The effect of TMI on the electric grid

Or: how we did not learn to stop worrying and love nuclear power

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Abstract

With the goal of 1000 nuclear power plants by the year 2000, the US was on the path to energy independence. However, the 1979 Three Mile Island accident turned public opinion against nuclear energy and spelled decades of stagnation for the industry. We show that the accident both halted the growth of the US reactor fleet, and stifled innovation in nuclear physics. We propose a mechanism by which accumulated scientific knowledge determines the capacity of nuclear reactors, and find that some 55 billion tons of CO_2 emissions, 2.3 million premature deaths, and 14 trillion USD in health costs could have been avoided, had we displaced fossil fuels with nuclear power.

1 Introduction

The atomic age began with the detonation of the first nuclear bomb in 1945, sparking an arms race between the United States and the Soviet Union, and raising immense public concern. In the famous 1953 "Atoms for Peace" speech, president Eisenhower called instead for the development of nuclear power for peaceful purposes, and the two superpowers began to share nuclear technology with other countries. The international cooperation that followed improved safety protocols and standards, and eventually led to the establishment of the International Atomic Energy Agency (IAEA) in 1957, and to the signing of the Nuclear Non-Proliferation Treaty in 1968. Soon after the speech, the new technology has been put to use for civilian purposes of electricity generation, with the construction of the first reactors in the 1950s. The first power plants were built in the USSR and UK in the early 1950s, and were primarily experimental, but by 1957 the first full-scale nuclear power plant came online in the United States. The Atomic Energy Commission stated that commercial electricity generation would become "too cheap to meter" within one generation, and the following decades witness a rapid expansion in both the number of reactors and in their generation capacity.

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Fast forward to today, we need to "prevent worsening and potentially irreversible effects of climate change"[1] by limiting global warming to 1.5°C. This requires the world to achieve net zero emissions by 2050, a goal that looks increasingly more challenging as years go by and negative global warming headlines accumulate. The results of a recent Lancet study (Hickman et al. 2021) on climate anxiety among young people (16-25 years of age) are disturbing: 62% and 39% feel anxious or depressed about climate change, respectively. 39% are hesitant to have children and 76% think the future is frightening.[2] Remarks from the UN secretary general, António Guterres, were hardly soothing, stating that "the era of global warming has ended, the era of global boiling has arrived, the air is unbreathable, the heat is unbearable."[3]

Yet, perhaps the next Lancet study should include 'regret' in its climate change related emotions. This paper explores the plausibility of a 'what if?' scenario, in which nuclear power does not achieve the 'successful failure' status described by Vaclav Smil. We consider a plausible scenario where nuclear power would have been a significant part of the solution to the energy transition; one which does not require, for example, unreasonable reduction in construction costs. Instead, we explore how better handling or the absence of the Three Mile Island (TMI) incident would have impacted the development of US nuclear power. We study whether there was a missed opportunity with nuclear power, and assess its consequences. While providing historical counterfactual outcomes, the exercise should also help explaining nuclear power's recent setbacks and inform on its role in the multi-trillion dollar per year energy transition.

Technological advances in nuclear physics and engineering indeed showed great promise in providing a cheap, clean, and abundant source of electricity, and many countries invested in a fleet of nuclear power plants, helping to reduce their dependence on fossil fuels and to mitigate the environmental impact of electricity generation. Another boost to nuclear power in the US came in the 1970s, when the Nixon administration announced 'Project Independence' - an initiative aimed to make the United States energy independent by 1980. In response to the 1973 oil crisis, the plan called for a massive expansion of nuclear power, and the construction of 1000 plants by the year 2000. However, the promise of nuclear energy was not to be fulfilled. The 1979 Three Mile Island accident in the United States fundamentally turned public opinion against nuclear energy, and together with the 1986 Chernobyl disaster spelled decades of stagnation for the industry.

This paper therefore relates the historical events to the current power grid, and investigates the impact of public opinion of nuclear energy on the development of nuclear physics and engineering, the construction and decommissioning of nuclear power plants, pollution, and public health. We argue that the extreme regulatory response to TMI had a two-pronged effect on the development of nuclear energy: it led to a de facto moratorium on new nuclear power plant construction in the United States, and it likely also put a stop to R&D efforts aimed at obtaining energy from nuclear sources, as there will be no market for the technology in the foreseeable future.

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[1] "Explained: The 1.5°C climate benchmark", MIT News.

[2] 55% go further and think humanity is doomed.

[3] The Guardian, 22 September 2022.

Using a synthetic control framework and data on nuclear power plant construction worldwide, we show that the US had fallen behind its peers, and could have had an additional 200 reactors today. We then document the strong contemporaneous link between technological advances in the field of nuclear physics that relate to obtaining energy and improvements in the capacity of nuclear reactors. Employing the same framework for patents in nuclear physics, we show that a particular subclass of nuclear physics that relates to obtaining energy from radioactive sources is missing about 3 billion USD in value, compared to where it would have been today. We propose a mechanism by which accumulated scientific knowledge determines the capacity of nuclear reactors, and show that the accident had a significant impact on the development of nuclear physics and engineering, and on the capacity of nuclear power plants. If not for TMI, our results suggest reactors would have been about 3 times more powerful. Finally, extrapolating from the link between patents and reactor capacity, we estimate the effect of TMI on the modern power grid. Our results suggest that the counterfactual grid would be nearly five times larger than the current, in terms of total generation capacity.

Holding the total required capacity constant, this implies that about 94% of the current grid would be supplied by nuclear power, compared to the actual 18%, which would have allowed for a significant reduction in emissions and pollution, entirely phasing out coal by 2002, and natural gas by 2010. This displacement would have saved about 55 Gt of carbon emissions between 1979 and 2020, preventing around 2.3M premature deaths related to air pollution, and between 8 and 14 trillion USD in health costs (associated with premature mortality, but also ER visits, asthma attacks, lost workdays and school absence days).

This paper contributes to several strands of literature. The first relates to the energy economics literature on nuclear power, which has focused on the cost of construction and operation (Shirvan 2022) and why they increased so markedly (Eash-Gates et al. 2020). It also considers the impact of nuclear power on electricity prices (Nestle 2012). Scholars of environmental and energy economics devote considerable attention to the energy transition and the optimal power grid (Sepulveda et al. 2018), focusing mostly on phasing-out fossil fuels for renewable energy sources, like wind and solar (Hansen, Breyer, and Lund 2019). The role of nuclear power in the transition has been largely overlooked at best, and at worst deemed to be part of the problem (Sovacool et al. 2020; Dittmar 2012). The energy mix in power generation has obvious implications for emissions of greenhouse gases (GHG), but also on electricity costs and prices for which the assessment is controversial and challenging (Paul L. Joskow 2011; Hirth 2013). This paper aims to fill this gap by providing a counterfactual scenario for the US power grid, suggesting that nuclear power can be a significant part of the solution to the energy transition.

Another is the literature on the history of the energy sector. A broad overview can be found in (Smil 2018), while a recent account of our focus area, civil nuclear energy, can be found in (Bersano and Segantin 2024). We participate in one of the many areas of debate around nuclear power and its history: the contribution of TMI to the downfall of the US nuclear industry. There seems to be few dedicated studies on the so-called 'TMI effect,' although the event is mentioned in adjacent work (Jurewitz 2002). The existing literature tends to classify TMI as one of many issues the industry had. One dedicated study is (Hultman and Koomey 2013), which rightfully highlights some pre-TMI headwinds. However, as they point that 40% of reactor cancellations happened before TMI, one can argue that even more cancellations occurred between 1979 and 1984, including 75% of all cancellations occurring during construction. We add to this relatively sparse literature by providing evidence of a stark TMI effect on the industry and assess its consequences on the US energy landscape.

The remainder of the paper is structured as follows. Section 2 offers historical context, discussing the early days of nuclear energy, notable accidents, and regulations that shaped the modern grid. Section 3 reviews the data sources used for the analysis, providing descriptive statistics and stylized facts on innovation and nuclear reactors. Section 4 presents the empirical strategies and modeling specifications, and discusses the results. Section 5 combines the empirical findings and considers several alternative scenarios for electricity generation today, as well as avoided emissions and mortality. Section 6 concludes.

2 The age of nuclear energy

2.1 Institutional background

After years of successful applications for nuclear marine propulsion by the US and USSR navies, the 1950s witnessed the construction of the first electricity generating reactors. The earliest power plants — Obninsk in the Soviet Union in 1954 and Calder Hall in the United Kingdom in 1956 — were experimental and on a small scale, but already in 1957 the Shippingport Atomic Power Station in Pennsylvania was the first full-scale nuclear power plant (NPP) to come online. The following decades witness a rapid expansion in both the number of reactors and in their generation capacity.

With other countries joining the nuclear club, the number of reactors and their capacity grew rapidly. The United States, the Soviet Union, and the United Kingdom were the first to build nuclear power plants, but by the 1970s, France, Germany, and Japan had also joined the nuclear club. The 1970s and 1980s were the peak of nuclear power plant construction, with the number of reactors and their capacity growing rapidly (Figure 2.1).

In the early years of the nuclear age there were multiple competing reactor designs, such as the BWR (boiling water reactor), PWR (pressurized water reactor), GCR (gas-cooled reactor), LWGR (light water graphite-moderated reactor), and PHWR (pressurized heavy water reactor). As development continued, the BWR and PWR designs became the most common and provided the highest output, reaching capacities of nearly 1.5 GW by the late 1970s. This dominance of light water reactors can be attributed to the technology's early adoption in the late 1940s by the US Navy for its submarine propulsion program. Despite the fact that light water is considered inferior to other technologies, like heavy water and gas graphite, the US government subsidized light water reactors for civilian use domestically and in Europe, entrenching the technology as the dominant design (Cowan 1990).

A major risk of the LWGR design was the potential for a positive feedback problem that could lead to a runaway reaction. The 1986 Chernobyl disaster was exactly that, after which the LWGR design was abandoned. As of today, the BWR and PWR designs remain the

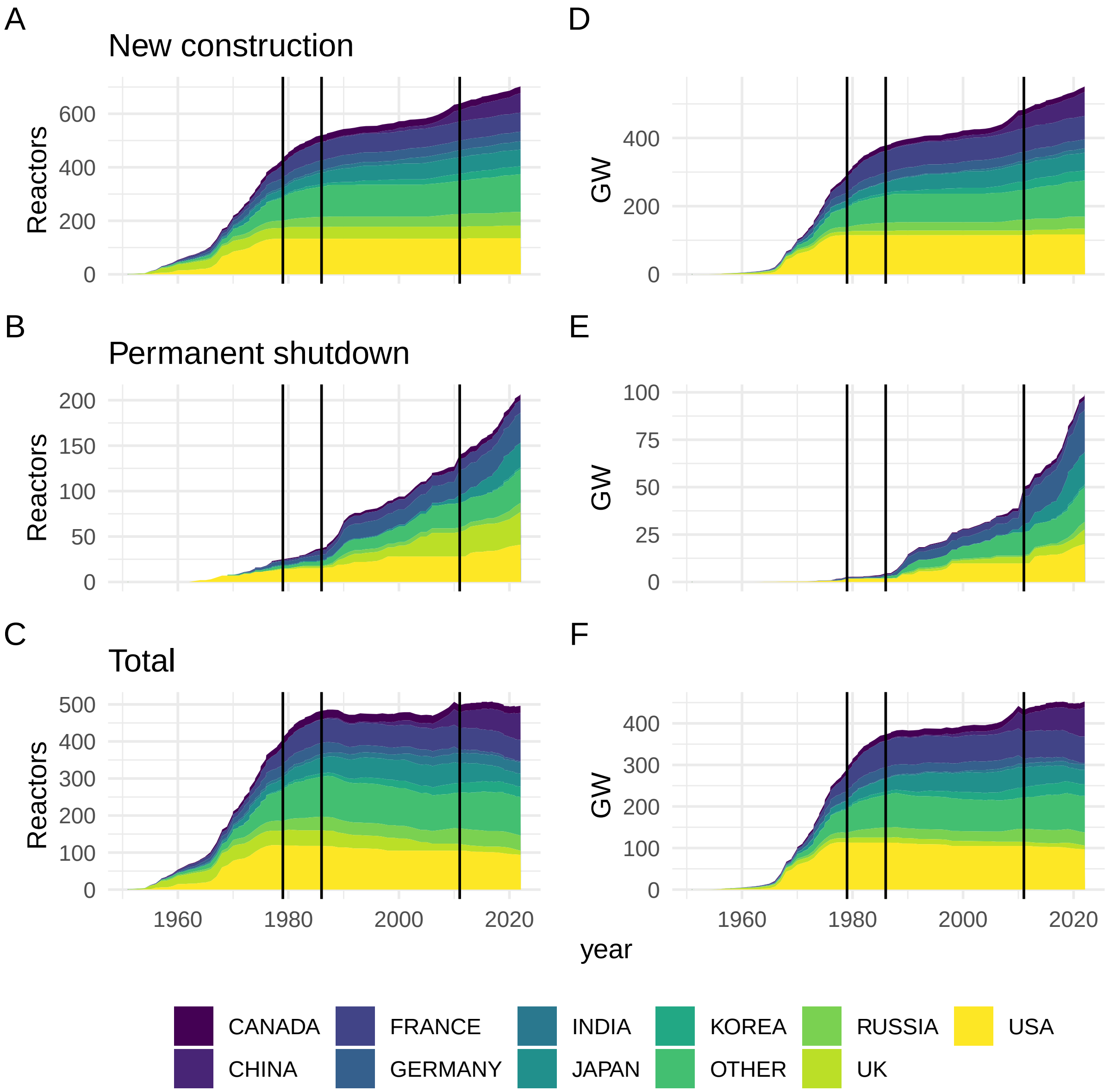

Figure 2.1: Total annual stock of constructed, decommissioned, and operating reactors. The left panels report individual reactors. The right panels report total capacity, in GW. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

most common, comprising about 90% of installed capacity worldwide. While the GCR and LWGR designs were abandoned, the FBR and PHWR designs account for some of the latest additions to the grid.

The US was at the forefront of the civil nuclear race, starting to build many reactors in the 1960s. The early 1970s oil shock added more fuel to this early expansion of nuclear power and had likely been a 'curse in disguise'. The technology saw disproportionate enthusiasm, further fueled by the emerging awareness of air pollution and environmental impacts,[4] and brazen political announcements like 'Project Independence.' Yet power demand was growing too slowly to sustain the announced supply gush and environmental concerns were too timid. This allowed coal power to expand substantially and compete with nuclear power. Cost overruns caused further problems but should have been expected: A young industry in an experimental phase tried to rapidly expand production.[5] Although the music started to slow down in the mid-to-late 1970s, the TMI incident (and its handling by the authorities) seem to have shaken the industry much further. Project cancellations - which indeed started before TMI - accelerated and 32 reactors were even canceled during construction between 1980 and 1984.[6] At the same time, there was increasing concern regarding pollution and air quality, and the emergence of global warming awareness, highlighted by the Intergovernmental Panel on Climate Change (IPCC) foundation in 1988. However, this renewed tailwind - and headwind for nuclear's coal rival - were not enough to trigger the first nuclear renaissance.

2.2 Nuclear accidents

This section provides a general overview of two of the most famous nuclear accidents, Three Mile Island and Fukushima. Notably, we do not discuss the Chernobyl disaster, as the accident is of a different nature and scale compared to the other two. Fukushima is included as it featured a similar reactor design, accident severity, and public discourse and political reactions to those of Three Mile Island.

2.2.1 Three Mile Island

The Three Mile Island accident was a partial meltdown of reactor number 2 at the Three Mile Island Nuclear Station (TMI 2) in Pennsylvania, United States. It was the most serious accident in US commercial nuclear power plant history. The accident began on March 28, 1979, and was caused by a combination of equipment failure and operator error. The reactor core suffered a partial meltdown due to a loss of coolant. The event led to the release of a small amount of radioactive gases and radioactive iodine into the environment. According

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[4] Some highlights were the EPA creation in 1970 or the Stockholm conference in 1972.

[5] The poster child here is the Washington Public Power Supply System (WPPSS), earning its 'Whoops' nickname after attempting to build 5 NPPs on 3 different sites using 3 different reactor designs. This ended in the second largest municipal bond default in US history. Another sign of the industry's immaturity was the fleet's average capacity factor stagnating around 60% until 1985, to then reach 90% by 2000.

[6] Only 3 reactors had such a fate before TMI.

to the 1979 NRC report, the accident caused no injuries or adverse health effects to plant workers or members of the nearby community. Residents in the nearby Harrisburg area were exposed to an average dose of 1.7 millirem (17 microsieverts) of radiation, which is less that the background dose the average person receives in 2 days (Corey 1979). The maximum off-site dose was about 83 millirem (830 microsieverts), roughly equivalent to two mammograms, while on-site, only four people received doses exceeding NRC regulatory standards of 3 rem (U. S. Nuclear Regulatory Commission 1980), which is similar to about four chest CT scans.

Nevertheless, the political and social fallout was quick to follow, as public opinion turned against nuclear power. Walter Cronkite, “the most trusted man in America”, opened his March 28, 1979, newscast with:

> The world has never known a day quite like today. It faced the considerable uncertainties and dangers of the worst nuclear power plant accident of the Atomic Age. And the horror tonight is that it could get much worse.

Yet, President Carter went for a personal inspection on April 1st. Carter possessed industry knowledge, having worked on naval nuclear reactors in his navy days, had hands-on experienced with safety operations following a core meltdown 25 years prior, and even participated in a course on NPP operation. Anecdotal evidence relates that President Carter told his staff the incident was not a disaster, further describing it as minor. He then reportedly refused to share these thoughts to the public, being concerned by the reactions of the anti-nuclear aisle of his party.

Some academics saw the grim implications for nuclear power. Rosalyn Yalow, Nobel prize winner for her work in radioimmunoassay, expressed her concerns and frustrations:[7]

> “An unreasonable fear of any level of radiation associated with radioactivity or nuclear energy generated by newspaper headlines and publicity seekers was now pervasive throughout our society,” Dr Yalow said. “Because of this we dissipate research talent and funding on make-work projects in response to unreasonable fears in make-work situations.” She cited, for example, the recent announcement that a number of research groups are to study possible long-range health effects secondary to the reactor accident at Three Mile Island. The maximum estimated dose received by anyone living near the reactor during the accident was bout 70 millirems, less than one third the amount they would have received by spending a year in Colorado. “If these were the maximal doses received one can predict with absolute certainty that, other than psychological effects, no physical aberration would be demonstrable. Yet we waste time, money and research talent - and generate more psychological stress than would otherwise occur in unnecessary make-work of no scientific merit.”

In the business world, GE’s 1979 annual report cautiously acknowledges TMI’s implications:

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[7] Nature, 17 January 1980, “Nuclear accident casts a long shadow”

> It is [GE managers'] belief that while the future for nuclear energy was made more difficult by the accident at Three Mile Island Unit 2 in 1979, nuclear power can and should still play a significant, and safe, role in reducing the present heavy dependence on oil imports.

A tone that could be explained by the company's commitment to the sector: Over the 5 years following this annual report, GE saw 14 of its reactors being canceled during construction. The accident led to an expected tightening of safety regulations, but also a de facto moratorium on new nuclear power plant construction in the United States, and the cancellation of many planned plants. Even though President Carter was still advocating a "speed up in the licensing of nuclear plants" in March 1979, by April he already stated that nuclear power should only be used "as a last resort" (Sylves 1980). The advisory panel he appointed - the Kemeny Commission - called to abolish the NRC and postpone the issuance of new nuclear power plant operating licenses. The commission's findings were generally endorsed and indeed no licenses were issued for new nuclear power plants over the next 30 years.

2.2.2 Fukushima Daiichi

The Fukushima incident's background and the reactions it generated resemble those of TMI in many ways, and could therefore call for applying our analysis to Japan or Germany, using Fukushima in lieu of TMI. In 2009, Germany was reconsidering its nuclear phaseout policy after Angela Merkel (a quantum chemistry PhD) accessed the chancellery without allying with a large left-wing anti-nuclear party (Grunen or SPD). But the table turned after the Fukushima incident, as the phaseout plan was reinstated and accelerated. The government canceled NPP license extensions only three days after the incident, and committed to phase out nuclear by 2022 three months later, well before the scientific community could assess the causes and consequences of the disaster.[8] Japan had a stronger reaction, quickly suspending operations in its 54 reactors. By 2015, its nuclear-related R&D spending are only half of what they were in 2010.

On March 11 2011, a magnitude 9.1 earthquake created a massive tsunami hitting the North-Eastern coast of Japan. Around 20,000 people subsequently died but the world's attention rather hung on the fate of several power plants. Three nuclear power plants, among which Fukushima-Daiichi (FD), were hit by tsunami waves reported to be as high as 14 meters. FD was flooded and lost its diesel generators, used as backup for the cooling system. Those were unsealed and located in the buildings' basement, leaving the 10m elevation of the plant and a 5.7m sea wall as the only two lines of defense. The Onagawa plant, closer to the epicenter and subject to similar height waves, is widely unknown to the public as it achieved cold shutdown. The plant was even used as a safe area following the tsunami. This is thanks to a higher elevation and a 14.7m sea wall. Such different fates for the two plants suggests that the FD disaster could have been avoided (Acton and Hibbs 2012). In this vein, the opening

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[8] The United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) started its investigation on May 2011 and released its first report in 2013. The Fukushima Nuclear Accident Independent Investigation Commission issued its report on 2012 (Commission 2012).

message from the chairman of the Nuclear Accident Independent Investigation Commission report is the following:

> The earthquake and tsunami of March 11, 2011 were natural disasters of a magnitude that shocked the entire world. Although triggered by these cataclysmic events, the subsequent accident at the Fukushima Daiichi Nuclear Power Plant cannot be regarded as a natural disaster. It was a profoundly manmade disaster - that could and should have been foreseen and prevented. And its effects could have been mitigated by a more effective human response.

The 'manmade' disaster unfolded as the absence of cooling led to the core meltdown of FD's operating reactors (units 1, 2, and 3). Release of radioactive material in the atmosphere began on March 12, amounts of which stayed significant for a couple of weeks. Authorities reacted by extending the initial evacuation order from 2 to 20 km around the plant. A confinement and voluntary evacuation order was issued for those living within 20 to 30 km. Around 170,000 people were eventually evacuated. A 2020 report from the Japanese Reconstruction Agency estimates 2,313 disaster-related deaths not linked to radiation among the evacuees.[9] As far as radiation impact, the 2013 UNSCEAR report (UNSCEAR 2014) states [p.10]:

> The doses to the general public, both those incurred during the first year and estimated for their lifetimes, are generally low or very low. No discernible increased incidence of radiation-related health effects is expected among exposed members of the public or their descendants. The most important health effect is on mental and social well-being, related to the enormous impact of the earthquake, tsunami, and nuclear accident, and the fear and stigma related to the perceived risk of exposure to ionizing radiation. Effects such as depression and post-traumatic stress symptoms have already been reported.

This was confirmed in the 2020/21 report (UNSCEAR 2022) [p.108]:

> No adverse health effects among Fukushima residents have been documented that are directly attributable to radiation exposure from the FDNPS [Fukushima-Daiichi nuclear power station] accident. The Committee's revised estimates of dose are such that future radiation-associated health effects are unlikely to be discernible.

The report states that 0.7% (174) of the emergency workers received effective doses higher than 100 mSv over the first year. This is the lowest level at which an increase in cancer risk has been detected,[10] the report estimates for this group "about two to three additional

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[9] 80% occurring within the first two years after the disaster, 90% of the deaths occurring for people over 66 years of age.

[10] Health Physics Society: "However, below levels of about 100 mSv above background from all sources combined, the observed radiation effects in people are not statistically different from zero."

cases of cancer in addition to about seventy cancers that would occur spontaneously, given the baseline risk of about 40%". The most exposed worker received an annual effective dose of 680 mSv.[11]

The UNSCEAR reported the mean averted radiation exposure for evacuated towns near FD: Two towns representing 10% of the evacuated population ranked significantly higher, with an average around 40 mSv per inhabitant. As stated before, such exposure is not expected to have any health consequences. Over the years following the incident, around 35% of the Fukushima prefecture population received a total radiation exposure (background + medical + FD related) larger than what the average American receives. This share, however, becomes negligible if we ask our benchmark american citizen to have a single CT scan. With these elements, one might question the effectiveness of evacuating 10% of the population. But the situation at the time was much more uncertain and dynamic; settling on a minimal evacuation would have likely been politically untenable.[12]

Another governmental decision likely had greater consequences: Within approximately a year, Japan suspended operation for inspection on all of its 54 reactors, which produced around 30% of the country's electricity. As of February 2024, only 12 reactors are back in operation while 33 remain operable. This shutdown increased electricity prices due to a larger reliance on fossil fuels, electricity demand contracted, and air pollution and CO_2 emissions increased. Figures stating 30 billion USD per year in fossil fuels imports following 2011 are circulating.[13]

The shutdown also had health and environmental implications: about 4500 cold related deaths are attributed to price increase between 2011 and 2014 (Neidell, Uchida, and Veronesi 2021). Around 23,000 premature air-pollution related deaths and the emission of 2.2 Gt CO_2[14] could have been avoided between 2011 and 2017 (Kharecha and Sato 2019). In 2016, the government estimated the cost of dealing with the FD disaster to be 21.5 trillion Yen (166 billion USD in 2024 terms).[15]

2.3 Nuclear costs

These major nuclear accidents resonate with historical arguments against nuclear power, like safety concerns and waste disposal. But those arguments are less and less audible as we look at the quantities of nuclear waste or actual dangers, and the deaths per energy produced for each power source. The industry's tribulations allowed much more grounded arguments to emerge: NPPs take a long time to build and cost a lot of money. This cost is especially hard to deal with because most of it is upfront fixed costs while stringent safety

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[11] To put this into perspective, 1000 mSv from short-term exposure is expected to increase fatal cancer incidence by 5 percentage points.

[12] Several countries advised their citizen to leave Tokyo (220km away from FD) or Japan altogether, and relocated their embassies south to Osaka.

[13] A very rough estimation of 250 TWh replaced at a price \$15/mmbtu (around \$50/MWh) using 40% plant efficiency lead to a very close number.

[14] Roughly 6% of the world's CO_2 emissions in 2023.

[15] This includes victim/evacuees compensations (37%), off-site decontamination (19%), storage of radioactive material (7%) and decommission costs (37%).

regulations and the industry's sluggishness mean long construction times, delaying the start of the well-needed payback period.

First, let us address the question of setup time. Historically, the construction of nuclear power plants has been a lengthy process with several important milestones. Those can be broken down into three phases: construction, from the start of construction to first criticality (when the reactor is able to sustain a controlled chain reaction); connection, from first criticality to grid connection; and operation setup, from grid connection to the start of commercial operation.

Figure 2.2 shows the distribution of the time it takes to set up a nuclear power plant from the start of construction to commercial operation, and Table A.1 reports summary statistics. The average reactor is commercially operational in almost 7.5 years after construction began. Almost all of that time goes toward construction, averaging just under 7 years, about 2 months are spent connecting the reactor to the grid, and roughly six months later commercial operation begins. On occasion, construction delays caused some plants to take more than 20 or even 30 years to construct, but 95% of plants are operational within 14 years from first laying of concrete.

An even more important part of the cost equation is the discount rate we use to evaluate future costs and benefits. The Levelized Cost of Energy (LCOE) gives the price (usually in $/MWh) at which the project has a net present value of zero at our chosen discount rate. Said differently, we are indifferent between not building a power plant or building it and then selling its production at the LCOE price.

A famous recurring LCOE study is carried out by Lazard (Lazard 2023). Over the years, it shows a decrease in wind and solar LCOE, yet an increase for nuclear power.[16] Using their numbers, we illustrate how high discount factors used in LCOE calculations can lead to puzzling conclusions. With a 7% discount factor, doubling Vogtle's lifetime from 40 to 80 years decreases its LCOE by less than 5%. Put differently, the plant owner should refuse to double its plant's lifetime if it increases construction costs by more than 6%. Another striking situation involves decommissioning costs. Suppose we assume 1 billion USD per GW in decommissioning costs (World Nuclear Association's upper scenario) and a 7% discount rate. In that case, we get an actualized decommissioning cost of 13M USD if the operation is realized 60 years from now. If so, the Vogtle operator should refuse to make its plant 'decommission-proof' if it increases construction costs by 0.1% or more.

These long-term actualized costs look too low, which suggests our discount rate is too large. Weitzman (2001) argues it is the case and goes further by suggesting a decreasing marginal discount rate (DDR). The idea is to reflect the increasing uncertainty around the economy's growth rate as we look further into the future. DDR is further discussed in Arrow et al. (2014). But first one needs to find the appropriate baseline rate that will then decrease over time. After surveying nearly three thousand economists, Weitzman settled on a 4%[17] real

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[16] This LCOE is based only on Vogtle units 3 and 4, however, which Lazard fail to mention until the latest edition of the study.

[17] The question was: "Taking all relevant considerations into account, what real interest rate do you think should be used to discount over time the (expected) benefits and (expected) costs of projects being proposed to mitigate the possible effects of global climate change?"

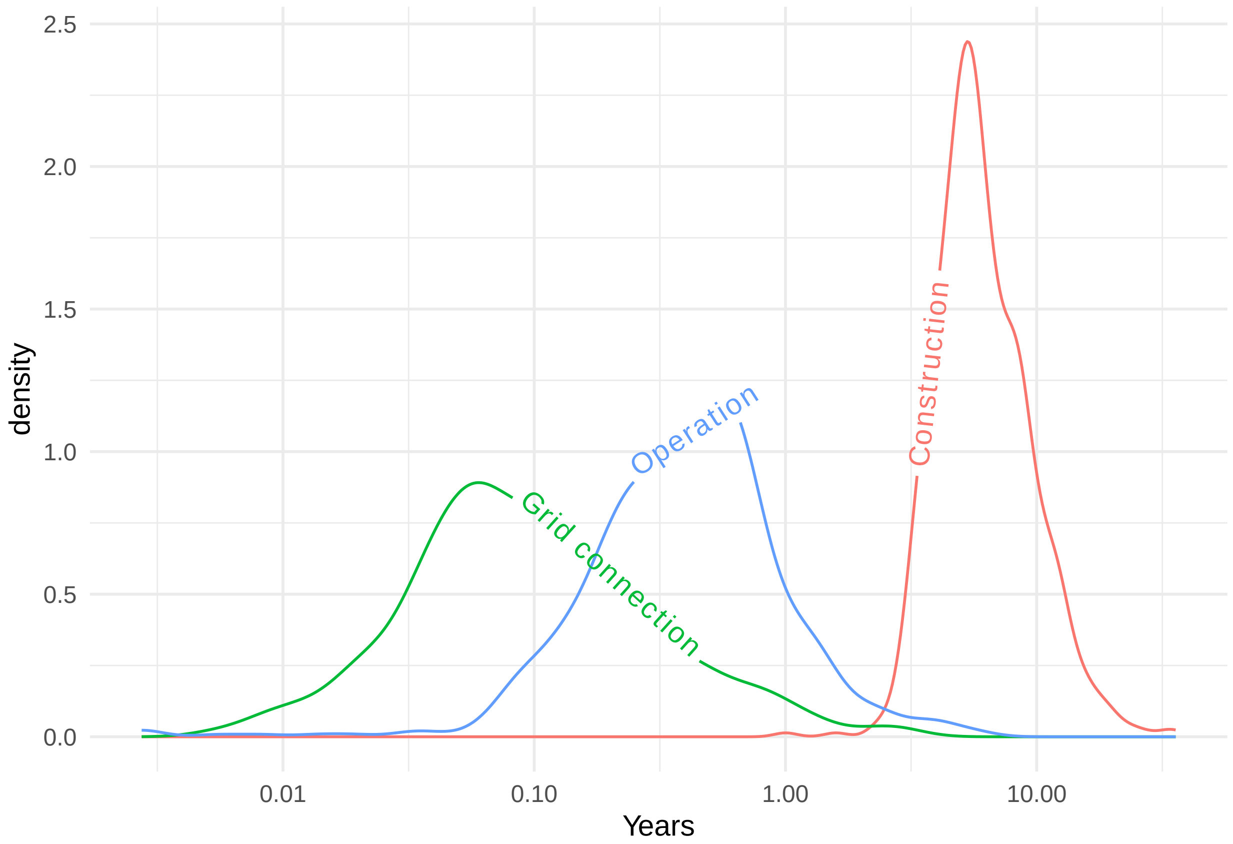

Figure 2.2: Distribution of time to completion of three steps in the process of setting up a nuclear power plant: construction time, from first laying of concrete to completion; operation, from completion to first criticality; and connection, from first criticality to first grid connection, for all reactors in the dataset.

discount rate and recommended marginal discount rate to decrease from 4% to 3%, 2%, 1%, and then 0% as we look further in time.[18] Using DDR in our decommission costs example gives an actualized cost representing 2% of the construction costs, more than 20 times what we had with a 7% discount rate.

When it comes to the NPP costs, Lazard's worst-case estimation (using a lifespan of 40 years, a discount factor of 7%, and a capital cost of 14 billion USD/GW) gives 228 USD/MWh. If instead we apply Weitzman's DDR, assume a lifespan of 80 years (where some current reactors are already heading) and a rather modest improvement in capital costs (10 billion USD/GW)[19], the LCOE fell to 81 USD/MWh. We also note that smaller capital costs and discount rates are also more favorable to wind and solar projects compared to fossil fuel ones, but nuclear power is the most sensitive technology to these factors.

So far we criticized the inputs in the LCOE formula, but its output also deserves scrutiny. We often see LCOE numbers brought up to argue for a wind and solar-based system over a nuclear one. But this means comparing two different power systems by looking only at production units. The transmission, backup, and firming parts of both systems should not be ignored, yet this is what LCOE does. This critique is not new (Paul L. Joskow 2011). In addition, LCOE is used as a breakeven power, so a project will move on if it expects to capture an average price at least as high as its LCOE when selling power to the market. However, this average sale price can be very different from the average market price. Let us take an extreme example: If solar produces only 1 hour a day and always covers demand during this hour, the market price will be zero (or even negative) during this one hour. This makes solar capacity unprofitable, no matter how low its LCOE is. More generally, a power source constrained to sell most of its production over a short period will likely sell lower than the average market price. The market value of electricity production can be an important cost characteristic and is not captured by LCOE. Wind and solar energy can see their market value going down significantly as they penetrate the market (Hirth 2013). In essence, it is quite a leap of faith to use the breakeven average selling price of a marginal unit of wind or solar capacity in the current system to inform us about the merit of a new wind and solar-dominated system.

LCOE does compare apples to apples when nuclear and fossil fuel plants are involved. Unfortunately, newly built NPPs usually don't fare well against fossil fuel plants, and this likely slowed down the energy transition. We argue that the TMI-induced nuclear hiatus bears a lot of responsibility for why the nuclear industry went back to first-of-a-kind building. This section shows that it further translates into larger LCOE due to longer construction times, higher discount rates, and higher construction costs. Had the industry only slowed down and kept building regularly, the price tag on new nuclear capacity would be much less scary (Shirvan 2022). Not considering NPPs as "utility killers" which require high discount rates, but rather seeing them as long-term climate-friendly projects for which we use DDR, means very different price tags for the very same plant.

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[18] For example, the suggested marginal discount rate is 4% for years 1 to 5 and then 3% for year 6 to year 25. Thus, the present value of 100 USD received on year 6 is $\frac{100}{(1.04)^5(1.03)}$.

[19] Shirvan (2022) has much lower estimates.

3 Data and stylized facts

We construct a novel data set, which combines data on individual patents and nuclear reactors. Plant-level micro data on nuclear reactors include its location, construction, criticality, grid connection, and commercial operation dates, reactor type and model, thermal, gross, and net capacities, owner, and operator. The data set is based on the Power Reactor Information System (PRIS) database, developed and maintained by the International Atomic Energy Agency. The data set also includes information on suspension and decommissioning of nuclear reactors, when applicable. For US power plants, we also include data on licensing and operation from the Nuclear Regulatory Commission (NRC), which cover issuance of construction permits, full-power operating licenses, and combined licenses, as well as permanent shutdowns.

Individual patent data come from the European Patent Office's (EPO) PATSTAT database, which contains bibliographical and legal event patent data from industrialized and developing countries. For each patent, the data set contains its application and publication dates, authority of application (country), and Cooperative Patent Classification (CPC) codes. For US patents, they are also matched to their forward citations and innovation value using Kogan et al. (2017).

Data on the labor supply of physicists and engineers come from the National Science Foundation (NSF), covering the number of PhDs awarded by field, in five-year bins. Data on R&D spending come from the International Energy Agency's (IEA) Energy Technology RD&D Budgets database. The latter includes annual data for 31 countries starting from 1974, reported separately by technology, like light water reactors (LWRs), breeder reactors, or fuel cycles.

Using the data above, this section documents a number of stylized facts about key features of the nuclear power industry, including details on the global and US nuclear power fleets, the history of nuclear power plant licensing and regulation, trends in patent issuance and R&D efforts, and advances in reactor capacity.

3.1 US nuclear power fleet

According to the US Energy Information Administration (EIA), as of 2023, there are 93 operating commercial nuclear reactors at 54 nuclear power plants in 28 states (Figure 3.1). The fleet is composed of 62 pressurized water reactors (PWRs) and 31 boiling water reactors (BWRs), whose combined installed capacity of 96 GW produces about 800 TWh, or 18%, of the country's annual electricity generation. The average reactor has been in operation for 41 years, and operates at a capacity factor of 93%. With 21 power reactors already undergoing decommissioning, and several others approaching retirement in the coming years, the EIA projects that total generation capacity will decline to about 76 GW by 2040, supplying 625 TWh of the total 4.5 PWh demand (14%).

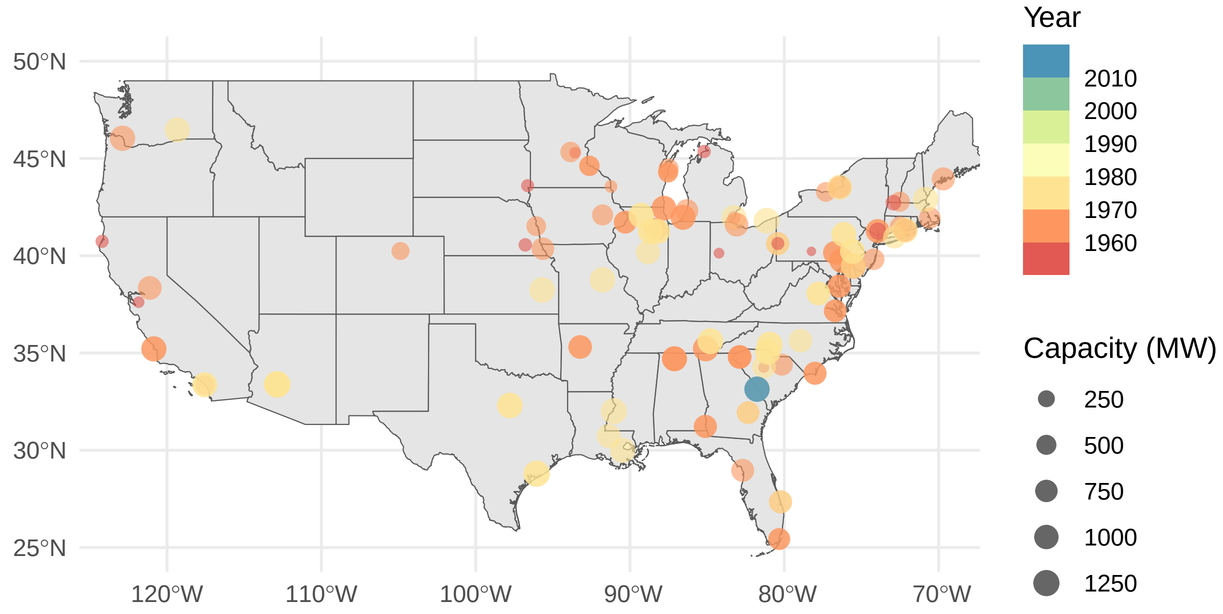

Figure 3.1: Nuclear power plants in the US by year of construction and installed capacity. Colors correspond to the decade when construction began, size corresponds to the reactor's capacity.

3.2 NRC licensing stops

After the Three Mile Island accident, the NRC came under great scrutiny by the Kemeny Commission over lax procedures and oversight, and stopped issuing construction permits for new nuclear power plants. Data from the NRC show the scope of this hiatus in Figure 3.2. The figure presents the annual number of issued construction permits (CP), full power operating licenses (OL), and combined licenses (COL). It also shows the number of reactors permanently shut down every year, and the total stock of operable units (reactors). The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986), and the Fukushima nuclear accident (2011).

CPs allow for the construction of a facility and have been issued before a license if the application is otherwise acceptable, and later converted into a license, upon completion of the facility. Full-power OLs permit licensees to commence commercial operation. This is in contrast to low-power OLs, which are issued first and allow the licensee to conduct tests and experiments at the reactor, but not to generate electricity at scale. COLs authorize the licensee to construct and operate a nuclear power plant at a specific site, are valid for 40 years, and can be renewed for an additional 20 years.

Beginning in the mid-1960s and throughout the 1970s, the NRC issued construction permits at a rate of 11 per year, peaking at 23 in 1974. This number dropped to zero after 1979, and remained so until 2012, when the NRC issued combined licenses for the Vogtle Electric Generating Plant in Georgia. At the time of TMI, there were 94 reactors in various stages of construction. Of those, 52 have eventually been completed, receiving full-power OLs in the 1980s and 1990s, while the remaining 42 were canceled. Over the years, some 39 reactors have been permanently shut down. Many of the earliest ones were experimental and relatively small: 14 reactors amounting to 1.8 GW combined. In contrast, the 15 reactors shut down in the 1980s and 1990s were commercial-scale units, with a combined capacity of 9.4 GW. This loss of capacity was not yet offset, as the next reactors to be build were Vogtle 3 and 4, whose construction started in 2013.

3.3 Patenting stagnation

We examine international patenting activity in nuclear physics, as measured by the number of patents issued in the field, using data from the European Patent Office's (EPO) PATSTAT database. Patents are a widely used measure of innovation and technological progress, and are often used as a proxy for R&D activity and knowledge creation. They are classified according to the Cooperative Patent Classification (CPC) system into sections, classes, and subclasses,[20] and each may relate to multiple subclasses. Patents that span multiple subclasses list them in order of relevance. To avoid double counting, such patents are assigned to the first subclass listed.

The class of nuclear physics and nuclear engineering (G21) is nested under the physics section (G), and covers multiple subclasses: patents related to fusion reactors (G21B), nu-

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[20] Patents can be broken down further into groups and subgroups. We use the subclass level of the CPC system.

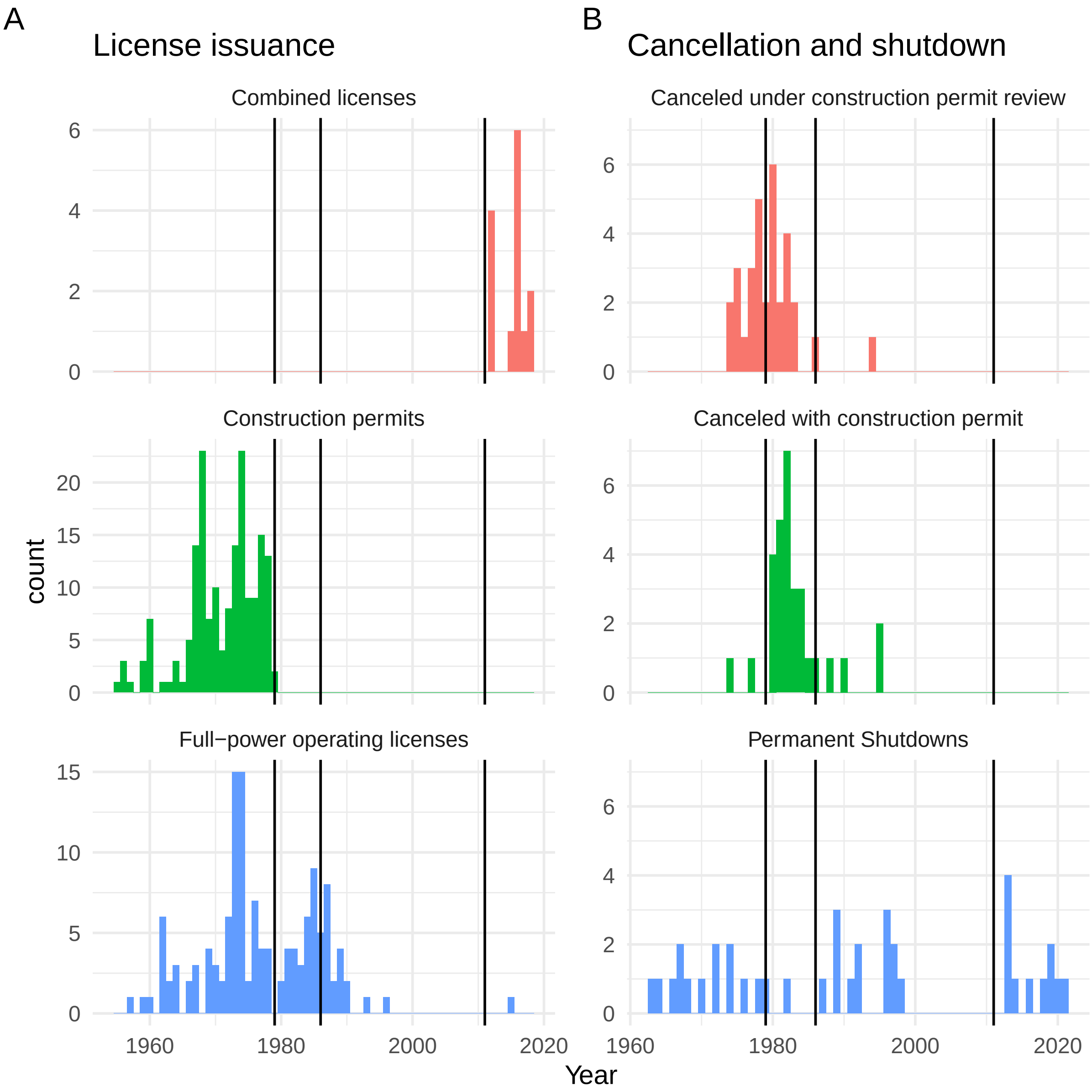

Figure 3.2: NRC licensing, cancellations, and shutdowns, reactors per year. Panel A plots the annual number of construction permits (CP), full-power operating licenses (OL), and combined operating licenses (COL) issued by the Nuclear Regulatory Commission (NRC). Panel B plots the annual number of reactors canceled under CP review, canceled with a CP, and entering permanent shutdown.

clear reactors (G21C), nuclear power plants (G21D), radiation protection, treatment, and decontamination (G21F), conversion of chemical elements (G21G), obtaining energy and applications of radiation from radioactive sources (G21H), nuclear explosives (G21J), and handling radiation (G21K). Figure 3.3 plots the number of patents issued in nuclear physics by year and subclass. The overlaying histograms correspond to the date of application and publication of the patents. Denied patent applications are not observed. We omit the fusion reactors and nuclear explosives subclasses since the former are not yet commercially viable, and the latter do not relate to civilian use for power generation.

Innovations across the different subclasses help tell the story of how the field has evolved over time: patents primarily relating to reactors, not power plants, comprise the majority and were the first to attract significant attention in the 1960s. This reflects the fact that early reactors were not designed for power generation, but for research and military purposes. Similarly, the rate of innovation in obtaining energy from radioactive sources has been increasing rapidly through the 1960s and 1970s, as scientists and engineers were experimenting with different fuels and reactor designs. Against the backdrop of the 1973 oil crisis, there was a major push in those years for the US to reach energy independence, and nuclear power was seen as a way to achieve that. At the same time, oil shocks drove the price of uranium up, increasing sixfold to an equivalent of about 400 USD/kg today.

Then TMI happened, and patenting in the field of obtaining energy plummeted. From an average of 250 patents issued annually in the years prior, the number dropped to around 30 in 1980, and remained under 50 for the next 20 years. A resurgence in patenting came only in the 2000s, and by 2020 we have reach pre-TMI levels of patenting for obtaining nuclear energy. No other subclass exhibited such a dramatic decline in patenting activity. If anything, the rate of innovation in radiation protection, treatment, and decontamination (G21F) had nearly tripled around TMI, which makes sense given the heightened public concern over radiation exposure and increased attention to safety and environmental concerns in the aftermath of the accident.

Figure 3.4 focuses only on the obtaining nuclear energy subclass, and shows the number of patents issued by year and country. Out of the 42 countries in the data, the figure plots the 12 countries with the highest total patent volume, and includes Austria, Belgium, Canada, Switzerland, Germany, France, the United Kingdom, Israel, Japan, the Netherlands, Sweden, and the United States. The figure shows that the drop in innovation is perhaps the most dramatic in the US, but is quite stark across all countries. The US, which had been the leader in patenting in the field, saw the annual number of patents drop from 60 in the late 1970s to single digits until the late 1990s. Some countries, like Canada, Germany, and Japan, have continued to innovate at substantially lower rates. Others, like Belgium, Sweden, and Switzerland, seem to have stopped patenting altogether for at least several decades. The comovement in patenting across countries could indicate that international collaboration and knowledge spillovers are important in the field, or perhaps that the same patents are registered in multiple jurisdictions, which we cannot rule out in the data.

Another way to illustrate the deviation from the path is by examining the cumulative number of patents. We use cumulative patenting by subclass to proxy for the stock of knowledge accumulated in the field, which is arguably more important than the flow of patents in

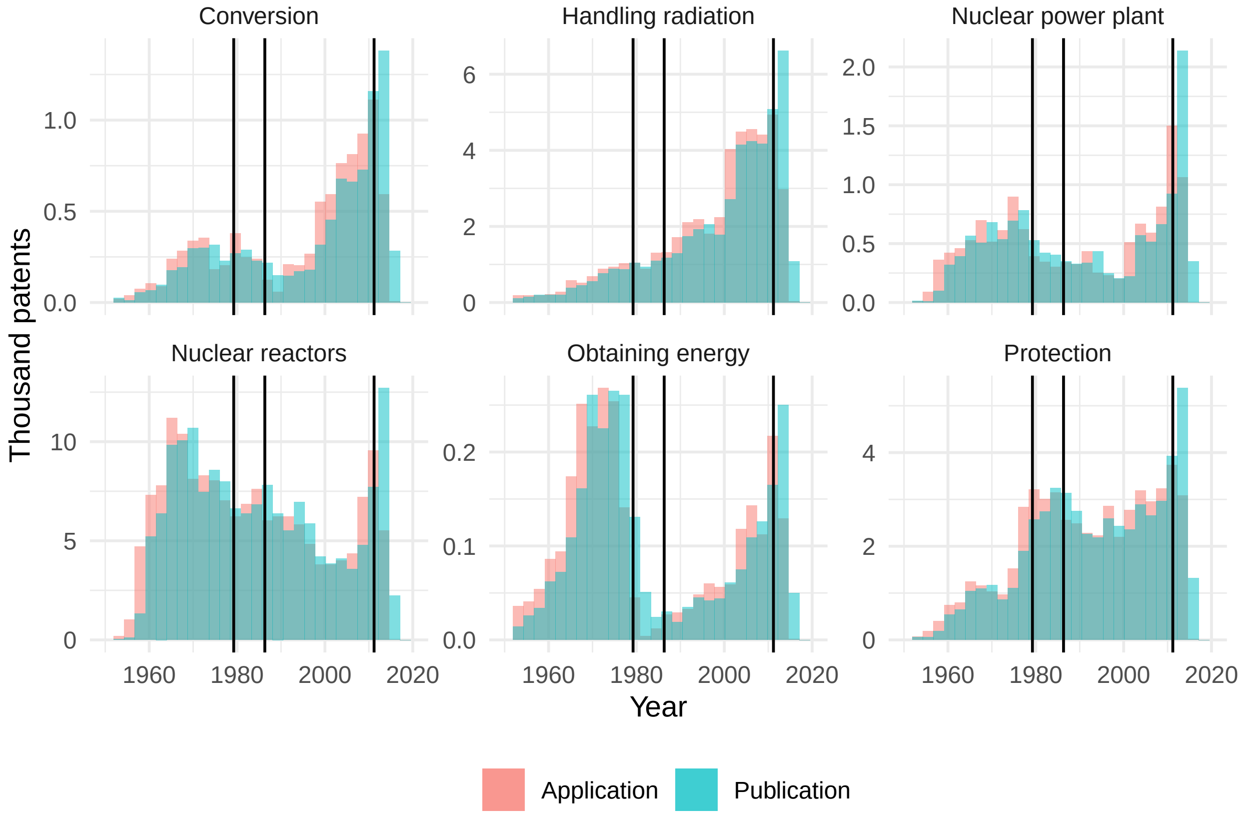

Figure 3.3: Time of application and publication of patents related to nuclear physics, by subclass.

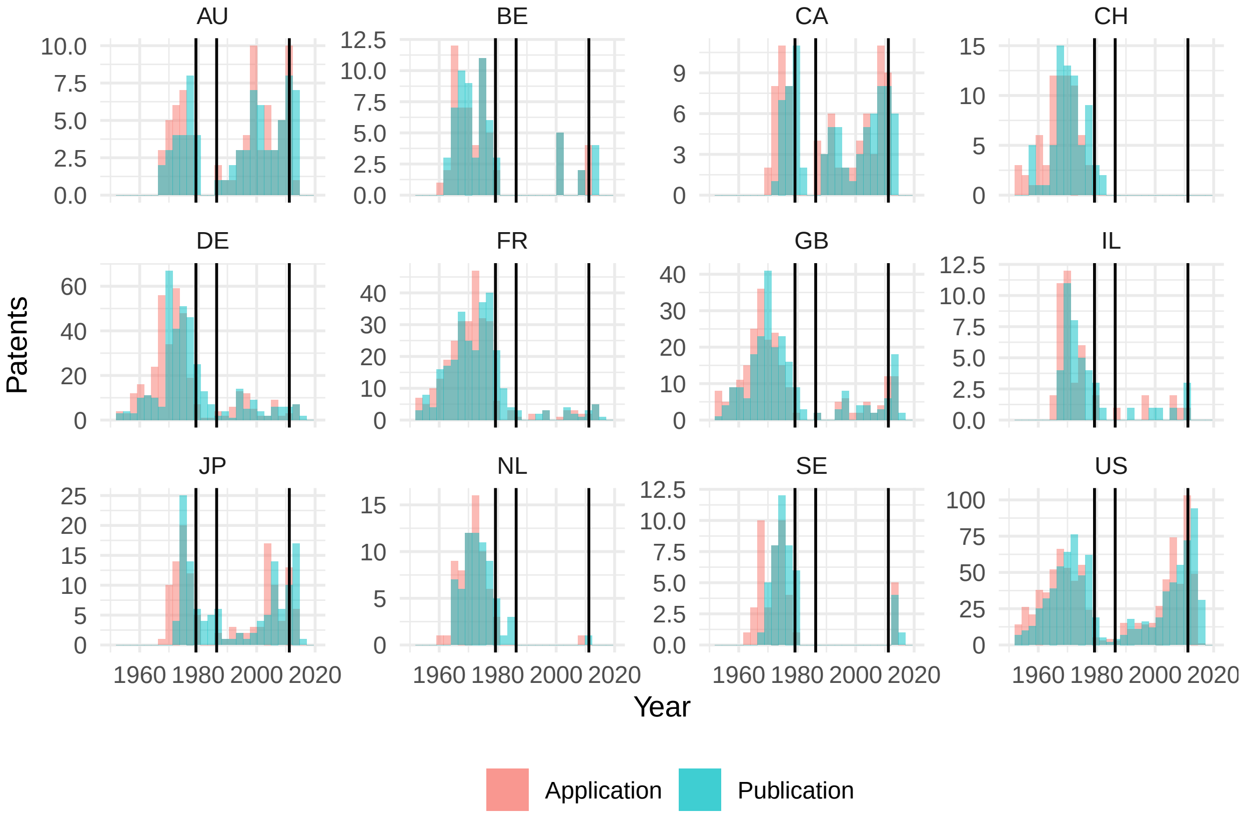

Figure 3.4: Time of application and publication of patents related to obtaining energy from radioactive sources, by country.

determining the state of the art in a field. Figure 3.5 plots the cumulative number of patents, in thousands, issued in nuclear physics by year and subclass. The subclass of obtaining energy is visibly an outlier, exhibiting a sharp break in the trend around TMI, unlike any other subclass. The same amount of knowledge was accumulated in the field in the 40 years following TMI as in the 10 years prior to it.

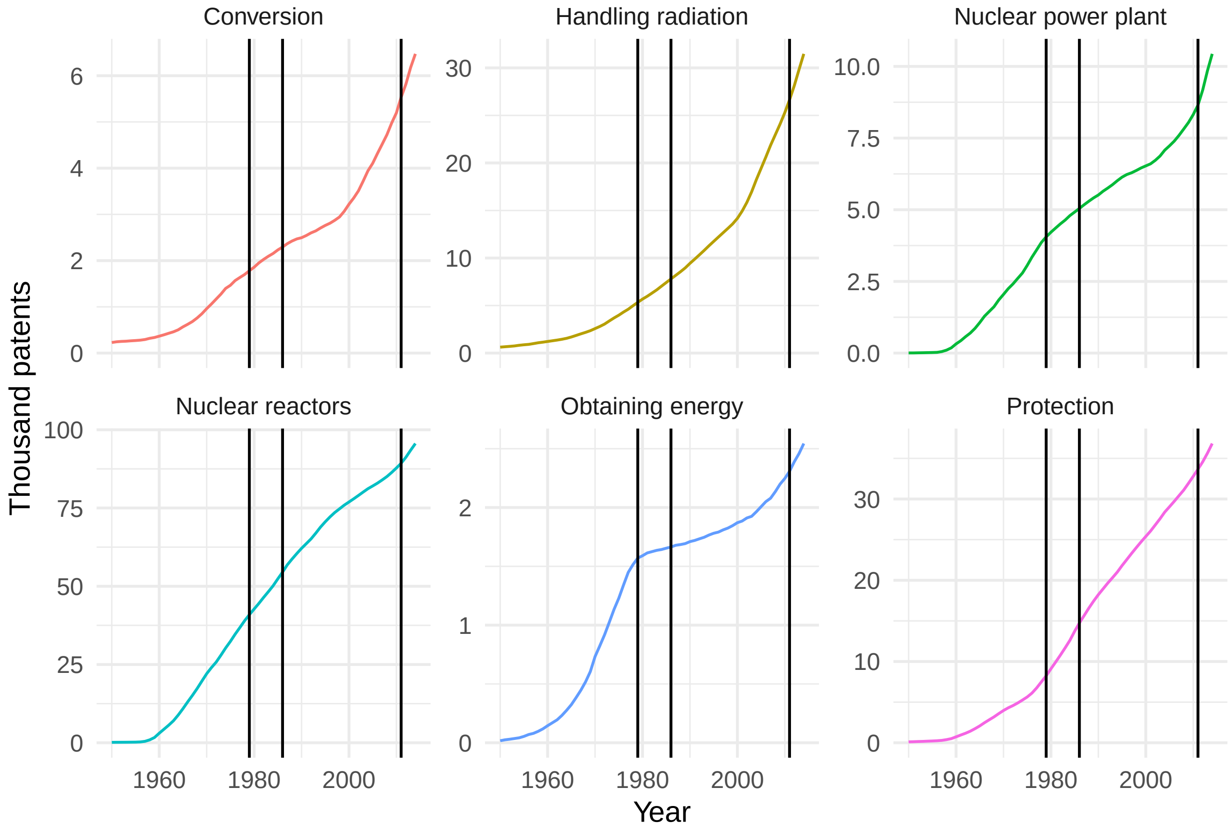

Figure 3.5: Cumulative patenting by subclass. This figure plots the total number of patents issued in nuclear physics (CPC class G21), by year and subclass.

3.4 Nuclear R&D defunded

According to the International Energy Agency, worldwide R&D spending on nuclear energy has been growing rapidly throughout the late 1970s, and almost doubled in five years: the total amount, in 2022 USD, had gone from 6.8 billion in 1974 to 12.6 billion in 1979, with the US accounting for about half of the total.[21] Figure 3.6 shows the R&D spending on nuclear energy in select countries by year, in billion USD, 2022 prices. Through the 1970s, the US has been by far the largest spender, followed by Germany, Japan, and the UK.

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[21] The data set is missing an important player, the Soviet Union, so the total amount is likely to be higher, and the US share lower.

However, ever since is peak in 1979, at nearly 6 billion USD, US R&D spending on nuclear energy has been declining. By the late 1990s, it has shrunk to about 0.5 billion, less than 10% of its peak value. Breaking down the US budget by technology, panel A of Figure 3.7 reveals that the decline is driven primarily by drying up of investments in nuclear fission, down to about 30 million USD - virtually zero - in the late 1990s. Nuclear fusion technologies, while also declining, have only lost 75% of their peak funding, from 1.6 billion in 1979 to 0.4 billion in 1996.

Diving deeper into fission technologies, we see in panel B of Figure 3.7 that the decline is driven primarily by breeder reactors, dropping from 2.5 billion in 1979 to 0.1 billion in 1986, and to a lesser extent by light water reactors, which experienced a gradual decrease from 2.5 billion in 1979 to under 60 million in the span of 5 years. A slower, yet persistent decline was also registered in fuel cycle technologies, from 1.2 billion in 1979 to 0 in 1992. Breeder reactors and fuel cycles are two particularly important fields of research for the efficiency of nuclear power and how much energy could be obtained from fuel: unlike the more common BWR and PWR models, breeder reactors can produce more fissile material than they consume, drastically reducing the amount of uranium required for operation; and fuel cycle technologies improve uranium utilization, energy generation and safety, while minimizing waste, and limiting proliferation risk. The decline in both was not an encouraging sign for the future of nuclear power.

3.5 Physicists and engineers

Could it be that TMI revealed important information to the scientific community about the prospects of nuclear technology, leading to a loss of interest in the field and lower supply of scientists, adversely affecting innovation? This does not seem to be the case, according to data from a 2006 special report by the National Science Foundation (NSF) (Golladay, Hill, and Thurgood 2007). We use the number of PhDs awarded as a proxy for the supply of highly trained professionals, and focus on the fields of nuclear chemistry, nuclear physics, and nuclear engineering. This measure is useful, as it reflects the expectations of both students and universities about the future prospects of the field and the demand for professionals in it.[22] Figure 3.8 plots the number of PhD degrees awarded across the three fields between 1975 and 1999, over 5-year periods. The figure shows that the number of PhDs awarded in nuclear physics and engineering has been stable over the 25-year period, at about 85 and 104 per year, while the number of PhDs in nuclear chemistry is substantially smaller, averaging 12 per year, and has been on a secular decline throughout the sample period.

3.6 Reactor capacity

Investments in nuclear R&D, and the resulting breakthrough innovations, likely contribute to increasing reactor capacity. Figures 3.10 and 3.11 plot the installed capacity of each reactor

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[22] It is also indirectly indicative of expectations by industry and government, which fund research and development and employ the graduates.

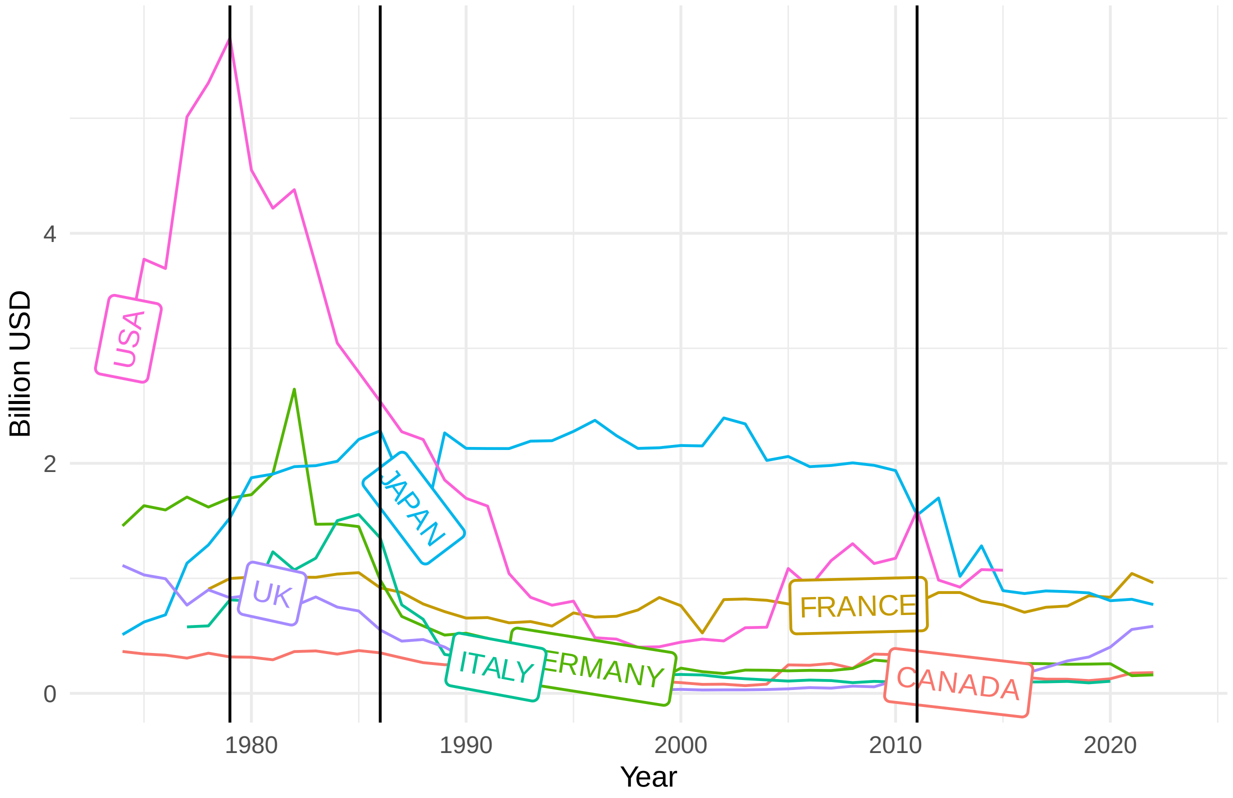

Figure 3.6: Research spending on nuclear energy in select countries by year, in billion USD, 2022 prices.

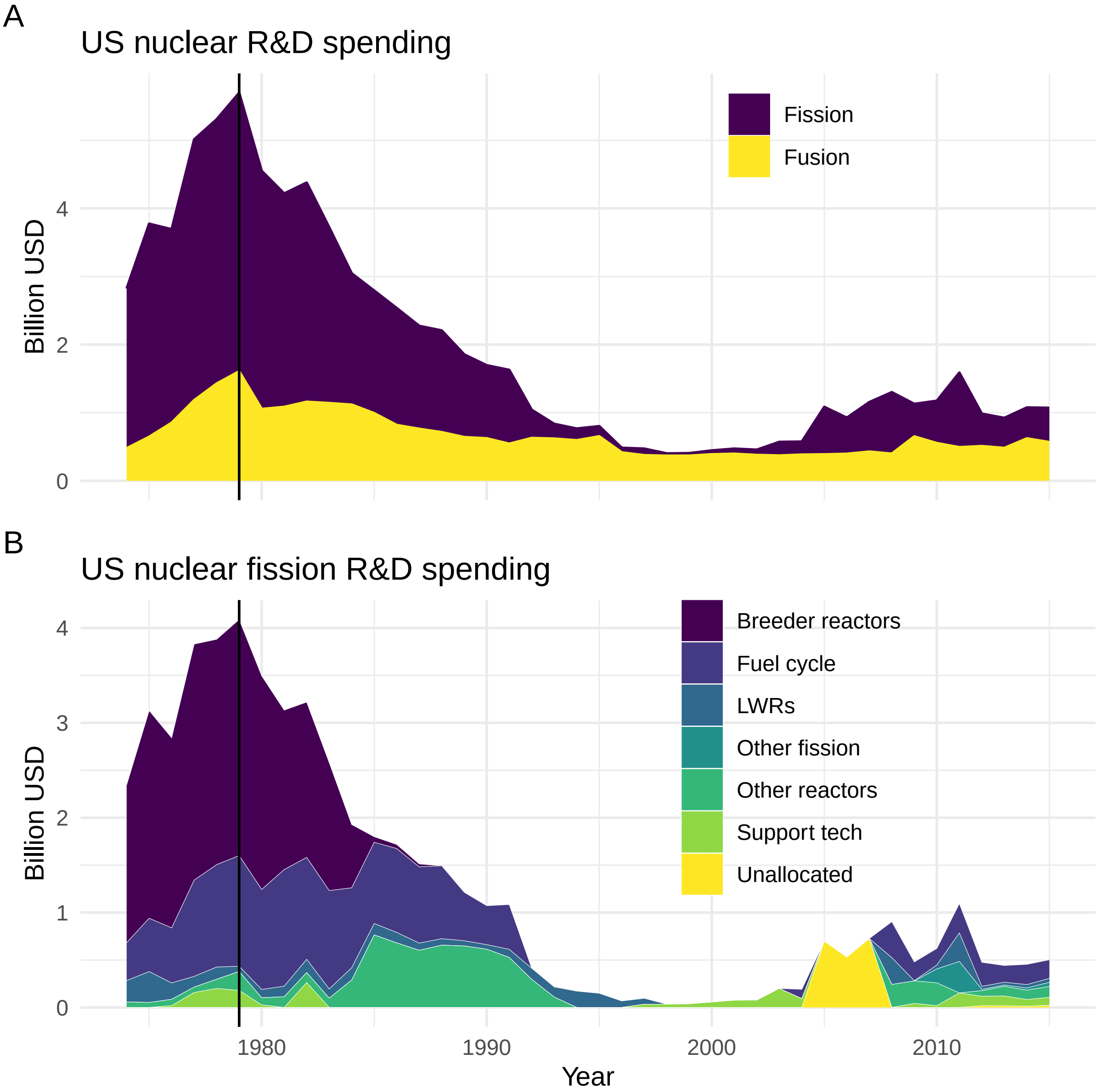

Figure 3.7: US research spending on nuclear energy by technology and year, in billion USD, 2022 prices. Panel A reports the aggregate amounts for fission and fusion. Panel B breaks down fission into more granular subcategories: LWRs, fuel cycle, nuclear supporting technologies, breeder reactors, and other.

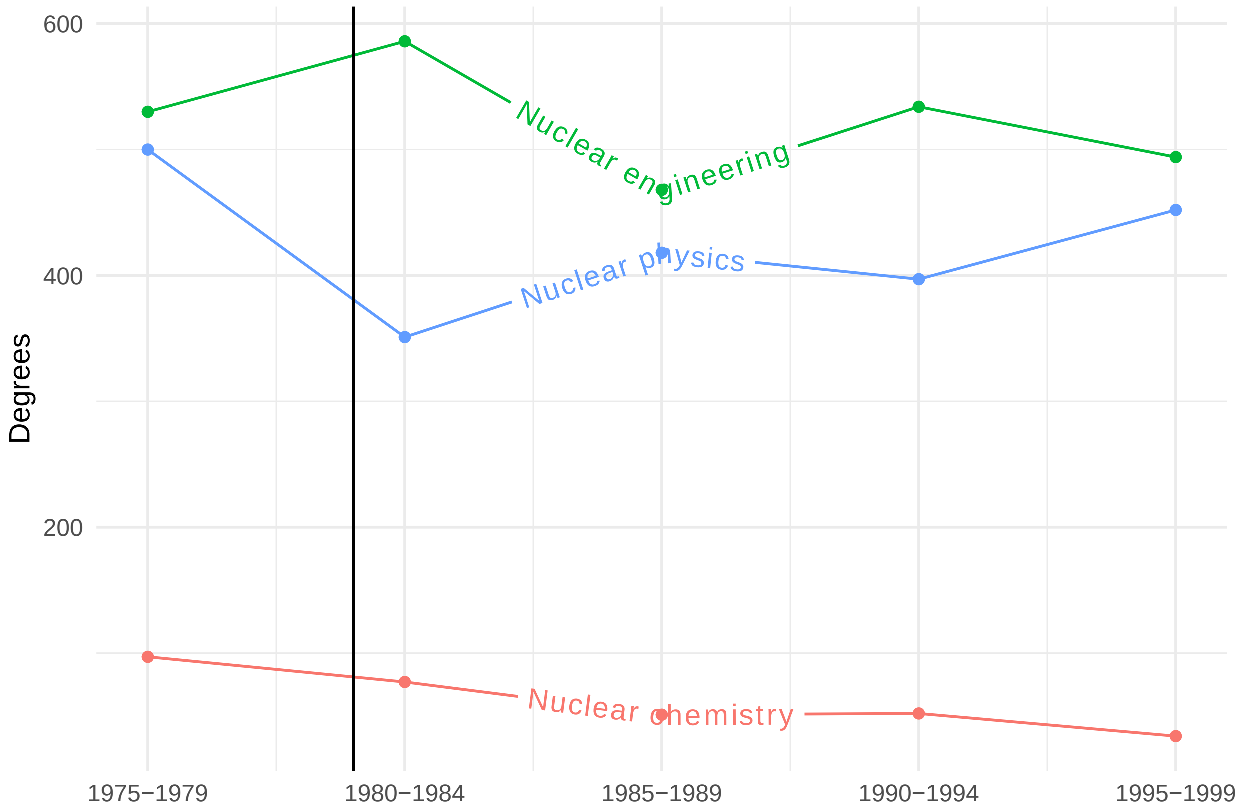

Figure 3.8: Number of PhD degrees awarded in the fields of nuclear physics, engineering, and chemistry in the US, binned in 5-year periods. Source: NSF.

as a function of construction start date, color-coded according to country and reactor type, respectively. The period before TMI was marked by a rapid increase in both the number of reactors and their capacity: the total stock of reactors in operation or under construction had gone from 54 in 1960 to 453 in 1980, while the average capacity of each additional reactor grew steadily from 100 MW to 1 GW in the same years. However, starting around 1980, the number of commissioned reactors drops, and growth in capacity seems to halt completely, staying at around 1 GW per reactor until at least the 2010s. This progress in reactor power was not driven by a single country or breakthrough technology, but were common across the world and across different reactor designs.

Throughout the first decades, as more and more reactors were commissioned and built, the United States has been the leader in the field, with the highest reactor capacity, and by far the greatest number of them. Still, the upward trend in state of the art capacity was similar for other nuclear countries: the Soviet Union, Japan, France, and Germany have also seen comparable progress in reactor power, even if less so in quantity.

There were also noticeable changes in reactor types and their market shares. From a multitude of experimental models in the 1950s and 1960s, light-water reactors quickly came to dominate the market. While not the most efficient, they have enjoyed a head start thanks to their previous deployment in nuclear marine propulsion by the US and USSR navies (Cowan 1990). Figure 3.11 illustrates, however, that the general trajectory of initial growth and later stagnation in reactor capacity was common across different reactor types, and that the stall in capacity was not driven by a single technology.

Finally, Table 3.1 reports the results of a series of linear regressions of the log of reactor capacity on construction start year as a continuous variable, interacted with dummy indicators for the periods after TMI, Chernobyl, and FD accidents. The different models gradually introduce fixed effect for reactor type, model, and country. The table captures the clear trend and shows that the construction start date is a significant predictor of reactor capacity, which had been increasing by about 10% per year until the late 1970s. TMI is then associated with a significant break in trend, essentially nullifying it. Changes to the slope after Chernobyl and Fukushima are statistically indistinguishable from zero. The results are robust to the inclusion of fixed effects for reactor type, model, and country, suggesting they are not a feature of shifts in the composition of reactors designs or the countries building them.

3.7 Construction and operation

In accordance with the Atomic Energy Act and NRC regulations, commercial power reactor licenses are issued for an initial period of 40 years. Licenses may be renewed for an additional 20 years to extend operation, as long as the plant meets NRC requirements, ensuring an adequate energy supply for the United States. Importantly, the 40 year cap was put in place not due to limitations of nuclear technology, but rather for economic and antitrust considerations. Indeed, as of February 2018, the NRC has renewed the operating licenses of 89 commercial nuclear reactors. Out of these, 47 reactors have already entered their extended period of operation, while three have ceased operations. The decision to seek license renewal

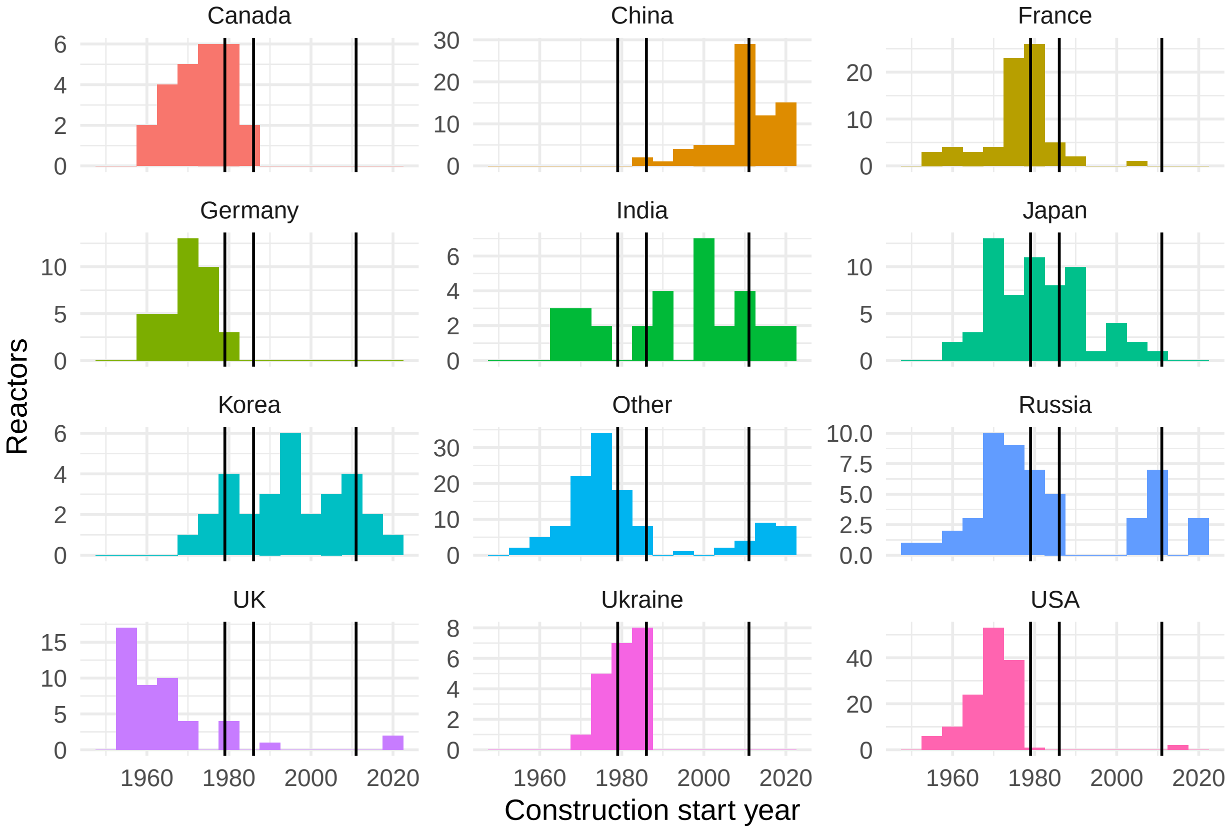

Figure 3.9: Commissioned reactors, by country and year. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

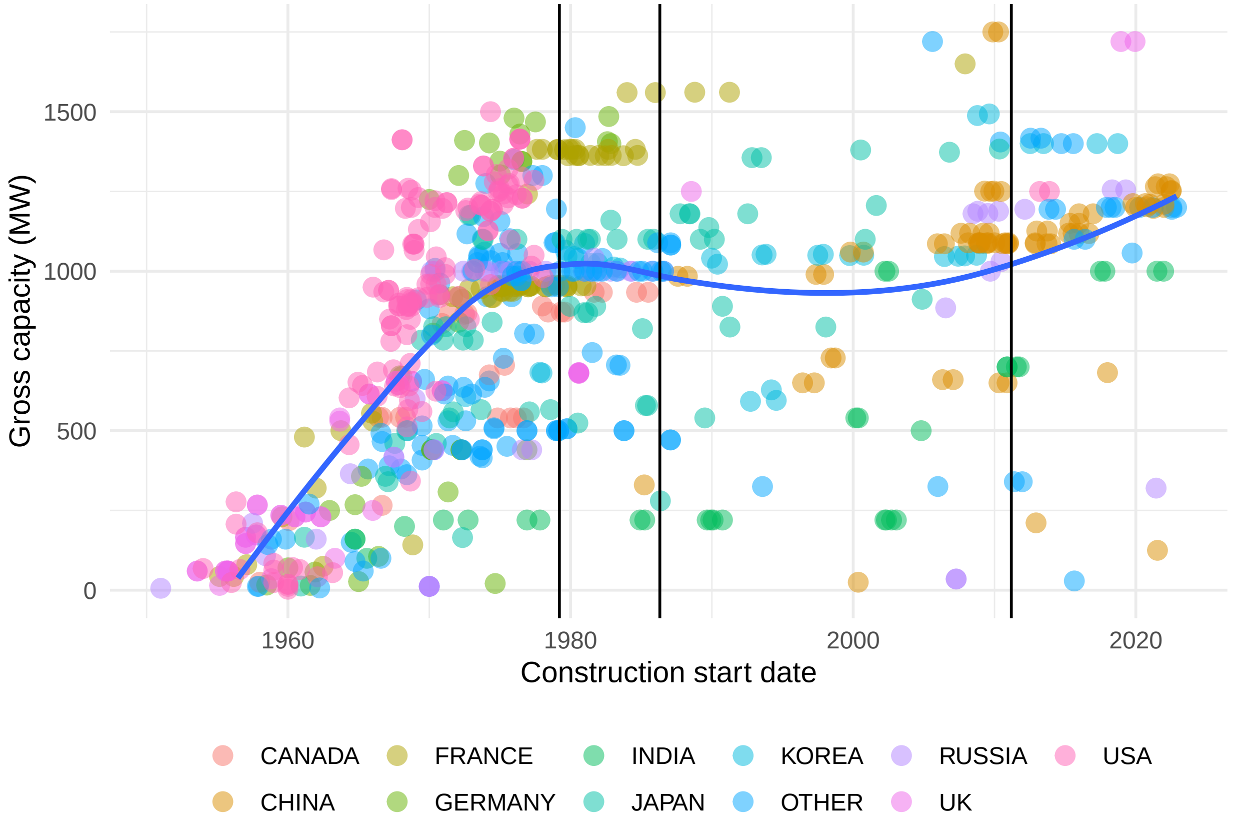

Figure 3.10: Scatter plot of installed capacity and construction start date, by country. Each point represents a reactor. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

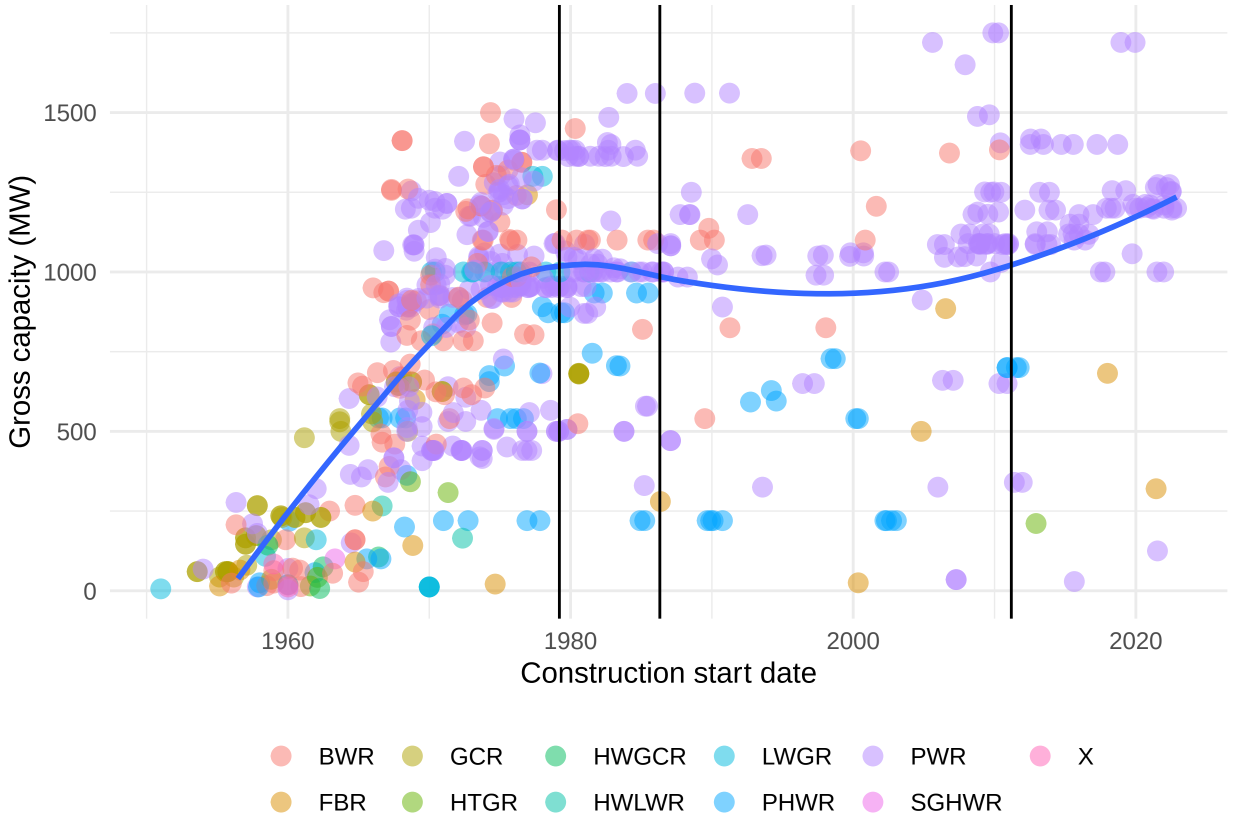

Figure 3.11: Scatter plot of installed capacity and construction start date, by reactor type. Each point represents a reactor. The different types include pressurized water reactors (PWR), boiling water reactors (BWR), pressurized heavy water reactors (PHWR), gas-cooled reactors (GCR), light water graphite-moderated reactors (LWGR), fast neutron reactor or fast breeder reactors (FBR), high temperature gas-cooled reactors (HTGR), heavy water gas-cooled reactors (HWGCR), heavy water light water reactors (HWLWR), steam-generating heavy water reactors (SGHWR), and other, experimental (X) reactor designs. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

Table 3.1: The growth trajectory of reactor capacity

	log(gross capacity)			
	(1)	(2)	(3)	(4)
Year	0.13***	0.13***	0.10***	0.10***
	(0.01)	(0.02)	(0.03)	(0.03)
Year × Post TMI	-0.15***	-0.13***	-0.10***	-0.10***
	(0.04)	(0.02)	(0.02)	(0.02)
Year × Post Chernobyl	0.03	0.00	0.01	0.01
	(0.04)	(0.01)	(0.01)	(0.01)
Year × Post Fukushima	0.01	0.01	-0.03	-0.03
	(0.03)	(0.01)	(0.04)	(0.04)
Standard-Errors	IID	Reactor type		
Observations	703	703	703	703
Dependent variable mean	6.438	6.438	6.438	6.438
R^2	0.477	0.581	0.922	0.934
Reactor type fixed effects		✓	✓	✓
Model fixed effects			✓	✓
Country fixed effects				✓

Notes: Observations are at the reactor level.

is voluntary, and plant owners must assess whether they can meet NRC requirements and if license renewal is cost-effective.

4 The effect of TMI on nuclear power

We make the case for a causal effect of the TMI accident on the nuclear power industry in the US through two main channels: the construction of nuclear power plants, and the development of nuclear power technology. As shown in the previous section, licensing and construction of nuclear power plants in the United States ceased after TMI. US R&D spending on nuclear power technology was slashed, and global innovation in obtaining nuclear energy came to a halt. We suggest a two-pronged mechanism: the construction moratorium led to a stagnation in the grid expansion, and the stop in R&D dramatically slowed down the advances in reactor capacity as shown in 3.11. Figure 4.1 illustrates the whole mechanism.

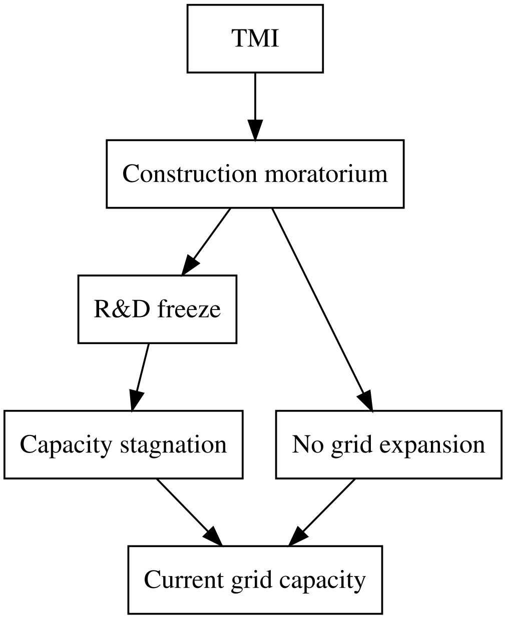

Figure 4.1: The effect of TMI on the current US grid.

The accident at TMI brought a cascade of events that has shaped the nuclear power industry in the US. The two main channels we put forth here are the construction of nuclear power plants, and the development of nuclear power technology. In this section, we estimate the effect of the TMI accident along these two dimensions individually. For each, we employ a synthetic control approach, which we briefly review here using the notation of Abadie, Diamond, and Hainmueller (2010). The method constructs a synthetic control unit that is a weighted average of other units that did not experience the intervention. The weights are chosen to minimize the difference between the synthetic control and the treated unit in the pre-intervention period.

In general, we are interested in the effect of the intervention, the TMI accident, for the affected unit, denoted as 1, at some time t. We denote the potential response under the intervention as $Y^I_{1,t}$, and the potential response without intervention as $Y^N_{1,t}$. The effect of the intervention is given by the difference between the observed and counterfactual outcomes:

$$\tau_{1,t} = Y^I_{1,t} - Y^N_{1,t} \tag{1}$$

If the intervention occurs at some time T_0, then for every $t > T_0$, $Y_{1,t} = Y^I_{1,t}$ is observed. The counterfactual $Y^N_{1,t}$ is never observed, but instead estimated by:

$$\hat{Y}^N_{1,t} = \sum_{j=2}^{N} w_j Y_{j,t} \tag{2}$$

and thus

$$\hat{\tau}_{1,t} = Y^I_{1,t} - \hat{Y}^N_{1,t} \tag{3}$$

The vector of weights, w, is chosen to minimize the difference between the synthetic control and the treated unit in the pre-intervention period, following Abadie, Diamond, and Hainmueller (2010).

4.1 Power plant construction

The TMI accident had a first-order effect leading to a moratorium on the construction of nuclear power plants in the US, which effectively halted the expansion of the nuclear power grid. Figure 3.2 shows the abrupt halt in the issuance of construction permits in 1979, following the recommendations of the Kemeny Commission. Based on the fact that 94 power plants were already at different stages of construction at the time, and evident by the many operating licenses issued in the following years, we argue that the decline in new construction after 1979 is not due to sudden changes in the demand side, like a shift in investor preferences. Indeed, data on NPP construction around the world at the time, seen in Figure 3.9, suggest that other countries continued to expand their nuclear power grid following their previous trend. Granted, the US was not the only one to cease its nuclear grid expansion, and other countries have also imposed stricter regulation and curtailed the construction of nuclear reactors, such as Belgium, Spain, and Sweden. Using those countries to construct a synthetic US would contaminate the control. The majority of countries, however, did not exhibit such apparent breaks in trend and continued on the same path - most notably France, Japan, and the USSR - and would therefore form a plausible control group.

We estimate Equation 4:

Table 4.1: Observed and synthetic count of US nuclear reactors. The table presents the stock of nuclear reactors in the United States, the synthetic control using other countries, and the difference between the observed and synthetic controls in both absolute value and percentage terms.

			Difference	
Year	Data	Synthetic	Abs	Pct
1960	15	2	-13	-86.7%
1970	78	49	-29	-37.2%
1980	119	116	-3	-2.5%
1990	114	199	85	74.6%
2000	105	225	120	114.3%
2010	105	295	190	181.0%
2020	96	284	188	195.8%

$$\hat{\tau}^{\text{NPP}}_{US,t} = \Delta\text{NPP}^{I}_{US,t} - \Delta\hat{\text{NPP}}^{N}_{US,t} \tag{4}$$

Where

$$\Delta\hat{\text{NPP}}^{N}_{US,t} = \sum_{j \neq \text{US}} w_j \Delta\text{NPP}^{I}_{j,t} \tag{5}$$

Figure 4.2 plots the observed and synthetic stock of nuclear reactors in the US. Panel A shows the observed and synthetic stock of nuclear reactors over time, while Panel B plots $\hat{\tau}^{\text{NPP}}_{US,t}$, the estimated difference between the two. The vertical line indicates the year of the TMI accident, 1979. The synthetic control closely tracks the observed stock of nuclear reactors in the US before TMI, and even slightly underestimates it, but rapidly overtakes and diverges after the accident. Had the US continued to expand its nuclear power grid at the same pace as other countries, its reactor fleet would have kept growing at about 4-5 per year. As of today, the estimates suggest that the TMI accident was responsible for about 200 reactors not being built in the US, which would have tripled the existing fleet of nuclear power plants. See Table 4.1 for more detail.

4.2 Nuclear physics R&D

Next, we argue that the TMI accident had a second-order effect on the modern power grid through its impact on technological progress. The imposed moratorium on the construction of new nuclear power plants, together with the wave of cancellations and decommissioning of existing ones, painted a bleak future for the nuclear power industry. We suggest that the uncertainty and negative sentiment diverted R&D efforts away from fields that are associated with reactor capacity, which effectively halted advances in that dimension.

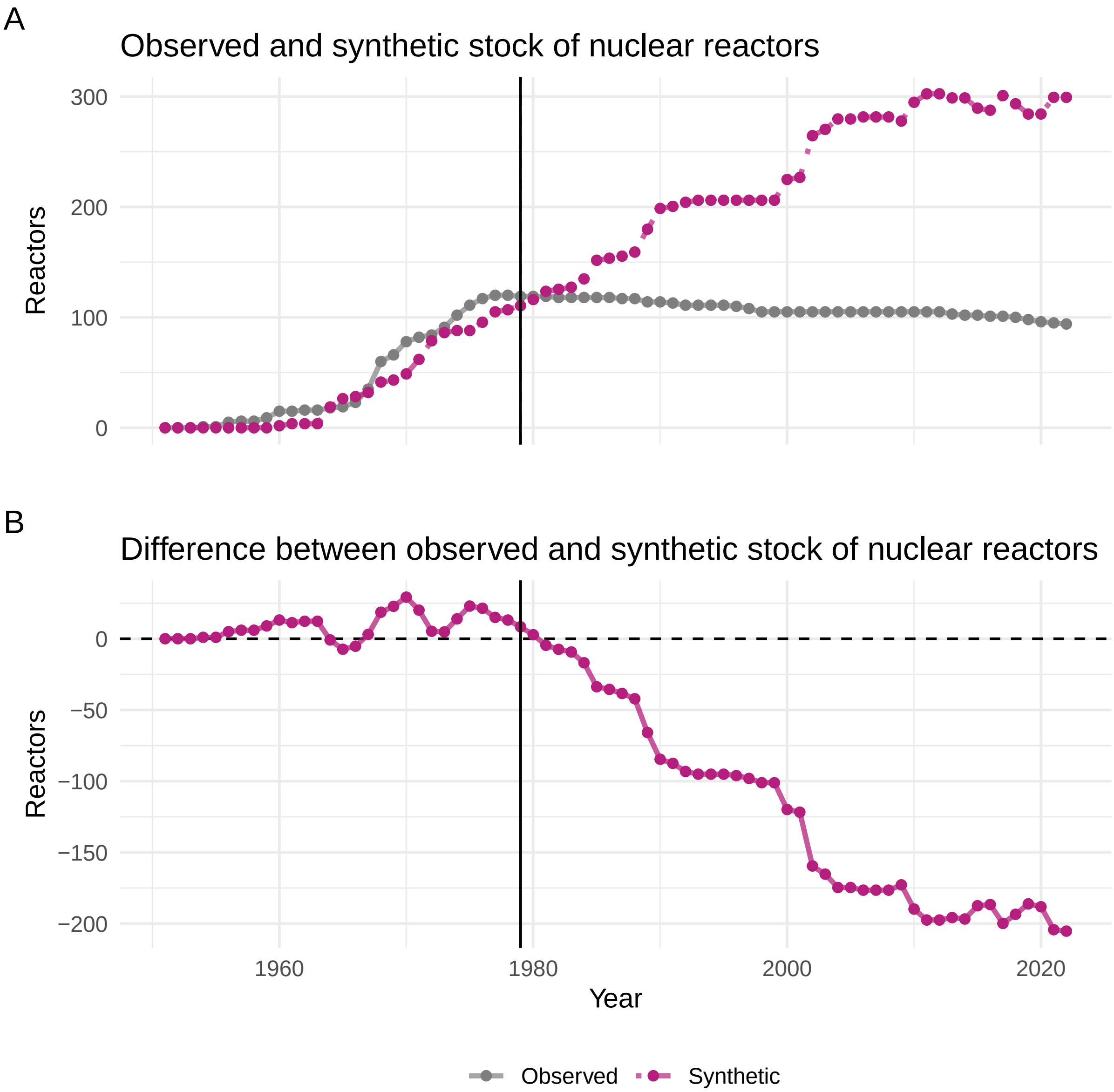

Figure 4.2: Synthetic control for the stock of nuclear reactors in the US. Panel A plots the observed and synthetic stock of nuclear reactors. Panel B plots the difference between the observed and synthetic stock of nuclear reactors.

We estimate the effect of the TMI accident on the development of nuclear power technology using data on patenting, by focusing on patents in the subclass of obtaining energy from radioactive sources, which is the single most important determinant of advances in reactor capacity (Table 4.3). All subclasses follow a very similar trend, albeit at different levels, in the pre-TMI period, and the obtaining energy subclass diverges from the rest after the accident, almost completely halting innovation and the issuance of new patents for decades (Figure 3.5). Using a panel of subclass-year level data, we construct a synthetic "obtaining energy" subclass as a weighted average of the other subclasses.

We estimate Equation 6:

$$\hat{\tau}_{OE,t}^{\text{patents}} = \Delta\text{patents}_{OE,t}^{I} - \Delta\hat{\text{patents}}_{OE,t}^{N} \tag{6}$$

Where

$$\Delta\hat{\text{patents}}_{OE,t}^{N} = \sum_{j \neq \text{OE}} w_j \Delta\text{patents}_{j,t}^{I} \tag{7}$$

Figure 4.3 plots the results in terms of patent count (panels A and C), and innovation value (panels B and D). Panels A and B shows the observed and synthetic cumulative patent number and value over time. Panels C and D plot $\hat{\tau}_{patents,t}^{\text{patents}}$, the estimated difference between the two. The vertical line indicates the year of the TMI accident, 1979. For both patent count and value, the synthetic control does very well at fitting the pre-intervention patenting in obtaining energy. After TMI, the estimate greatly diverges: the synthetic control implies a steady increase in patenting, slightly picking up the pace in patent count in the 2010s, and quickly ramping up in terms of value in the late 1990s, all while the observed patenting stagnates. In terms of technological progress, the analysis suggests about 500 accumulated patents, valued at over 4 billion USD, if it were not for TMI. Compared to the current patent stock, this implies roughly 350 missing patents, valued at about 3 billion USD.[23] See Table 4.2 for more detail.

4.3 Patenting and reactor capacity

Finally, we relate the issuance of patents in nuclear physics to the capacity of nuclear reactors. In practice, the causal effect of patenting on reactor capacity is incredibly difficult to model or estimate, and goes way beyond the scope of this paper. It is likely that patents interact non-linearly with each other and with external factors, such as the availability of funding, the regulatory environment, both contemporaneously and with delay. Instead, we draw on the observed patterns in the data and estimate the linear relationship between improvements in reactor capacity and the flow of patents in the field of nuclear physics. We estimate Equation 8:

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[23] Equivalent to 233% and 240% of today's stock and value of patent, respectively.

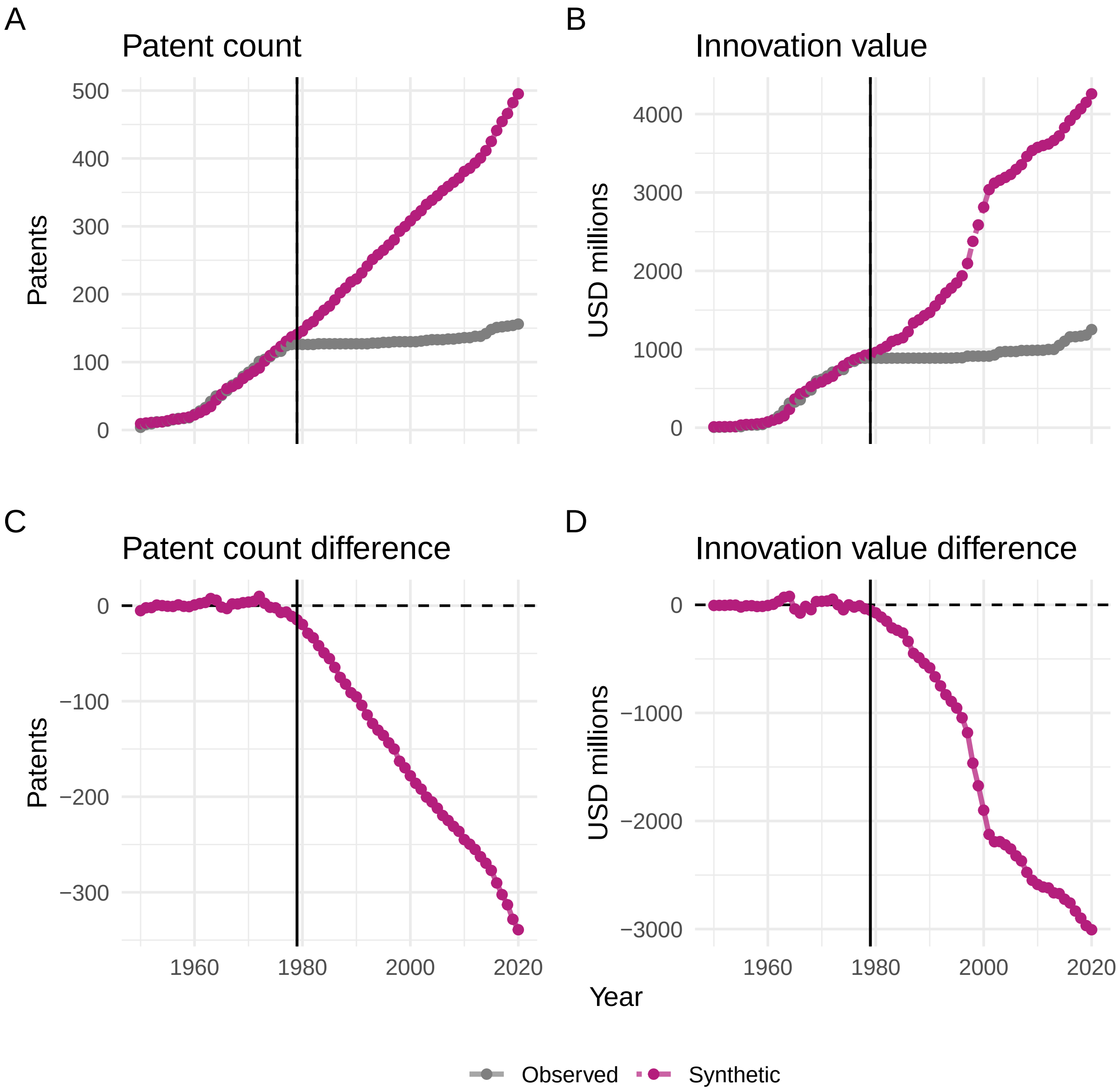

Figure 4.3: Synthetic control for cumulative patenting in the field of obtaining energy (G21H: obtaining energy from radioactive sources; applications of radiation from radioactive sources). Panel A plots the observed and synthetic cumulative patenting. Panel B plots the difference between the observed and synthetic cumulative patenting. Patenting value follows Kogan et al. (2017). The synthetic control is constructed using cumulative patenting of all other subclasses in the same patent class (G21: nuclear physics and engineering).

Table 4.2: Observed and synthetic patents in the field of obtaining energy. The table presents the number and value of patents issued in the field of obtaining energy, their synthetic controls estimated using patents in other subclasses of nuclear physics, and the difference between the observed and synthetic controls in both absolute value and percentage terms.

	Count				Value (billion USD)			
			Difference				Difference	
Year	Data	Synthetic	Abs	Pct	Data	Synthetic	Abs	Pct
1950	4	9	5	125.0%	0.01	0.01	0.01	98.5%
1960	23	22	-1	-4.3%	0.07	0.07	0.01	8.7%
1970	85	81	-4	-4.7%	0.62	0.58	-0.03	-5.3%
1980	126	146	20	15.9%	0.89	0.96	0.07	8.4%
1990	127	222	95	74.8%	0.89	1.47	0.58	65.7%
2000	130	308	178	136.9%	0.91	2.81	1.90	208.4%
2010	136	381	245	180.1%	0.99	3.57	2.59	262.0%
2020	156	495	339	217.3%	1.25	4.26	3.01	240.2%

$$Y_t = \beta_0 + \sum_{j=1}^{J} \beta_j \text{Patents}_{jt} + \epsilon_t \tag{8}$$

with $Y_t \in \{\text{Reactors}_t, \text{Capacity}_t\}$, where t and j enumerate years and CPC subclasses of nuclear physics. Reactors_t is the number of reactors whose construction started at time t, Capacity_t is average capacity of reactors whose construction started at time t, and Patents_{jt} is the number of patents issued at time t in subclass j.

Table 4.3 reports the results of the estimation. The four columns correspond to different dependent variables - the number of reactors, and three measures of reactor capacity: net, gross, and thermal. The strongest predictor of all outcome variables is, by far, the number of patents in the subclass of obtaining energy. Patents in the subclass correspond to a 0.2 increase in the number of reactors, and nearly a 7 MW increase in reactor capacity, for every additional patent issued. In percentage terms, these numbers are substantial. 0.2 reactors and 7 MW amount to about 2% and 1% of the average number of reactors and reactor capacity, respectively.

5 Counterfactual analysis

The previous section provided evidence for the causal effect of the TMI accident on the US power grid through two channels: it directly limited the number of nuclear power plants due to the construction moratorium; and indirectly held back technological progress by discouraging research and development in key fields of nuclear physics. In this section we relate the historical events to the modern US power grid by estimating the counterfactual

Table 4.3: Reactor construction, capacity, and patenting

		Capacity		
	Reactors (1)	Net (2)	Gross (3)	Thermal (4)
Protection	0.00	1.12***	1.15***	3.19***
	(0.01)	(0.27)	(0.28)	(0.77)
Nuclear reactors	0.00	-0.09	-0.10	-0.17
	(0.00)	(0.12)	(0.12)	(0.34)
Handling radiation	-0.01**	0.11	0.11	0.28
	(0.01)	(0.27)	(0.28)	(0.76)
Conversion	0.04	-1.42	-1.38	-3.76
	(0.03)	(1.22)	(1.28)	(3.47)
Obtaining energy	0.21***	6.63***	6.87***	18.77***
	(0.04)	(1.88)	(1.99)	(5.37)
Nuclear power plant	-0.02	-0.35	-0.36	-1.44
	(0.01)	(0.52)	(0.55)	(1.48)
Observations	65	65	65	65
Dependent variable mean	10.2	686.9	728.3	2,117.1
R^2	0.701	0.650	0.646	0.663

Notes: The table presents estimates from Equation 8. The dependent variable is the number of reactors, and three measures of reactor capacity. The independent variables are the number of patents issued in each subclass of nuclear physics. Observations are at the year level.

Table 5.1: Observed and estimated capacity of nuclear reactors, in GW. The table presents the observed, fitted and counterfactual capacity of nuclear reactors, and the difference between fitted and counterfactual in both absolute value and percentage terms.

	Capacity			Difference	
Year	Data	Fitted	Synthetic	Abs	Pct
1960	0.09	0.15	0.17	0.01	6.9%
1970	0.75	0.68	0.65	-0.03	-4.6%
1980	1.03	0.91	0.94	0.03	3.7%
1990	0.69	0.90	1.36	0.46	51.1%
2000	0.81	0.93	2.88	1.95	210.5%
2010	1.08	1.01	3.66	2.65	262.7%
2020	1.21	1.30	4.19	2.89	223.4%

total installed nuclear capacity, had the TMI accident not triggered such drastic response, and consider the implications for greenhouse gas (GHG) emissions and related deaths.

5.1 Electricity generation

We proceed in two steps. First, we estimate how the counterfactual capacity of nuclear reactors would have evolved without the intervention. We do this using the above mapping of patents in nuclear physics to growth in reactor capacity, together with the counterfactual estimates of patent output in the field of obtaining energy. This exercise yields the counterfactual capacity of new reactors that could have been built each year, had the technology kept moving forward. Second, we combine this counterfactual state-of-the-art capacity estimate with the counterfactual number of reactors that would have been built in the US, if it had continued to expand its nuclear power grid at the same pace as other countries, as discussed in Section 4. Combining both channels provides two baseline scenarios for the current grid: one where the US had continued to expand its nuclear power grid, but without technological advancements; and one where both construction and innovation in obtaining energy continued.

For the first step, Figure 5.1 plots the observed, fitted, and counterfactual capacity of nuclear reactors by year. The observed capacity is the worldwide annual average of all reactors whose construction started that year. The fitted line is the predicted capacity using patent data across subclasses of nuclear physics (Equation 8). The counterfactual capacity is the predicted reactor capacity using observed and synthetic patents, given by Equation 6. The results suggest that capacity of newly built reactors would have continued to grow at an average pace of roughly 75 MW per year, had R&D in obtaining energy not stopped after TMI. By 2020, state-of-the-art reactors would have reached capacities of about 4000 MW, compared to the 1250 MW reactors currently being built. These estimates are likely conservative, as they tend to under-estimate the data in the pre-period, yet substantially surpass in the post-period. See Table 5.1 for more detail.

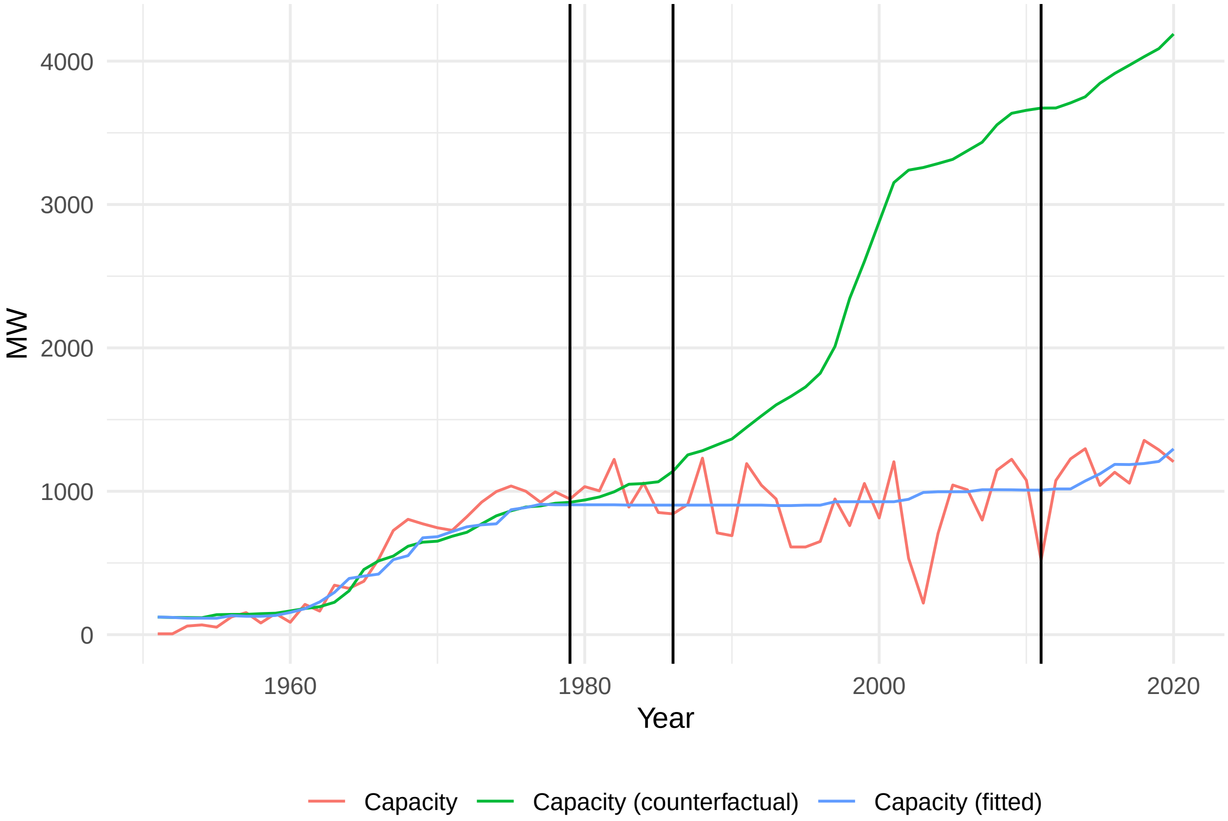

Figure 5.1: Observed, fitted, and counterfactual capacity of nuclear reactors. The observed capacity is the annual average of all reactors whose construction started that year. The fitted line is the predicted capacity using patents (Equation 8). The counterfactual capacity is estimated using the fitted values from the synthetic control of patenting in the field of obtaining energy (Equation 6) as input for the mapping of patents to capacity (Equation 8).

We can now combine the counterfactual capacity of nuclear reactors with the counterfactual number of reactors to estimate the counterfactual total installed capacity of nuclear power in the US, and report the results in Figure 5.2. In Section 4 we show that in the counterfactual state of the world, the US would have constructed about 200 more nuclear reactors by 2020, tripling the headcount of its current fleet (Figure 4.2). If reactor capacity stagnates at around the 1 GW level of the late 1970s, as it did, the counterfactual total installed capacity would have been about 200 GW, or double the current installed nuclear power capacity in the US.

If, in addition to grid expansion, innovation in nuclear physics had also stayed the course, we would have witnessed a much larger increase in the total installed capacity. The missing innovation implied reactor capacities that are about 2750 MW, or three times, higher than the current state-of-the-art: 4000 MW instead of 1250 MW. Taken together, these results imply that the modern US fleet could have reached a total installed capacity of around 450 GW, or roughly 5 times the current installed nuclear power capacity. About 30% of this capacity would be due to the construction of new nuclear power plants, while the remaining 70% would be due to technological advances in reactor capacity. See Table 5.2 for more detail.

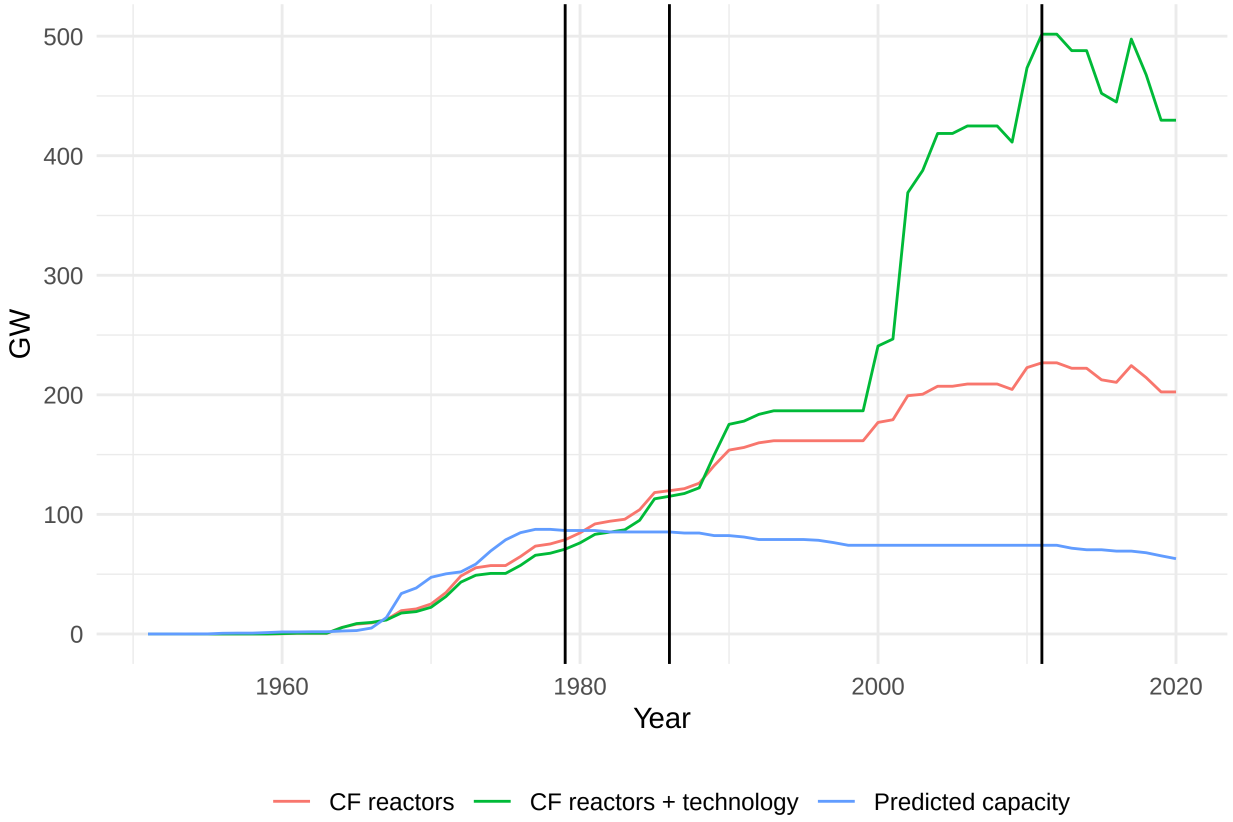

Figure 5.2: Counterfactual nuclear grid: construction and technology. The figure plots the fitted values for the US total nuclear capacity and the counterfactual values had construction and innovation not stopped.

What are the implications of having 450 GW of nuclear power capacity? First, let us convert

Table 5.2: Counterfactual nuclear grid: construction and technology. The table presents the fitted total installed capacity in the US, in GW, and two counterfactual scenarios: one where reactor construction did not stop but technological progress did; and one where neither stopped. For each, the table also reports the difference between the fitted and counterfactual capacities, in GW and percent.

		Reactors			Reactors + R&D		
			Difference			Difference	
Year	Fitted	Synthetic	Abs	Pct	Synthetic	Abs	Pct
1960	1.67	0.16	-1.51	-90.4%	0.31	-1.37	-81.6%
1970	47.38	25.08	-22.30	-47.1%	22.32	-25.06	-52.9%
1980	86.54	84.56	-1.97	-2.3%	76.18	-10.36	-12.0%
1990	82.28	153.77	71.49	86.9%	175.32	93.05	113.1%
2000	74.17	176.93	102.75	138.5%	240.84	166.67	224.7%
2010	74.17	222.78	148.60	200.3%	473.43	399.25	538.3%
2020	62.95	202.43	139.49	221.6%	429.69	366.74	582.6%

this capacity to annual electricity generation. A 1 GW generator running at full capacity for a year (8760 hours), generates 8.76 TWh of electricity. Generators rarely run at full capacity, as there is a need for maintenance, refueling, and demand fluctuates throughout the day and the year. Still, existing US reactors operate at a relatively high and stable capacity factor, reaching an average of 93% in recent years. The 96 GW currently installed generate about 780 TWh annually, representing nearly 20% of electricity generated nationwide, estimated at about 4000 TWh across all energy sources. Increasing nuclear installed capacity fivefold could meet nearly all electric demand in the US, and displace most of the electricity generated from coal, petroleum, and natural gas power plants, drastically reducing GHG emissions.

One way to illustrate the magnitude is using manual labor, or the human version of horsepower. A healthy laborer can sustain a 75W energy output for an 8-hour shift (Marks 1978), thus producing 600 Wh a day. This amounts to 218.4 kWh per year, working every day. We can illustrate energy consumption by the number of such workers, sometimes called 'energy slaves', that is required to generate it. According to the EIA, the average US household uses 10.5 MWh of electricity per year, which corresponds to the work of around 50 energy slaves. However, residential electricity consumption represents hardly 5% of the US primary energy consumption. The average US household therefore requires a lofty 1,000 energy slaves to power its lifestyle. How much do these slaves cost? The February 2024 monthly spot price (Henry Hub) for US gas settled at a historically very low 5.87 USD per MWh. It therefore prices 1 year of energy slave work at 1.30 USD. At the average residential price of US electricity - 15.98 cents per kWh in 2023 - the cost of a year's worth of work rises to 27.2 USD (or less than 1 cent per hour worked).

Considering the economy as a whole, the US uses roughly 4000 TWh of electricity annually. These 4 PWh require around 11.3 PWh of primary energy due to energy losses. Generating that much energy would require a bit more than 400 AP-1000 nuclear reactors, like the two

Table 5.3: Carbon intensity of electricity generation. CO_2 emissions by fuel, as of 2022. Sources: EIA, IPCC.

Energy Source	kg per kWh
Petroleum	1.08
Coal	1.05
Natural gas	0.44
Solar	0.05
Wind	0.01
Nuclear	0.01

units built in the Vogtle NPP, or 52 billion energy slaves.

5.2 Displacement of fossil fuels

Figure 5.3 illustrates the displacement of different energy sources by the increase in nuclear power. In this exercise, total electricity generation is held constant at the observed level, and nuclear installed capacity is considered under the two counterfactuals. We assume the order in which nuclear power displaces other energy sources is according to their CO_2 emissions, detailed in Table 5.3. That is, any added nuclear capacity first displaces petroleum, then coal, and so on down the list.

Each panel in Figure 5.3 plots the electricity generated by each energy source, in TWh, as observed in the data, and under two counterfactual states: expansion of the nuclear fleet, with and without technological advancement. Noticeably, in both scenarios, oil is completely phased out from day one. Coal, on the other hand, is only entirely displaced by 2020 in the first scenario, where only construction is allowed, but as early as 2002 if technological advancement is also considered. Natural gas is the next to go, beginning to shut down once coal is completely gone, which only occurs in the second scenario, and is completely gone only by 2010, when nuclear generation reaches about 3750 TWh. Finally, even renewables are displaced by nuclear power after all fossil fuels are gone, though never entirely.

The counterfactual power grids look markedly different from the observed one. Beside direct effects, like on the price of electricity and independence of energy supply, which we do not explore here, the displacement of fossil fuels by nuclear power has important implications for GHG emissions.

5.3 Emission of greenhouse gases

Greenhouse gases emitted into the atmosphere due to human activity receive much attention in the current policy debate, both in immediate effects of air pollution on health and quality of life, and in long-term effects in the context of global warming. By replacing carbon-intense fossil fuels, nuclear power can have a substantial impact on both.

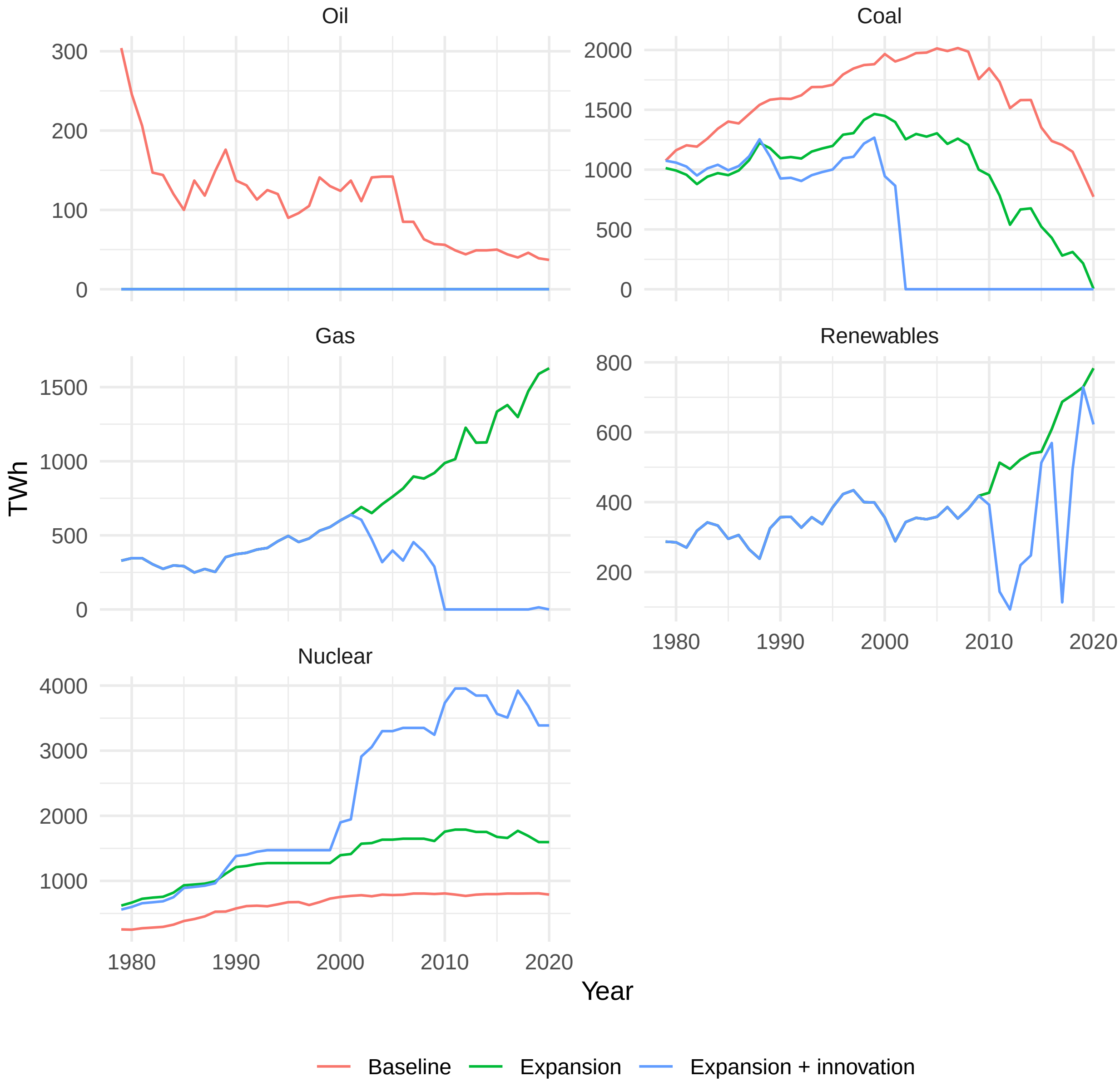

Figure 5.3: Observed and counterfactual electricity generation, by energy source. The figure plots electricity generated by each energy source, in TWh, as observed in the data, and under two counterfactual states: expansion of the nuclear fleet, with and without technological advancement.

Figure 5.4 plots the total annual emission flows of CO_2 in each scenario, in Gt per year, and the ratio of carbon emissions to electricity generated, in kg per kWh. The total emissions are the sum of emissions by each energy source, as estimated by multiplying the electricity generated by each energy source by its carbon intensity, as detailed in Table 5.3. The ratio of carbon emissions to electricity generated is the total sum of emissions, divided by the total sum of electricity generated.

The first panel shows that the counterfactual expansion of the nuclear fleet alone would have led to a substantial reduction in total CO_2 emissions, from roughly 25% in early years, to 50% in 2020. With technological advancement, the reduction would have been even more substantial, reaching 90% in the mid 2000s, with the grid almost entirely cleaned up by 2020. The second panel shows that the carbon intensity of electricity generated, although steadily declining over the years, would have been reduced by up to 50% due to construction of reactors in the first scenario, and effectively driven to 0 in the second, especially once coal is phased out.

In comparison to the baseline scenario, Figure 5.5 shows the avoided annual flow of emissions, and the avoided cumulative emissions, in each counterfactual scenario. The avoided annual flow of emissions is the annual difference between the baseline and counterfactual emissions. The avoided cumulative emissions is the cumulative sum of the avoided annual flow of emissions, starting from TMI. In the first scenario, the avoided annual flow of carbon emissions ranges between 0.5 and 1 Gt, steadily growing over the years. The avoided cumulative emissions reach about 30 Gt by 2020. In the second scenario, the avoided annual flow of emissions is very similar in the 1980s, at about 0.5 Gt, but grows rapidly in the 2000s to almost 2.5 Gt, as coal is replaced, totaling about 55 Gt between 1979 and 2020. To get a sense of scale, 55 Gt of CO_2 roughly equal 1.5 times the total global emissions in 2023, or US emissions alone for through the 2010s. Using the IMF's evaluation for developed countries, of 75 USD per ton of CO_2, we arrive at a present value of avoided emissions of 4.13 trillion USD, just shy of Germany's GDP.

We find it useful to have a tangible benchmark for the avoided emissions. The world emits around 37 Gt of CO_2 annually, of which the US emits 13.5% (5 Gt). The US grid emits on average 430g of CO_2 per kWh, which means the average US household emits 4.3 tons of CO_2 each year through electricity consumption. A model 2024 ICE Toyota Corolla emits 250 grams of CO_2 per mile, so it emits one ton of CO_2 per 4000 miles (around 6400 km). 1 TWh of coal-based electricity production will emit roughly 1 Mt of CO_2. In 2022, coal generation was 830 TWh, representing 20% of US electricity[24] This means that US coal-generated electricity accounts for a bit more than 2% of global CO_2 emissions. Using numbers from (Markandya and Wilkinson 2007),[25] getting rid of 1 Gt of CO_2 from coal generation (1000 TWh) would avoid 24,500 excess deaths.

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[24] Down from nearly 50% in 2007.

[25] 24.5 excess deaths, 225 serious illnesses including hospital admissions, congestive heart failure, and chronic bronchitis, and 13 288 minor illnesses for every Terrawatt-hour (TWh) of electricity produced from coal (in Europe).

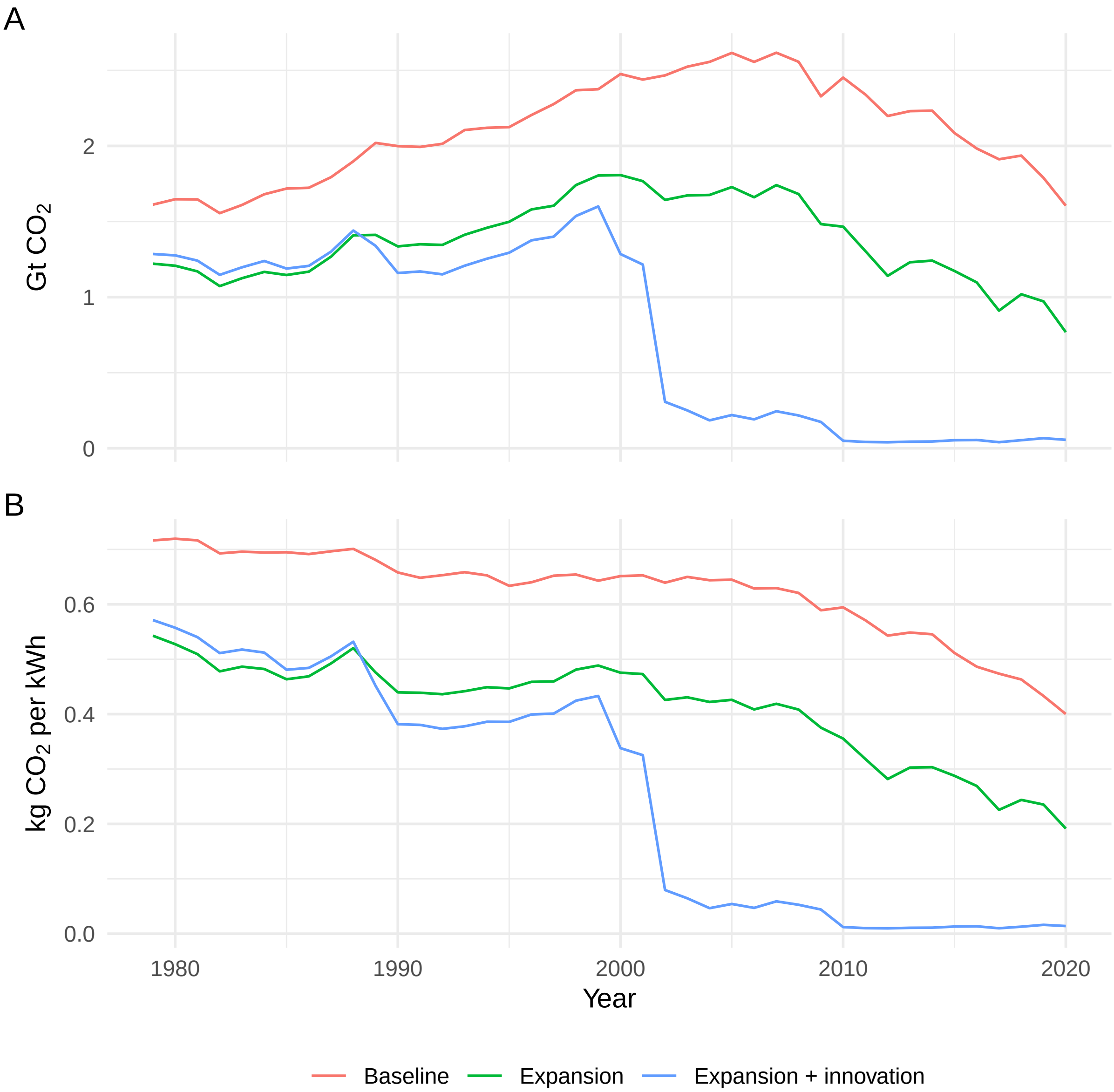

Figure 5.4: Total emissions and carbon intensity since TMI under the baseline and two counterfactual scenarios. Panel A shows the total annual emission flows of CO_2 in each scenario, in Gt per year. Panel B shows the ratio of carbon emissions to electricity generated.

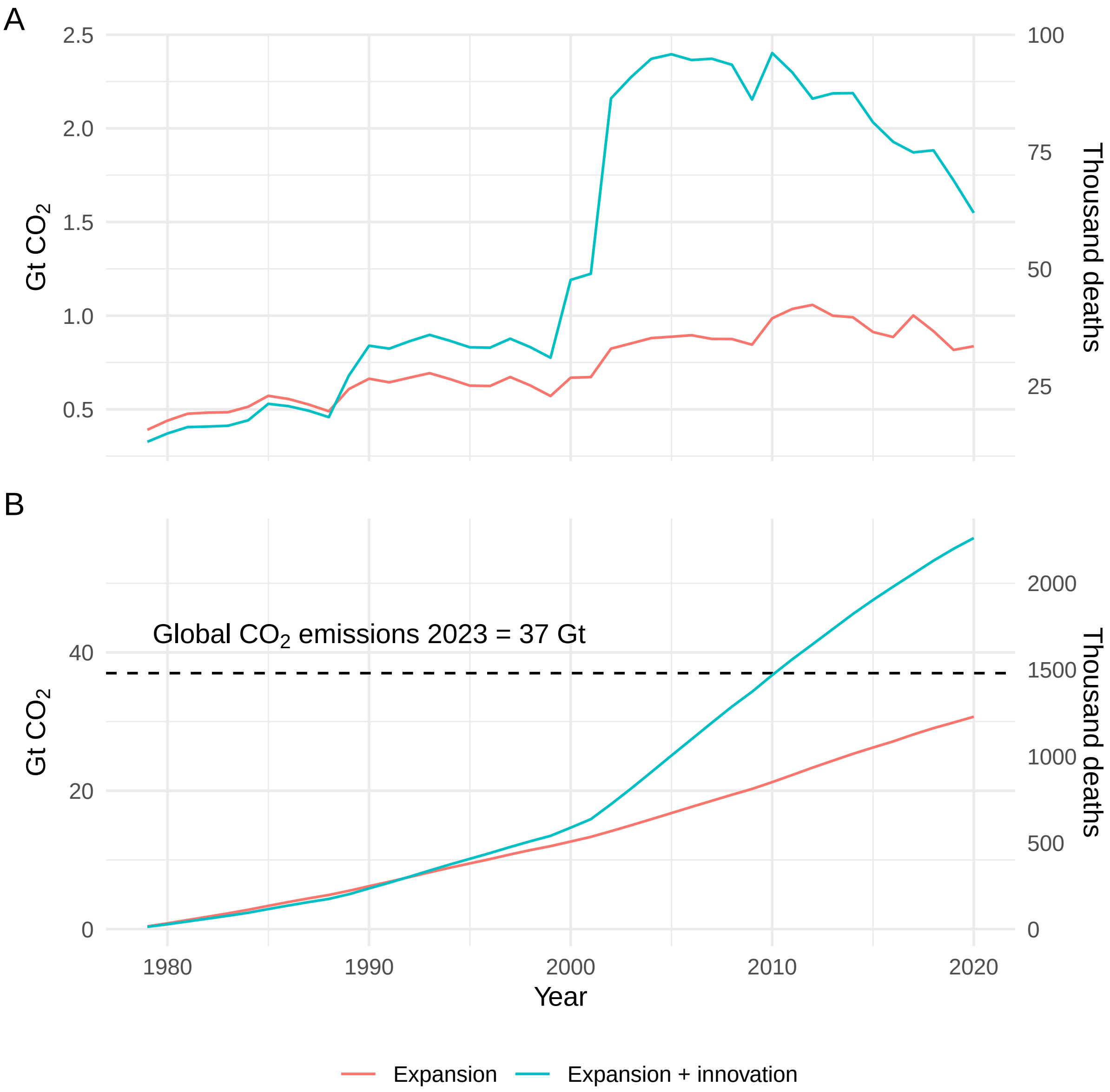

Figure 5.5: Flow and stock of avoided emissions and premature mortality in counterfactual scenarios since TMI. Emissions appear on the left axis, in Gt CO_2. Premature mortality, based on EPA estimates, is on the right axis, in thousands. Panel A shows the avoided annual flow of emissions, and panel B shows the avoided cumulative emissions, in each counterfactual scenario compared to the baseline.

Table 5.4: Total emissions, mortality, and carbon intensity. The table presents the total emissions (in Gt CO_2) and premature mortality (in millions) associated with carbon emissions, and the mean and last intensity of CO_2 emissions (in Mt / TWh), for each scenario.

	Total (1979-2020)				CO_2 intensity	
	Emissions (Gt CO_2)		Deaths (millions)			
Scenario	Estimated	Avoided	Estimated	Avoided	Mean	Last
Baseline	88.39	0.00	3.54	0.00	0.62	0.40
Expansion	57.68	30.71	2.31	1.23	0.41	0.19
Expansion + innovation	31.85	56.54	1.27	2.26	0.26	0.01

5.4 Public health

According to recently proposed pollution standards by the Environmental Protection Agency (EPA),[26] avoiding 617 million metric tons of total carbon dioxide through 2042 would prevent approximately 1300 premature deaths annually. This is equivalent to about 40 deaths per 1 million metric tons of CO_2 emissions. We use the EPA's estimates to calculate the avoided premature mortality in each counterfactual scenario, and report the results on the right-axis of Figure 5.5 and summarized in Table 5.4.

We estimate that the expansion of the nuclear fleet alone would have avoided about 1.23 million premature deaths between 1979 and 2020, or about 30,000 every year. With technological advancement, the avoided premature mortality would have been about 2.26 million, or 55,000 a year. The annual rate is heavily skewed toward the 2000s and 2010s, by when coal could have been phased out. In comparison, our avoided excess deaths figure ranges from nearly twice to more than three times that of opioid-related deaths from 1999 to 2021 (around 645,000 according to the CDC).

When it comes to monetary health costs, we extrapolate the EPA estimation - 85 billion USD in health and environmental costs for 0.6 Gt of CO_2 avoided - and obtain cumulative avoidable health costs of nearly 8 trillion USD, in the case of grid expansion with capacity improvements. Similarly, Machol and Rizk (2013) calculated the monetary health costs per kWh of fossil fuel generation. Using their midpoint estimates for coal, oil, and gas, we obtain more than 14 trillion USD in cumulative costs since 1979, for the same scenario.

6 Conclusion

Nuclear power promised to revolutionize the energy sector, providing a clean and abundant source of electricity. With high rates of technological advances in the 60s and 70s and ambitious national goals, the US was on track to eliminate fossil fuels from its electric grid

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[26] https://www.epa.gov/newsreleases/epa-proposes-new-carbon-pollution-standards-fossil-fuel-fired-power-plants-tackle

and poised to lead the world in nuclear power. Today, nuclear power accounts for less than 20% of the electricity generated in the US. In the past 46 years, only two reactors successfully obtained permits and were constructed, bankrupting Westinghouse's nuclear division in the process. What went wrong?

This paper argues that the Three Mile Island accident in 1979 was a turning point in the history of nuclear power in the US. Although not a single person was injured and no civilian was exposed to harmful levels of radiation, the accident had a profound effect on the public perception of nuclear power. The de facto moratorium on the construction of new nuclear power plants, and the halt in the development of new reactor designs, effectively stopped the expansion of the nuclear power grid and the advancement of reactor capacity. The US nuclear power industry has been in a state of stagnation ever since.

If not for the public response and ensuing policy changes, the US would have constructed about 200 more nuclear reactors since 1979, tripling the number currently operating. If scientists and engineers had continued to innovate and improve reactor designs, the US would have tripled the number - and quadrupled the value - of patents relating to obtaining nuclear energy. This would have led to a total installed capacity of around 450 GW today, or roughly 5 times the current installed capacity of nuclear power in the US. About 30% of this capacity would be due to the construction of new nuclear power plants, while the remaining 70% would be due to technological advances in reactor capacity.

The implications of having 450 GW of nuclear power capacity are vast. The US could have met nearly all its electric demand, and displaced most of the electricity generated from coal, petroleum, and natural gas power plants, drastically reducing GHG emissions. The avoided emissions would have been about 55 Gt of CO_2 between 1979 and 2020, saving about 2.26 million premature deaths. Comically, this massive missed opportunity is made all the more salient by the recent Department of Energy 'Pathways to Commercial Liftoff' report (Kozeracki et al. 2023) on the feasibility of US nuclear capacity to expand from 100 to 300 GW by 2050.

7 References

Abadie, Alberto, Alexis Diamond, and Jens Hainmueller. 2010. "Synthetic Control Methods for Comparative Case Studies: Estimating the Effect of California's Tobacco Control Program." *Journal of the American Statistical Association* 105 (490): 493–505. https://doi.org/10.1198/jasa.2009.ap08746.

Acemoglu, Daron, Ali Kakhbod, and Asuman Ozdaglar. 2017. "Competition in Electricity Markets with Renewable Energy Sources." *The Energy Journal* 38: 137–55. https://www.jstor.org/stable/26294154.

Acton, James M., and Mark Hibbs. 2012. *Why Fukushima Was Preventable.* JSTOR. https://www.jstor.org/stable/pdf/resrep12839.pdf.

Ahearne, John F. 2011. "Prospects for Nuclear Energy." *Energy Economics*, Special Issue on The Economics of Technologies to Combat Global Warming, 33 (4): 572–80. https://doi.org/10.1016/j.eneco.2010.11.014.

Allcott, Hunt, and Michael Greenstone. 2012. "Is There an Energy Efficiency Gap?" *Journal of Economic Perspectives* 26 (1): 3–28. https://doi.org/10.1257/jep.26.1.3.

Ambec, Stefan, Albert Banal, Estelle Cantillon, Claude Crampes, Anna Creti, Francesco Decarolis, Natalia Fabra, et al. 2023. "Electricity Market Design: Views from European Economists," no. 120.

Ambec, Stefan, and Claude Crampes. 2021. "Real-Time Electricity Pricing to Balance Green Energy Intermittency." *Energy Economics* 94 (February): 105074. https://doi.org/10.1016/j.eneco.2020.105074.

Arrow, Kenneth J., Maureen L. Cropper, Christian Gollier, Ben Groom, Geoffrey M. Heal, Richard G. Newell, William D. Nordhaus, et al. 2014. "Should Governments Use a Declining Discount Rate in Project Analysis?" *Review of Environmental Economics and Policy* 8 (2): 145–63. https://doi.org/10.1093/reep/reu008.

Barrett, W. Brian, Andrea J. Heuson, and Robert W. Kolb. 1986. "The Effect of Three Mile Island on Utility Bond Risk Premia: A Note." *The Journal of Finance* 41 (1): 255–61. https://doi.org/10.2307/2328357.

Bersano, Andrea, and Stefano Segantin. 2024. "History of Nuclear Power Plants Development." In *Nuclear Power Reactor Designs*, edited by Jun Wang, Sola Talabi, and Sama Bilbao y Leon, 3–40. Academic Press. https://doi.org/10.1016/B978-0-323-99880-2.00001-1.

Bizet, Romain, Petyo Bonev, and François Lévêque. 2022. "The Effect of Local Monitoring on Nuclear Safety and Compliance: Evidence from France." *Journal of Environmental Economics and Management* 113 (May): 102651. https://doi.org/10.1016/j.jeem.2022.102651.

Boer, Connie de, and Ineke Catsburg. 1988. "A Report: The Impact of Nuclear Accidents on Attitudes Toward Nuclear Energy." *The Public Opinion Quarterly* 52 (2): 254–61. https://www.jstor.org/stable/2749279.

Boffa, Federico, Viswanath Pingali, and Davide Vannoni. 2010. "Increasing Market Interconnection: An Analysis of the Italian Electricity Spot Market." *International Journal of Industrial Organization* 28 (3): 311–22. https://doi.org/10.1016/j.ijindorg.2009.10.003.

Bointner, Raphael. 2014. "Innovation in the Energy Sector: Lessons Learnt from R&D Expenditures and Patents in Selected IEA Countries." *Energy Policy* 73 (October): 733–47. https://doi.org/10.1016/j.enpol.2014.06.001.

Borenstein, Severin. 2012. "The Private and Public Economics of Renewable Electricity Generation." *Journal of Economic Perspectives* 26 (1): 67–92. https://doi.org/10.1257/jep.26.1.67.

Carter, Luther J. 1979. "Political Fallout from Three Mile Island." *Science* 204 (4389): 154–55. https://doi.org/10.1126/science.204.4389.154.

Cicala, Steve. 2015. "When Does Regulation Distort Costs? Lessons from Fuel Procurement in US Electricity Generation." *American Economic Review* 105 (1): 411–44. https://doi.org/10.1257/aer.20131377.

Commission, Fukushima Nuclear Accident Independent Investigation. 2012. "The Fukushima Nuclear Accident Independent Investigation Commission." The National Diet of Japan.

Corey, G. R. 1979. "A Brief Review of the Accident at Three Mile Island." *IAEA Bulletin* 21 (5): 54–59. https://www.iaea.org/sites/default/files/publications/magazines/bullet in/bull21-5/21502795459.pdf.

Cowan, Robin. 1990. "Nuclear Power Reactors: A Study in Technological Lock-in." *The Journal of Economic History* 50 (3): 541–67. https://www.jstor.org/stable/2122817.

De Groote, Olivier, and Frank Verboven. 2019. "Subsidies and Time Discounting in New Technology Adoption: Evidence from Solar Photovoltaic Systems." *American Economic Review* 109 (6): 2137–72. https://doi.org/10.1257/aer.20161343.

Dittmar, Michael. 2012. "Nuclear Energy: Status and Future Limitations." *Energy*, 7th Biennial International Workshop "Advances in Energy Studies," 37 (1): 35–40. https://doi.org/10.1016/j.energy.2011.05.040.

Dooley, JJ. 1998. "Unintended Consequences: Energy R&D in a Deregulated Energy Market." *Energy Policy* 26 (7): 547–55. https://doi.org/10.1016/S0301-4215(97)00166-3.

Eash-Gates, Philip, Magdalena M. Klemun, Goksin Kavlak, James McNerney, Jacopo Buongiorno, and Jessika E. Trancik. 2020. "Sources of Cost Overrun in Nuclear Power Plant Construction Call for a New Approach to Engineering Design." *Joule* 4 (11): 2348–73. https://doi.org/10.1016/j.joule.2020.10.001.

Eisenberg, Thomas. 2020. "Regulatory Distortions and Capacity Investment: The Case of China's Coal Power Industry." Mimeo.

Elliott, Jonathan T. 2022. "Investment, Emissions, and Reliability in Electricity Markets." Working Paper.

Fabra, Natalia. 2018. "A Primer on Capacity Mechanisms." *Energy Economics* 75 (September): 323–35. https://doi.org/10.1016/j.eneco.2018.08.003.

———. 2021. "The Energy Transition: An Industrial Economics Perspective." *International Journal of Industrial Organization* 79 (December): 102734. https://doi.org/10.1016/j.ijindorg.2021.102734.

Fabra, Professor Natalia, Dr Felix Christian Matthes, and Professor David Newbery. n.d. "The Energy Transition in Europe: Initial Lessons from Germany, the UK and France."

Feinstein, Jonathan S. 1989. "The Safety Regulation of U.S. Nuclear Power Plants: Violations, Inspections, and Abnormal Occurrences." *Journal of Political Economy* 97 (1): 115–54. https://doi.org/10.1086/261595.

Fowlie, Meredith, Mar Reguant, and Stephen P. Ryan. 2016. "Market-Based Emissions Regulation and Industry Dynamics." *Journal of Political Economy* 124 (1): 249–302. https://doi.org/10.1086/684484.

Golladay, Mary J., Susan T. Hill, and Lori Thurgood. 2007. "US Doctorates in the 20th Century. Special Report."

Gowrisankaran, Gautam, Ashley Langer, and Wendan Zhang. 2023. "Policy Uncertainty in the Market for Coal Electricity: The Case of Air Toxics Standards," January.

Gowrisankaran, Gautam, Stanley S. Reynolds, and Mario Samano. 2016. "Intermittency and the Value of Renewable Energy." *Journal of Political Economy* 124 (4): 1187–1234. https://doi.org/10.1086/686733.

Hansen, Kenneth, Christian Breyer, and Henrik Lund. 2019. "Status and Perspectives on 100% Renewable Energy Systems." *Energy* 175 (May): 471–80. https://doi.org/10.1016/j.energy.2019.03.092.

Hausman, Catherine. 2014. "Corporate Incentives and Nuclear Safety." *American Economic Journal: Economic Policy* 6 (3): 178–206. https://www.jstor.org/stable/43189396.

Hickman, Caroline, Elizabeth Marks, Panu Pihkala, Susan Clayton, R. Eric Lewandowski, Elouise E. Mayall, Britt Wray, Catriona Mellor, and Lise van Susteren. 2021. "Climate Anxiety in Children and Young People and Their Beliefs about Government Responses to Climate Change: A Global Survey." *The Lancet Planetary Health* 5 (12): e863–73. https://doi.org/10.1016/S2542-5196(21)00278-3.

Hill, Joanne, and Thomas Schneeweis. 1983. "The Effect of Three Mile Island on Electric Utility Stock Prices: A Note." *The Journal of Finance* 38 (4): 1285–92. https://doi.org/10.2307/2328026.

Hirth, Lion. 2013. "The Market Value of Variable Renewables: The Effect of Solar Wind Power Variability on Their Relative Price." *Energy Economics* 38 (July): 218–36. https://doi.org/10.1016/j.eneco.2013.02.004.

Hultman, Nathan, and Jonathan Koomey. 2013. "Three Mile Island: The Driver of US Nuclear Power's Decline?" *Bulletin of the Atomic Scientists* 69 (3): 63–70. https://doi.org/10.1177/0096340213485949.

Idel, Robert. 2022. "Levelized Full System Costs of Electricity." *Energy* 259 (November): 124905. https://doi.org/10.1016/j.energy.2022.124905.

Joskow, Paul L. 2019. "Challenges for Wholesale Electricity Markets with Intermittent Renewable Generation at Scale: The US Experience." *Oxford Review of Economic Policy* 35 (2): 291–331. https://doi.org/10.1093/oxrep/grz001.

Joskow, Paul L. 2011. "Comparing the Costs of Intermittent and Dispatchable Electricity Generating Technologies." *American Economic Review* 101 (3): 238–41. https://doi.org/10.1257/aer.101.3.238.

———. 2012. "Creating a Smarter U.S. Electricity Grid." *Journal of Economic Perspectives* 26 (1): 29–48. https://doi.org/10.1257/jep.26.1.29.

Joskow, Paul L., and John E. Parsons. 2009. "The Economic Future of Nuclear Power." *Daedalus* 138 (4): 45–59. https://doi.org/10.1162/daed.2009.138.4.45.

Joskow, Paul L., and Catherine D. Wolfram. 2012. "Dynamic Pricing of Electricity." *American Economic Review* 102 (3): 381–85. https://doi.org/10.1257/aer.102.3.381.

Joskow, Paul, and Jean Tirole. 2007. "Reliability and Competitive Electricity Markets." *The RAND Journal of Economics* 38 (1): 60–84. https://doi.org/10.1111/j.1756-2171.2007.tb00044.x.

Jurewitz, John L. 2002. "The U.S. Nuclear Power Industry: Past, Present, and Possible Futures." *Energy & Environment* 13 (2): 207–37. https://doi.org/10.1260/0958305021501182.

Kellogg, Ryan, and Mar Reguant. 2021. "Chapter 17 - Energy and Environmental Markets, Industrial Organization, and Regulation." In *Handbook of Industrial Organization*, edited by Kate Ho, Ali Hortaçsu, and Alessandro Lizzeri, 5:615–742. Handbook of Industrial Organization, Volume 5. Elsevier. https://doi.org/10.1016/bs.hesind.2021.11.017.

Kharecha, Pushker A., and Makiko Sato. 2019. "Implications of Energy and CO2 Emission Changes in Japan and Germany After the Fukushima Accident." *Energy Policy* 132 (September): 647–53. https://doi.org/10.1016/j.enpol.2019.05.057.

Kim, Younghwan, Minki Kim, and Wonjoon Kim. 2013. "Effect of the Fukushima Nuclear Disaster on Global Public Acceptance of Nuclear Energy." *Energy Policy* 61 (October): 822–28. https://doi.org/10.1016/j.enpol.2013.06.107.

Kogan, Leonid, Dimitris Papanikolaou, Amit Seru, and Noah Stoffman. 2017. "Technological Innovation, Resource Allocation, and Growth." *The Quarterly Journal of Economics* 132

(2): 665–712. https://doi.org/10.1093/qje/qjw040.

Kozeracki, Julie, Chris Vlahoplus, Katheryn Scot, Melissa Bates, Billy Valderrama, Erica Bickford, Tim Stuhldreher, Andrew Foss, and Tom Fanning. 2023. *Pathways to Commercial Liftoff, Advanced Nuclear.* US Department of Energy.

Lazard. 2023. "2023 Levelized Cost of Energy+."

Lovering, Jessica R., Arthur Yip, and Ted Nordhaus. 2016. "Historical Construction Costs of Global Nuclear Power Reactors." *Energy Policy* 91 (April): 371–82. https://doi.org/10.1016/j.enpol.2016.01.011.

Machol, Ben, and Sarah Rizk. 2013. "Economic Value of U.S. Fossil Fuel Electricity Health Impacts." *Environment International* 52 (February): 75–80. https://doi.org/10.1016/j.envint.2012.03.003.

Malmsheimer, Lonna M. 1986. "Three Mile Island: Fact, Frame, and Fiction." *American Quarterly* 38 (1): 35–52. https://doi.org/10.2307/2712592.

Markandya, Anil, and Paul Wilkinson. 2007. "Electricity Generation and Health." *The Lancet* 370 (9591): 979–90. https://doi.org/10.1016/S0140-6736(07)61253-7.

Marks, Lionel S. 1978. "Marks' Standard Handbook for Mechanical Engineers." *Standard Handbook for Mechanical Engineers.*

Melber, Barbara D. 1982. "The Impact of TMI Upon the Public Acceptance of Nuclear Power." *Progress in Nuclear Energy*, Impact of the Three Mile Island Accident on the Nuclear Power Industry, 10 (3): 387–98. https://doi.org/10.1016/0149-1970(82)90015-4.

Neidell, Matthew, Shinsuke Uchida, and Marcella Veronesi. 2021. "The Unintended Effects from Halting Nuclear Power Production: Evidence from Fukushima Daiichi Accident." *Journal of Health Economics* 79 (September): 102507. https://doi.org/10.1016/j.jhealeco.2021.102507.

Nestle, Uwe. 2012. "Does the Use of Nuclear Power Lead to Lower Electricity Prices? An Analysis of the Debate in Germany with an International Perspective." *Energy Policy*, Modeling Transport (Energy) Demand and Policies, 41 (February): 152–60. https://doi.org/10.1016/j.enpol.2011.09.043.

Newbery, David. 2018. "Evaluating the Case for Supporting Renewable Electricity." *Energy Policy* 120 (September): 684–96. https://doi.org/10.1016/j.enpol.2018.05.029.

Newbery, David, Michael G. Pollitt, Robert A. Ritz, and Wadim Strielkowski. 2018. "Market Design for a High-Renewables European Electricity System." *Renewable and Sustainable Energy Reviews* 91 (August): 695–707. https://doi.org/10.1016/j.rser.2018.04.025.

NRC, US. 2012. "Three Mile Island Accident of 1979 Knowledge Management Digest." NUREG/KM-001, December.

Perrow, Charles. 2013. "Nuclear Denial: From Hiroshima to Fukushima." *Bulletin of the Atomic Scientists* 69 (5): 56–67. https://doi.org/10.1177/0096340213501369.

Petersen, Claire, Mar Reguant, and Lola Segura. 2022. "Measuring the Impact of Wind Power and Intermittency." SSRN Scholarly Paper. Rochester, NY. December 2, 2022. https://doi.org/10.2139/ssrn.4291672.

Popp, David. 2002. "Induced Innovation and Energy Prices." *American Economic Review* 92 (1): 160–80. https://doi.org/10.1257/000282802760015658.

Reichenberg, Lina, Fredrik Hedenus, Mikael Odenberger, and Filip Johnsson. 2018. "The Marginal System LCOE of Variable Renewables – Evaluating High Penetration Levels of Wind and Solar in Europe." *Energy* 152 (June): 914–24. https://doi.org/10.1016/j.ener gy.2018.02.061.

ROSA, EUGENE A., and RILEY E. DUNLAP. 1994. "THE POLLS—POLL TRENDS: NUCLEAR POWER: THREE DECADES OF PUBLIC OPINION." *Public Opinion Quarterly* 58 (2): 295–324. https://doi.org/10.1086/269425.

Sepulveda, Nestor A., Jesse D. Jenkins, Fernando J. de Sisternes, and Richard K. Lester. 2018. "The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation." *Joule* 2 (11): 2403–20. https://doi.org/10.1016/j.joule.2018.08.006.

Shirvan, Koroush. 2022. "Overnight Capital Cost of the Next AP1000." *Center for Advanced Nuclear Energy Systems (CANES), MIT-ANP-TR-193. Massachusetts Institute of Technology, Cambridge, MA, USA.*

Sinn, Hans-Werner. 2017. "Buffering Volatility: A Study on the Limits of Germany's Energy Revolution." *European Economic Review*, Combating Climate Change. Lessons from Macroeconomics, Political Economy and Public Finance, 99 (October): 130–50. https://doi.org/10.1016/j.euroecorev.2017.05.007.

Smil, Vaclav. 2018. *Energy and Civilization: A History.* MIT Press. https://books.google.com?id=Br74DwAAQBAJ.

Sovacool, Benjamin K., Patrick Schmid, Andy Stirling, Goetz Walter, and Gordon MacKerron. 2020. "Differences in Carbon Emissions Reduction Between Countries Pursuing Renewable Electricity Versus Nuclear Power." *Nature Energy* 5 (11): 928–35. https://www.nature.com/articles/s41560-020-00696-3.

Steele, Amanda Harker, Smriti Sharma, Ivonne Pena Cabra, Luke Clahane, and Arun Iyengar. 2023. "A Tool for Measuring the System Cost of Replacement Energy." *Energy* 275 (July): 127394. https://doi.org/10.1016/j.energy.2023.127394.

Sylves, Richard T. 1980. "Carter Nuclear Licensing Reform Versus Three Mile Island." *Publius* 10 (1): 69–79. https://www.jstor.org/stable/3329804.

U. S. Nuclear Regulatory Commission. 1980. "Annual Report (1979)." NUREG-0690. Nuclear Regulatory Commission, Washington, DC (USA). https://www.osti.gov/biblio/6662111.

Ueckerdt, Falko, Lion Hirth, Gunnar Luderer, and Ottmar Edenhofer. 2013. "System LCOE: What Are the Costs of Variable Renewables?" *Energy* 63 (December): 61–75. https://doi.org/10.1016/j.energy.2013.10.072.

UNSCEAR. 2014. "UNSCEAR 2013 Report to the General Assembly with Scientific Annexes VOLUME I Scientific Annex A: Levels and Effects of Radiation Exposure Due to the Nuclear Accident After the 2011 Great East-Japan Earthquake and Tsunami."

———. 2022. "UNSCEAR 2020/21 Report to the General Assembly VOLUME I SCIENTIFIC ANNEX a: Evaluation of Medical Exposure to Ionizing Radiation."

Valentine, Benjamin K. Sovacool, Scott Victor. 2012. *The National Politics of Nuclear Power: Economics, Security, and Governance*. London: Routledge. https://doi.org/10.4324/9780203115268.

Weitzman, Martin L. 2001. "Gamma Discounting." *American Economic Review* 91 (1): 260–71. https://doi.org/10.1257/aer.91.1.260.

Wilson, Robert. 2002. "Architecture of Power Markets." *Econometrica* 70 (4): 1299–1340. https://doi.org/10.1111/1468-0262.00334.

Wolak, Frank A. 2022. "Long-Term Resource Adequacy in Wholesale Electricity Markets with Significant Intermittent Renewables." *Environmental and Energy Policy and the*

Economy 3 (January): 155–220. https://doi.org/10.1086/717221.

Zerrahn, Alexander, Wolf-Peter Schill, and Claudia Kemfert. 2018. “On the Economics of Electrical Storage for Variable Renewable Energy Sources.” *European Economic Review* 108 (September): 259–79. https://doi.org/10.1016/j.euroecorev.2018.07.004.

A Additional figures and tables

Table A.1: Summary statistics on global nuclear power plant set up time. The entire duration is divided into three stages: construction time, from first laying of concrete to first criticality; connection, from first criticality to grid connection; and operation setup, from grid connection to commercial operation.

	Obs	Mean	Std. dev.	5%	25%	50%	75%	95%
Construction	640	6.77	3.59	3.33	4.58	5.70	8.09	12.87
Grid connection	639	0.19	0.34	0.02	0.05	0.09	0.18	0.79
Operation	628	0.56	0.64	0.06	0.22	0.41	0.66	1.47
Total	628	7.43	3.62	4.01	5.13	6.33	8.64	14.10

Table A.2: Summary statistics of US reactors. The table presents the mean, standard deviation, median, and 5th and 95th percentiles of reactor characteristics: licensed capacity (MW thermal), net capacity (MW electric); age, license length, and time remaining (years), and share of license remaining.

	Obs	Mean	Std. dev.	Median	5%	95%
Licensed MWt	93	3193.41	613.39	3411.00	1830.00	3990.00
Capacity MWe	93	1030.85	203.22	1120.00	611.40	1287.80
Current Reactor Age	93	41.20	8.52	41.00	32.00	51.40
License Length	93	59.25	8.11	60.00	40.00	80.00
Time Remaining	93	17.46	7.70	17.73	6.69	30.18
% License Remaining	93	0.29	0.14	0.30	0.11	0.43

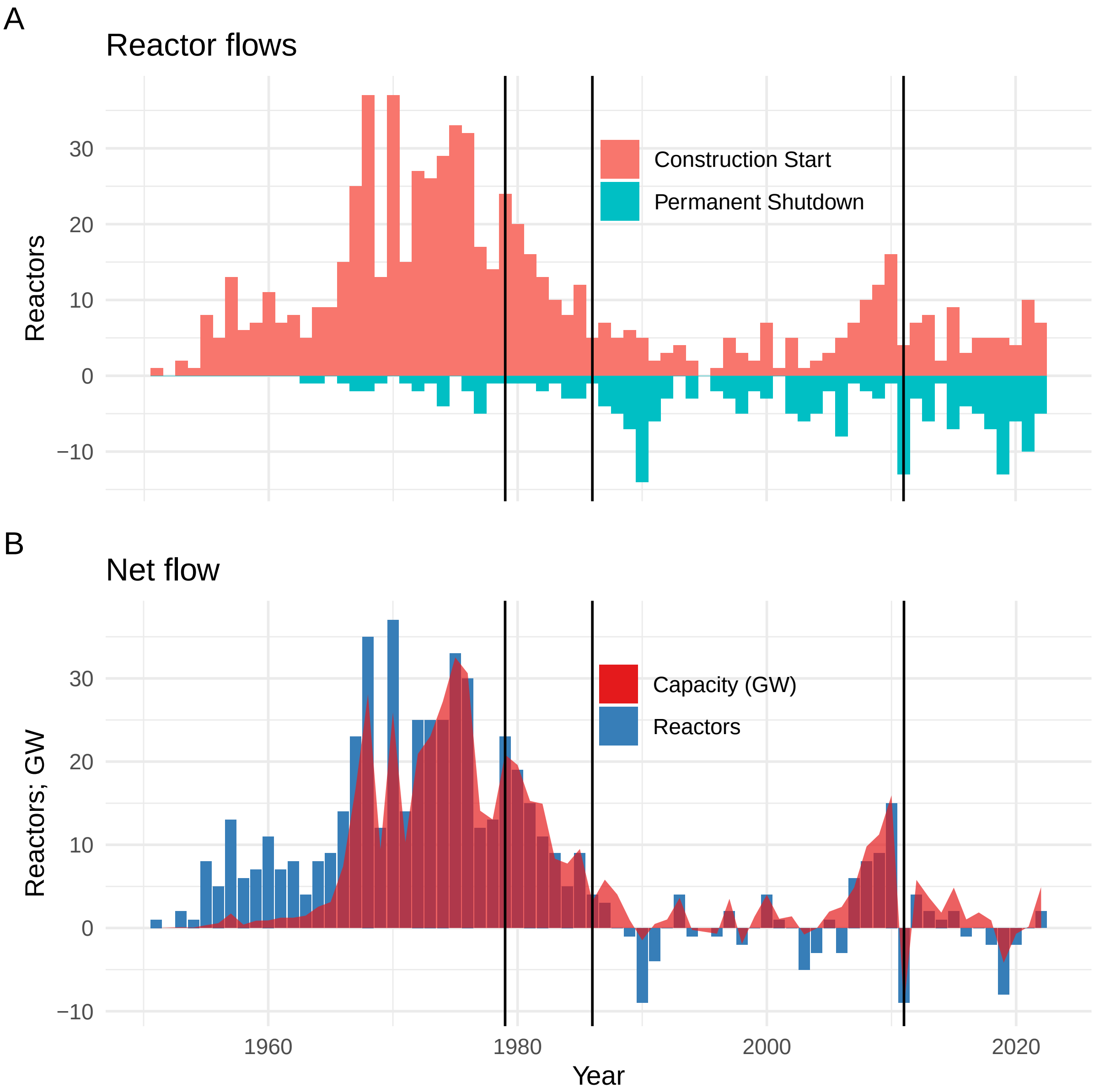

Figure A.1: Reactor construction, shutdown, and net flow. Panel A shows the number of reactors starting construction and decommissioned. Panel B shows the annual net flow of reactors and installed capacity. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

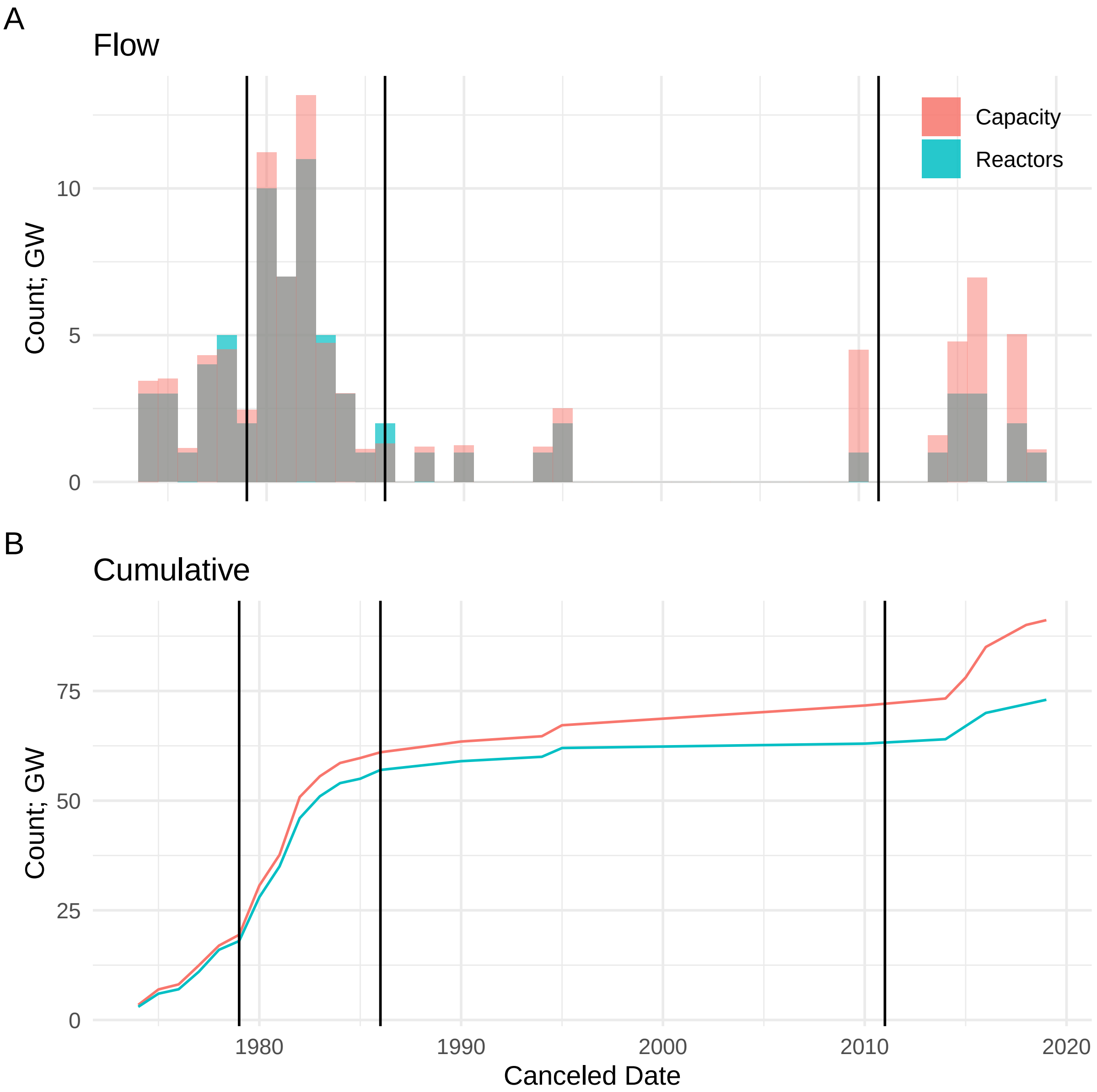

Figure A.2: Cancelled nuclear reactors. Panel A shows the number and capacity of canceled reactor by year. Panel B shows the cumulative canceled number of reactors and capacity. The vertical lines indicate the Three Mile Island accident (1979), the Chernobyl disaster (1986) and the Fukushima nuclear accident (2011).

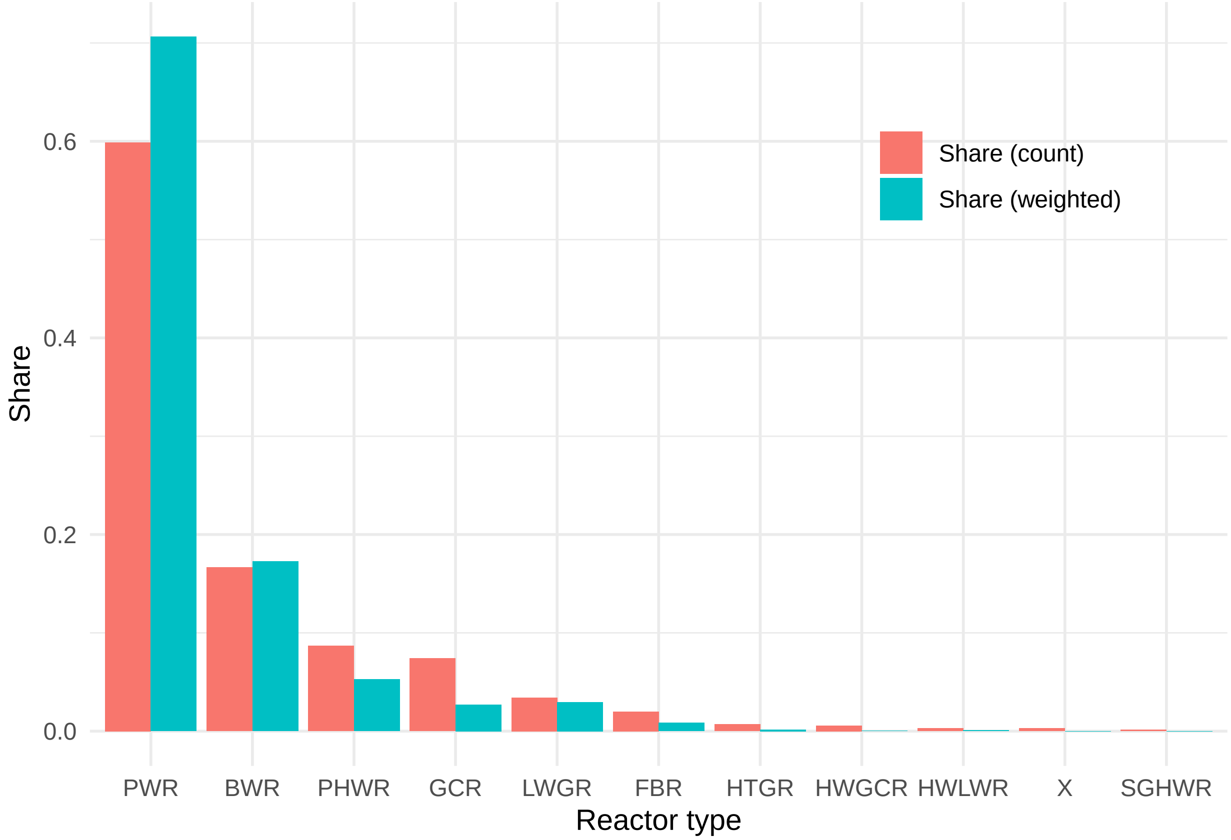

Figure A.3: Global distribution of reactor types. The figure shows the share of each reactor type in the global nuclear fleet, both in terms of a simple reactor count and weighted by installed capacity.

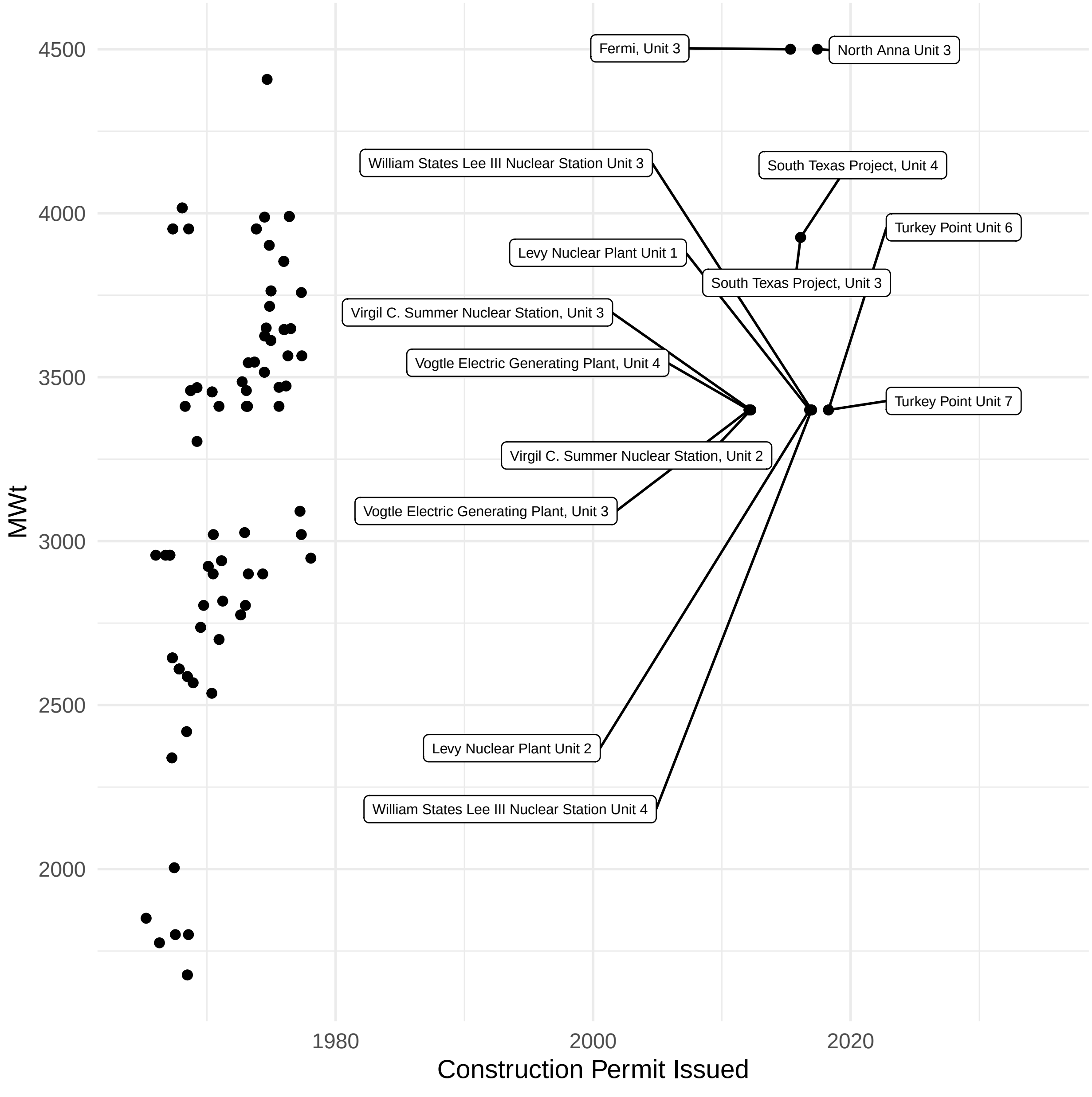

Figure A.4: Construction permit date and licensed thermal capacity of US reactors. The 14 reactors licensed after 2010 are individually labeled.

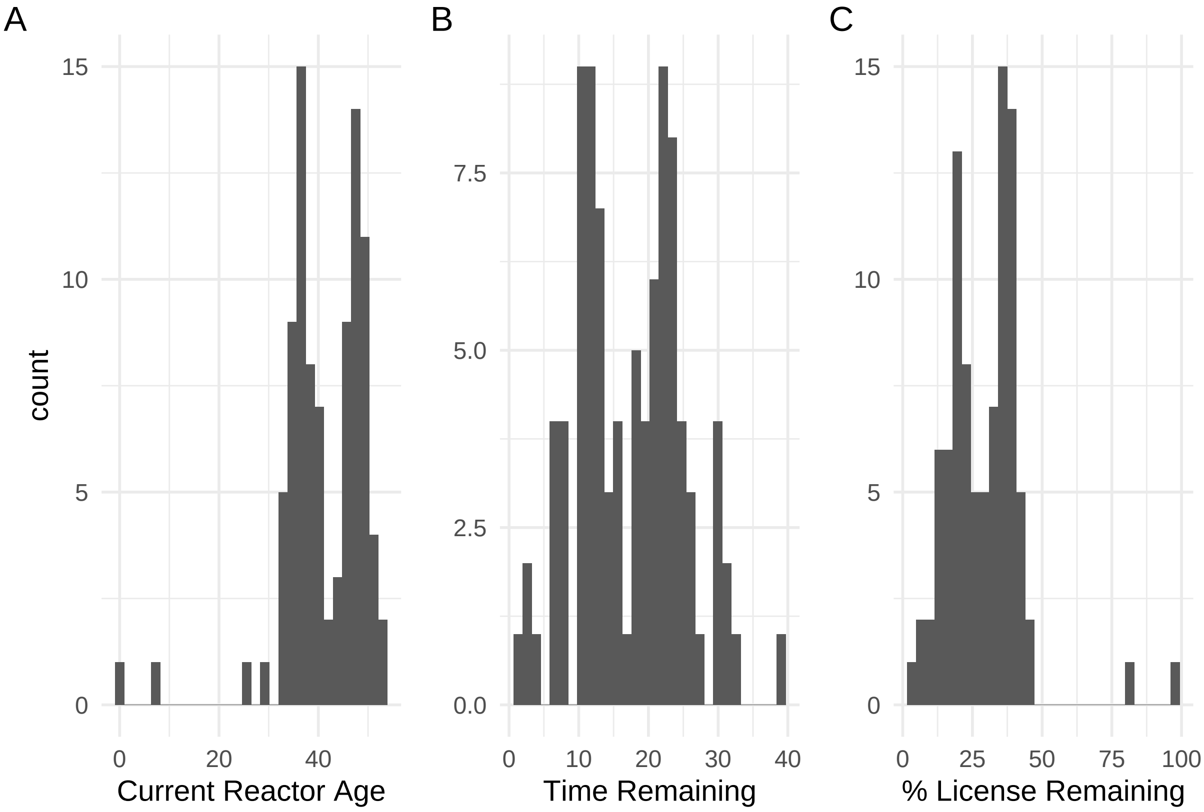

Figure A.5: Lifespan of current US reactors. Panel A plots the distribution of reactor age, in years. Panel B shows the distribution of remaining license time in years, amd panel C shows the distribution of remaining license time as a share of its duration.

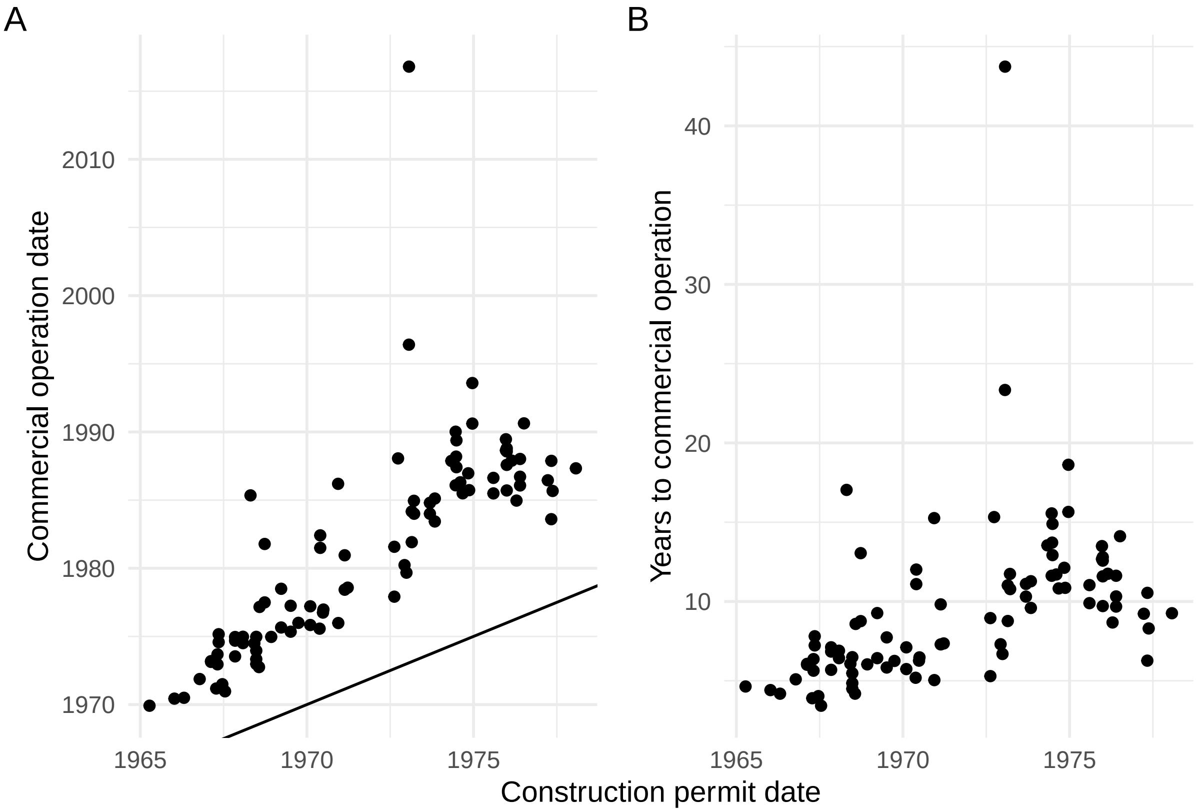

Figure A.6: US reactors time to commercial operation. Panel A is a scatter plot of construction permit and commercial operation dates. The solid line is the 45-degree slope. Panel B plots the evolution of time from construction permit to commercial operation, in years.

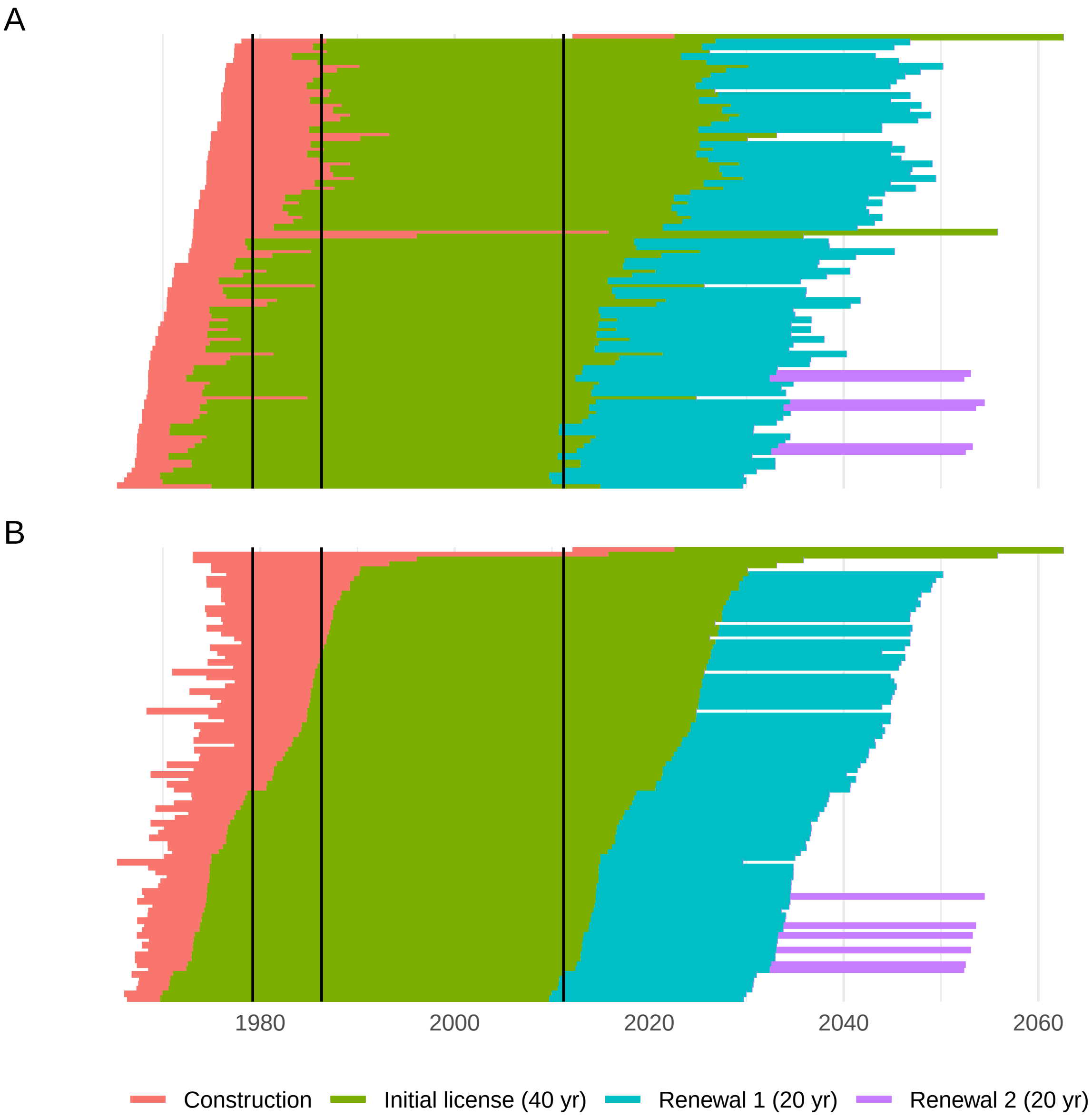

Figure A.7: Operating history of US commercial nuclear reactors. The figure plots the timeline of each operating reactor: durations of construction time, initial operating license, and periods of renewal. Panel A sorts reactors by construction start date. Panel B sorts by commercial operation start date.

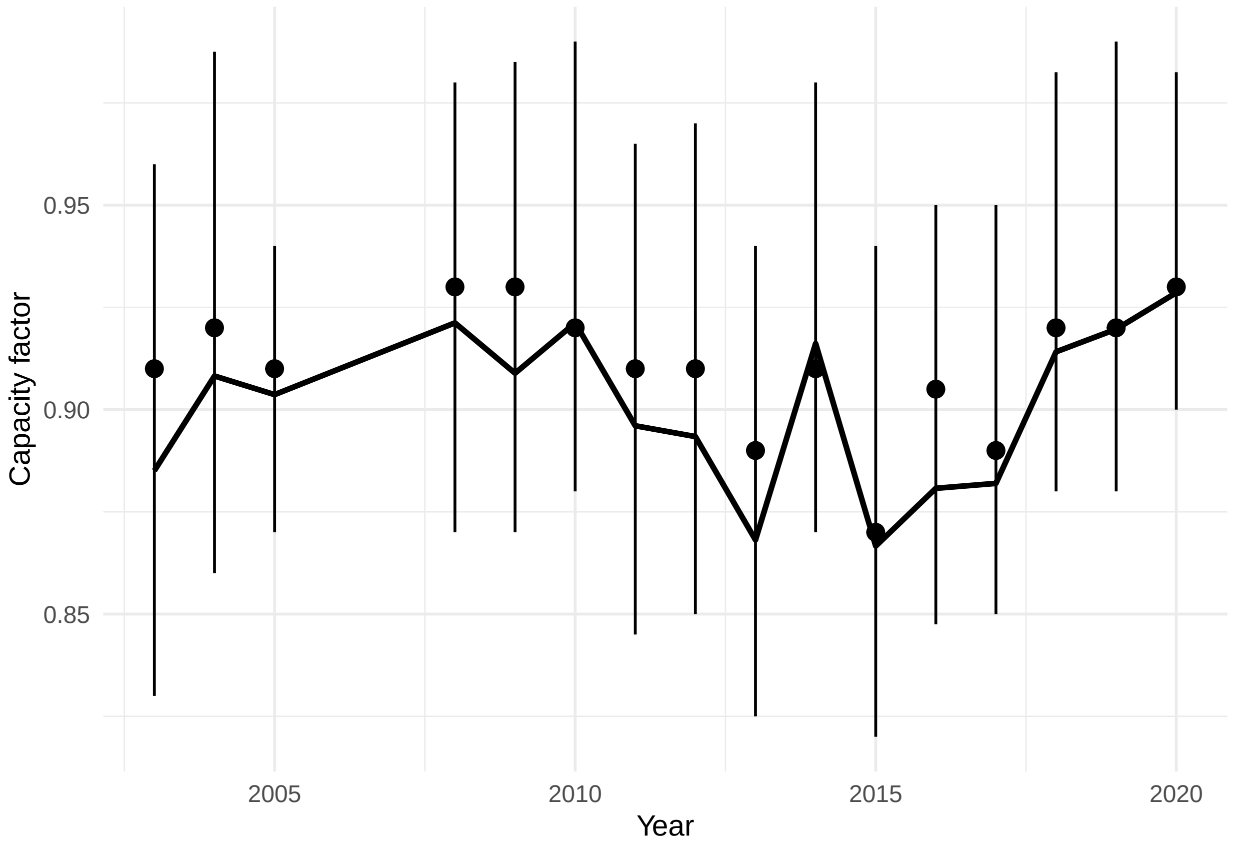

Figure A.8: Capacity factors of US nuclear power plants by year. The figure plots mean (solid line) and median (points) capacity factor, by year. The vertical lines correspond to the interquartile range, marking the 25th and 75th percentiles. Data for 2006, 2007, and years prior to 2003 were not reported by the NRC.

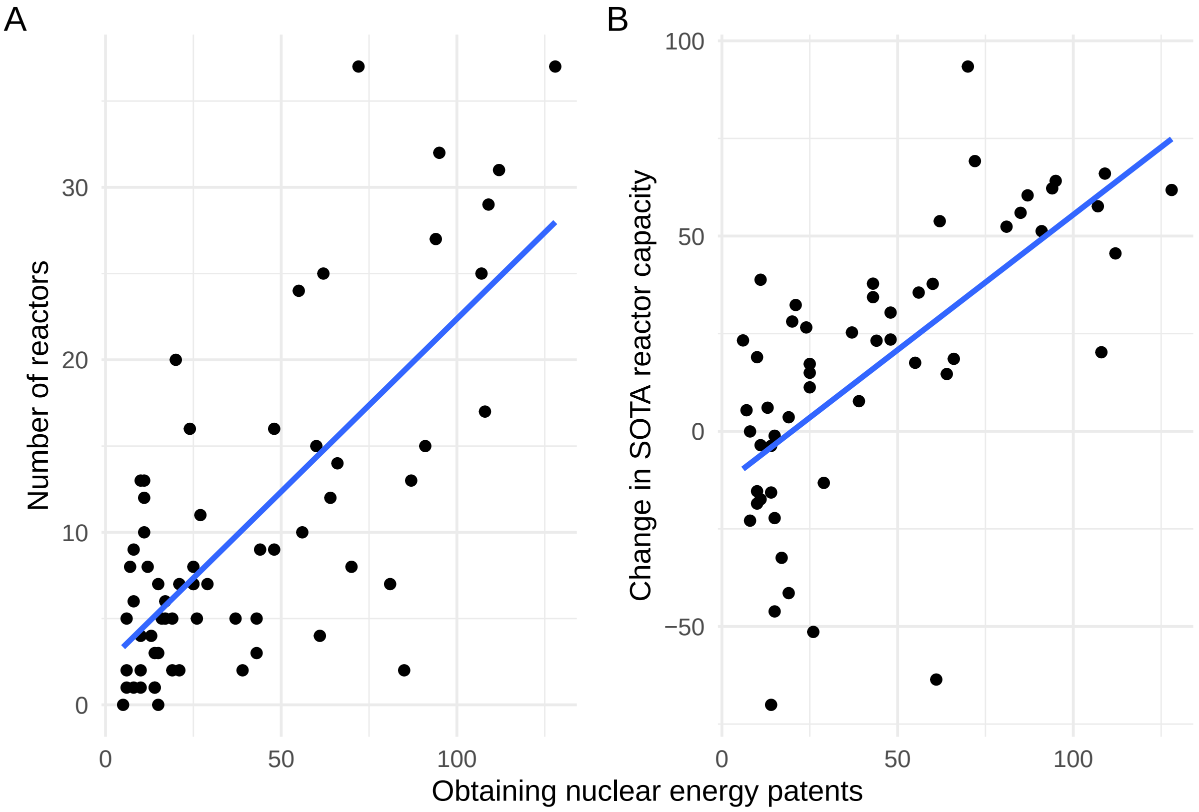

Figure A.9: Obtaining nuclear energy patents, new reactors, and capacity growth. Panel A plots the number of patents related to obtaining nuclear energy against the number of commissioned reactors, by year. Panel B plots the number of patents related to obtaining nuclear energy against a 10-year moving average of the change in state-of-the-art reactor capacity, by year. The solid lines are linear fits.

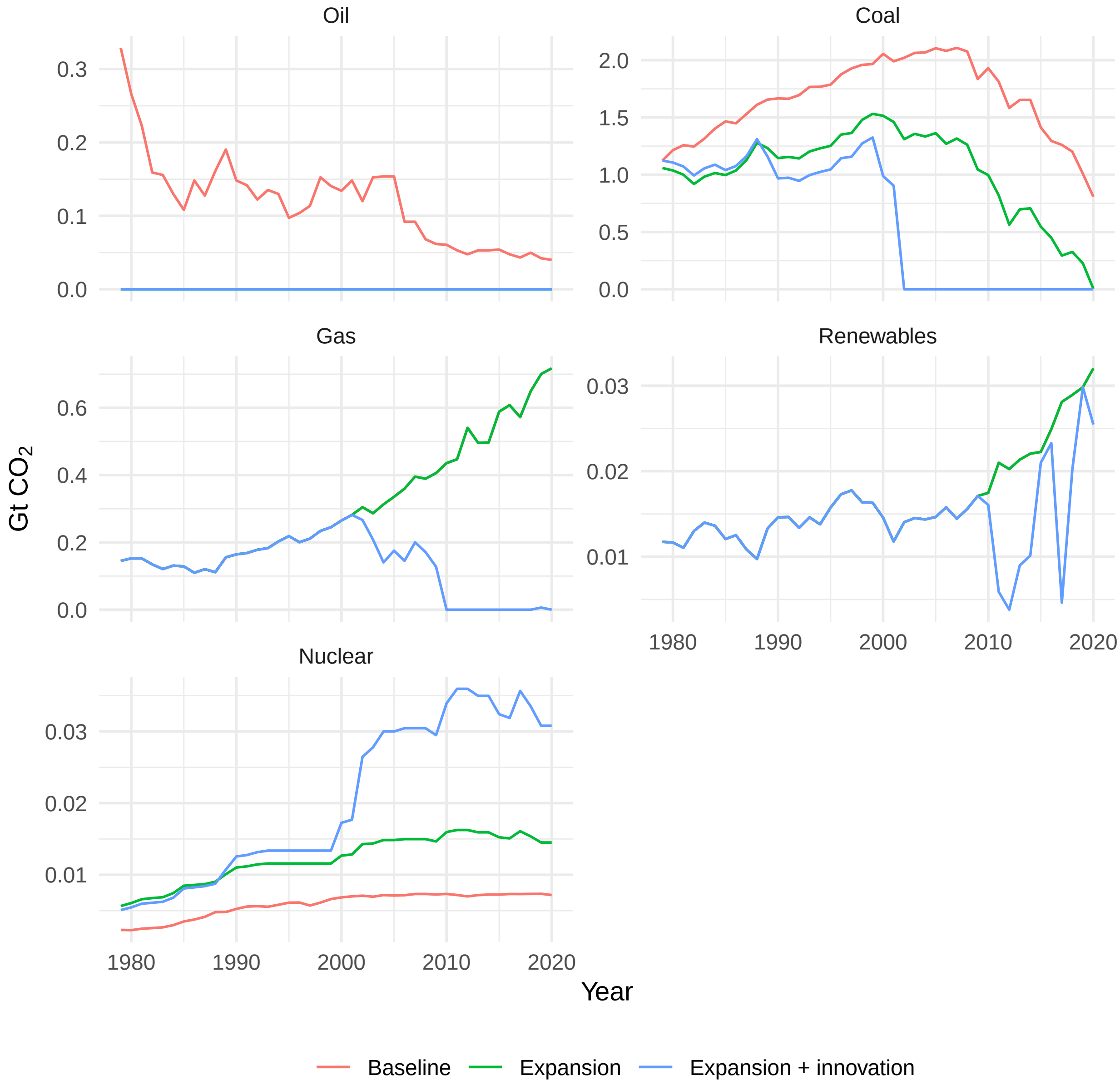

Figure A.10: Observed and counterfactual emissions, by energy source. The figure plots CO_2 emitted by each energy source, in Gt, as observed in the data, and under two counterfactual states: expansion of the nuclear fleet, with and without technological advancement.

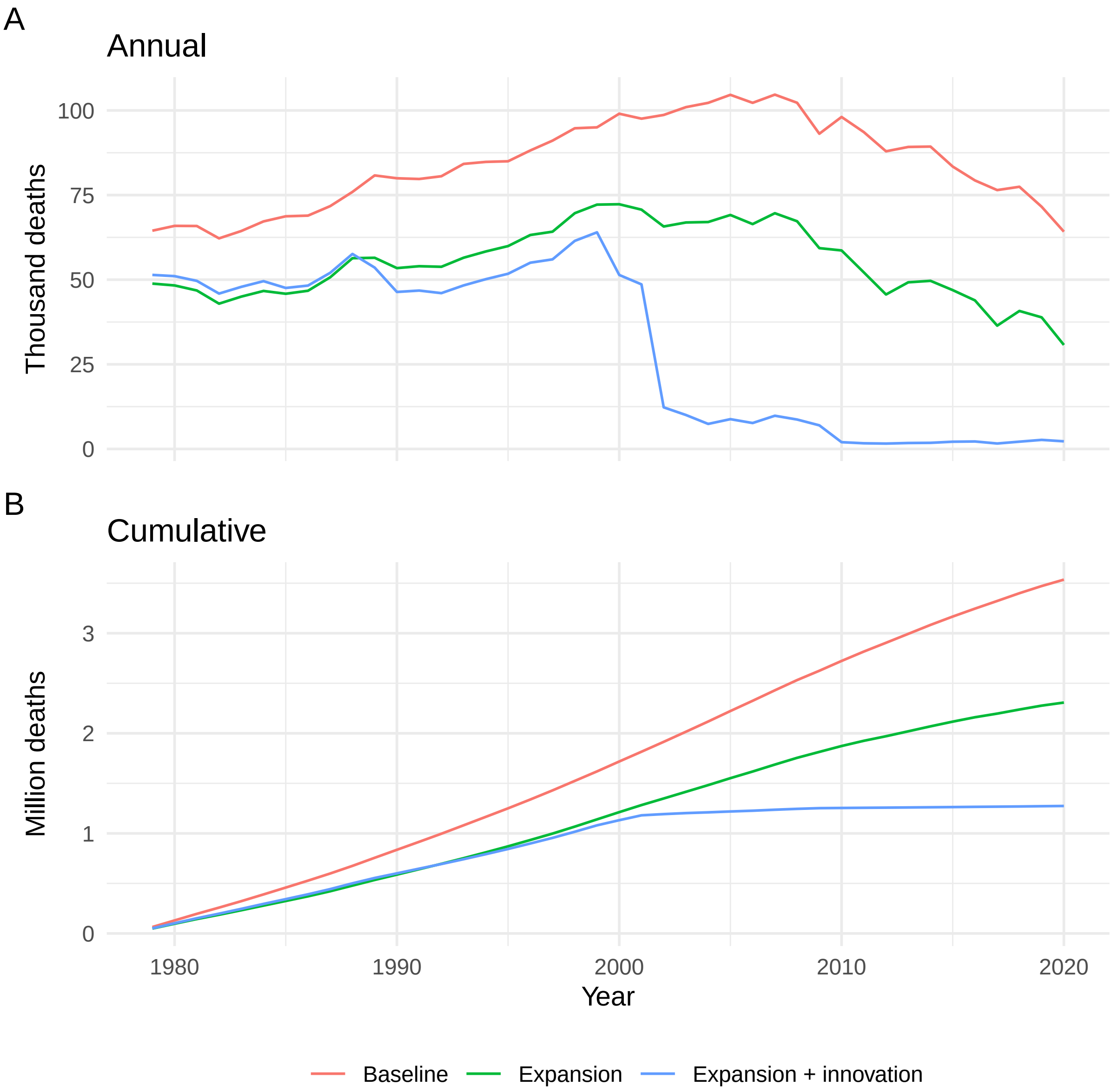

Figure A.11: Total mortality related to CO_2 emissions, by year and scenario. Panel A plots the total number of deaths related to CO_2 emissions, in thousands, by year and scenario. Panel B plots the cumulative emissions-related mortality since TMI, in millions, by year and scenario.

Table A.3: US reactor fleet age and capacity, by reactor type and design. The table summarizes the age and capacity of the US reactor fleet, by type and containment design. BWR and PWR refer to boiling water and pressurized water reactor types. DRYAMB, DRYSUB, and ICECND refer to dry ambient, dry subatmospheric, and ice condenser containment types. Age is reported in years.

				Capacity (MW)	
Reactor	Containment	Count	Mean age	Mean	Total
BWR	MARK 1	19	47.32	986.26	18739
BWR	MARK 2	8	37.50	1182.00	9456
BWR	MARK 3	4	36.50	1168.50	4674
PWR	DRYAMB	46	41.39	994.98	45769
PWR	DRYSUB	5	44.20	957.60	4788
PWR	ICECND	10	36.20	1132.60	11326
PWR	OTHER	1	0.00	1117.00	1117
Total		93	41.20	1030.85	95869

Table A.4: US reactor fleet types and designs. The table summarizes the number of currently operating reactors by manufacturer, type, and containment. BWR and PWR refer to boiling water and pressurized water reactors. DRYAMB, DRYSUB, and ICECND refer to dry ambient, dry subatmospheric, and ice condenser containment types. GE, B&W, CE, and WEST refer to General Electric, Babcock & Wilcox, Combustion Engineering, and Westinghouse. LLP and RLP refer to lowered loop and raised loop pressurized water reactors. 2LP, 3LP, and 4LP correspond to two, three, and four loop pressurized water reactors.

	BWR			PWR			
Supplier / Design	MARK 1	MARK 2	MARK 3	DRYAMB	DRYSUB	ICECND	OTHER
GE 2	1	0	0	0	0	0	0
GE 3	5	0	0	0	0	0	0
GE 4	13	4	0	0	0	0	0
GE 5	0	4	0	0	0	0	0
GE 6	0	0	4	0	0	0	0
B&W LLP	0	0	0	4	0	0	0
B&W RLP	0	0	0	1	0	0	0
CE	0	0	0	7	0	0	0
CE 80-2L	0	0	0	3	0	0	0
WEST 2LP	0	0	0	5	0	0	1
WEST 3LP	0	0	0	9	4	0	0
WEST 4LP	0	0	0	17	1	10	0