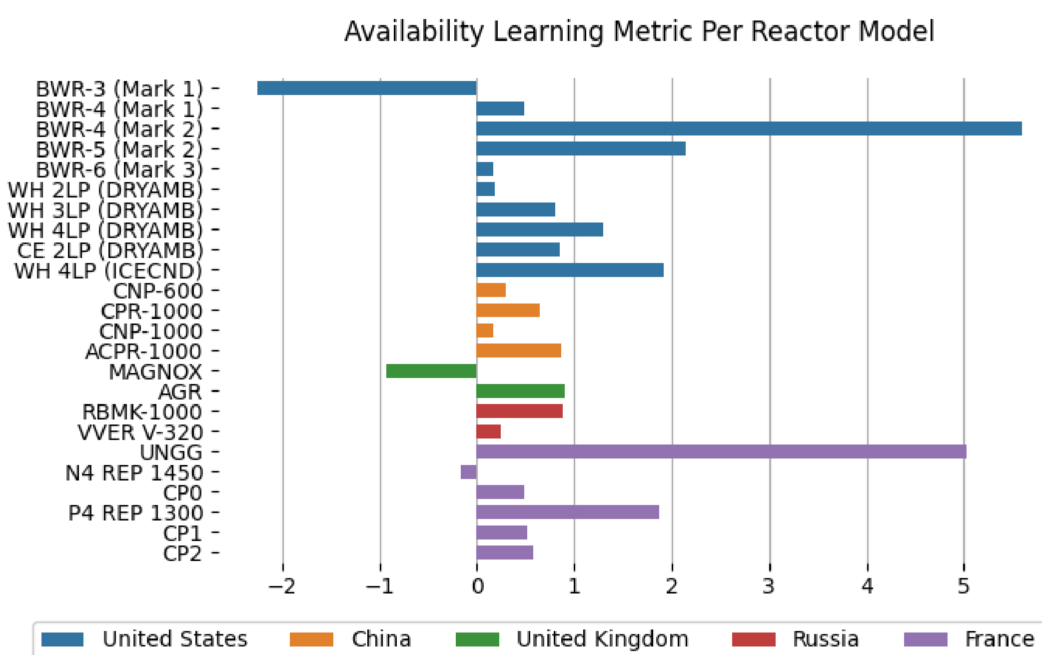


Figure 21: Availability learning rate by reactor model summary in units of percent.

V. THE ROLE OF POLICY AND DISASTER IN NUCLEAR DEVELOPMENT

The capacity learning rate analysis in Figure 13 showed the nuclear industry's ability to scale up reactor technologies like pressured water reactors by 10-50 MW/year on average over multiple decades. The effective learning rate identified reactor models that saw some combination of improved engineering design, operations, and labor productivity over consecutive iterations on average. These metrics can be used to compare efficiencies in the nuclear industry before and after major events and key policy to gain insight into their effects on nuclear development. For example, the 1979 Three Mile Island disaster in Middletown, Pennsylvania marked a turning point in US public opinion on nuclear energy. This in part led to changes in nuclear policy like the 1982 US Nuclear Waste Act that negatively impacted nuclear development efficiency.

This shift can be measured with the learning metrics to gauge changes in policy like additional licensing procedures and increased oversight and regulation. Figure 22 shows the capacity learning and effective learning for US PWR nuclear reactors color-coded by reaching criticality before (blue) or after (orange) the Three Mile Island nuclear disaster. The capacity learning rate decreases significantly, while the effective learning rate in MW/year^2 stays approximately constant while showing a drop-off in efficiency reflecting the change in slope in the capacity learning plot for plants that were still under construction or hadn't yet begun construction at the time of the Three Mile Island disaster. This clearly reflects the effects of increased regulation in the nuclear industry causing a measurable decline in development efficiency by 58 MW/year for PWR technology in the US.

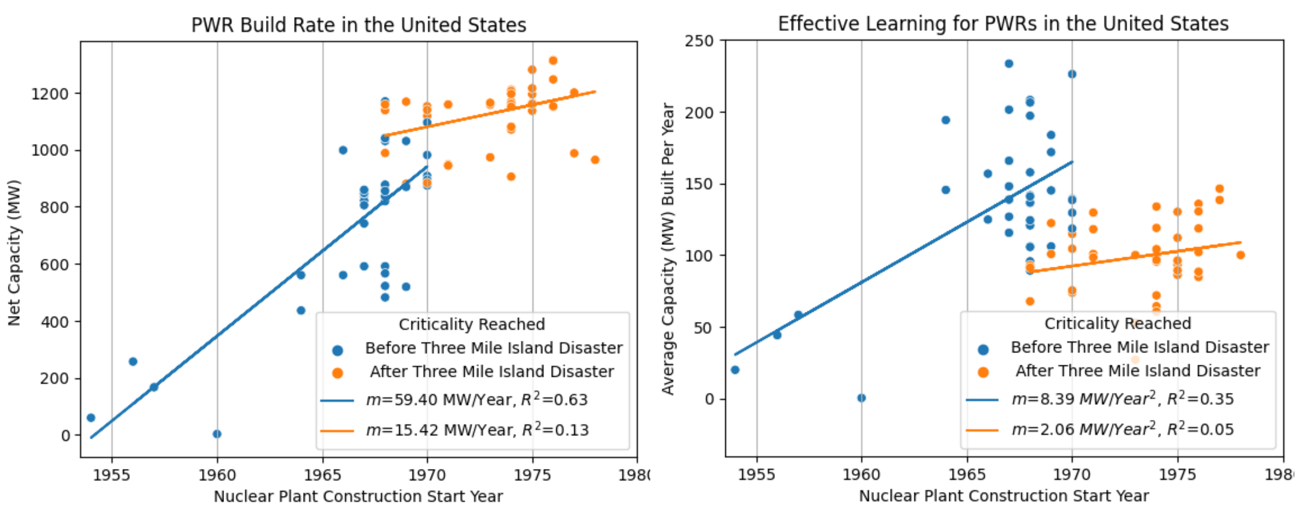


Figure 22: (Left) capacity learning rate and (right) effective learning rate in MW/year^2 for PWRs in the US that finished construction before (blue) and after (orange) the Three Mile Island nuclear disaster.

The capacity learning rate and effective learning rates before and after relevant nuclear disasters are shown per country by nuclear technology in Figure 23. The nuclear disasters used as inflection points are Three Mile Island for the US, Fukushima for China, and Chernobyl for Russia, the UK, and France. This was chosen based on proximity for the UK and France. While some of this difference may be accounted for by a converging learning rate, the stark discontinuity signals a shift in public opinion and subsequent public policy affecting nuclear development.

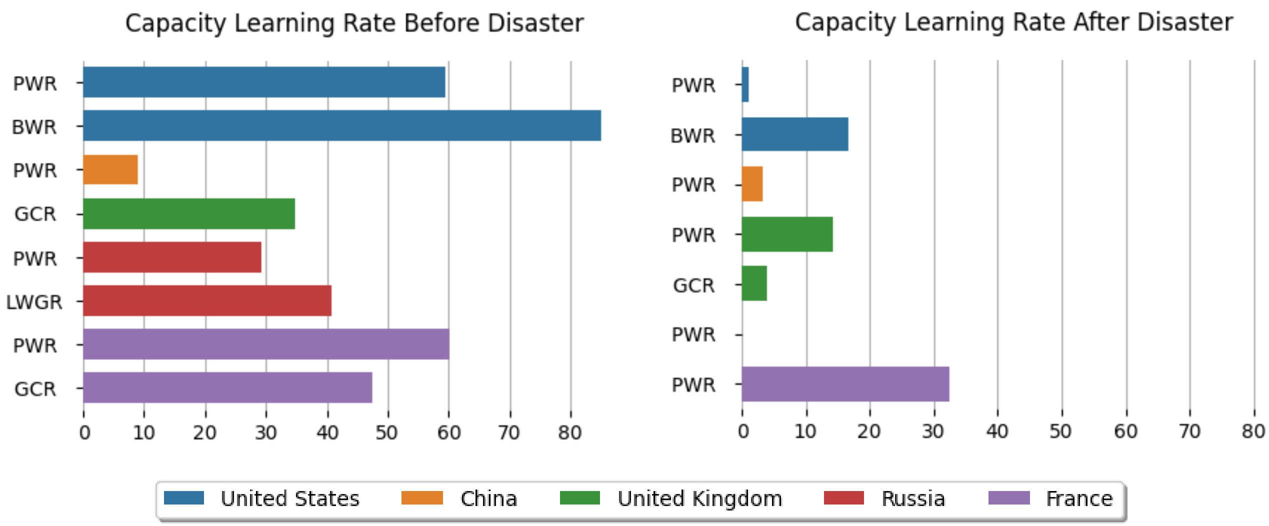


Figure 23: Capacity learning rate measured in Megawatts per year (Left) before and (right) after nuclear disaster.

A. UNITED STATES

Key policies that influenced the trajectory of nuclear development in the United States include the 1974 Energy Reorganization Act and the 1982 Nuclear Waste Policy Act which established the Nuclear Regulatory Commission and charged nuclear generators a $750 million annual nuclear waste disposal fee [37], respectively. The only federal tax incentive in US history is the Energy Policy Act of 2005, which provided up to $125 million annually in production tax credits for electricity from new nuclear plants; however, no money has been paid under the program so far since no planes have been built since 2005. This Act also authorized $2 billion in cost-overrun support for up to six new reactors, acknowledging the troubled state of nuclear development in the US [38]. These policies combined with the 1979 Three Mile Island disaster explain why no nuclear power plants were started for 33 years from 1979 to 2012 and why development efficiency diminished for plants still under construction in 1979 or started constructed after 1979 as shown in Figure 22.

B. CHINA

In 1970, China issued its first nuclear power plan which founded the Shanghai Nuclear Engineering Research and Design Institute [39] and led to the first nuclear power plant being connected to the grid in 1991. In the 21st century, a key pillar of China's tenth Five-Year Plan for 2001 to 2005 was to “guarantee energy security, optimize energy mix, improve energy efficiency, protect the ecological environment” [40], pushing the nation to invest further in nuclear. Due to this belief in the importance of energy security provided by nuclear energy, China’s response to the nearby nuclear disaster in Fukushima, Japan was measured. Following the Fukushima accident in March 2011, the State Council suspended approvals for new nuclear power stations and conducted comprehensive safety checks of all nuclear projects [41]. After three months, the inspections of operating plants had been completed, and inspections on plants under construction were completed by October 2011.

Despite the commitment to nuclear energy seen in the 1990s and 2000s, China’s main electricity fuel source remained coal, accounting for 62% of its energy production in 2019 [42], which has historically caused issues with pollution and smog in China. In 2014 the State Council published the Energy Development Strategy Action Plan for 2014-2020 which planned to cut China's reliance on coal with a target of 58 GW of nuclear capacity in 2020 [43] in an effort to combat pollution. This sustained commitment to nuclear energy is reflected in steady growth of capacity through Fukushima as shown in Figure 24.

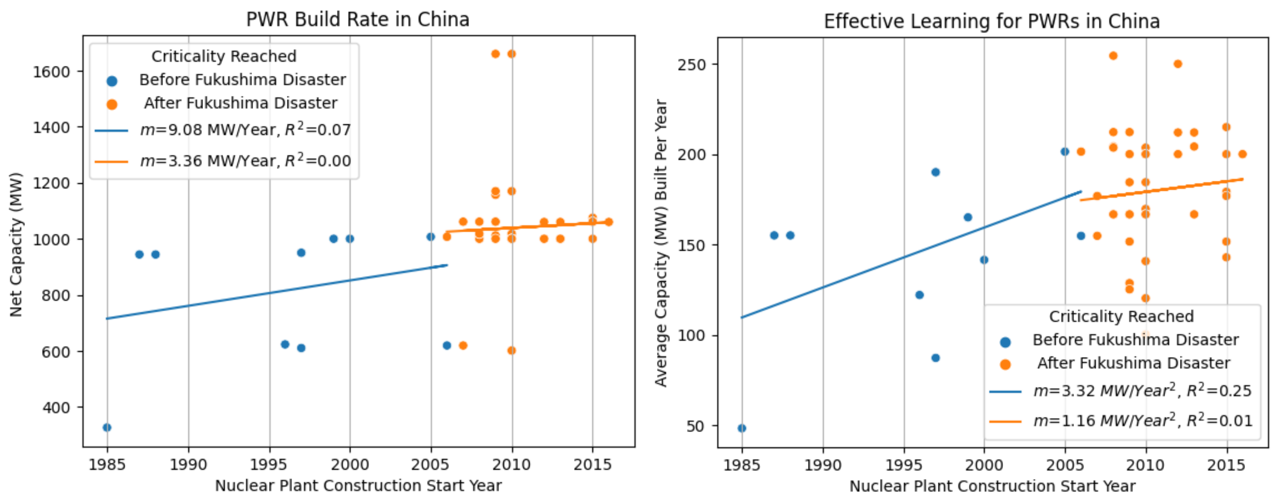


Figure 24: (Left) capacity learning rate and (right) effective learning rate in MW/year² for PWRs in China that finished construction before (blue) and after (orange) the Fukushima nuclear disaster.

C. FRANCE

Nuclear power in France is controlled by Électricité de France (EDF), the country's main electricity generation and distribution company, which manages all of France's 56 power reactors [44]. In contrast to the United States, EDF is substantially owned by the French Government, with around 85% shares controlled by the French government [45]. France has the highest share of nuclear energy production in the world, generating 72% of its energy from nuclear reactors in 2018 [46].

This reliance on nuclear energy is an intentional policy decision of the French government prioritizing energy security following the 1956 Suez Crisis where France invaded Egypt in support of Israel [47] and following the 1973 oil crisis when members of the Organization of Arab Petroleum Exporting Countries (OAPEC) proclaimed an oil embargo on nations that supported Israel in the Suez Crisis and the Yom Kippur War [48].

In reaction to the oil embargo, French Prime Minister Pierre Messmer signed the Messmer Plan into action in 1974, a domestic energy strategy centered around nuclear power to remove France's dependence on foreign oil given its lack of indigenous energy resources [49]. This directly led to the rapid development of dozens of nuclear reactors in the late 1970s as shown in Figure 10.

In the 1980s, France's nuclear power capacity factor dropped to 60% as a result of demand falling short of estimates and the 1986 Chernobyl disaster occurred [50]. With the country's energy needs met with the established nuclear generation capacity, nuclear plant production in France slowed such that only three nuclear plants started construction between 1985 and 2020. The inflection point of nuclear development in France before and after the Chernobyl accident is shown in Figure 25. While the build rate in MW/year remains drops modestly from 38.71 MW/year to 26.75 MW/year, the effective learning rate is inverted from 6.31 MW/year² to -3.51 MW/year². This means that nuclear development is decreasing in efficiency and taking longer per Megawatt to construct each year.

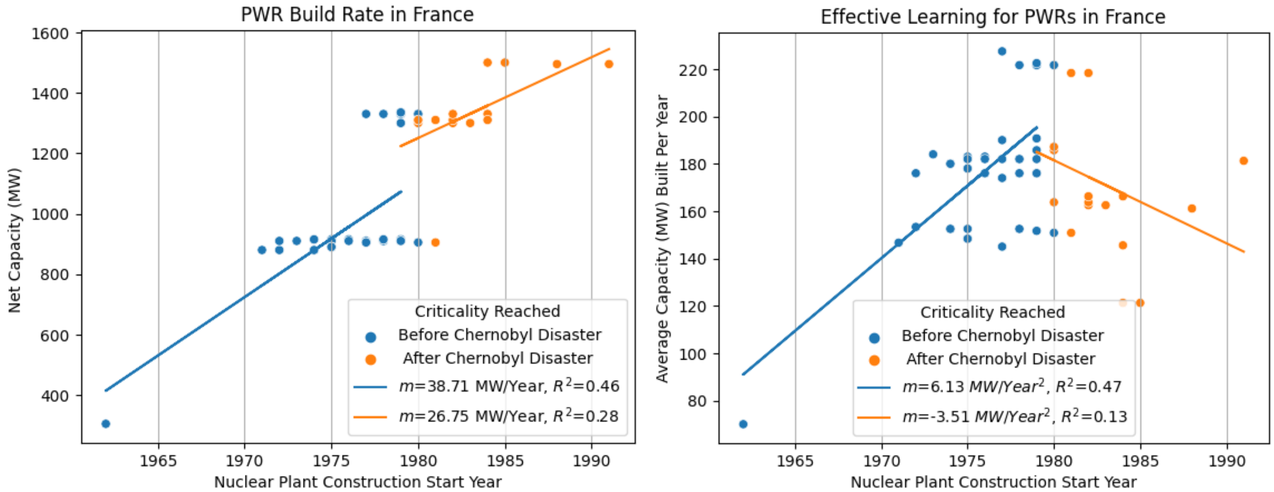


Figure 25: (Left) capacity learning rate and (right) effective learning rate in MW/year² for PWRs in France that finished construction before (blue) and after (orange) the Chernobyl nuclear disaster.

D. UNITED KINGDOM

Calder Hall was the first nuclear power station in the United Kingdom. Built from 1952 to 1956, its primary purpose was producing weapons-grade plutonium [51]. The United Kingdom steadily built gas-cooled reactors through the 1950s and 1960s. In 1971, British Nuclear Fuels Limited was established from the demerger of the UK Atomic Energy Authority [52], followed by a period of no new construction for the remainder of the 1970s. In 1979, the UK Winter of Discontent [53] and 1979 oil crisis caused by the Iranian revolution [54] urged the United Kingdom to improve its energy security with increasing its supply of nuclear power. This led to four gas-cooled reactors beginning construction in 1980 and plans for Westinghouse PWRs, the latter of which was interdicted by changes in government leadership [55]. Only one of these PWR plants was built in 1988, followed by a 30 year pause in new plant development until 2018 when two new PWRs began construction. This history is reflected in Figure 26, where development is increasing in efficiency until 1970 when nuclear development pauses in the United Kingdom, and only five nuclear plants projects are started over the next 50 years.

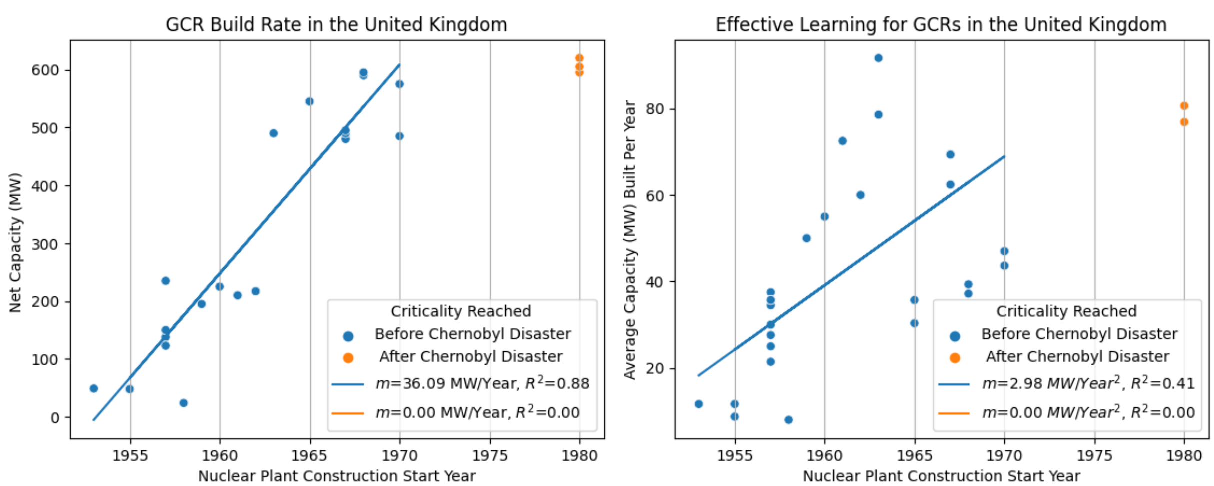


Figure 26: (Left) capacity learning rate and (right) effective learning rate in MW/year² for PWRs in the United Kingdom that finished construction before (blue) and after (orange) the Chernobyl nuclear disaster.

E. RUSSIA

Nuclear power share in the Soviet Union peaked at 6.5% of total energy production in 1982 [56]. Nuclear plants were a mix of light water graphite reactors (LWGR) and pressurized water reactors (PWR). The Chernobyl disaster reactor was an LWGR, which effectively ended the development of these reactors due to safety concerns [57] as shown in Figure 27, where no LWGRs began construction after the disaster and only one reactor finished construction after 1986.

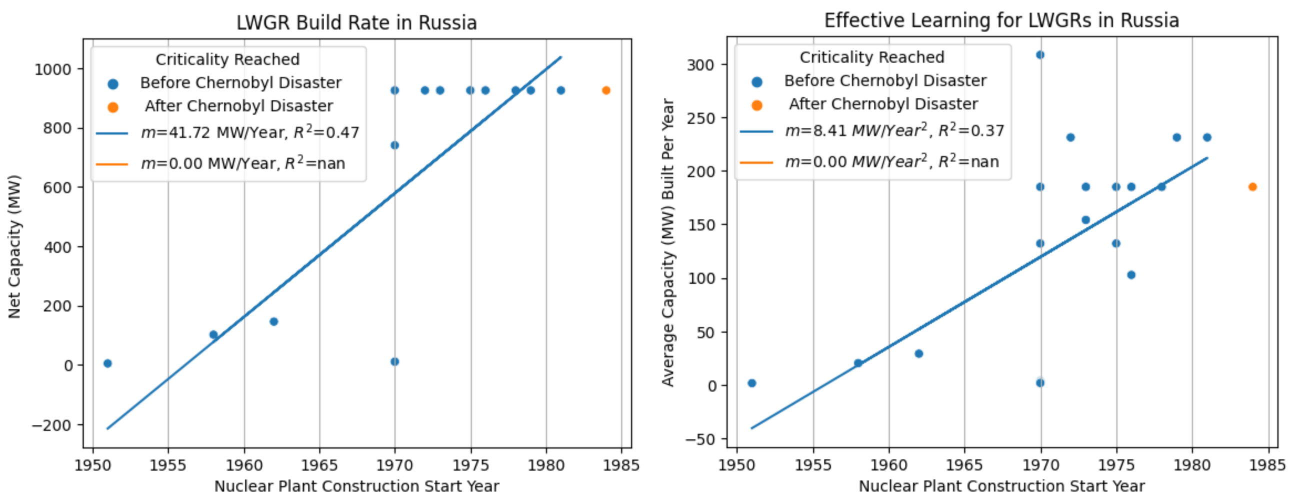


Figure 27: (Left) capacity learning rate and (right) effective learning rate in MW/year² for LWGRs in Russia that finished construction before (blue) and after (orange) the Chernobyl nuclear disaster.

The Soviet Union and later Russia developed PWRs through the 1960s and 1970s. A fifteen year pause in new nuclear projects followed the Chernobyl accident, along with a decline in efficiency once development restarted as seen in Figure 28.

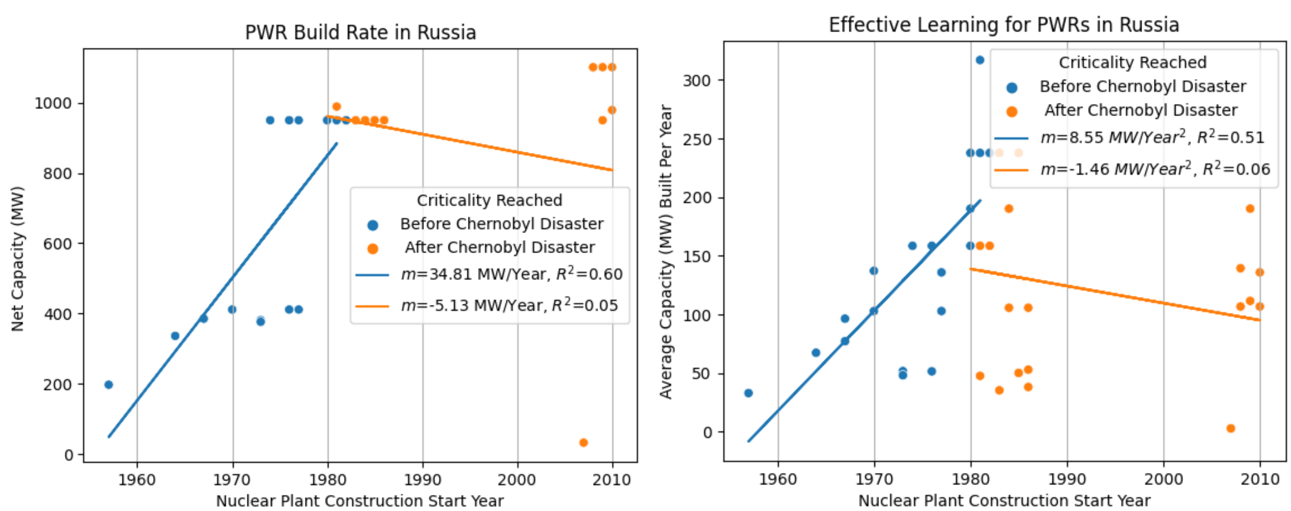


Figure 28: (Left) capacity learning rate and (right) effective learning rate in MW/year² for PWRs in Russia that finished construction before (blue) and after (orange) the Chernobyl nuclear disaster.

VI. THE ROLE OF RESEARCH FUNDING IN NUCLEAR DEVELOPMENT

The United States Atomic Energy Commission (AEC) was the agency established after World War II to develop atomic science and technology, effectively transferring the control of atomic energy from military to civilian oversight in 1947 [59]. The AEC was abolished by the 1974 Energy Reorganization Act, which divided the AEC into Nuclear Regulatory Commission (NRC) and Energy Research and Development Administration, the latter of which became the Department of Energy (DOE) with the 1977 Depart of Energy Organization Act [60]. The AEC, NRC and DOE account for a vast majority of the nuclear research and development funding in the United States. The funding data for these entities from 1950 to 2016 was summarized in [61]. The full scope of this data broken down by funding category is shown in Figure 29. The period 1986 to 2016 is detailed in the Appendix.

It's evident that military weapons funding drove nuclear investment from 1950 to 1974. The fuel cycle category includes generation of plutonium and other fissile products for building weapons. Common throughout most of the funding history is investment in some form of civilian reactor, either the light water reactor, breeder reactor, other reactors, or advanced reactors.

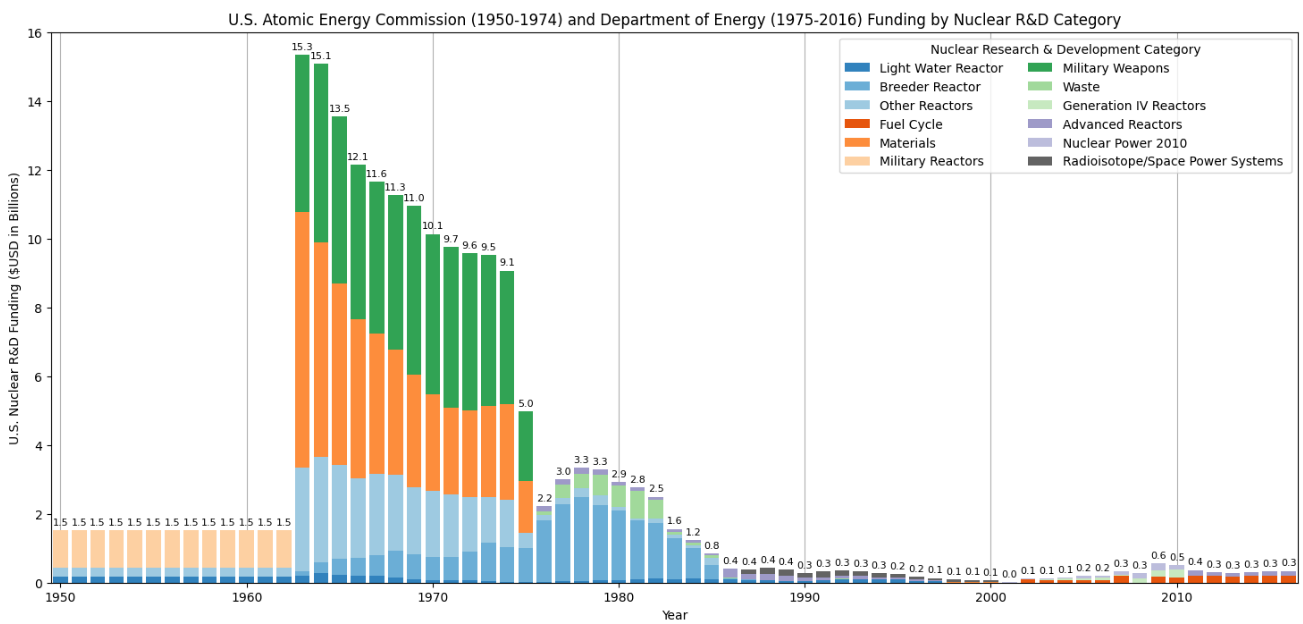


Figure 29: United States nuclear research and development funding 1950-2016 by research category.

The vast $9-15 billion annual research budget from 1963 to 1974 undoubtedly fostered nuclear science expertise in the military, academia, and industry. Figure 30 shows the total US research and development funding for 1950 to 2016 and a histogram of US nuclear power plant first grid connection years with a gaussian density fit. Each of these macrotrends have two peaks with a larger leading peak. Using US nuclear construction data from Figure 8, the average construction duration for nuclear plants in the US completed between 1950 to 1990 is approximately five years. Additionally, the average planning in licensing time for a nuclear plant in the US is five years [62]. Together, US nuclear power plants take ten years on average to make a first grid connection from the time planning is started.

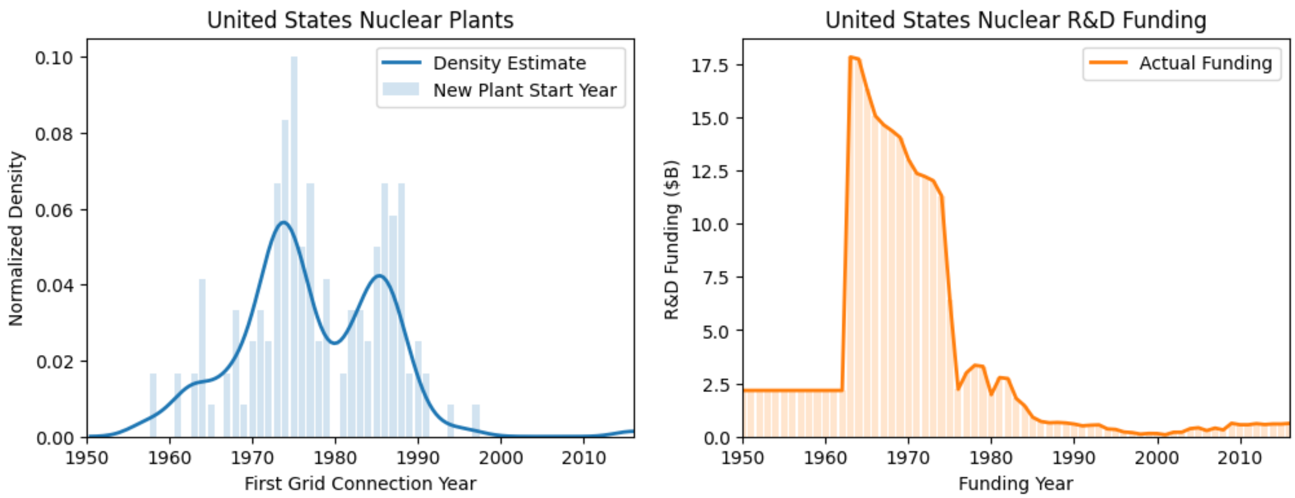


Figure 30: (Left) US nuclear power plant histogram by year of first connection to grid and (right) US nuclear R&D funding.

The impact of research and development funding can be estimated by shifting the nuclear plant construction data by the average time to first connection and comparing it to the research funding trend. The idea is that this shift allows an aligned view of what research funding impacted industry nuclear development. This shifted comparison is shown in Figure 31. This shows that the peak in nuclear research funding aligns with the peak in nuclear power plant development ten years later—which matches the industry average licensing and construction duration for this period of time. In fact, the Pearson's correlation coefficient is 0.70 with a p-value less than 0.001 to confirm its statistical significance. Therefore, investing in nuclear research clearly leads to increases in nuclear power plant development.

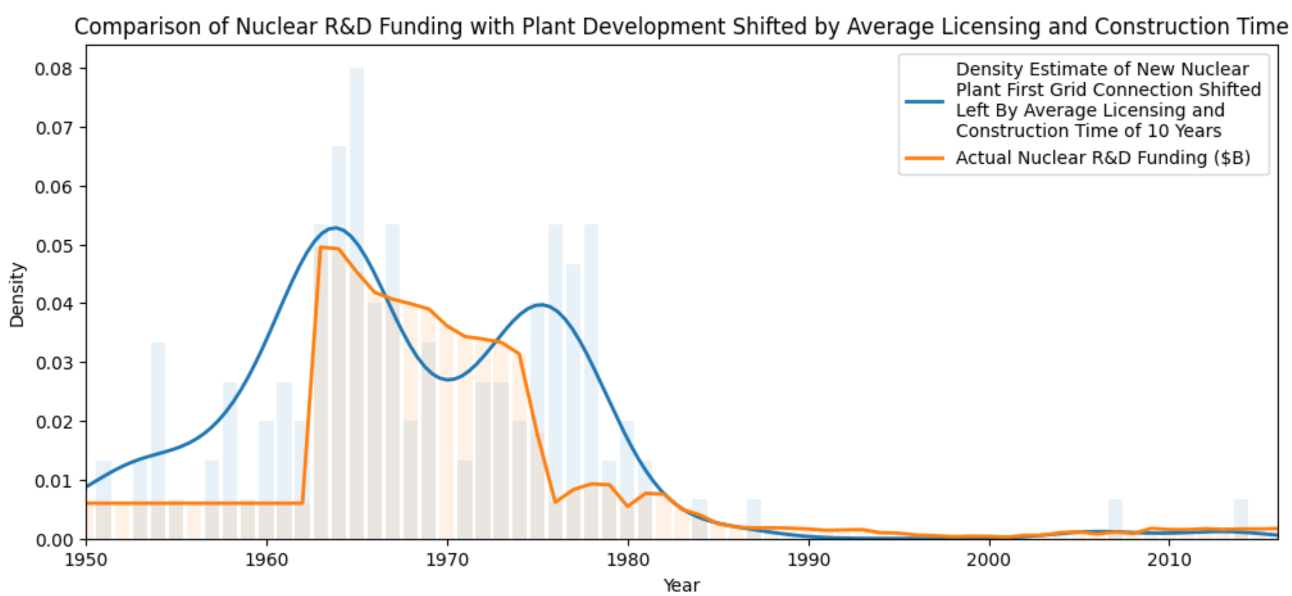


Figure 31: US nuclear R&D funding overlayed US nuclear construction data shifted by 10 years to account for the average time of licensing and construction. The first peak aligns showing research investment correlates with nuclear development.

VII. CONCLUSIONS

Each country in this study began its nuclear enterprise with state-sponsored nuclear weapon development. In most cases, this was followed by nuclear propulsion development for submarines. This nuclear expertise then entered the commercial industry allowing for the development of civilian nuclear power plants. The development of these three domains was evaluated for efficiency in nuclear weapon yield, submarine reactor capacity, and power plant reactor capacity to show that the maximum efficiencies in each domain occurred in a predictable sequence. This trend demonstrates learning by doing in nuclear technology and emphasizes the importance of government action and support in driving nuclear development.

Second to war and the nuclear arms race, energy security strategy appears to motivate direct sponsorship of nuclear development most. Both France and the United Kingdom have limited indigenous fossil fuel resources and therefore rely on imports from Russia and the Middle East. Geopolitical conflicts involving oil exporters have led to multiple oil crises that highlighted the lack of energy security in many European countries. France has responded the most resoundingly by generating 72% of its electricity with nuclear power.

While all countries experience a decrease in nuclear development efficiency following nuclear disaster events, it appears that China and France were the most robust in their responses and continued development. Given the clear necessity of government intervention in nuclear development, it's not surprising that China, the only country with state-owned nuclear corporations, and France, whose government owns 85% of the shares in country's main electricity generation company, were the most equipped to endure nuclear disaster events and continue nuclear development.

The efficiency analysis also showed that pressurized water reactors often carry lower capacity learning rates (MW/year) and effective learning rates (MW/year^2), but they appear to be the safest and most reliable.

Lastly, research funding drives nuclear development on with a ten-year lag, allowing for licensing and construction of new technology to be realized in an operational nuclear power plant. Moreover, nuclear plant development relies on learning by doing to scale down costs over time and make nuclear development profitable. When countries pause development with policies hindering development with regulations or removal of research funding, the effects can last for decades as expertise, supply chain efficiency, and labor productivity declines. For these reasons, nuclear power development requires long term planning and conviction from the government.

VIII. REFERENCES

1. D'Agati, C. (2019, July 13). 5 DARPA Inventions That Changed The World. ClearanceJobs. Retrieved March 8, 2023, from https://news.clearancejobs.com/2019/07/13/5-darpa- inventions-that-changed-the-world/
2. Arrow, Kenneth J. "The Economic Implications of Learning by Doing." The Review of Economic Studies, vol. 29, no. 3, 1962, pp. 155–73. JSTOR, https://doi.org/10.2307/2295952. Accessed 3 May 2023.
3. Otto Hahn, Lise Meitner, and Fritz Strassmann. Science History Institute.
4. Fermi, E. Artificial radioactivity produced by neutron bombardment. Nobel Lecture.
5. Von Halban, jun., H., Joliot, F., Kowarski, L., NATURE, 143, 470 (1939).
6. Bendjebbar, André (2000). Histoire secrète de la bombe atomique française. Documents (in French). Paris. Cherche Midi. ISBN 978-2-862-74794-1. OCLC 45842105.
7. Rhodes, R. The Making of the Atomic Bomb.

8. Chicago Pile-1. Manhattan Project History. Atomic Heritage Foundation. December 1, 2016.
9. Smyth, Henry DeWolf (1945). Atomic Energy for Military Purposes: the Official Report on the Development of the Atomic Bomb under the Auspices of the United States Government, 1940–1945. Princeton, New Jersey: Princeton University Press
10. Hoddeson, Lillian; Henriksen, Paul W.; Meade, Roger A.; Westfall, Catherine L. (1993). Critical Assembly: A Technical History of Los Alamos During the Oppenheimer Years, 1943–1945. New York: Cambridge University Press.
11. Hewlett, Richard G.; Anderson, Oscar E. (1962). The New World, 1939–1946 (PDF). University Park: Pennsylvania State University Press
12. Non-technical personnel. The Manhattan Project. U.S. Department of Energy.
13. Nuclear Reactors in Operation & Suspended. Power Reactor Information System. IAEA. Retrieved March 8, 2023, from https://pris.iaea.org/PRIS/WorldStatistics/OperationalReactorsByCountry.aspx
14. Fact Files. United States Navy. Retrieved March 8, 2023 from https://www.navy.mil/Resources/Fact-Files/Category/20159/
15. Erickson, Andrew Erickson; Lyle Goldstein (Winter 2007). "China's Future Nuclear Submarine Force: Insights from Chinese Writings" (PDF). Naval War College Review. 60 (1): 54–79. Retrieved 25 August 2009
16. Fast Attacks and Boomers: Submarines in the Cold War. An online exhibition from the National Museum of American History, Smithsonian Institution
17. Kristensen, H. M., & Norris, R. S. (2013). Global nuclear weapons inventories, 1945–2013. Bulletin of the Atomic Scientists, 69(5), 75–81. https://doi.org/10.1177/0096340213501363
18. Khalturin, Vitaly I.; Rautian, Tatyana G.; Richards, Paul G.; Leith, William S. (1 January 2005). "A Review of Nuclear Testing by the Soviet Union at Novaya Zemlya, 1955–1990" (PDF). Science & Global Security.
19. Rhodes, Richard (1 August 1995). Dark Sun: The Making of the Hydrogen Bomb. Simon & Schuster. ISBN 978-0-68-480400-2
20. Hewlett, Richard G. and Francis Duncan. Nuclear Navy: 1946-1962. Chicago: The University of Chicago Press, 1974.
21. "Nautilus IV (SSN-571)". Dictionary of American Naval Fighting Ships. Naval History & Heritage Command. 1970.
22. "From Obninsk Beyond: Nuclear Power Conference Looks to Future". International Atomic Energy Agency. 2004-06-23.
23. "22 November 1955 - RDS-37: CTBTO Preparatory Commission".
24. Arnold, Lorna; Pyne, Katherine (2001). Britain and the H-bomb. Houndmills, Basingstoke, Hampshire; New York: Palgrave.
25. Patrick E. Tyler (21 September 1986). "The Rise and Fall Of the SSN 688". The Washington Post. Washington, D.C
26. Nash, Philip (1 December 1993). "Nuclear Weapons in Kennedy's Foreign Policy". The Historian. 56 (2): 285–300.
27. "Tsar Bomba". Atomic Heritage Foundation. Retrieved 29 July 2016.
28. Sokolski, Henry D.; Tertrais, Bruno (2013). Nuclear Weapons Security Crises: What Does History Teach?. Strategic Studies Institute and U.S. Army War College Press. p. 31.
29. Fravel, Taylor (23 April 2019). Active Defense: China's Military Strategy Since 1949. p. 254.
30. Nuclear Non-Proliferation Treaty (NPT)" (PDF). Defense Treaty Inspection Readiness Program - United States Department of Defense. Defense Treaty Inspection Readiness Program.
31. "Strategic Arms Reduction Treaty (START I): Executive Summary". The Office of Treaty Compliance. Archived from the original on 6 January 2011

32. Romanov, D. A., Fire at Sea: The Tragedy of the Soviet Submarine Komsomolets. Edited by K. J. Moore. Washington, DC:

33. Alchlan, Armen, "Reliability of Progress Curves In Airframe Production." Econometrica. October, 1963.

34. Searle, A. D. and C. S. Goody. "Productivity Increases in Selected Wartime Shipbuilding Programs." Monthly Labor Review. Vol. 61, No. 6, 1945.

35. Joskow, P. L., & Rozanski, G. A. (1979). The effects of learning by doing on Nuclear Plant Operating Reliability. The Review of Economics and Statistics, 61(2), 161. https://doi.org/10.2307/1924583

36. Cardwell, D. Westinghouse Files for Bankruptcy, in Blow to Nuclear Power. March 29, 2017.

37. Comprehensive nuclear waste plan enacted. Congressional Quarterly Almanac 1982. Washington, DC: Congressional Quarterly, Inc., 304–310

38. Congress Passes First Comprehensive Energy Bill in 13 Years, Nuclear Energy Institute, 2005

39. Minor, Michael S. (1976). "China's Nuclear Development Program". Asian Survey. 16 (6): 571–579.

40. Kadak, Andrew C. (2006). "Nuclear Power: "Made in China"". The Brown Journal of World Affairs. 13(1): 77–90.

41. Maintain nuclear perspective, China told, World Nuclear News (11 January 2011)

42. Cost of Pollution in China: Economic Estimates of Physical Damages, The World Bank, State Environmental Protection Administration, P. R. China (February 2007)

43. "Start-up nearing for Chinese units". World Nuclear News. 25 March 2014.

44. "Nuclear Power in France". World Nuclear Association. September 2020. Archived from the original on 24 November 2020.

45. "Shareholding policy". Électricité de France. 31 December 2007

46. "Nuclear share figures, 2009-2019". World Nuclear Association. May 2020. Retrieved 27 June2020.

47. Adamthwaite, Anthony (1988). "Suez revisited". International Affairs. 64(3): 449–464.

48. Smith, Charles D. (2006), Palestine and the Arab–Israeli Conflict, New York: Bedford, p. 329.

49. World Nuclear Association (August 2007). "Nuclear Power in France". Retrieved 25 August 2007.

50. Electricité de France Company History Electricité de France.

51. "Calder Hall Power Station". The Engineer. 5 October 1956.

52. "Obituary: Coningsby Allday". The Telegraph. London. 26 December 2011.

53. Hay, Colin (2009). "The Winter of Discontent Thirty Years On". The Political Quarterly. 80 (4): 545–552.

54. "Another Crisis for the Shah". Time. November 13, 1978.

55. Peter Pearson; Jim Watson (2012). UK Energy Policy 1980–2010 (PDF) (Report). The Parliamentary Group for Energy Studies.

56. Semenov, B.A. "Nuclear power in the Soviet Union" (PDF). IAEA.

57. Morrissey, John (March 15, 2015). "Obninsk Nuclear Power Plant". Stanford University.

58. "Licenses, Certifications and Approvals for Nuclear Power Plants," U.S. Code of Federal Regulations, 10 CFR 52, (U.S. Government Printing Office, 2017).

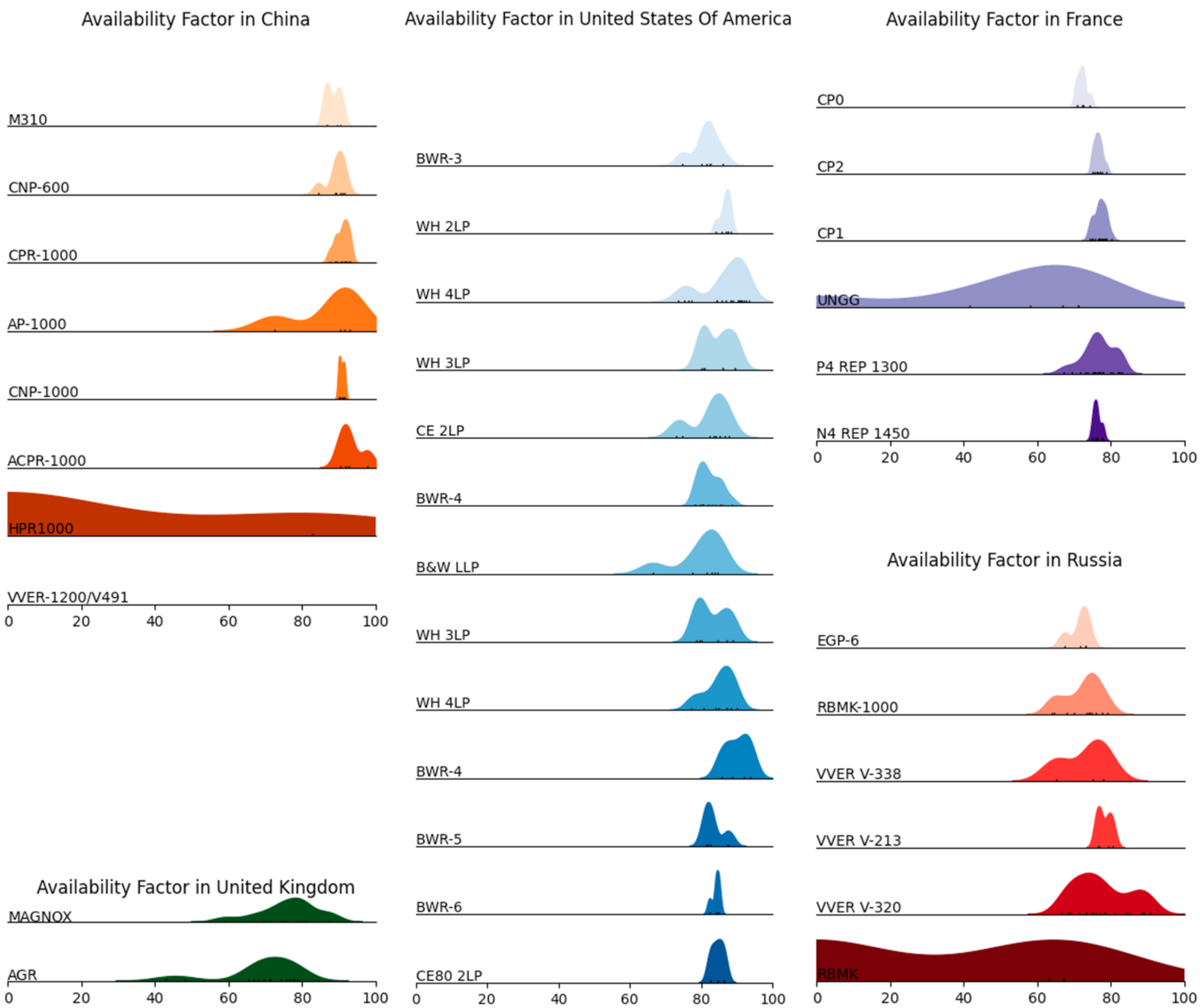
59. Atomic Energy Act of 1946 (Pub. L. 79–585, 60 Stat. 755, enacted August 1, 1946)

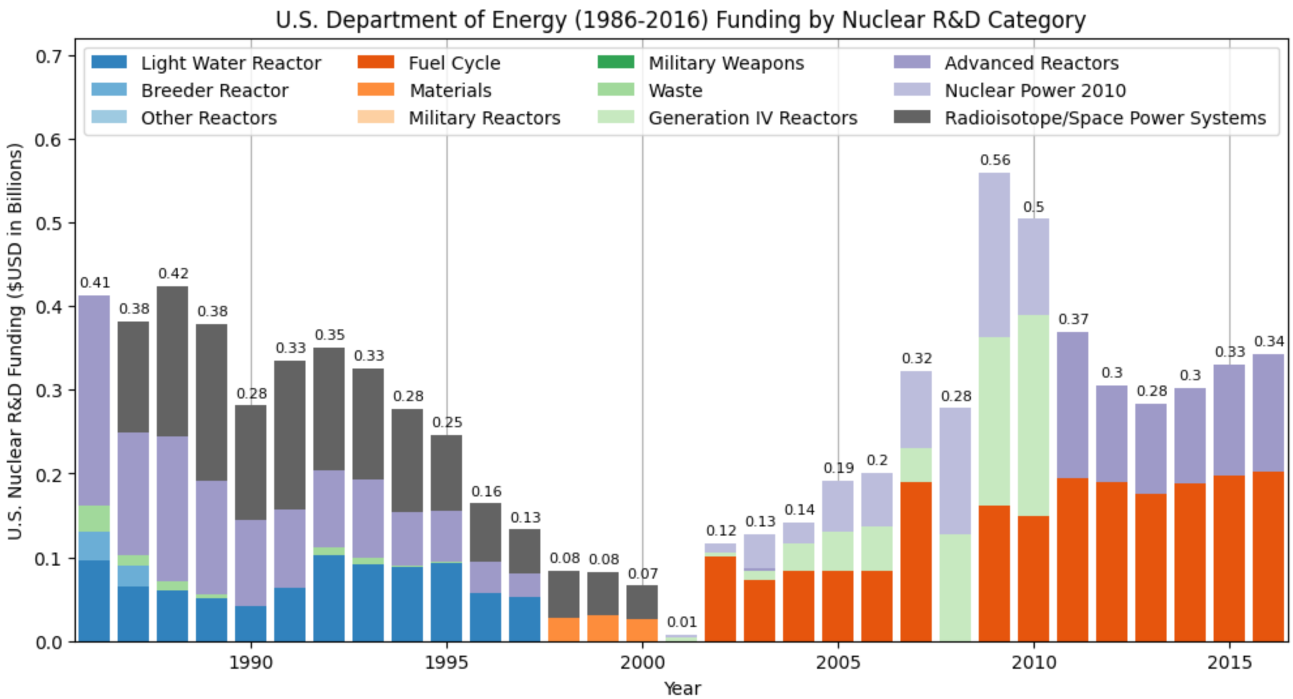
60. Buck, Alice L. (July 1983). A History of the Atomic Energy Commission (PDF). Washington, D.C.: U.S. Department of Energy.

61. Incentives. Analysis of Federal Expenditures for Energy Development, 1950-2016. May 2017.

62. Management Information Services, Inc. Two Thirds of a Century and $1 Trillion+ U.S. Energy.

IX. APPENDIX





United States Nuclear Submarine Data

Name/Class	Built Start	Built End	Commis-sioned	Decommi-ssioned	Reactor	Number Reactors	PWR (MW)	Turbine (MW)	Speed Knots	Crew	Count	Active	Retired
USS Nautilus	1952		1954	1980	S2W	1	70	10	23	105	1	0	1
USS Seawolf	1953		1957	1987	S2W	1	70	11	23	101	1	0	1
Skate Class	1955	1959	1957	1989	S3W	1	38	6	22	84	4	0	4
USS Triton	1958		1959	1969	S4G	2	78	34	27	172	1	0	1
USS Halibut	1959		1960	1976	S3W	1	38	6	20	97	1	0	1
Skipjack Class	1956	1961	1959	1990	S5W	1	78	11	33	93	6	0	6
USS Tullibee	1960		1960	1988	S2C	1	13	2	15	66	1	0	1
George Washington Class	1958	1961	1959	1985	S5W	1	78	11	22	112	5	0	5
Ethan Allen Class	1959	1963	1961	1992	S5W	1	78	11	22	140	5	0	5
Permit Class	1958	1967	1961	1996	S5W	1	78	11	28	112	14	0	14
Sturgeon Class	1963	1975	1967	2004	S5W	1	78	11	26	107	37	0	37
Lafayette Class	1961	1964	1963	1994	S5W	1	78	11	21	140	9	0	9
James Madison Class	1962	1964	1964	1995	S5W	1	78	11	21	140	10	0	10
Benjamin Franklin Class	1963	1967	1965	2002	S5W	1	78	11	21	140	12	0	12
USS Narwhal	1967		1969	1999	S5G	1	90			107	1	0	1
USS Glenard P. Lipscomb	1973		1974	1990	S5W	1	78	11	23	131	1	0	1
Los Angeles Class	1972	1996	1976		S6G	1	165	24	20	129	62	26	34
Ohio class	1976	1997	1981		S8G	1	312	26	20	155	18	18	0
Seawolf Class	1989	2005	1997		S6W	1	270	39	35	140	3	3	0
Virginia Class	2000		2004		S9G	1	210	30	25	135	22	22	0

United Kingdom Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
HMS Dreadnought	1959	1960	1963	1980	S5W	0	1	1	78
Valiant Class	1960	1963	1966	1994	RR	0	2	2	78
Resolution Class	1964	1968	1967	1996	RR	0	4	4	78
Churchill Class	1964	1967	1970	1992	RR	0	3	3	78
Swiftsure Class	1967	1970	1973	2010	RR	0	6	6	78
Trafalgar Class	1977	1986	1983			1	6	7	150
Vanguard Class	1986	1998	1993		RR	4	0	4	150
Astute Class	2001		2010		RR	5	5	5	200

China Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
91	1974	1990	1974			3	2	5	40
92	1981		1983			1	0	1	58
93	1980	2009	2006			6	0	6	58
94	2000		2007			6	0	6	58

Russia Nuclear Submarine Data

Name	Built Start	Built End	Commissioned	Decommissioned	Reactor	Active	Retired	Number	PWR (MW)
November Class	1957	1963	1959	1990	VM-A 70	0	14	14	70
K-27	1958		1963		VT-1	0	1	1	146
Hotel Class	1956	1960	1960	1991		0	8	8	60
Echo I Class	1960	1965	1960	1994		0	5	5	66
Echo II Class	1960	1965	1960	1994		0	29	29	104
K-222	1963	1970	1970	1988		0	1	1	118
Yankee Class	1964	1974	1967	1995		0	34	34	100
Delta Class	1972	1990	1972			6	28	34	82
Charlie Class	1964	1979	1967	1996		0	17	17	11
Victor Class	1959	1988	1967		VM-4P	2	46	48	150
K-278	1978	1983	1983	1990	OK-650	0	1	1	190
Alfa Class	1968	1981	1971	1996	OK-550	0	7	7	155
Yasen Class	1993		2013		OK-650KPM	4	0	4	200
Borei Class	1996		2013		OK-650V	7	0	7	200
Typhoon Class	1976	1989	1981		OK-650	0	6	6	380
Sierra Class	1979	1992	1984		OK-650	4	0	4	190
Oscar Class	1975		1980			6	8	14	140
Akula Class	1983	1999	1984		OK-650B	4	4	8	190

Year	US Sub Count	US Sub Power	US Plant Count	US Plant Power	US Weapon Count	US Weapon Power	UK Sub Count	UK Sub Power	UK Plant Count	UK Plant Power	UK Weapon Count	UK Weapon Power
1940	0	0	0	0	0	0	0	0	0	0	0	0
1941	0	0	0	0	0	0	0	0	0	0	0	0
1942	0	0	0	0	0	0	0	0	0	0	0	0
1943	0	0	0	0	0	0	0	0	0	0	0	0
1944	0	0	0	0	0	0	0	0	0	0	0	0
1945	0	0	0	0	2	0	0	0	0	0	0	0
1946	0	0	0	0	9	15	0	0	0	0	0	0
1947	0	0	0	0	13	21	0	0	0	0	0	0
1948	0	0	0	0	50	21	0	0	0	0	0	0
1949	0	0	0	0	170	21	0	0	0	0	0	0
1950	0	0	0	0	299	31	0	0	0	0	0	0
1951	0	0	0	0	438	120	0	0	0	0	0	0
1952	0	0	0	0	841	160	0	0	0	0	0	0
1953	0	0	0	0	1169	8000	0	0	0	0	1	10
1954	1	70	0	0	1703	15000	0	0	0	0	7	10
1955	1	70	0	0	2422	15000	0	0	0	0	14	10
1956	1	70	0	0	3692	18000	0	0	1	60	21	15
1957	6	292	2	92	5543	18000	0	0	2	120	28	15
1958	6	292	2	92	7345	18000	0	0	3	180	31	400
1959	18	1228	2	92	12298	18000	0	0	7	420	35	1100
1960	20	1279	4	479	18638	18000	0	0	8	480	42	1100
1961	39	2761	4	479	22229	25000	0	0	8	480	70	1100
1962	39	2761	6	827	25540	25000	0	0	13	1119	288	1100
1963	48	3463	11	1031	28133	25000	1	78	14	1155	394	1100
1964	58	4243	12	1049	29463	25000	1	78	16	1501	436	1100
1965	70	5179	12	1049	31139	25000	1	78	22	2965	436	1100
1966	70	5179	14	1177	31175	25000	3	234	24	3455	380	1100
1967	107	8065	18	2281	31255	25000	7	546	26	3785	380	1100
1968	107	8065	19	2336	29561	25000	7	546	27	4015	394	1100
1969	108	8155	22	4238	27552	25000	7	546	27	4015	433	1100
1970	107	8077	26	7292	26008	25000	10	780	27	4015	394	1100
1971	107	8077	29	9768	25830	25000	10	780	29	5085	309	1100
1972	108	8242	37	16253	26516	25000	10	780	29	5085	309	1100
1973	111	8737	47	25325	27835	25000	16	1248	29	5085	387	1100
1974	115	9310	59	36499	28537	25000	16	1248	29	5085	457	1100
1975	117	9640	65	42430	27519	25000	16	1248	30	5335	492	1100
1976	121	10447	73	50276	25914	25000	16	1248	33	7289	492	1100
1977	123	11051	76	53009	25542	25000	17	1398	34	7933	492	1100
1978	127	11858	81	58175	24418	25000	18	1548	34	7933	492	1100
1979	130	12500	81	58175	24138	25000	19	1698	34	7933	492	1100
1980	134	13307	83	60407	24104	25000	19	1698	34	7933	492	1100
1981	136	13879	87	64950	23208	25000	19	1770	34	7933	492	1100
1982	139	14374	91	69620	22886	25000	20	1920	34	7933	471	1100
1983	142	15016	94	73012	23305	25000	20	1920	37	9828	450	1100
1984	146	15823	100	80711	23459	25000	21	2070	39	11108	380	1100
1985	150	16630	108	90497	23368	25000	22	2220	40	11723	422	1100
1986	148	16882	115	98969	23317	25000	23	2370	40	11723	422	1100
1987	151	17377	123	108448	23575	25000	24	2520	39	11663	422	1100
1988	153	17949	123	110940	23205	25000	24	2520	41	13645	422	1100
1989	157	19013	126	114717	22217	25000	24	2520	41	14267	422	1100
1990	157	19773	128	117272	21392	25000	24	2520	37	14027	422	1100
1991	154	20034	126	116885	19008	25000	25	2670	36	13967	422	1100
1992	156	20364	126	116885	13708	25000	25	2670	36	13967	422	1100
1993	155	20781	125	117787	11511	25000	22	2436	31	13328	422	1100

1994	158	21423	120	117583	10979	25000	22	2436	30	13292	352	1100
1995	153	21528	119	117565	10904	25000	21	2430	29	14196	422	1100
1996	146	21390	120	118775	11011	25000	21	2430	23	12732	422	1100
1997	132	20298	118	118647	10903	25000	17	2118	21	12242	366	1100
1998	133	20568	114	117543	10732	25000	17	2118	19	11912	281	1100
1999	133	20568	113	117488	10685	25000	17	2118	18	11682	281	1100
2000	133	20688	112	116836	10577	25000	17	2118	18	11682	281	1100
2001	135	21108	111	116152	10526	25000	18	2318	18	11682	281	1100
2002	136	21318	110	115302	10457	25000	19	2518	16	10612	281	1100
2003	125	20592	107	113056	10027	25000	19	2518	16	10612	281	1100
2004	126	20802	103	109307	8570	25000	19	2518	16	10612	281	1100
2005	89	17961	99	106291	8360	25000	17	2168	16	10612	281	1100
2006	88	17808	98	105136	7853	25000	17	2265	15	10362	281	1100
2007	87	17655	96	103709	5709	25000	17	2161	12	8408	225	1100
2008	85	17502	95	102819	5273	25000	16	2058	11	7764	225	1100
2009	84	17349	94	101860	5244	25000	16	1955	11	7764	225	1100
2010	83	17196	94	101860	5244	25000	15	1851	11	7764	225	1100
2011	82	17043	94	101860	5244	25000	9	1480	11	7764	225	1100
2012	81	16890	94	101860	5244	25000	9	1377	11	7764	225	1100
2013	79	16737	93	100733	5244	25000	8	1273	11	7764	225	1100
2014	78	16584	92	99606	5244	25000	8	1170	10	7149	225	1100
2015	77	16431	92	99606	5244	25000	7	1067	10	7149	225	1100
2016	76	16278	93	100824	5244	25000	7	1163	9	6534	225	1100
2017	75	16125	92	99975	5244	25000	7	1060	9	6534	225	1100
2018	73	15972	92	99975	5244	25000	6	957	9	6534	225	1100
2019	72	15819	92	99975	5244	25000	6	853	9	6534	225	1100
2020	71	15666	92	99975	5244	25000	5	750	9	6534	225	1100

Year	China Sub Count	China Sub Power	China Plant Count	China Plant Power	China Weapon Count	China Weapon Power	Russia Sub Count	Russia Sub Power	Russia Plant Count	Russia Plant Power	Russia Weapon Count	Russia Weapon Power
1940	0	0	0	0	0	0	0	0	0	0	0	0
1941	0	0	0	0	0	0	0	0	0	0	0	0
1942	0	0	0	0	0	0	0	0	0	0	0	0
1943	0	0	0	0	0	0	0	0	0	0	0	0
1944	0	0	0	0	0	0	0	0	0	0	0	0
1945	0	0	0	0	0	0	0	0	0	0	0	0
1946	0	0	0	0	0	0	0	0	0	0	0	0
1947	0	0	0	0	0	0	0	0	0	0	0	0
1948	0	0	0	0	0	0	0	0	0	0	0	0
1949	0	0	0	0	0	0	0	0	0	0	1	0
1950	0	0	0	0	0	0	0	0	0	0	5	0
1951	0	0	0	0	0	0	0	0	0	0	25	0
1952	0	0	0	0	0	0	0	0	0	0	50	38
1953	0	0	0	0	0	0	0	0	0	0	120	38
1954	0	0	0	0	0	0	0	0	1	6	150	28
1955	0	0	0	0	0	0	0	0	1	6	200	28
1956	0	0	0	0	0	0	0	0	1	6	426	1600
1957	0	0	0	0	0	0	0	0	1	6	660	1600
1958	0	0	0	0	0	0	0	0	1	6	869	1600
1959	0	0	0	0	0	0	15	1130	1	6	1060	1600
1960	0	0	0	0	0	0	59	5256	1	6	1605	1600
1961	0	0	0	0	0	0	61	5556	1	6	2471	1600
1962	0	0	0	0	0	0	62	5706	1	6	3322	51000
1963	0	0	0	0	0	0	65	6152	1	6	4238	51000

1964	0	0	0	0	1	0	67	6452	3	324	5221	51000
1965	0	0	0	0	5	22	68	6602	3	324	6129	51000
1966	0	0	0	0	20	22	70	6902	3	324	7089	51000
1967	0	0	0	0	25	22	122	10639	4	484	8339	51000
1968	0	0	0	0	35	3300	124	10939	4	484	9399	51000
1969	0	0	0	0	50	3300	126	11239	5	849	10538	51000
1970	0	0	0	0	75	3300	128	11507	5	849	11643	51000
1971	0	0	0	0	100	3300	137	12892	6	1266	13092	51000
1972	0	0	0	0	130	3300	140	13274	7	1683	14478	51000
1973	0	0	0	0	150	3300	143	13588	9	3123	15915	51000
1974	1	40	0	0	170	3300	147	14052	12	3587	17385	51000
1975	2	80	0	0	180	3300	151	14506	14	4599	19055	51000
1976	2	80	0	0	180	3300	156	15110	16	5611	21205	51000
1977	2	80	0	0	180	3300	160	15574	16	5611	23044	51000
1978	2	80	0	0	190	3300	162	15806	16	5611	25393	51000
1979	3	120	0	0	195	3300	168	16600	18	7611	27935	51000
1980	4	178	0	0	205	3300	173	17254	20	9211	30062	51000
1981	6	294	0	0	225	3300	182	19848	22	10651	32049	51000
1982	6	294	0	0	235	3300	187	20452	23	11651	33952	51000
1983	7	334	0	0	240	3300	192	21146	24	12651	35804	51000
1984	7	334	0	0	249	3300	197	21908	26	14091	37431	51000
1985	7	334	0	0	243	3300	201	22372	28	17085	39197	51000
1986	8	392	0	0	230	3300	206	23016	29	18085	45000	51000
1987	9	432	0	0	230	3300	210	23480	30	19085	43000	51000
1988	9	432	0	0	240	3300	215	24174	31	20085	41000	51000
1989	9	432	0	0	238	3300	217	24360	31	20085	39000	51000
1990	9	432	0	0	232	3300	219	24632	32	21085	37000	51000
1991	9	432	1	330	234	3300	204	23462	32	21085	35000	51000
1992	10	490	1	330	234	3300	196	22982	32	21085	33000	51000
1993	10	490	2	1314	234	3300	199	23512	33	22085	31000	51000
1994	10	490	3	2298	234	3300	200	23712	33	22085	29000	51000
1995	10	490	3	2298	234	3300	167	20556	31	21767	27000	51000
1996	10	490	3	2298	234	3300	135	17496	31	21767	25000	51000
1997	10	490	3	2298	232	3300	113	16614	31	21767	23000	51000
1998	11	548	3	2298	232	3300	113	16614	30	21607	22500	51000
1999	11	548	3	2298	232	3300	113	16614	30	21607	22000	51000
2000	12	606	3	2298	232	3300	114	16754	29	21242	21500	51000
2001	13	664	3	2298	235	3300	115	16954	30	22283	21000	51000
2002	13	664	7	5656	235	3300	115	16954	29	21866	20000	51000
2003	13	664	8	6384	235	3300	117	17294	29	21866	19000	51000
2004	14	722	9	7034	235	3300	117	17294	29	21866	18000	51000
2005	14	740	9	7034	235	3300	114	16932	28	21854	17000	51000
2006	14	737	10	8094	235	3300	109	16231	27	20854	16000	51000
2007	14	735	11	9154	235	3300	104	15670	26	19854	15000	51000
2008	14	732	11	9154	235	3300	99	14969	26	19854	14000	51000
2009	15	787	11	9154	240	3300	94	14468	26	19854	13000	51000
2010	15	785	13	10900	240	3300	90	13907	27	20854	12000	51000
2011	15	782	16	12671	260	3300	84	13206	28	21854	11000	51000
2012	15	779	17	13760	280	3300	80	12705	28	21854	10000	51000
2013	15	835	20	17084	300	3300	75	12205	28	21854	9000	51000
2014	15	832	23	20351	320	3300	71	11644	29	22854	8000	51000
2015	15	829	31	28645	340	3300	65	10943	30	23739	7000	51000
2016	15	827	36	33678	360	3300	60	10242	31	24919	6000	51000
2017	16	882	39	36979	380	3300	56	9881	31	24919	5889	51000
2018	16	879	46	45943	400	3300	51	9180	33	27137	5889	51000
2019	16	877	48	48779	410	3300	45	8479	36	28388	5889	51000
2020	16	874	50	51047	410	3300	40	7778	37	29576	5889	51000

Year	France Plant Count	France Plant Power	France Sub Count	France Sub Power	France Weapon Count	France Weapon Power
1940	0	0	0	0	0	0
1941	0	0	0	0	0	0
1942	0	0	0	0	0	0
1943	0	0	0	0	0	0
1944	0	0	0	0	0	0
1945	0	0	0	0	0	0
1946	0	0	0	0	0	0
1947	0	0	0	0	0	0
1948	0	0	0	0	0	0
1949	0	0	0	0	0	0
1950	0	0	0	0	0	0
1951	0	0	0	0	0	0
1952	0	0	0	0	0	0
1953	0	0	0	0	0	0
1954	0	0	0	0	0	0
1955	0	0	0	0	0	0
1956	0	0	0	0	0	0
1957	0	0	0	0	0	0
1958	0	0	0	0	0	0
1959	1	43	0	0	0	0
1960	2	86	0	0	0	0
1961	2	86	0	0	0	60
1962	2	86	0	0	0	60
1963	3	166	0	0	0	60
1964	3	166	0	0	4	60
1965	4	396	0	0	32	60
1966	5	876	0	0	36	60
1967	7	1271	0	0	36	60
1968	7	1271	0	0	36	70
1969	8	1771	0	0	36	2600
1970	8	1771	0	0	36	2600
1971	9	2301	6	72	45	2600
1972	10	2856	6	72	70	2600
1973	11	2998	6	72	116	2600
1974	11	2998	6	72	145	2600
1975	11	2998	6	72	188	2600
1976	11	2998	7	120	212	2600
1977	13	4838	8	168	228	2600
1978	15	6728	8	168	235	2600
1979	17	8562	9	216	235	2600
1980	24	15199	9	216	250	2600
1981	31	21842	9	216	274	2600
1982	33	23747	10	264	274	2600
1983	37	27559	10	264	279	2600
1984	43	34142	10	264	280	2600
1985	47	39238	11	312	360	2600
1986	53	46941	12	462	355	2600
1987	56	50620	13	612	420	2600
1988	57	51983	14	660	410	2600
1989	57	51983	14	660	410	2600
1990	59	56047	14	660	505	2600
1991	59	57366	14	660	540	2600
1992	60	58748	14	660	540	2600
1993	61	60111	14	660	525	2600

1994	60	60031	14	660	510	2600
1995	60	60031	15	810	500	2600
1996	60	61361	15	810	450	2600
1997	61	64002	15	810	450	2600
1998	59	63607	15	810	450	2600
1999	60	65168	15	810	450	2600
2000	59	64668	15	810	470	2600
2001	59	64668	15	810	350	2600
2002	58	64138	15	810	350	2600
2003	57	63583	16	960	350	2600
2004	56	63441	16	960	350	2600
2005	56	63441	15	912	350	2600
2006	56	63441	15	909	350	2600
2007	56	63441	16	1056	350	2600
2008	54	61601	17	1202	300	2600
2009	54	61601	11	1127	300	2600
2010	54	61601	11	1124	300	2600
2011	54	61601	11	1121	290	2600
2012	54	61601	11	1118	290	2600
2013	54	61601	10	1114	290	2600
2014	54	61601	10	1111	290	2600
2015	54	61601	10	1108	290	2600
2016	54	61601	10	1105	290	2600
2017	53	60359	10	1102	290	2600
2018	53	60359	10	1098	290	2600
2019	53	60359	10	1095	290	2600
2020	53	60359	10	1092	290	2600

```
#!/usr/bin/python3
# PRIS WEB SCRAPER PYTHON SCRIPT
import requests
from bs4 import BeautifulSoup
import time
import pandas

# Info
country = []
reactor_name = []

# Timeline
start_construction = []
criticality = []
shutdown = []
long_term_shutdown = []
restart_date = []

# Reactor Specs
reactor_type = []
reactor_model = []
net_capacity = []
net_capacity_design = []
gross_capacity = []
thermal_capacity = []

# Use
total_gen = []
avail_factor = []
operation_factor = []
unavail_factor = []
load_factor = []

for web_id in range(1200):

    # Scrape
    URL = f"https://pris.iaea.org/PRIS/CountryStatistics/ReactorDetails.aspx?current={web_id}"
    page = requests.get(URL)

    if str(page)!='<Response [500]>':
        soup = BeautifulSoup(page.content, "html.parser")
        results = soup.find(id="content")

        if results.find("h3").text.strip() != 'Unauthorized Access':

            # Country
            header = soup.find(id="MainContent_litCaption")
            country.append(header.find("body").text.strip())
            reactor_name.append(results.find("span", id="MainContent_MainContent_lblReactorName").text)

            # Timeline
            start_construction.append(results.find("span",
id="MainContent_MainContent_lblConstructionStartDate").text)
            criticality.append(results.find("span",
id="MainContent_MainContent_lblFirstCriticality").text)
            shutdown.append(results.find("span",
id="MainContent_MainContent_lblPermanentShutdownDate").text)
            long_term_shutdown.append(results.find("span",
id="MainContent_MainContent_lblLongTermShutdownDate").text)
            restart_date.append(results.find("span", id="MainContent_MainContent_lblRestartDate").text)

            # Reactor Specs
            reactor_type.append(results.find("span", id="MainContent_MainContent_lblType").text)
            reactor_model.append(results.find("span", id="MainContent_MainContent_lblModel").text)
            net_capacity.append(results.find("span", id="MainContent_MainContent_lblNetCapacity").text)
            net_capacity_design.append(results.find("span",
id="MainContent_MainContent_lblDesignNetCapacity").text)
            gross_capacity.append(results.find("span",
id="MainContent_MainContent_lblGrossCapacity").text)
```

```
            thermal_capacity.append(results.find("span",
id="MainContent_MainContent_lblThermalCapacity").text)

            # Use
            try:
                total_gen.append(results.find("span", id="MainContent_MainContent_lblGeneration").text)
            except:
                total_gen.append('')
            try:
                avail_factor.append(results.find("span", id="MainContent_MainContent_lblEAF").text)
            except:
                avail_factor.append('')
            try:
                operation_factor.append(results.find("span",
id="MainContent_MainContent_lblOperatingFactor").text)
            except:
                operation_factor.append('')
            try:
                unavail_factor.append(results.find("span", id="MainContent_MainContent_lblEUL").text)
            except:
                unavail_factor.append('')
            try:
                load_factor.append(results.find("span",
id="MainContent_MainContent_lblLoadFactor").text)
            except:
                load_factor.append('')

        time.sleep(0.25)


reactor_dict = {
    'country': country,
    'reactor_name': reactor_name,
    'start_construction': start_construction,
    'criticality': criticality,
    'shutdown': shutdown,
    'long_term_shutdown': long_term_shutdown,
    'restart_date': restart_date,
    'reactor_type': reactor_type,
    'reactor_model': reactor_model,
    'net_capacity': net_capacity,
    'net_capacity_design': net_capacity_design,
    'gross_capacity': gross_capacity,
    'thermal_capacity': thermal_capacity,
    'total_gen': total_gen,
    'avail_factor': avail_factor,
    'operation_factor': operation_factor,
    'unavail_factor': unavail_factor,
    'load_factor': load_factor
}

df = pandas.DataFrame(reactor_dict)
df.to_csv('reactor_scrape.csv')
```