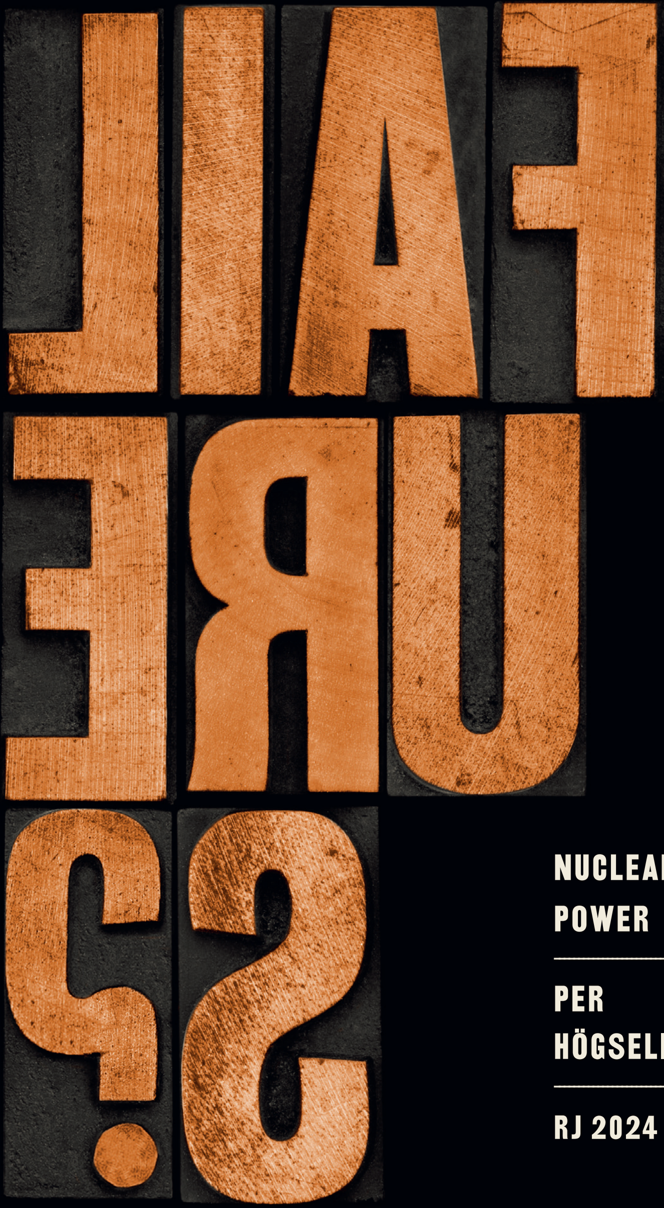

NUCLEAR POWER

PER HÖGSELIUS

RJ 2024

FAILURES?

RJ 2024

Nuclear power

PER HÖGSELIUS

Translated
by Clare Barnes

Riksbankens Jubileumsfond
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Foreword: Failures?

"Try again. Fail again. Fail better." Samuel Beckett's words are now legendary. There seems to be no crisis, setback or adversity from which it is impossible to learn. Failure carries its counterpart – success – within. Listen to the countless biographical radio programmes about fiascos that turn to triumphs, Google for failures, see how self-help books are structured. Perhaps it has always been this way – or is this a consequence of our era's accelerating demands for success, growth, advancement and evolution?

The American historian Scott A. Sandage, who researched the cultural history of failure in the US, claims that failure has become personal since the mid-nineteenth century – you don't just fail, you are a failure. He even talks of a nation of winners and losers, in which everyone is either the one or the other. Failure is thus a constant and shadowy companion to the American dream, an ever-present component of the American experience. Sandage links this to several factors, including modern society's perpetual evaluation and our time's statistical exposure of private lives. In the nineteenth century, the innovation of statistics collection seemed to reveal in real time previously hidden – or at least obscured – connections relating to the population and society. In the US, this also coincided with the credit institutes' division of the populace into those who were creditworthy and others – which is to say, losers. In addition, Sandage sees a link with the rise of meritocracy. The statistics demonstrated, incontrovertibly, that the masses were nothing other than mediocre.[1]

Sweden is also a nation of mediocrity, just like every other nation, and here too – even if we are not as influenced by the idea of an American dream – mediocrity is associated with a lack of success, rather than a normal distribution. There are people who believe that we are now living in an age of perfectionism, placing sky-high expectations on ourselves. Nothing other than flawless will do, and everything that doesn't make it is pretty much a failure. These growing demands for ultimate excellence are regarded by the Public Health Agency of Sweden as one reason for the current rise in mental illness.[2] The same trend seems to be occurring in the rest of the West, and perfectionism is said to have increased since the 1980s.[3] In his most recent book, the British psychologist and researcher Thomas Curran writes of a hidden epidemic that is haunting the modern, capitalist Western world, where the tougher demands we wrestle with mean that we are increasingly likely to fail – and are particularly likely to dread this failure.[4] That fear inhibits us, Curran claims.

Our contemporary individualism, enthusiasm for evaluation and constant searching for something that is occasionally vague but better – yes, "more perfect" – makes us ever-more vulnerable to failure. However, in itself, of course, failure is nothing new. Quite the opposite, setbacks and adversity are part and parcel of being human.

Mistakes, errors and a lack of success have, for centuries, comprised the very foundation of science and research as we know it. Trial and error. We could even claim that, fundamentally, science is about daring to get things wrong and then learning from your mistakes. A researcher makes predictions and finds regularities, patterns and laws in what appears to be chaos. The periodic table and the discoveries of Newton, Linnaeus and Einstein are just a few examples; new theories replace old ones, errors are found, and systems improved or discarded. Faults and troubleshooting are part of the process, and what the Enlightenment, modernity, progress, was all about was this: taming and mastery through rules, predictions and – yes – finding mistakes.

We are now seeing indications that fewer scientific breakthroughs are occurring – at least if by breakthrough we mean scientific achievements that move our knowledge in a completely new direction. This is happening despite our faith in research and all the global resources invested in it.[5] Is the lack of breakthroughs a failure of our times? And, if so, is it our fear of failure that makes us less bold and thus less likely to explore new directions?

We could ask ourselves whether anyone now believes in progress and the future in the way that people did in the 1960s. In this way, we live in a darker world – or are we just less naïve? And there are fiascos, for individuals and for societies, that are difficult to learn from, and where the lesson is perhaps just to put it all behind you and move on.

Still, if we swept all those fiascos under the rug, if all our setbacks were hidden and forgotten, we would not have made any progress. We are somewhere between these extremities, daring to see the mistake for the shambles it is, sometimes with no lesson to be learned, and to use it. In this essay collection, six researchers from the humanities and social sciences take a closer look at failure and the unintended consequences of success.

They range from what the constant evaluations of modern life do to us, to medical advances that inadvertently change the perception of the body and create illegal markets. In this essay, the historian of technology Per Högselius writes about nuclear power – a technology that promised a great deal and rarely lived up to expectations. But does this mean it is a failure?

Almost everything we do has unintended consequences, and it is far from obvious what constitutes a failure – particularly when little time has passed. According to Walter

Benjamin, the angel of history sees the past as a long chain of catastrophes, while being propelled back-first into the future on a storm called progress.

Someone who continues to read Samuel Beckett's famous lines on having another go, soon realises that he is not delivering an optimistic call for success, but rather a pitch-black description of failure:

> Try again. Fail again. Better again. Or better worse. Fail worse again. Still worse again. Till sick for good. Throw up for good. Go for good. Where neither for good. Good and all.[6]

Jenny Björkman

Notes

1. Scott A. Sandage, *Born Losers: A History of Failure in America*, Cambridge, MA: Harvard University Press, 2005.

2. Public Health Agency of Sweden, "Varför har den psykiska ohälsan ökat bland barn och unga i Sverige?", Solna: Folkhälsomyndigheten, 2018, www.folkhalsomyndigheten.se/publicerat-material/publikationsarkiv/v/varfor-har-den-psykiska-ohalsan-okat-bland-barn-och-unga-i-sverige/. See also "Young people drowning in a rising tide of perfectionism", *The Conversation* 5 February 2019, https://theconversation.com/young-people-drowning-in-a-rising-tide-of-perfectionism-110343.

3. Thomas Curran & Andrew P. Hill, "Perfectionism is increasing over time: A meta-analysis of birth cohort differences from 1989 to

2016", *Psychological Bulletin* vol. 145, no. 4, 2019, pp. 410–429.

4. Thomas Curran, *The Perfection Trap: The Power of Good Enough in a World that Always Wants More*, London: Cornerstone Press, 2023.

5. Michael Park, Erin Leahey & Russell J. Funk, "Papers and patents are becoming less disruptive over time", *Nature* no. 613, 2023, pp. 138–144.

6. Samuel Beckett, *Worstward Ho*, 1983.

ERRARE HUMANUM EST


LINJE 2
AVVECKLING MED FÖRNUFT GER SÄKERHET OCH TRYGGHET!
AVVECKLA KÄRNKRAFTEN! 2 MEN MED FÖRNUFT!
RIKSKOMMITTEN FÖR LINJE 2
Kärnkraften är livsfarlig!
En reaktorolycka kan döda tusentals människor i strålsjuka och tiotusentals i cancer.
Rösta Nej! Linje 3.
1
ENERGI FÖR SVERIGE
Strömmen räcker!
Även utan kärnkraft kan Sveriges elproduktion öka med 10% under 80-talet. Det räcker gott och väl till både industrin och hemmen.
Rösta Nej! Linje 3.
AVVECKLA KÄRNKRAFTEN! 2 MEN MED FÖRNUFT!

A failed technology?

We all know that science and technology play important roles in contemporary society – for better or worse. At its best, technology solves problems, simplifies our lives and fuels dreams of a better world. We utilise it constantly, every day, in its many different incarnations – but things do not always go to plan. Many inventions, perhaps most of them, never have a major impact, while others cause accidents and disasters, or are used for the 'wrong' purposes and by the 'wrong' people. The history of technology is full of artefacts and systems that have not behaved as intended in their societal context; the historical drama of technology not only includes successes. History would not be complete without the other stories: those of inventors and engineers who have seen their careers – and fortunes – go to waste, of governments held accountable for extravagant and failed investments, and of large corporations that have gone under due to disasters in which their technology has, at worst, claimed human lives.

This duality can hardly be better illustrated than by nuclear power. The Janus face of nuclear power – half destructive and dangerous, half productive and helpful – sparked a heated debate from the outset, eventually leading to the now familiar controversies of the 1970s and 1980s. Today, nuclear power is once again the topic of intense debate. Almost everyone has an opinion about whether nuclear power is a good or bad technology, whether it is hazardous or safe, and whether power companies should build more nuclear power plants or, on the contrary, decommission the ones already in operation. One underlying question is whether nuclear power should be considered a 'successful' or 'unsuccessful' technology, and how we should deal with the many unforeseen consequences that investments in this power source have resulted in over the years. Here, an historical perspective can help us to nuance the picture, letting us see how grand visions of the future, high-tech triumphs and unexpected shortcomings have shaped – and been shaped by – the interaction of technology and society.

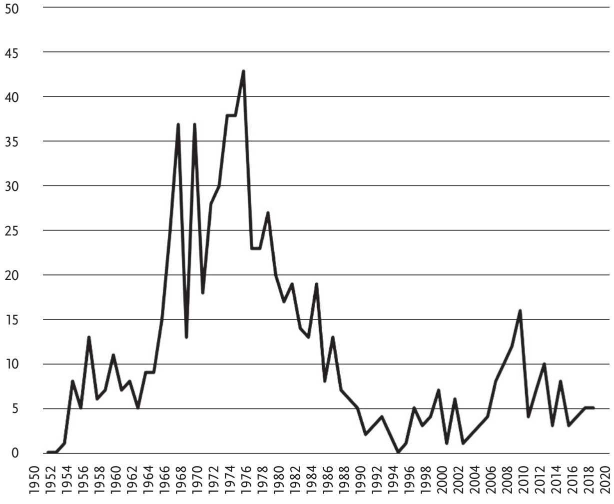
Nuclear power as it was and is

Nuclear power dates back to the late nineteenth century, when Henri Becquerel and Marie and Pierre Curie discovered and began to study the phenomenon of radioactivity. The first decades of the twentieth century saw a series of findings in physics and chemistry which eventually, around the turn of 1938/1939, led to German and Austrian scientists being able to demonstrate fission – the splitting of atomic nuclei. Researchers from several countries contributed to the scientific progress in this area, but much of this transnational knowledge exchange ceased after the outbreak of World War Two, because nuclear research was considered of strategic military importance. What had until this point primarily been purely scientific research laid the basis – in the United States, the United Kingdom and eventually the Soviet Union – for practically focused experimental activities that aimed to build an atomic bomb.[1]

After the bombing of Hiroshima and Nagasaki, civilian nuclear technology developed as a spin-off from the work on nuclear weapons. The period from 1950 to 1965 was a dynamic time of experimentation with many different reactor types, most of which were inspired by military experience with uranium enrichment and plutonium production. These reactors initially competed with each other but, in the second half of the 1960s, near consensus emerged that the light-water reactor was the most suitable for large-scale civilian nuclear power.[2] Today, this reactor type still dominates nuclear power around the world, including in Sweden. Light-water technology became the basis of civilian nuclear power's commercial breakthrough and paved the way for what can be described as the golden age of nuclear power, from the mid-1960s to the mid-1980s. Virtually all nuclear power plants now in operation were built during this period, with the exception of a few countries – primarily South Korea and China – whose expansion in this area is more recent.[3]

However, if we look at statistical data for the historical growth of nuclear power, we see that the number of new nuclear power plants being constructed has been in decline since 1976, as shown in the figure on the next page. The underlying reasons for this turn are not easy to unravel; they include technical problems in getting them to work as intended, but also stricter demands from regulatory authorities, growing anti-nuclear sentiments among the public and a slowdown in the demand for electricity following the 1973 oil crisis.

Nuclear power's expansion further stagnated in the



Annual construction starts for commercial nuclear reactors, 1950–2020.

1980s and 1990s, following the Three Mile Island accident in 1979 and the Chernobyl disaster in 1986 – but it had begun prior to this. There is a common misconception, even among respected scholars, that nuclear power only stopped expanding after the Three Mile Island accident.[4]

If we look at the atomic age in Europe specifically, we see that nuclear power's contribution to overall energy supply grew rapidly, sometimes exponentially, for 25 years. By the end of the 1980s, no fewer than 182 reactors were operating in Europe. However, almost no new ones were built after this and increasing numbers of nuclear power plants were decommissioned. European nuclear power thus entered its stagnation and decommissioning phase. At present, only around 120 European reactors are still operating, and the number continues to decline from year to year.[5] Still, in some countries – not least Sweden – hope of a nuclear power comeback remains high. For example, alongside interest in conventional nuclear power plants, we have seen a growing interest in 'small modular reactors' (SMRs). These are, or so their proponents claim, cheaper, safer and more flexible than the large-scale, traditional reactors of the 'golden age'. The extent to which such visions can be put into practice will become apparent in the coming years.

A generic technology?

There are several ways to approach the question of whether nuclear power, as it has taken shape in society, should be considered a success or a failure. One particularly appealing way is to examine what was expected of nuclear technology at different points in time, and then compare this with the actual outcome. In other words, how has nuclear power succeeded in delivering on the comprehensive promises with which it was associated?

From the very start, there were many ideas about the future of nuclear power. Early twentieth-century science fiction expressed the dream of a new, nuclear-powered energy source, and this also found its way into that era's radical political movements. Bolshevik leader Lev Trotsky was one of many people who saw radioactivity as a possible ally in the struggle against old, outmoded social orders.[6] These visions faded somewhat with the militarisation of nuclear technology, but were immediately and forcefully revived following the destruction of Hiroshima and Nagasaki. The most far-reaching ideas about how nuclear power could contribute to a better, richer and fairer world took shape in the 1950s, when the United States, led by President Dwight Eisenhower, relaxed the secrecy around civilian applications for nuclear technology and invited international cooperation on "peaceful atoms".[7] In 1955, the US took the lead in organising a major international conference on civilian nuclear technology in Geneva. Enthusiasm was further boosted by the Suez crisis of 1956–1957, which exposed the vulnerability of Western oil supplies, along with a parallel crisis in European coal mining that led to sharp increases in energy prices and intense debate about impending fuel shortages.[8] Nuclear power was framed as an attractive alternative energy source, particularly in countries and regions that were poor in fossil fuels – such as Sweden. Fantastic ideas about how nuclear technology could revolutionise modern society made their way into the popular science contexts of the 1950s. On the whole, nuclear technology was considered a generic technology, one whose enormous societal potential was comparable only to previous pioneering innovations, such as the steam engine in the early stages of industrialisation, or the internal combustion engine and electricity in what is commonly referred to as the second industrial revolution. There was a belief that, in the future, nuclear power plants would supply vast amounts of electricity, as well as heat, which could be used for domestic heating, producing hot water, in industrial processes and agriculture. And, just as steam engines and internal combustion engines had once been mounted on vehicles, mobile nuclear power plants were expected to have a huge impact on railways and shipping, as well as in the expanding aviation industry. Another radical vision concerned the potential of nuclear energy for powering large-scale seawater desalination plants, a technology that was notorious for its extreme requirements for fossil fuel. Nuclear technology would thus solve the world's growing problem with water supplies. There were also high hopes that radioactive isotopes could be utilised in agriculture (in plant breeding, for example) and in the food industry (for preservation), as well as in medicine, so eradicating famine and disease.[9]

Nuclear power failed to live up to most of these very high expectations and never became a generic or universal technology used throughout our lives; instead, it has had to settle for a niche role in the field of electricity production, although this is complemented by the importance that radioactive isotopes now have in healthcare (particularly for cancer treatments and in diagnostics).

Why did nuclear power never become more vital to modernity than this? And does that make it a failed technology?

If we focus on the transport sector, we can see that it did appear, initially, as if reactor-powered ships would make a breakthrough. As early as 1954, the US Navy launched a nuclear-powered submarine that exceeded expectations.

More submarines were introduced and other countries followed in the United States' footsteps. A few years later, the Soviet Union expanded nuclear-powered transportation with icebreakers driven by nuclear reactors. For its part, West Germany constructed the Otto Hahn research vessel, a pilot project for the nuclear-powered merchant ships of the future, and there was also a great deal of optimism regarding the future of nuclear-powered air and space transportation.[10] However, development in the maritime sector appears to have stalled due to high costs and safety concerns, particularly at the end of the 1950s, when an abundance of cheap oil eradicated the fear of a coming fossil fuel crisis and made a technically and economically risky transition to nuclear-powered transportation anything but compelling. Even after fossil fuel prices skyrocketed in the wake of the oil crises in the 1970s, nuclear-powered transport did not become sufficiently attractive to follow up those early investments with upscaling and expansion into the market. However, nuclear-powered submarines remained strategically important for the naval forces of the major powers, where cost was less of an issue; the submarines were expensive, but this was offset by greatly improved functionality because they did not need to be regularly refuelled.[11] Similar arguments could have paved the way for reactors in space, but the world's space agencies chose to rely on more conventional fossil and synthetic fuels combined with early attempts to utilise solar cells. For rail and air travel, the risk of collisions and accidents seems ultimately to have been assessed as being too high. Some engineers believed that solutions to these problems existed, but as fossil fuels remained affordable they found asserting themselves difficult. It will be interesting to see whether enthusiasm for reactor-powered aeroplanes will resurface in the coming decades, as alternative technologies are now in demand due to the efforts to eliminate aviation's high carbon emissions.

More surprisingly, nuclear power never played more than a marginal role in the world's heat supply, despite early expectations that this would become one of nuclear technology's great successes. It was not by chance that Sweden's first nuclear power plant primarily supplied heat, not electricity. The Ågesta nuclear plant, as it was called, was built on the edge of Stockholm, next to the Modernist suburb of Farsta, and was expected to be the first in an envisioned series of urban nuclear thermal power plants.[12] After Ågesta started operating, in 1964, Swedish engineers began to design the next heating plant, intended for construction in a rock cavern in Värtan. However, shortly afterwards, when nuclear technology began to scale up dramatically, these small-scale urban reactors were sidelined and eventually disappeared from the agenda. For a while, many visionaries believed that large-scale nuclear power plants could also supply heating as a complement to electricity generation. In Sweden, Sydkraft planned for the Barsebäck plant to supply both Malmö and Copenhagen with district heating, while Vattenfall wanted Forsmark to supply Stockholm via long heat tunnels.[13] This was technically possible, but advocates ultimately failed to garner support for their ideas and their sketches remained in the desk drawer. A few large-scale reactors in Switzerland, East Germany and the Soviet Union, among others, did supply district heating as a by-product of nuclear power, but these were the exceptions that proved the rule.[14] In the 1980s, the Soviet Union had comprehensive plans for replacing coal and oil with nuclear heat in urban areas using a unique reactor design, but these were shelved following the Chernobyl accident and the subsequent collapse of the Soviet Union.[15]

But is it reasonable to interpret nuclear power's failure to become a generic technology as the failure of nuclear technology as such? This is not entirely clear. In particular, it could be argued that it is only natural for inventors and engineers, especially in the early stages of a technology's life, to explore its potential – practically and discursively – by widening the scope onto the full range of potential applications. That most of these ideas eventually prove unfeasible is not necessarily surprising or unexpected. The same pattern can be seen in many other, indeed most, areas of technology. Innovation theorists have shown that the majority of what engineers and entrepreneurs devote time to is abandoned after an experimental and pilot phase; only the most promising leads can justify investing in the large-scale completion of the original visions.[16]

Importance for the electricity supply

Having discussed the vision of nuclear power as a generic technology, let us now examine its importance for the world's electricity supply. What were the expectations and to what extent was nuclear power able to meet society's rapidly growing demand?

After Hiroshima and Nagasaki were bombed, there was soon a consensus that nuclear technology was destined to be beneficial in the field of electricity, but opinion was divided on how quickly the military plutonium-producing reactors could be upgraded to power-generating reactors and how difficult – and expensive – this would be. There was initial uncertainty and then growing optimism after 1953. In 1954 and 1956, respectively, the Soviet Union and the United Kingdom led the way by starting to use nuclear reactors that fed electricity into public grids.[17]

This fuelled expectations for the future. In a much-cited 1954 speech, the chairman of the US Atomic Energy Commission, Lewis Strauss, prophesised that nuclear power would become "too cheap to meter" – a phrase that has gone down in history. Strauss drew parallels with water supplies in the world's cities; charging for these was often considered unnecessary as managing the resulting bureaucracy cost more than the water did.[18] His statement quickly became controversial. Strauss' optimistic forecast was not shared by his colleagues and was never accepted by nuclear professionals. However, it gained enormous traction in popular science and cultural contexts, and has been used by the anti-nuclear movement to ridicule the visionaries of nuclear power.[19]

Leading scientists and engineers hoped that nuclear power would at least be cheap enough to compete with coal, but the uncertainties were significant. The big power companies, which were expected to build and operate the nuclear power plants, were initially sceptical. In general, they were cautious and rarely demonstrated any tendency to assume leadership of what they perceived to be a financially and technologically risky development. In countries such as Sweden and West Germany, state actors had great difficulty in getting power companies on board, and when these eventually showed greater enthusiasm they chose to invest in variants of nuclear technology that differed radically from those that featured most prominently in the state's visions.[20]

However, for these early nuclear power ventures, we must remember that it was in commercial actors' self-interest to highlight – and exaggerate – technical and economic difficulties, as these could be used to justify public funding for research and development.

In terms of future expectations, the years around 1960 were a pessimistic period. There was talk of an 'atomic ice age', marked by frustration at the lack of a commercial breakthrough, one many people had expected after the optimism of the 1950s. Observers instead designated nuclear power a failed technology; "What has gone wrong with nuclear power?" asked the *Financial Times* in a widely circulated article in 1962.[21] The very next year, however, hopes for the future were revived when Jersey Central Power & Light, a US power company, announced that it had ordered a complete, large-scale nuclear power plant from General Electric at the surprisingly low price of $66 million. Shortly afterwards, a competitor, Westinghouse, sold a nuclear power plant of the same size at a similarly low price.[22] Word was spreading that nuclear power had become competitive with coal and oil.

This breakthrough had a profound impact on further global development, particularly regarding the power companies' technological choices. Both American manufacturers' reactor models were based on light-water technology and, as we have already seen, this type of reactor became completely dominant in the years that followed. One effect of this was that other reactor types came to be seen as failures, including the Swedish heavy-water reactors, which had formed the backbone of the Swedish nuclear power programme since the late 1940s. In 1969, the Swedish government decided that the heavy-water plant in Marviken, which had already been completed, should not start operations. The reactor was considered less economical and less safe than light-water reactors. Abandoning it meant a huge loss of prestige for the 'Swedish line' and was naturally interpreted as an exceptional waste of taxpayers' money. At that time, a considerable proportion of the total Swedish research budget was ploughed into nuclear research, most of which went to the development of heavy-water technology. Marviken's fate was therefore a trauma that foreshadowed the hard-drawn politicisation of nuclear power in Sweden in the 1970s.[23] Nevertheless, Sweden became one of the countries that made the biggest investments in the expansion of large-scale nuclear power. Both state-owned Vattenfall and regional actors were caught up in an expansive international trend. When they found that light-water technology worked and construction costs were affordable, they concluded that even more reactors could be built, boosting optimism about the future. In many countries, governments and power companies predicted exponential growth for nuclear power at a time of steadily increasing electricity consumption. The US Atomic Energy Commission predicted that the United States would have no fewer than a thousand reactors operating by the year 2000.[24]

The West German government expected nuclear power to provide around 85 per cent of the country's total energy needs in the long term.[25] And, in Sweden, a total of 24 large reactors were planned in the early 1970s. Energy experts increasingly envisioned a future in which nuclear power would be completely dominant.

In Sweden, that vision was to some extent realised, with twelve large reactors commissioned between 1972 and 1985. Nuclear power accounted for around half of the country's total electricity production. France became the most nuclear-dependent country of all, following massive government investment in the wake of the 1973 oil crisis; by the end of the century, no less than 75 per cent of the French electricity supply was nuclear. However, from a global perspective, Sweden and France were the exceptions. In most countries, nuclear power was never anywhere near to becoming dominant, and many countries chose not to invest in nuclear technology at all. In Western Europe, this included Denmark and Norway, as well as Austria, Portugal, Greece and the Republic of Ireland.

Most strikingly, nuclear power did not spread at all, or at least only marginally, in the Global South. In the 1950s and 1960s, in parallel with the decolonisation of Africa and Asia, there were high hopes that nuclear power would help the rapid transformation of former colonies into modern industrial nations.[26] By the 1970s, countries such as South Korea, Taiwan, Brazil, Argentina, Mexico, South

Africa and Iran had built or begun to build their first large-scale nuclear power plants, and nuclear visionaries anticipated that these pioneering projects would be followed by others.

This never happened. In 1976, the International Atomic Energy Agency (IAEA), predicted that after "a relatively slow start", nuclear power would "go ahead fast in the Latin American region in the 1980's and 1990's".[27] However, in reality, neither Latin America nor other countries in the poorer regions of the world – except East Asia – came to base their energy provision on nuclear power to any great extent. Nuclear power now provides around 10 per cent of the world's electricity needs, and this share is falling. In the world's two largest countries, India and China, it stands at 2 and 5 per cent respectively. If we calculate nuclear power's contribution to the primary energy supply, including all forms of energy and not just electricity, its share remains 4 per cent.[28] For the analysts and visionaries who once predicted that nuclear power would become a globally dominant energy source, this is a disappointing outcome.

Combining the exceptional with the banal

So, why did nuclear power not become a globally dominant source of energy? To understand this, we need to examine not only the now well-known political controversies surrounding it, but also its internal technical dilemmas.

The first and biggest challenge for designers of nuclear power plants was bringing together two very different technological traditions: working with atomic bombs on the one hand, and conventional power plant technology on the other. The atomic bomb had been created under exceptional circumstances and was unlike anything humanity had previously achieved; accelerated research in physics and chemistry had been combined with tough military leadership. For its part, conventional power plant technology was ubiquitous in Western industrial societies – commonplace engineering rooted in James Watt's eighteenth-century steam engine. The challenge was finding a viable way of merging these very different technologies. Nowadays, nuclear engineers jokingly, but not entirely incorrectly, refer to nuclear power plants as a type of nuclear-powered steam engine; the difference between a fossil-fuel power plant and a nuclear power plant is 'just' that the latter utilises uranium to generate heat and steam, while coal, oil and gas power plants are based on the combustion of fossil fuels.[29] This analogy is strengthened by the now established concept of 'nuclear fuel', which misleadingly conveys the idea that uranium is a material that can be burnt.

In reality, combining the experiences of producing nuclear weapons with those from the established art of building coal-fired power plants presented considerable difficulties, which explains why two decades passed between the dropping of the first atomic bomb and the commercial breakthrough of nuclear power. These fields of knowledge – nuclear physics and power plant construction – had their own professional communities, and they were radically different, particularly in countries where nuclear weapons' development took priority over civilian nuclear power. The two communities found it difficult to interact at all, as the military technology was subject to the highest level of secrecy. For nuclear physicists, the challenges of power plant technology were generally of secondary interest or, quite simply, of no interest at all due to their apparent banality, which resulted in them being underestimated. Power companies that showed an early interest in nuclear power downplayed the differences between a nuclear reactor as a heat source and a traditional steam boiler. In the 1950s, companies with experience in fossil fuel power plant construction often undertook the construction of the 'conventional' part of a nuclear power plant without making more than marginal adjustments to the drawings. Eventually, both professional communities came to recognise that the synthesis of atoms and coal posed unique problems and unexpected phenomena, and so required a new form of engineering.

The most important insight concerned what came to be called 'decay heat'. A nuclear reactor generates most of its heat through fission, which is the splitting of atomic nuclei. Fission products, such as caesium-137 and strontium-90, are unstable and decay into more stable states. This process generates heat which, in normal operations, can be converted into steam and thus contribute to the nuclear power plant's functioning. The problem is that the decay heat cannot be fully controlled; it is unstoppable, so heat continues developing for a long time, even after a reactor has been shut down. If, in such situations, the heat is not removed, the reactor may suffer a meltdown. The engineers concluded that the cooling water pumps must remain functional in every possible circumstance, including under severe earthquake conditions, floods or aeroplane accidents. In other words, the flow of cooling water must never stop. This insight resulted in additional systems being designed, ones with no real counterpart in fossil-fuel power generation, and for which the need was not initially foreseen. An emergency cooling system was needed as it was thought that this could come to the rescue if the regular cooling water pumps stopped working. A secure power supply also became imperative in all possible situations, and this usually led to the installation of diesel generators that could run the water pumps in the event of an external power outage. The origin of the Chernobyl disaster was an experiment that, ironically, was intended to improve safety along these lines.[30]

Moreover, the realisation that a nuclear accident could have enormous consequences resulted in requirements for materials and components that were as perfect as possible. Nuclear power needed to be protected from contaminants in the cooling water and in the alloys used to make fuel elements, pipes and valves. One undesirable consequence of this was a significant increase in the cost of nuclear power plant construction, compared to constructing fossil fuel power plants that did not require such a high level of purity. For example, a valve in a nuclear power plant's cooling system could be four times as expensive as the equivalent valve in a coal-fired power plant.[31]

We are now seeing the results of nuclear power's increased price tag, as many of the nuclear power plants being built are on the list of the world's most expensive buildings. This is as far as we can get from the hopes that nuclear power would be “too cheap to meter”, reflecting the atom’s failure to live up to the high expectations placed upon it.

Useful accidents

Despite emergency cooling systems, sophisticated safety components and exclusive material choices, many nuclear power plants have suffered incidents, accidents and, in the cases of Chernobyl and Fukushima, full-scale disasters. It is tempting to interpret such events as evidence that nuclear power is a failed technology. The most serious accidents which, more than anything else, exemplify nuclear technology's undesirable consequences, have undoubtedly strengthened the anti-nuclear movement and, in many countries, contributed to a critical attitude towards nuclear technology.

However, if we examine how engineers approached nuclear technology in its infancy, in the 1950s and 1960s, we see how nuclear accidents were not only regarded as problems. Quite the opposite, many observers interpreted them as natural elements of a longer historical development process, in which unforeseen and unwanted events created opportunities for improving the technology. In this respect, nuclear technology is not very different from other technological fields: its engineers are simply working in the tradition of trial and error. Things going wrong along the way thus turn into something positive.

One interesting example is the US National Reactor Testing Station, founded in 1950 by the Atomic Energy Commission for testing different types of reactors. The station was located in a sparsely populated area of Idaho, because it was believed there could well be a major accident. Over the years, several of the test station's reactors did indeed suffer a number of accidents, but this was not considered problematic. On the contrary, the scientists and engineers involved in the tests were very happy with the way these accidents contributed to knowledge development. In extreme cases, they even tested the reactors' resilience by deliberately placing so much stress on them that they were eventually destroyed. This was seen as a creative way to improve the understanding of the technology, allowing completely safe and efficient nuclear power plants to be built in the future.[32]

Similarly, the nuclear accidents at Three Mile Island, Chernobyl and Fukushima have aroused a kind of paradoxical enthusiasm among nuclear professionals, because they exposed shortcomings that they were able to address in inventive ways, precisely because of these accidents. By extension, this has created a consensus within the nuclear industry that the accidents and the lessons learned from them have made nuclear power safer. The flip side of this development is, once again, that the technical solutions have often proved costly, so helping make nuclear power increasingly expensive and less competitive than other energy sources. They have also made nuclear power increasingly complex, with new safety systems gradually being added to old ones, which can be interpreted as a problem in its own right.

Generations of nuclear power

A favourite topic when researching nuclear history has long been the fierce competition between different reactor types. In Sweden, as we have seen, the heavy-water reactor was outcompeted by the light-water reactor. West Germany saw a similar trend. In France, the state nuclear agency CEA's investments in graphite-moderated and gas-cooled reactors did not survive the competition with US-style light-water reactors, which were favoured by the state electricity company, Électricité de France (EDF). In the UK, on the other hand, the domestically designed gas-graphite reactors managed to hold their own against the light-water reactor for a long time.

Historically, all these reactor types – the light-water reactor, the heavy-water reactor and the gas-graphite reactor – have been considered relatively similar in their operation, as they are all based on the utilisation of a 'thermal' neutron flux. The neutrons are slowed down by a moderator – the water or graphite in the reactor – which is the easiest way of achieving a chain reaction. However, this has some fundamental disadvantages. Just a small part of the uranium in the nuclear fuel can be used for fission; only the directly fissile isotope U-235 is utilised, while the much more common isotope U-238, which comprises 99 per cent of all naturally occurring uranium, is unusable. Leading physicists and nuclear engineers were unhappy about this and, even in the 1950s, disparaged thermal reactors for being 'primitive'.[33]

The first reactor constructed in the US reactor park in Idaho was radically different. An AEC nuclear physicist, Walter Zinn, had decided to demonstrate how a more advanced type of reactor could convert non-fissile U-238 into fissile plutonium-239, using a process that has come to be known as breeding.[34] The plutonium is the basis for the production of new nuclear fuel, so the 'breeder reactor' could, in theory, utilise the uranium up to a hundred times better than thermal reactors. This vision quickly spread to other countries, including Sweden, whose breeder reactor history is analysed in detail in Maja Fjæstad's excellent doctoral thesis.[35] Internationally, consensus grew that it was only a matter of time before thermal reactors would be replaced by breeder reactors. In this context, the visionaries started to refer to the 'primitive' thermal reactors as the 'first generation' of nuclear power, while the future breeder reactors were classified as the 'second generation'.

In parallel, research was underway into nuclear fusion, and hopes were high – most people were convinced that fusion reactors would be built in the not-too-distant future, albeit at a later stage than breeder reactors. In these projected futures, fusion reactors were therefore categorised as nuclear power's 'third generation'.[36]

However, 70 years later, breeder reactors represent only about 1 per cent of the nearly 500 large-scale reactors to have been built. No fusion reactors have started operating. The breeder reactors that were built proved to be difficult to manage, with several suffering serious accidents. From the 1970s, more and more countries abandoned their breeder projects. As a result, the nuclear industry remained focused on the 'primitive' reactors of the first generation. Nuclear power operators have not managed to progress, in the way once taken for granted, from first to second and third generation nuclear power.

However, developments over the past 25 years demonstrate how the concept of generations in nuclear energy is flexible. In 1998, the US initiated a revitalisation of nuclear power, seeking cooperation with other pro-nuclear countries.[37] After a lull in the wake of the 1979 and 1986 disasters, nuclear power was predicted to undergo a renaissance in the twenty-first century. In this context, there was a revival of interest in the advanced reactor types that had featured prominently in the nuclear visions of the 1950s and 1960s, including several variants on the breeder reactor. The most enthusiastic countries came together in 2000, in what became known as the Generation IV

Forum, which launched a new approach to nuclear power's generations. The thermal reactors that still dominated the world, and were previously considered the first generation of nuclear power, were split into three 'new' generations: the pilot projects of the 1950s became Generation I, the larger-scale projects that followed from the mid-1960s became Generation II, and the newest and most modern thermal reactors were grouped into Generation III. The breeder reactors, which previously constituted second-generation nuclear power, were upgraded (along with several other reactor types) to Generation IV. This allowed the visionaries to free themselves from the gloomy conclusion that they were still stuck with nuclear power's first generation. The aim was to avoid a sense of failure, which could have inhibited enthusiasm about the future.[38] In the 2020s, however, the concept of 'fourth generation nuclear power' has been overshadowed by the focus on small modular reactors, including innumerable tentative models for reactors of both the well-known thermal type and more untested variants, such as the Swedish-developed SEALER reactor, which is non-thermal and lead-cooled.[39]

The rise and fall of the nuclear fuel cycle

Breeder reactors are closely linked to another important theme in nuclear energy history: the nuclear fuel cycle. This is a utopian concept inspired by nineteenth-century visions of a circular economy, championed by leading scientists like the German chemist Justus von Liebig.[40] A closer source of inspiration was the modern chemical industry, with its astonishing ability to recycle residues and turn them into valuable resources in an almost-closed system.[41] In the early days of nuclear technology, when the world's uranium resources were believed to be limited, the temptation was to develop technologies that would allow spent nuclear fuel to be reused. In breeder reactors, the depleted uranium, consisting of the non-fissile isotope U-238, which was available in large quantities as waste from enrichment plants (both military and civilian), would be used for energy production. Breeder reactors were also designed to 'burn' the plutonium that formed in thermal reactors.[42] However, to remove the plutonium and the remaining non-fissile uranium from the thermal reactors' spent fuel, the fuel elements must be reprocessed

– a complex radiochemical process in which the spent fuel is dissolved in large acid baths, after which the various elements are separated out.

In the early stages of nuclear power, it was generally taken for granted that all spent nuclear fuel would undergo reprocessing. Overall, thermal nuclear power plants were regarded as just one component among many, in an advanced system through which nuclear fuel circulated in a variety of forms. All the nations with nuclear ambitions planned to build reprocessing plants, including Sweden, where the intention was to build one on the west coast. However, similarly to breeder reactors, these reprocessing visions proved difficult to implement in practice. Unforeseen problems arose, not least in terms of waste management, as the reprocessing created huge quantities of liquid radioactive waste. Initially, attempts were made to deal with this by dumping the waste at sea; it is no coincidence that both the British and French reprocessing plants were constructed on the coast, where special pipelines carried waste out to the ocean currents. But, over time, the public and regulators alike became increasingly concerned about the safety of such arrangements and about their impact on the environment. By the 1970s, releasing radioactive waste into the environment had become unacceptable. In parallel, the world's uranium reserves turned out to be larger than expected, questioning the very idea of the need for reprocessing and a circular nuclear economy.

Concerns that plutonium from reprocessing plants would fall into the wrong hands and be used for military purposes also made this technology appear risky. In 1977, the United States decided that its spent nuclear fuel would no longer be reprocessed but would instead be disposed of directly – buried in the ground without undergoing any reprocessing, although it remained unclear where such a disposal site could be located. Other countries, such as Sweden and Finland, followed suit, although it was painful for nuclear power enthusiasts to abandon their apparently elegant vision of a closed nuclear fuel cycle.[43] Today, only a few countries continue to reprocess their spent nuclear fuel. Overall, we can conclude that the attempts to achieve a circular economy for nuclear power have failed.

Epilogue

So, is nuclear power a failed technology? There are many possible ways to answer this question. It may seem counter-intuitive to point to nuclear power as a failure in countries like Sweden and France, where it accounts for a very large – in France, a completely dominant – share of electricity generation. And the nuclear industry remains proud of its achievements; from its perspective, nuclear power is by no means a failed technology, rather a misunderstood one. On the other hand, if we look back at the grandiose original visions of nuclear power's role in energy provision and the wider development of society, and compare them with the outcome, we find that development was unequivocally bleak. What emerges are broken dreams, repeated disappointments and frustration with the unforeseen consequences of nuclear technology. The question is whether nuclear power, in the future, can turn this trend around.

Notes

The figure on p. 19 is a graph based on data from IAEA, *Nuclear Power Reactors* in *the World 2022*, Vienna: IAEA, 2022.

1. This story has been told in numerous works on the history of science and technology. See, e.g., Richard Rhodes, *The Making of the Atomic Bomb*, New York: Simon & Schuster, 1986; David Holloway, *Stalin and the Bomb: The Soviet Union and Atomic Energy 1939–1956*, New Haven: Yale University Press, 1994.

2. The competition or rivalry between different types of reactors is one of nuclear historians' favourite topics. See, e.g., Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity after World War II*, Cambridge, MA: MIT Press, 1998; Joachim Radkau, *Aufstieg und Krise der deutschen Atomwirtschaft 1945–1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse*, Reinbek bei Hamburg: Rowohlt, 1983; Sonja Schmid, *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry*, Cambridge, MA: MIT Press, 2015.

3. For a statistical overview, I recommend the IAEA's annual publication, *Nuclear Power Reactors in the World*, which is available on the internet and contains historical data for all commercial nuclear power plants: www.iaea.org/publications/15485/nuclear-power-reactors-in-the-world.

4. See, e.g., John McNeill & Peter Engelke, *The Great Acceleration: An Environmental History of the Anthropocene*, Cambridge, MA: Harvard University Press, 2016.

5. The figures here are based on IAEA, *Nuclear Power Reactors in the World 2022*, Vienna: IAEA, 2022. I have included all Western European countries and all of Central Europe including the Baltic States, but not Russia, Ukraine and Belarus, in my calculation.

6. Leon Trotsky, *Problems of Everyday Life, and other Writings on Culture & Science*, New York: Monad, 1973.

7. See, e.g., George T. Mazuzan & J. Samuel Walker, *Controlling the Atom: The Beginnings of Nuclear Regulation 1946–1962*, Berkeley: University of California Press, 1984.

8. See, e.g., C. N. Hill, *An Atomic Empire: A Technical History of the Rise and Fall of the British Atomic Energy Programme*, London: Imperial College Press, 2013; Radkau 1983.

9. Steven L. Del Sesto, "Wasn't the future of nuclear energy wonderful?", in Joseph J. Corn (ed.), *Imagining Tomorrow: History, Technology, and the American Future*, Cambridge, MA: MIT Press, 1987, pp. 58–76; Dick Van Lente (ed.), *The Nuclear Age in Popular Media: A Transnational History, 1945–1965*, New York: Palgrave Macmillan, 2012.

10. Richard Hewlett & Francis Duncan, *Nuclear Navy, 1946–1962*, Chicago: University of Chicago Press, 1974; Paul R. Josephson, *Red Atom: Russia's Nuclear Power Program from Stalin to Today*, Pittsburgh: University of Pittsburgh Press, 2000; Radkau 1983.

11. Hewlett & Duncan 1974; Radkau 1983; Schmid 2015.

12. Magdalena Tafvelin Heldner, Per Lundgren & Eva Dahlström Rittsél, *Ågesta: Kärnkraft som kulturarv*, Stockholm: Tekniska museet, 2008.

13. "Fjärrvärme från Forsmark", report by Storstockholms Energi AB (STOSEB) and Vattenfall, 28 November 1980.

14. See, e.g., Per Högselius, *Die deutsch-deutsche Geschichte des Kernkraftwerkes Greifswald: Atomenergie zwischen Ost und West*, Berlin: Berliner Wissenschafts-Verlag, 2005.

15. Per Högselius & Achim Klüppelberg, *The Soviet Nuclear Archipelago: A Historical Geography of Atomic-Powered Communism*, Budapest:

Central European University Press, 2024.

16. See, e.g., Joe Tidd, John Bessant & Keith Pavitt, *Managing Innovation: Integrating Technological, Market and Organizational Change*, Hoboken: Wiley, 2005.

17. Josephson 2000; Hill 2013.

18. "Remarks prepared by Lewis L. Strauss, Chairman of the United States Atomic Energy Commission, For Delivery at the Founders' Day Dinner, National Association of Science Writers, on Thursday, September 16, 1954, New York", US Nuclear Regulatory Commission, www. nrc.gov/docs/ML1613/ML16131A120.pdf.

19. Thomas Wellock, "Too cheap to meter: The history of a phrase", US Nuclear Regulatory Commission, 3 June 2016, https://public-blog. nrc-gateway.gov/2016/06/03/too-cheap-to-meter-a-history-of-the-phrase/.

20. Jonas Anshelm, *Mellan frälsning och domedag: Om kärnkraftens politiska idéhistoria i Sverige 1945–1999*, Stockholm: Symposion, 2000; Radkau 1983.

21. "What has gone wrong with nuclear power?", *Financial Times*, 16 March 1962.

22. Thomas Wellock, *Safe Enough? A History of Nuclear Power and Accident Risk*, Oakland: University of California Press, 2021, p. 15.

23. Anshelm 2000.

24. Wellock 2021, p. 51.

25. Stephen G. Gross & Andrew Needham (eds.), *New Energies: A History of Energy Transitions in Europe and North America,* Pittsburgh: University of Pittsburgh Press, 2023.

26. See, e.g., Jacob Darwin Hamblin, *The Wretched Atom: America's Global Gamble with Peaceful Nuclear Technology*, Oxford: Oxford University Press, 2021.

27. "Latin America and nuclear energy", *IAEA Bulletin* vol. 18, no. 3–4, pp. 19–20. www.iaea.org/sites/default/files/183_404701920.pdf.

28. See, e.g., "BP Statistical Review of World Energy 2022", p. 10,

www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2022-full-report.pdf.

29. See, e.g., James Mahaffey, *Atomic Accidents: A History of Nuclear Meltdowns and Disasters, from the Ozark Mountains to Fukushima*, New York: Pegasus Books, 2014.

30. Per Högselius, "Atomic shocks of the old: Putting water at the center of nuclear energy history", *Technology and Culture* vol. 63, no. 1, 2022, pp. 1–30.

31. Wellock 2021, p. 191.

32. Susan M. Stacy, *Proving the Principle: A History of the Idaho National Engineering and Environmental Laboratory, 1949–1999*, Idaho Falls: Idaho Operations Office of the Department of Energy, 2000.

33. Per Högselius, "Das Neue aufrechterhalten: Die Neue Kernenergie in historischer Perspektive", in Christian Kehrt, Peter Schüssler & Marc-Denis Weitze (eds.), *Neue Technologien in der Gesellschaft: Actors, expectations, controversies and economic cycles*, Bielefeld: Transcript, 2011.

34. Mazuzan & Walker 1984.

35. Maja Fjæstad, *Visionen om outtömlig energi: Bridreaktorn i svensk kärnkraftshistoria, 1945–1980*, Hedemora: Gidlunds, 2010.

36. Radkau 1983.

37. Wellock 2021.

38. Högselius 2011.

39. See https://blykalla.com/.

40. See, e.g., Joachim Radkau, *Nature and Power: A Global History of the Environment*, New York: Cambridge University Press, 2008.

41. Cf. Per Högselius, Arne Kaijser & Erik van der Vleuten, *Europe's Infrastructure Transition: Economy, War, Nature,* Basingstoke & New York: Palgrave Macmillan, 2016.

42. Fjæstad 2010.

43. Per Högselius, "Spent nuclear fuel policies in historical perspective: An international comparison", *Energy Policy* vol. 37, no. 1, 2009, pp. 254–263.

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RJ 2024

Failures?

Editor: Jenny Björkman

Nuclear power: destructive and dangerous, but also productive and helpful. That was the case in the 1970s, and remains so today. The dream of clean and stable nuclear power emerged back in the science fiction literature of the early twentieth century and, during the Western nuclear age, fiction seemed to become reality. Nuclear power's contribution to energy supplies grew rapidly, and Sweden became one of the countries that invested most in large-scale nuclear power expansion.

In recent decades, nuclear power has stagnated and the number of reactors is steadily decreasing. Still, many hope that nuclear power will make a comeback; it has become safer – but also more expensive.

In 2024, Riksbankens Jubileumsfond publishes an essay collection under the title *Failures?*. Historian of technology Per Högselius discusses nuclear power as both a threat and an opportunity.

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