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Nuclear Power in the Twenty-first Century (Part II) - The economic value of plutonium

Christian von Hirschhausen[1]

Abstract

Although plutonium has been studied by different disciplines (such as technology and innovation studies, political sciences) since its discovery, back in 1940 at the University of California (Berkeley), the resource and environmental economic literature is still relatively scarce; neither does the energy economic literature on nuclear power consider plutonium specifically, e.g. Davis (2012) or Lévêque (2014). However, interest in the topic is increasing, driven by a variety of factors: Thus, in the context of the low-carbon energy transformation and climate change mitigation, interest in non-light-water nuclear technology, including so-called "Generation IV" fast neutron reactor concepts and SMR ("small modular reactors") non-light-water reactor concepts, supposedly to become competitive in some near time span, is rising, not only in Russia and China, but also in the US, Japan, Korea, and Europe (IAEA 2018; MIT 2018; Zhang 2020; Murakami 2021). This paper provides a review of resource and environmental economic issues related to plutonium, and presents insights from ongoing research. In particular, we ask whether after decades of unsuccessful attempts to use plutonium for electricity generation in the 20th cenutry, resource and energy economic conditions have changed sufficiently to reverse this result in the 21st century. In the analytical framework, we explore determinants of the value of plutonium, by comparing it with the economics of the dominant nuclear energy, the light-water reactor (LWR) using a once-through fuel process. Three questions emerge and are addressed subsequently: i/ Can plutonium benefit from shortages of uraniumand binding constraints on uranium supply for light-water nuclear power plants?; ii/ can future nuclear reactors developments become competitive through standardized mass production of SMRs ("small modular reactors"); and iii/ can plutonium be efficiently abated? We find that the answer to the three questions is negative, and conclude that there are no indications of more favorable economic conditions for the commercial deployment of plutonium today than there were in the last cenutry.

Keywords: nuclear power, uranium, plutonium, resources, economics, technology, innovation

JEL-codes: O33, Q53, Q47, L97

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1 Introduction

Although plutonium has been studied by different disciplines (such as technology and innovation studies, political sciences) since its discovery, back in 1940 at the University of California (Berkeley), the resource and environmental economic literature is still relatively scarce; neither does the energy economic literature on nuclear power consider plutonium specifically, e.g. Davis (2012) or Lévêque (2014). However, interest in the topic is increasing, driven by a variety of factors: Thus, in the context of the low-carbon energy transformation and climate change mitigation, consideration for nuclear technology, including so-called "Generation IV" fast neutron reactor concepts and SMR ("small modular reactors") non-light-water concepts, supposedly to become competitive at some point in time, is rising (IAEA 2017, 2018). In particular, Russia and China are currently developing their fuel cycles quite ambitiously, with a reactor (CFR 600) and two new nuclear fuel reprocessing facilities in China (Bunn, Zhang, and Kang 2016), and one new breeder reactor (BN 800 at Beloyarsk-4, online since 2015) and one in planning (BN 1200) in Russia (IAEA PRIS Database). Other countries are pursuing reprocessing of plutonium (Japan) or are considering it (Korea, USA). Plutonium is also an important resource for space missions (through radioisotope thermoelectric generators, RTGs), boosting interest in the start-up scene in the US and elsewhere (Gates 2021). Last but not least, research is emerging on the reduction of plutonium from the existing stockpiles through a process of partitioning and transmutation, sometimes called "plutonium burning" (MIT 2018, 82).

The recent interest in plutonium and the fast neutron reactors that both produce and use large quantities of plutonium can also be explained by structural changes in the nuclear industry. To some extent, it recalls the 1940s/50s, when the plutonium route was considered to become the pathway to roll out commercial nuclear power, as a low-cost by-product of nuclear weapons (Szilard 1947; Strauss 1954). Therefore, the current debates very much resemble those in the early years of nuclear power. Back then, fast reactors were considered the natural pathway forward, and to solve "civilization's energy problems for millennia" (von Hippel, Takubo, and Kang 2019, 2). Today, considerations of the plutonium economy are coming back, because the dominant form of using nuclear energy, the once-through fuel light water reactor based on uranium, has not become economically competitive in any energy system (Davis 2012; MIT 2003, 2018; Wealer et al. 2021). Alternatives are now being explored, under the heading of the "Generation IV International Forum" (GIF), supposed to develop successful replacements for the Generation III reactors currently in the market. The GIF has a special focus on fast reactors, and among them, "the sodium-cooled reactor is considered the most technically advanced of the Generation IV reactors." (Frieß et al. 2021, 31).

After decades of unsuccessful attempts to use plutonium for electricity generation, have resource and energy economic conditions changed sufficiently to reverse this trend?

In this paper, we reconsider economic issues related to plutonium, and present insights from ongoing research by the author and the research group, amongst others on the economics of nuclear power (Wealer and Hirschhausen 2020; Wealer et al. 2021), and on the technical developments in the context of the Generation IV developments, including SMR-reactors ("small modular reactors") under development (Pistner et al. 2021). We take the environmental dangers and security issues (proliferation) as given and only explore the resource and energy economic aspects, comparing them with non-light

water-cooled nuclear power. After a brief recap of the physical and technical basics (Section 2), Section 3 provides a survey of the development of plutonium, and then sketches out an analytical framework, i.e. an economics comparison between the role of the traditional nuclear energy, the light-water reactor (LWR) using a once-through fuel process, with the plutonium route using a fast reactor with plutonium reprocessing. Until now, the plutonium route has not been able to establish itself as an economic form of electricity, due to technical problems, security issues (proliferation) and subsequently high costs. Each of the Section 4 to 6 then address one part of the value chain, and whether these could change the relative economics going forward, i.e. in favor of plutonium breeding and burning:

- In Section 4 we analyze whether resource economic foundations have changed that would make the use of plutonium economic vis-à-vis its backstop resource, natural uranium.
- In Section 5 we analyze recent trends in SMR ("small modular reactors") with low capacities (< 300 MW_{el}) including reactors based on a fast neutron spectrum, checking under which conditions these innovations might become competitive with existing nuclear facilities.
- In Section 6, we discuss options to abate plutonium, through processes of partitioning and transmutation, and whether these provide an option to reduce the negative environmental impact, or, eventually, even combine it with additional energy production.

The last section concludes and provides a research outlook.[2]

2 Background

In this section, we provide an overview of the physical and technical basics of plutonium that allows us to identify some relevant research questions. Within the nuclear industry, plutonium plays a very specific role: It is the only element that can contribute to large-scale energy production by generating new fuel from spent fuel (uranium 238) through a process called "breeding". This comes with additional environmental and economic costs, though.

2.1 Pu-239

Plutonium (Pu) is a heavy metal with 94 protons in the core, and consists of notoriously unstable phases with temperature, pressure, chemical additions and time (Morss et al. 2006, 814). It sits near middle of the family of actinides, i.e. heavy metals with an atomic number of 89 (actinide) and above, which are spontaneously inflammable in contact with air. Plutonium is a so-called "trans-uranium" element, i.e.

[2] This paper is an output of a transdisciplinary research project on nuclear waste disposal in Germany ("TRANSENS"), funded by the Federal Ministry for Economic Affairs and Energy (BMUV) and the Volkswagen Foundation on behalf of the Ministry for Science and Culture of Lower Saxony (NMWK); it is inserted into a larger research program on nuclear power carried out jointly by DIW Berlin (German Institute for Economic Research), and Berlin University of Technology (TU Berlin). Thanks to Björn Steigerwald for research assistance, and Ben Wealer, Joachim Schleich, and Anne Neumann for comments, as well as discussions with participants in the DIW Brown Bag Seminar (July 2021), the Committee for Environmental and Resource Economics of the German Verein für Socialpolitik, (AURÖ) (September 2021), the University of Cambridge Electricity Policy Research Group (EPRG) Energy & Environment Seminar Programme (February 2022), the TRANSENS-ITAS Research Seminar on Nuclear Waste Management (February 2022), and the DTU Nordic PhD Workshop (June 2022). The title of the paper ("Nuclear power in the 21nd century – Part II") refers to a "Part I", assessing the 2nd nuclear age, geopolitical conflicts, and other topics, published as DIW Discussion Paper 1700 (von Hirschhausen 2017). The usual disclaimer applies.

heavier than the heaviest naturally occurring chemical product, uranium (with an atomic number of 92 protons).

Plutonium emerges in the process of nuclear fission of enriched uranium (e.g. 3-5% of uranium-235) with thermal ("slow") neutrons. About 1% of the original uranium is converted to plutonium, mainly plutonium-239, plus some other isotopes such as Pu-238, Pu-240, Pu-244. Pu-239, by far the most commonly produced isotope, has a half-life of more than 24,000 years, and thus, is very long lived (Lucas, Noyce, and Coursey 1978, 501).

Plutonium can be generated in much larger quantities when "fast" neutrons (not moderated) fission uranium-238, which makes up 99.7% of uranium and is not fissionable with thermal neutrons (Neles and Pistner 2012, 38). This process includes several steps by which fast neutrons fission uranium-238, through which it becomes plutonium-239, via several steps, including the formation of neptunium and two beta decays; here, too a smaller share of even higher isotopes (Pu-240, Pu-241, and Pu-242) occurs (Neles and Pistner 2012, 37):

$$^{238}_{92}U + ^{1}_{0}n \rightarrow ^{239}_{92}U \rightarrow ^{239}_{93}Np + \beta^{-} \rightarrow ^{239}_{94}Pu + 2\beta^{-}$$

Provided a sufficient flow of neutrons, more plutonium can be generated than is used as fuel, a process called "breeding". The opposite process is called "burning": "If the ratio of final to fissile content is less than one, the reactors are burners, consuming more fissile material (U-235, Pu, and minor actinides) than they produce (fissile Pu)" (WNA 2021). Both processes require complex reprocessing facilities to separate the transuranium metals from each other and the rest of the material.

The research team of Glen Seaborg and Edwin McMillan isolated plutonium for the first time, on Dec. 14, 1940, by deuteron bombardment of uranium in the cyclotron at the University of California at Berkeley. This research was continued in the context of the Manhattan Project, including work at the University of Chicago, by Enrico Fermi and Leo Szilard to develop nuclear weaponry to be used in World War II. The first nuclear test, July 16 1945, used plutonium as fuel, as did the nuclear bomb on Nagasaki, August 9, 1945.[3]

2.2 Plutonium in the nuclear power system

2.2.1 The system good nuclear power

The nuclear power sector consists of a front-end (mining and processing, enrichment, fuel fabrication), the nuclear power plant itself, and a back-end (reprocessing, interim storage, final disposal) (Figure 1).[4] In addition, (high-level) uranium and plutonium are used for the production of nuclear weapons (step J in Figure 1). Within that system, plutonium plays a critical role in the development of specific nuclear power plants (E.), e.g. fast neutron reactors, the reprocessing (I.), and the subsequent reuse for fuel fabrication in the form of mixed uranium-plutonium-oxide fuel (MOX-fuels) (C.). Plutonium also poses

[3] The other weapon-grade fuel developed was highly enriched uranium (HEU), which was used in the Hiroshima bombing, August 6, 1945.

[4] For a general system analysis of the nuclear industry see (Rothwell 2016; Wealer and Hirschhausen 2020).

specific challenges to interim storage and final disposal, due to the long half-life (24,000 years) and the high activity of its fission products (technetium, iodine, cesium, G. and H).

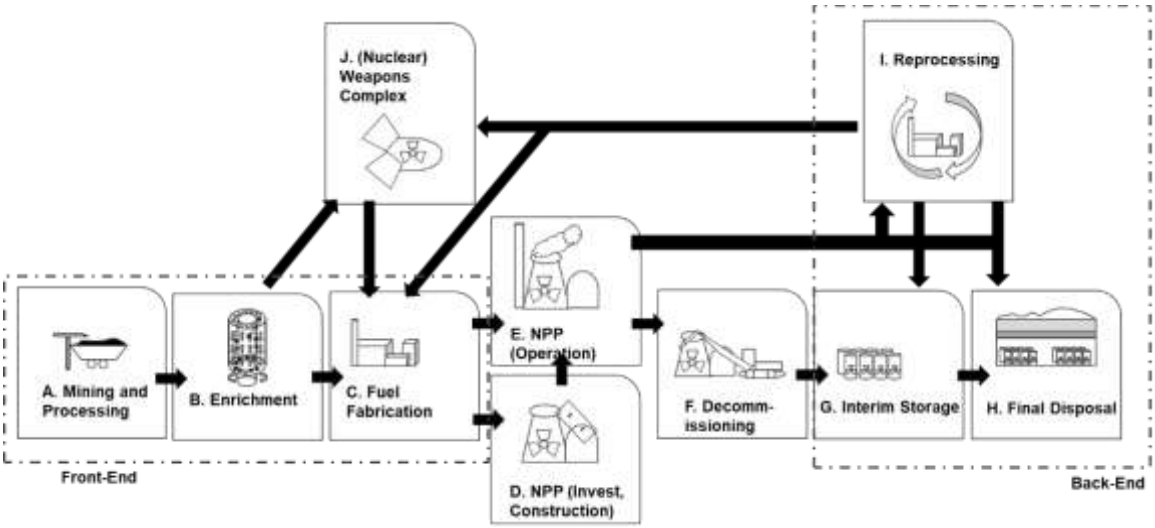

Figure 1: The system good nuclear power

Source: (Wealer and Hirschhausen 2020, 13).

2.2.2 Two common designs for nuclear energy production

2.2.2.1 Light water reactor (LWR) and the once-through fuel process

In the light-water reactor, uranium-235 is split, and the uranium-238 catches some neutrons that generate the plutonium-239. In what has become the dominant way of generating electricity, the spent fuel is put in water pools ("spent fuel pools") on site, to be cooled for about 5-10 years, after which it is placed in interim storage (~ 20-40 years), and should then be placed in a geological repository. This is called the "once-through" process (Figure 2).

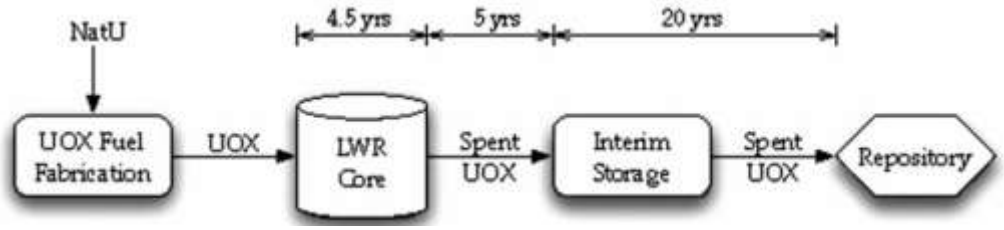

Figure 2: The once-through process

Source: DeRoo et al. (2011, 827).

2.2.2.2 Fast reactor (FR) and plutonium processing

The specifics of plutonium consist of the fact that it can be used to generate additional fuel, theoretically generating up to 60 -100 times more heat than the once-through fuel process. This requires the reprocessing of the plutonium-containing spent fuel, the fabrication of a specific mixed-oxide (MOX) uranium-plutonium fuel for the fast reactor, the neutron chain reaction in a fast reactor, and subsequent reprocessing (Figure 3). This is called the "fast reactor route/cycle", we will also refer to it as the

"plutonium route". Thus, in addition to the fast reactor, a specific piece of equipment is required, the reprocessing plant.[5]

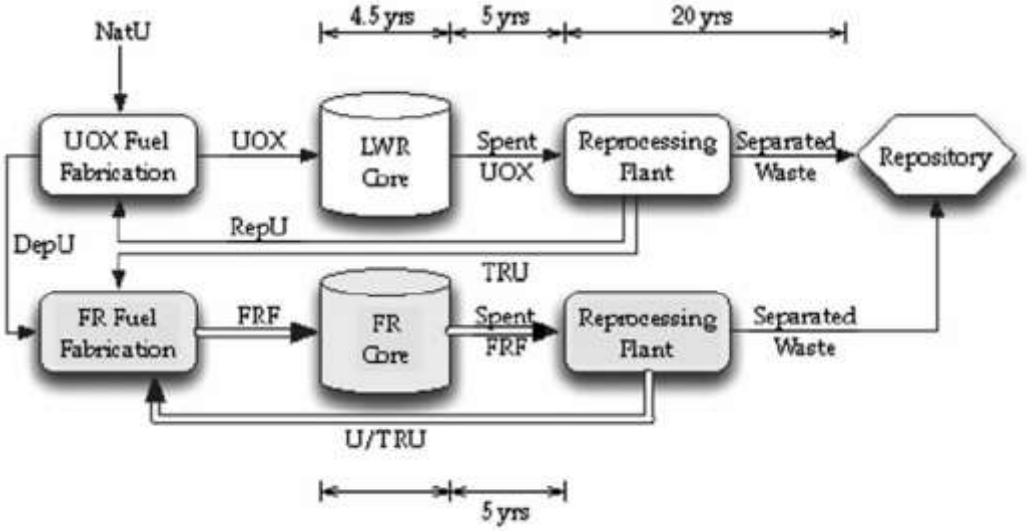

Figure 3: The fast reactor with reprocessing

Source: DeRoo et al. (2011, 828).

2.2.3 Current stocks of plutonium

Actors dealing with plutonium involve both commercial nuclear companies, e.g. electricity generation, and public institutions in the nuclear sector (research reactors, military, etc.). The first 100 tons of plutonium were produced for military purposes. In the late 1960s, with commercial nuclear electricity generation at scale, the stocks of commercial (civilian) plutonium started to pile up. Today, there are about 300 t of plutonium for commercial use stored in other countries (e.g. France, UK, and China, (von Hippel, Takubo, and Kang 2019, 8)). Since the end of the cold war, about 180 tons of previously military plutonium were dismantled. Thus, today the supply of plutonium is composed of (Figure 4):

- Military plutonium, either in operational warheads (~ 20 tons) or in previously dismantled warheads (~ 180 tons).
- Civilian (or: commercial) plutonium, based on reprocessing of spent fuel from breeder commercialization and conventional light-water power reactors (~ 300 tons).

[5] "Reprocessing was developed to produce a fuel for the fast reactors. Later, when this did not develop into industrial scale, reprocessing and production of MOX-fuels was continued with the justification to substitute for uranium fuel for Light Water Reactors (LWRs)" (Besnard et al. 2019, 55).

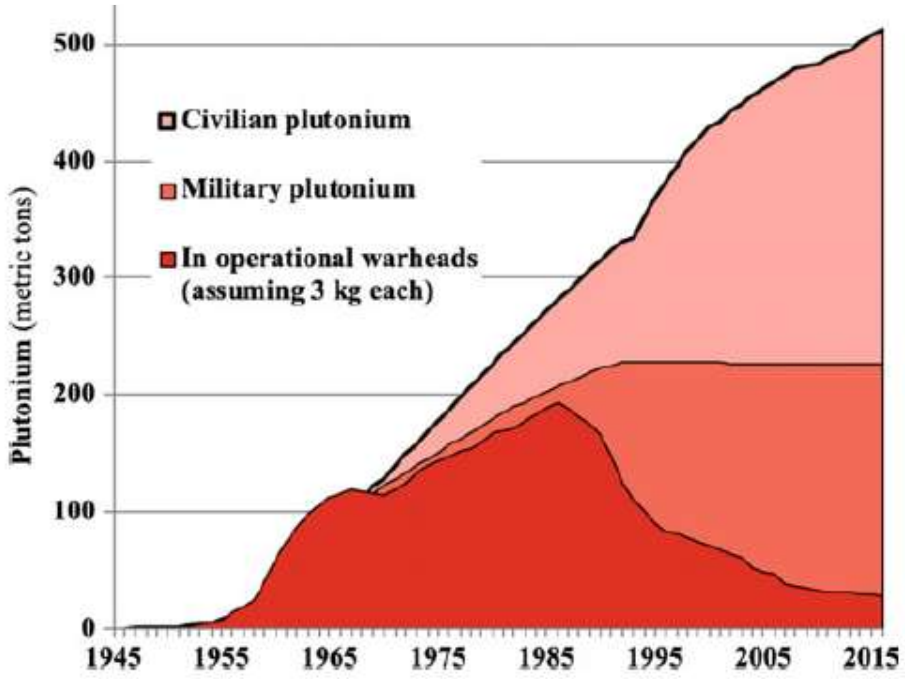

Figure 4: Global stock of separated plutonium

Source: (von Hippel, Takubo, and Kang 2019, 8).

2.3 Environmental aspects and proliferation

2.3.1 Toxicity and radioactivity

Plutonium is very toxic, radioactive and can cause harmful radiation effects, mainly through alpha-radiation (helium particles) and gamma (electromagnetic) radiation. Plutonium can be inhaled and then accumulates in the bones, the liver, and lymph nodes, with long retention times (~ 50-100 years in bones), leading to cancer risk.[6]

Plutonium has a very long half-life period of over 24,000 years, and therefore (like many other radioactive products) needs very long-term safe depositories. In the decay process, fission products include mainly technetium (Tc-99), iodine (Io-129) and cesium (Cs-135), likewise very detrimental when brought in contact with human beings or the environment.[7]

Reprocessing is a particularly complex process that involves high risks for workers and the environment. In addition to plutonium, the other minor actinides separated in the process, too, are also highly

[6] See https://www.bfs.de/EN/topics/ion/effect/radioactive-materials/plutonium/plutonium_node.html (last accessed 2021-06-08), and https://world-nuclear.org/information-library/nuclear-fuel-cycle/fuel-recycling/plutonium.aspx (last accessed 2021-06-08).

[7] If not mentioned otherwise, most of the physical and chemical information in this paper is taken from Moors (2006).

radioactive. At present, about 15% of the world's spent nuclear fuel is reprocessed (Besnard et al. 2019, 55).[8]

2.3.2 Proliferation

Small amounts of plutonium (few kilograms) are sufficient to produce a nuclear bomb. Not only countries working on military plutonium reactors, but also individuals or terrorist groups can get hold of weapon grade plutonium relatively easily. The danger of controlling proliferation has been raised after World War II (Acheson-Lilienthal Report 1946), and attempts started to control proliferation. However, until today the dangers of proliferation persist, which is why arguments can be made, independent of economic considerations, to ban plutonium processing and recycling.[9]

2.4 Environmental economic assessment

The environmental economic literature does not deal with the specific externalities of plutonium. However, it can be assumed that the plutonium route generates more negative externalities than the once-through route: In addition, proliferation risks, though difficult to assess quantitatively, are particularly high. Thus, in 2007, the UK's Royal Society warned that the potential consequences of a major security breach or accident involving the UK's stockpile of separated plutonium "are so severe that the Government should urgently develop and implement a strategy for its long term use or disposal." (Besnard et al. 2019, 55).

The only environmental economic reference to plutonium is found in a classical textbook and seems to share this assessment, qualifying plutonium as a substance where "the optimal level of the pollution may be zero, or close to it." (Tietenberg and Lewis 2016, 374).[10]

3 Economic aspects

In this section, we focus on the economic "benefits" of the plutonium route, i.e. its potential role as a producer of heat and electricity. We first analyze the economic development of plutonium reactors in the past, and then establish an analytical framework to compare the plutonium route with the dominant route, the light-water once-through reactors.

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[8] "Reprocessing involves the dissolution of spent fuel in boiling concentrate of nitric acid, followed by the physico-chemical separation of plutonium and uranium from the dissolved fuel. This difficult, complex, expensive and dangerous process results in numerous nuclear waste streams, very large releases of nuclide waste to air and sea, and large radiation exposures to workers and to the public." (Besnard et al. 2019, 54).

[9] See for details (von Hippel, Takubo, and Kang 2019) and the work by the International Panel on Fissile Materials (IPFM); von Hippel et al. (2019, 142) conclude: "Global stocks of uniradiated civilian plutonim – about 300 tons in 2019 – would supply the equivalent of only three weeks of global electricity production if they were made into mixed-oxide (MOX) fuel. If diverted, however, only 1% of that same plutonium would be sufficient for hundreds of Nagasaki bombs."

[10] "In some circumstances the optimal level of the pollution may be zero, or close to it. This situation occurs when the damage caused by even the first unit of pollution is so severe that it is higher than the marginal cost of controlling it. … This circumstance seems to characterize the treatment of highly dangerous radioactive pollutants such as plutonium." (Tietenberg and Lewis 2016, 374).

3.1 Three phases of development

3.1.1 Phase I: Planning for the "plutonium economy" (1946-1970s)

The early enthusiasm about the economic perspective of nuclear power were based on the assumption that breeders were the way forward to use the scare resource uranium adequately (Szilard 1945, 1947; von Hippel, Takubo, and Kang 2019, 2). The initial focus on fast reactors was based on the much higher energetic use of uranium, by activating uranium isotope U-238, and the assumed shortage of uranium ore. Szilard (1947) observed that if more than one atom of plutonium could be produced from U-238 for every atom of plutonium fissioned, "the resource base for nuclear power would become U-238 and it would be possible to produce about 100 times more energy from the same amount of uranium. … Therefore, it was considered that if what Szilard called the plutonium "breeder" reactor could be designed, civilization's energy problems would be solved for millennia" (von Hippel, Takubo, and Kang 2019, 2). The Swiss economist Edgar Salin (1955), too, placed significant hopes in the development of nuclear fission and breeder technology, that would lead to the end of the coal era, and, thus, open up a new step of industrial revolution. Nothing short of a "plutonium economy" was expected.[11]

Until the 1970s, longer-term planning of nuclear power relied on the breakthrough of the plutonium route. In the US, Glenn Seaborg, the "father" of plutonium back in 1940, had become Chairmen of the Atomic Energy Commission that foresaw breeders to become the dominant source of nuclear energy once implemented (Figure 5). Similar expectation prevailed in Europe, too (Midttun and Baumgartner 1986). In Germany, significant resources went into the fast breeder research, mainly in Karlsruhe, as the basis for demonstrator and commercial reactors to be built later on, e.g. the development of a commercial breeder reactor in Kalkar (North Rhine Westphalia, NRW) (Radkau 1983). Table 1 presents a list of experimental fast breeder reactors developed mainly in that period.

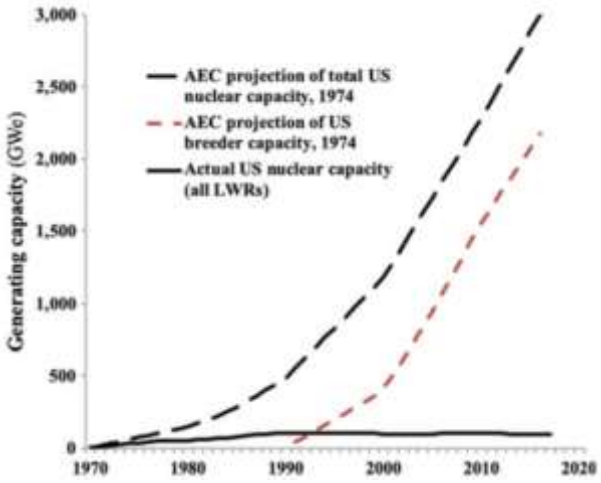

Figure 5: US Atomic Energy Commission (AEC) growth projections for US nuclear generating capacity, and the role of breeders therein, in 1974

[11] "Thirty years from now this same man-made elment can be expected to be a predominant energy source in our lives. … Plutonium, as the key to electrical energy production in the future, is thus a vital element of the overall economic well-being of this country. … I wish to speak of plutonium as the energy cornerstone of our future economy and to speak of that economy as the plutonium economy of the future." (Seaborg 1970, 1/2).

Source: (von Hippel, Takubo, and Kang 2019, 33).

Country	Reactor	Construction start	Power (MW_{th})	Operation
China	CEFR	2000	65	Since 2010
France	Rapsodie	1962	40	1967-1983
Germany	KNK-II	1975	52	1977-1991
Great Britain	DFR	1954	60	1957-1977
India	FBTR	1972	40	Since 1985
Italy	PEC	1974	120	(1)
Japan	JOYO	1970	140	1977-2007
Russia	BR-10 BOR-60	1956 1964	55 9	1959-2002 (2) Since 1958 (3)
USA	EBR-I EBR-II Fermi FFTF	1947 1958 1956 1970	1,2 62,5 200 400	1951-1963 (4) 1963-1994 1965-1972 1980-1992

(1) Construction interrupted in 1987
(2) Core meltdown
(3) 1955 partial core meltdown
(4) 1955 partial core meltdown

Table 1: List of experimental fast breeder reactors

Source: (Pistner and Englert 2017, 42), with further references.

Note, however, that the early phase of what was expected to become the plutonium economy was based on a purely technical vision, and ignored economic facts. Thus, already in the early days of research on sodium-cooled fast reactors, some skepticism prevailed among economists. The President of the Institute of World Economy (IfW Kiel), Fritz Baade, published a critical assessment of the plutonium route as early as 1958, suggesting that it was expensive and not competitive: While he shared the high technical expectations, he stressed that, back in the 1950s, plutonium had a negative value, due to high processing costs, that even the extraordinary energetic characteristics would not compensate.[12] Baade

[12] "Über Reaktoren vom Brüter-Typ kann man daher wohl mit großer Sicherheit feststellen: 1. Daß sie in Zukunft einmal einen entscheidenden Beitrag für die Atomenergieliefern könnten, die die Energiebilanz der Welt entscheidend entlastet und ein Vielfaches der Leistungen des klassischen Energieträgers Kohle erreichen kann; … 3. Daß diese Reaktoren heute noch weit von der Möglichkeit der Produktion von Energie zu einem mit Kohlekraftwerken vergleichbaren Preis entfernt sind. … Viele Leser mögen überrascht sein, daß bei einem Atomkraftwerk, das in populären Artikeln häufig als die Lösung des Atomenergieproblems dargestellt wird, tatsächlich mit der Möglichkeit gerechnet werden muß, daß die Kosten der Aussonderung des erbrüteten Plutoniums unter Umständen so hoch werden könnten, daß ein Debet entsteht, solange nicht Aufbereitungsprozesse gefunden werden, die viel billger arbeiten als die heute üblichen." Baade (1958, 138/139).

English translation: "Therefore, it can be stated with great certainty about reactors of the breeder type: 1. that in the future they could make a decisive contribution to atomic energy, which would decisively relieve the energy balance of the world and could achieve a multiple of the performance of the classical energy source coal; ... 3. that today these reactors are still far from the possibility of producing energy at a price comparable to coal-fired power plants. ... Many readers may be surprised to learn that in the case of a nuclear power plant, which is often presented in popular articles as the solution to the atomic energy problem, one must actually reckon with the possibility that the cost of separating out the incubated plutonium may become so high as to create a debit unless reprocessing processes can be found which will work much more cheaply than those now in use."

relied on extensive economic analyses carried out already, both on a light water reactor in the US (Shippingport), and a plutonium-reactor in the UK (Calder Hall).[13]

3.1.2 Phase II: Technical and economic obstacles (1970s - today)

Until today, the expected economic breakthrough of the plutonium reactor has not come about. In addition to the general economic risks of nuclear power (such as the absence of insurance against accidents), specific obstacles have prevented the diffusion of fast reactors thus far. Pistner et al (2017) provide a comprehensive survey of prototype and demonstrator fast reactors (Table 2). None of these reactors succeeded in providing reliable electricity over significant periods, such that demonstrators could be scaled and become commercial reactors. In sum, economic cost escalations have led to the abandonment of most of the pilot plants. The World Nuclear Association (2021) concluded that fast reactors are "expensive to build and operate, including the reprocessing".[14]

The literature identifies a number of technical obstacles that explain the low load factors, and high costs (Ramana and Suchitra 2007; Suchitra and Ramana 2011; Pistner and Englert 2017; MIT 2018; von Hippel, Takubo, and Kang 2019). Most fast reactors use sodium as coolant, which in case of leakages leads to immediate fire; other coolants such as lead or helium also have their specific problems. Transuranium physics and the translation into industrial machinery turned out to be more complicated than expected. Corrosion was and remains a major problem. In addition, plutonium does not behave as properly as expected as a fuel, so that enriched uranium often had to be used. As a result, construction costs for the plutonium reactor tend to be significantly higher than for the light water reactors, at least 25% higher, often significantly more; operational costs, too, are higher because of the fuel treatment.

The high costs of reprocessing added to the unfavorable economics, and have prohibited an economic use of plutonium. Initially believed to decrease with increasing use, reprocessing costs have stayed high and presented, in combination with other factors, an obstacle to the fast breeder (Pistner and Englert 2017; von Hippel, Takubo, and Kang 2019). In France, costs for plutonium and uranium recycling tend to be five times higher than the savings in enriched fuel costs (Commissariat Général du Plan 2000); by today, with lower capacity factors due to loss of foreign clients, this ratio is likely to have gone up. In Japan, the Japan Atomic Energy Commission (JAEC) estimated costs of recycling about ten times higher than the savings in low enriched uranium (LEU) fuels (JAEC 2011). Case studies in India confirm these results (Ramana and Suchitra 2007; Suchitra and Ramana 2011).

[13] Allocating the plutonium costs to the military (and making several very optimistic assumptions), Jukes (1956, 186, cited in Bade (1958)) calculated costs of 0.76 UKpence/kWh (6.5 Pfg/kWh)13 for a (hypothetical) Calder Hall plant with 150 MWel (the original was 60 MWel). This would already be twice the price of electricity from coal. On the contrary, Loebl (1956) estimated fuel costs at 11.45 Pfg/kWh for a total cost of 17.84 Pfg/kWh. Admiral Hyman Rickover, the "father" of the Nuclear Navy and subsequent manager of the fist commercial nuclear power plant (Shippingport, PA, USA) also reports costs corresponding to 21,8 Pfg./kWh (all citations from Bade (1958, 123sq.)).

[14] "Today there has been progress on the technical front, but the economics of FNRs (fast neutron reactors) still depends on the value of the plutonium fuel which is bred and used, relative to the cost of fresh uranium. … They are however expensive to build and operate, including the reprocessing, and are only justified economically if uranium prices are reasonably high, or on the basis of burning actinides in nuclear wastes." (WNA 2021).

Country	Reactor	Construction start	Power (MW_{th})	Operation	Average load factor
Germany	SNR-300	1973	762	No operation license	
France	Phoenix	1968	563	1973-2009	~ 0.50
Great Britain	PFR	1966	650	1974-1983	0.07
India	PFBR	2003	1250	Since 2012	
Japan	Monjou	1985	714	1994-2016	1996-2010 out of operation after accident
Kazakhstan	BN-350	1964	750	1972-1999	0,85
Russia	BN-600 BN-800	1967 2006	1470 2100	Since 1980 Since 2016	0.74 (1982-2009) 0.71
USA	CRBRP	1982		Abandonded in 1983	

Table 2: Prototype and demonstrator breeder reactors

Source: (Pistner and Englert 2017, 42).

3.1.3 Phase III: Emergence of the plutonium economy?

Despite its technical and economic failure thus far, one observes a renaissance of the idea of fast reactors, both in countries that previously experienced with the technology (e.g. Russia, India, Japan) and others (such as China and the USA). Fundamental research, experimental reactors and demonstrator reactors are again being explored, under the heading of the “Generation VI International Forum” (GIF), supposed to develop successful replacements for the Generation III reactors currently in the market, more economic, more secure, etc. The GIF has a special focus on fast reactors, and among them, “the sodium-cooled reactor is considered the most technically advanced of the Generation IV reactors.” (Frieß et al. 2021, 31).

Table 3 provides the presentation of the World Nuclear Association of fast reactor designs for near- to mid-term development. Even though some of the projects are planned in the future, with uncertain starting dates, concrete work is ongoing for some of them. Russia is particularly active, with a high-power demonstrator already running (BN-800, breeder, but potentially also a burner), a concept under development for commercial use (BN-1200, breeder), and two reactors of smaller power rating (BREST, MBIR). China has entered the sector with an experimental reactor (CEFR), followed by two breeder reactors with higher power (CFR-600), and the purchase of two reprocessing plants, one from Russia and one from France (Zhang 2020). Even in the US, breeder and burner technologies with fast neutron reactors are being explored in the context of SMR-concepts (PRISM, ARC-100), and a traveling wave reactor (TWR). Other countries and regions (e.g. the European Union) are also active (Murakami 2021).

Note that ten out of the 14 concepts use fast sodium-cooled technology, i.e. the one initially proposed by Szilard and others at the end of the Manhattan Project. Other types of fast reactors in the Gen IV program include gas- and lead-cooled reactors (Locatelli, Mancini, and Todeschini 2013; Pistner and Englert 2017; GIF 2018; WNA 2020a).

Reactor	Type, coolant	Power thermal/elec (MW)	Fuel (future)	Country	Notes
PRISM & Natrium	Demonstration, pool, sodium	840/311	metal	USA	From 2020s
ARC-100	Prototype, pool, sodium	260/100	metal	USA	Working with GEH
Allegro	Experimental, loop, gas	50-100 MWt	oxide (carbide)	Visegrád countries, with France	From 2030
MYRRHA	Experimental, Pb-Bi	57 MWt	oxide?	Belgium, with China	Early 2020s
ALFRED	Demonstration, lead	300/120	oxide	Romania, with Italy & EU	From 2025
BN-1200	Commercial, pool, sodium	2800/1220	oxide, nitride	Russia	From 2030
BREST-300	Demonstration, loop, lead	700/300	nitride	Russia	From 2021
MBIR	Experimental, loop, sodium (Pb-Bi, gas)	100-150 MWt	oxide	Russia	From 2020, under const.
CDFR-600	Demonstration, pool, sodium	600 MWe	oxide	China	From 2023, under const.
CDFR-1000	Commercial, pool, sodium	1000-1200 MWe	metal	China	From 2034
PGSFR	Prototype, pool, sodium	392/150	metal	South Korea	From 2028
JSFR	Demonstration, loop (now pool), sodium	500 MWe	oxide	Japan	From 2025?
TWR	Prototype, sodium	600 MWe	metal	China, with USA	From 2023?
FBR 1&2	Commercial, sodium	600 MWe	oxide, metal	India	?

Table 3: Current and planned fast neutron reactors (FNR) activities according to the World Nuclear Association

Source: (WNA 2021).

3.2 Analytical framework

The value of plutonium mainly depends on the costs of the next best alternative: If this alternative is expensive, plutonium, in conjunction with reprocessing, can be used economically. However, if the so-called “once-through fuel” process is cheaper, e.g. because uranium is relatively cheaply available, the value of plutonium is negative. This is the result, for example, of an interdisciplinary research activity “where to go with plutonium”, conducted by the Research Center of the Protestant Institute for Advanced Study (FEST: Eisenbarth, et al. (2004)): From a commercial perspective, “the use of plutonium can not be justified, because uranium and thorium are sufficiently available and are cheaper to produce than plutonium” (translated from German in Eisenbarth, Pistner, et al. (2004, 55)).

The energy economic literature contains several approaches to modeling the two idealtype concepts for nuclear electricity generation (Bunn et al. 2003; De Roo and Parsons 2011; Suchitra and Ramana 2011). In this subsection, we present the simplified linear model developed by Bunn et al. (2003) that results in breakeven conditions for the choice between the two routes: They benchmark the plutonium route to

the light-water, once through route, and identify conditions under which the former could become economic (which it is not at present).[15]

3.2.1 Comparing once-through process and plutonium recycling

The following analysis follows (Bunn et al. 2003), including a simplified numerical solution. The economic analysis needs to take into account the fuel costs of reprocessing and recycling the spent fuel from a light reactor, including eventual disposal costs for waste (right-hand side of equation **Fehler! Verweisquelle konnte nicht gefunden werden.**), with the alternative, once-through, interim storage and direct disposal of spent fuel (left-hand side of equation **Fehler! Verweisquelle konnte nicht gefunden werden.**). At equilibrium, both costs should match:

$$\begin{bmatrix} cost\ of\ interim\ storage \\ and \\ disposal\ of\ spent\ fuel \end{bmatrix} = \begin{bmatrix} cost\ of\ reprocessing \\ and \\ disposal\ of\ wastes \end{bmatrix} - \begin{bmatrix} value\ of\ recovered\ plutonium \\ and \\ uranium \end{bmatrix} \quad (1)$$

The cost of interim storage and disposal of spent fuel, the cost of reprocessing, and the cost of disposal of waste are constants, estimated from a complex techno-economic analysis (Bunn et al. 2003). The value of the recovered fuels (plutonium and uranium) is a function of the uranium price, because the recovered fuels displace a certain amount of low-enriched uranium (LEU); it also takes into account the cost of producing the fuels.

$$\begin{bmatrix} value\ of\ recovered\ plutonium \\ and \\ uranium \end{bmatrix} = \begin{bmatrix} cost\ of\ LEU\ fuel \\ made\ with\ natural \\ uranium \end{bmatrix} - \begin{bmatrix} cost\ of\ equivalent\ fuel \\ made\ with\ recovered \\ plutonium\ and\ uranium \end{bmatrix} \quad (2)$$

Bunn et al. (2003, 14 sq.) apply the following values (USD_{2000}):

~ Cost of interim storage: $ 200/kg

~ Present value of the cost of direct disposal of spent fuel (including transportation): $ 400/kg

~ Cost of reprocessing: $ 1,000/kg

~ Present value of disposing radioactive waste from reprocessing: $ 200/kg

In that case, the costs of interim storage & disposal of fuel ($ 200 + $ 400) is lower than the cost of reprocessing & disposal of waste ($ 1,000 + $ 200); in that case, the value of recovered plutonium and uranium would have to be $ 600 to breakeven.

3.2.2 Value of recovered plutonium and uranium

How can the value of the recovered uranium and plutonium be assessed?

1 kg of spent fuel yields about 95% uranium and 1% plutonium, in addition to 4% radioactive fission products and minor actinides (Bunn et al. 2003, 14). The value of the recovered uranium can be

[15] This analysis does not include energy economic evaluation vis-à-vis other fuels, neither is an energy-environmental cost-benefit analysis intended.

estimated with the price of the fresh uranium produced from ore. The value of plutonium consists of the economies of displacing enriched uranium (LEU) as fuel, minus the cost of producing the fuel (MOX, including final disposal):

$$\text{Value of recovered plutonium} = \text{Cost of displaced LEU} - \text{cost of MOX} \quad (3)$$

6 kg of fuel has to be processed to produce 1 kg of fresh fuel. Fabricating the fresh mixed oxide fuel (MOX) costs $ 1,500, and the costs of the (displaced) LEU are the following:[16]

~ Uranium: 7 kg for enrichment to (7 x 0,7% = 4,9%)@ $ 50 /kg	= $ 350
~ Conversion: 7 kg@ $ 5/kg	= $ 35
~ Enrichment: 6 separating work units (SWU)@ $ 100/SWU	= $ 600
~ Fabrication: 1 kg@ $ 250/kg	= $ 250
	$ 1,235

The cost of producing MOX is $ 1,500/kg is higher than the $ 1,235 of savings on LEU. Given these estimates for the varliables at a price of $ 50/kg of uranium the difference of both provides a negative value of plutonium:

$$\text{Value of recovered plutonium} = \$\ 1{,}235 - \$1{,}500 = -\$\ 265. \quad (4)$$

According to Bunn (2003), given these estimates for the variables, at a price of $ 50/t of uranium, the value of plutonium is negative.

3.2.3 Breakeven price of uranium

The overall value of the recovered plutonium and uranium becomes:

$$\begin{bmatrix} value\ of\ recovered\ uranium \\ and\ plutonium \end{bmatrix} = \begin{bmatrix} value\ of \\ recovered \\ uranium \end{bmatrix} + \begin{bmatrix} value\ of \\ recovered \\ uranium \end{bmatrix}$$

$$= 0.95C_u + \left[\frac{(cost\ of\ LEU) - (cost\ of\ MOX)}{6}\right] \quad (5)$$

$$= 0.95C_u + \left[\frac{(7C_u + 885) - 1500}{6}\right]$$

$$= 2.12C_u - 102.5$$

Finally, the initial equation (5) becomes:

[16] If not mentioned otherwise, all values refer to Bunn, et al. (2003).

$$\begin{bmatrix} cost\ of\ interim\ storage \\ and\ disposal\ of\ spent\ fuel \end{bmatrix} = \begin{bmatrix} cost\ of \\ reprocessing \\ and\ disposal\ of\ wastes \end{bmatrix} - \begin{bmatrix} value\ of\ recovered \\ uranium\ and\ plutonium \end{bmatrix} \quad (6)$$

$$[600] = [1200] - [2.12C_u - 102.5]$$

$$2.12C_u = 702.5$$

$$C_u = 332$$

The uranium price required for the plutonium route to breakeven with the once-through fuel cycle is $ 332/t, about seven times higher than the prevailing one at the time.

3.3 Three critical parameters: Uranium price, construction cost, disposal cost

The analytical framework is useful to identify three critical parameters that will be studied in the next three sections: The breakeven price of uranium, the capital cost of the respective reactor technologies, and the cost of interim and final storage.

3.3.1 Breakeven price of uranium

One can display the above analysis as the relation between the uranium price and the cost of reprocessing: Figure 6 shows the results of the breakeven price of uranium (vertical) as a function of the reprocessing costs (horizontal). The light bar at the bottom indicates that at a uranium price of $ 50/kg, the equilibrium cost of reprocessing would need to decrease to $ 420, a 58% reduction.

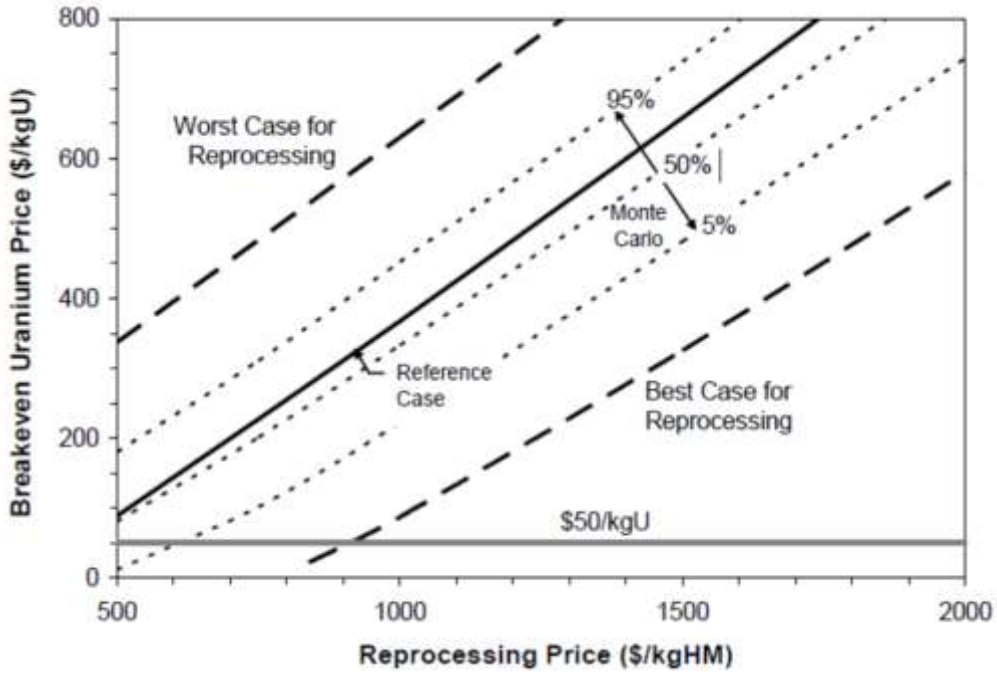

Figure 6: Breakeven uranium price as a function of the cost of reprocessing

Source: (Bunn et al. 2003, 18).

3.3.2 Introducing construction cost differences

Until now, we have ignored the capital costs of the reactors, i.e. the light water rector (LWR) and the fast neutron liquid metal reactor. To keep things simple, we consider the linear approximation of Bunn et al. (2003, 104) for the breakeven uranium price as a function of the difference in capital costs (ΔC_{cap}). In equilibrium, the difference of the (per unit) capital cost between the light water and the fast reactor route would equal the difference of the (per unit) variable fuel costs (Bunn et al. 2003, 104):

$$\frac{\Delta C_{cap} * F}{8776\ \eta} = C_{LWR}\ fuel\ (C_u) - C_{LMR}\ fuel$$

where

~ ΔC_{cap} is the difference in the overnight construction costs ($/) kW_{el} between the light-water reactor (LWR, "once through") and the (hypothetical) fast reactor

~ F is a simplified term for interest during construction

~ η is the thermal efficiency of the plant

~ 8766 is the average number of hours per mean year

~ $C_{LWR}\ fuel\ (C_u)$ and $C_{LMR}\ fuel$ are the respective fuel costs.[17]

Given the cost disadvantage of plutonium reprocessing (the "negative value" of plutonium), the capital costs of the fast reactor would have to be lower than the capital cost of the light water reactor, in order to breakeven on the levelized cost of electricity. However, as discussed above the opposite was the case, and still is: The construction costs of fast reactors are significantly higher than those of light water reactors (Bunn et al. 2003, 70).

In that case, one can once again determine a breakeven price of uranium that would equalize the difference in capital costs (Figure 7). Note that the estimated difference at the time (early 2000s) was considered to be significantly lower than today, so the values are only indicative. They confirm, however, that a very significant increase in uranium prices would be required for the plutonium route to become economic. As an approximation, we retain that the price of uranium has to be in the 4-digit range (> $ 999/kg) to become relevant.

[17] In this specification, only $C_{LWR}\ fuel\ (C_u)$ depends on the costs of the fresh uranium. Theoretically, CLMRfuel is a function of Cu, too, but due to the high capital costs for reprocessing, this can be neglected.

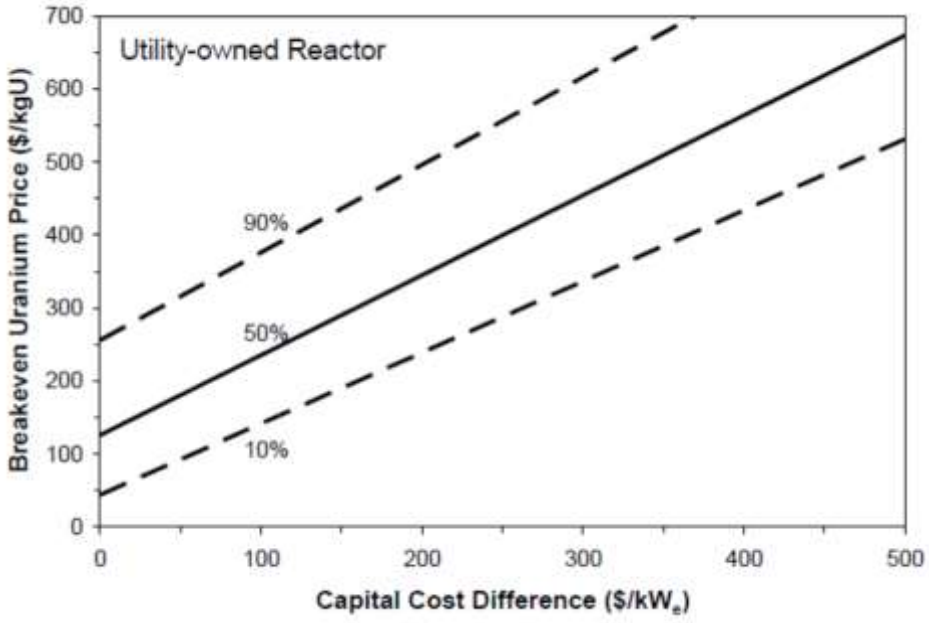

Figure 7: Breakeven uranium price for utility-owned reactor as a function of the capital cost difference between a fast reactor (FR) and a light-water reactor (LWR)

Source: (Bunn et al. 2003, 70, Figure 3.2).[18]

3.3.3 Cost of nuclear waste disposal

Finally, yet importantly, equation (1) also indicates that the different routes imply different costs of disposal of spent fuel (once-through process) and wastes (plutonium process). Direct disposal of spent fuel is more expensive than the disposal of "only" the radioactive waste after the multiple reprocessing (Bunn et al. 2003, 52 sq.). In that case reducing the volume of the high-level waste, and/or reducing the specific substances that cause high disposal costs (e.g. because of heat development) could reduce storage costs. This is particularly important in cases where the available volume of the depository is constrained, such as in the US Yucca Mountain site (currently abandoned, located within a mountain, not underground).

3.4 Intermediate conclusion

After decades of unsuccessful attempts to use plutonium for electricity generation, have resource and energy economic conditions changed sufficiently to reverse this trend? In this section, we have reported the development of the plutonium route through different historical phases. Even though neither the technological nor the economic success expected have materialized, one observes a "renaissance" of breeder (and burner) research and the idea of a plutonium economy in some countries. The analytical framework reduces the economic analysis to a comparison between the plutonium route and the light-water once-through route. It allows to identify three topics to explore, i.e. i/ potential constraints on the availability of uranium ore; ii/ the perspective of construction costs for new designs, e.g. reactors of low

[18] Assumptions in this specification differ slightly from the above in Figure 6.

capacity (SMR); and iii/ the option to abate plutonium through burning. These three topics will be explored in the next three sections, respectively.

4 Can plutonium benefit from binding constraints on uranium supply?

If, as shown in the previous section, the plutonium fast reactor route is much more expensive than the traditional once-through cycle, could constraints on the latter, e.g. unavailability of uranium or extremely high prices, change the relation in favor of plutonium?[19] Due to the high capital intensity of the industry, in particular the plutonium route including reprocessing, the cost of the resource plays only a minor role in total costs. In this section, we assess whether uranium supply could become a binding constraint, and open a case for the plutonium route.[20]

4.1 Historical perspective

"For decades, consideration of reprocessing, recycling, and breeding plutonium has been driven in significant partly by concerns that resources of uranium would not be sufficient to support a growing nuclear energy system operating on a once-through cycle for long." (Bunn et al. 2003, 105). The initial hypothesis of the success of the plutonium breeder reactor was the danger of a shortage of uranium available to produce nuclear energy. This fear was not only expressed by physicists and engineers (such as Szilard (1945, 1947),[21] but also shared by economists fearful of the combination of low availability of uranium and the high costs of enriching the uranium oxide to usable levels (Salin 1955; Baade 1958, 114). Advocates of reprocessing and breeding continue to argue that available resources of low-cost uranium are quite limited, making breeding and reprocessing essential in the relative near term (Bunn et al. 2003, 105).[22]

The lack of international trade of uranium in the early period of nuclear power further contributed to the effect and favored the fast-reactor plutonium route. In fact, only the United States, Canada, the Soviet Union and India had uranium (and/or thorium) resources available, while all others, including the UK and Germany, did not (Baade 1958, 121 sq). Thus, for countries not equipped with domestic resources, the contribution of nuclear to energy independence was very low at best.

However, by the late 1970s, the situation had shifted, both on the supply side and on the demand side: On the supply side, much more uranium was found, and known resources of uranium had increased manifold (Bunn et al. 2003, 4). On the demand side, less nuclear power plants than expected were built.

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[19] Theoretically, thorium (90) can also be used for chain reactions, and it is more abundant than uranium, yet it is more complex to use and has not been developed at scale thus far (Nelson 2012).

[20] The significant environmental effects of uranium mining are not described here, but should be part of an environmental assessment of the overall uranium market, see (Neles and Pistner 2012, 152 sq.).

[21] „In a talk on nuclear energy in 1947, Szilard assumed it would be feasible to import 400 tons of natural uranium per year, an amount that would be sufficient to fuel only two 1,000 MWel ligt water reactors today." (von Hippel, Takubo, and Kang 2019, 10).

[22] Reference is made to a rather pressimistic document by the US Department of Energy (2003, I–4), stating that uranium "is not an infinite resource. Expert organizations such as the World Nucler Association project that between 2050 and 2080, nuclear power plnats worldwide will encounter a seriours shortage of uranium needed to produce nuclear fuel."

Holdren (1975) was among the first to make the case that “uranium resources were sufficient at that time to delay deployment of breeder reactors”.[23] It seems that this has become the mainstream assessment in the literature (Hall and Coleman 2013; Rooney, Nuttall, and Kazantzis 2015; von Hippel, Takubo, and Kang 2019).

Nonetheless, the issue of tight uranium supply is maintained in some of the literature. Time frames and expected dynamics of prices and reserves vary in this strand of the literature, in particular with respect to the forecast demand. Liebert and Englert (2015) and Muellner (2021) argue that with very high demand for nuclear energy, uranium supply could not be able to follow suit, both due to an inability “to produce enough uranium within the expansion phase of the growth scenario”, and because the insufficient “overall amount of uranium available for the total operating time of current and future plants.” (Muellner et al. 2021, 6). Subsequently, it is concluded that “limited uranium-235 supply inhibits substantial expansion scenarios with the current nuclear technology” (Muellner et al. 2021, abstract). Based on a uranium market model, Monet et al. (2017) conclude that with rapidly growing demand, the uranium market may prove to be under stress in some periods of the 21st century. The textbook of Tietenberg (2005, 148) also makes this argument.[24]

The assessment of the resource situation by the nuclear industry itself is split, between optimism regarding resources, but pessimism about low prices and investment incentives. On the one hand, the industry regularly assures stakeholders and the public that “sufficient uranium resources exist to support continued use of nuclear power and significant growth in nuclear capacity for low-carbon electricity generation and other uses … in the long term. Identified recoverable resources … are sufficient for over 135 years.” (IAEA and NEA 2020, 14). But on the other hand, it insists on the high investment requirements to maintain the ample resource base, particularly in times of rather prices.[25]

4.2 Short-term price volatility …

Given the complexity of technology, the secondary fuels available (e.g. recoverable resources from weapons, and highly enriched uranium), and other idiosyncrasies, the modeling of the uranium market seems to be more complex than for simpler metals or energy fuels, such as copper or coal. The uranium market is complex and dynamic, and there is no standard model that has emerged in the literature. On the supply side, the amount of uranium recoverable depends on resources, technology, and prices. The demand for uranium depends on the amount of nuclear power generation, and the forecasts thereof.

Different streams in the literature all suggest a high short-term price volatility. Owen (1983) highlights the role of inventories that lead to a constant difference between current production and current

[23] Cited according to (Bunn et al. 2003, 105, footnote 212).

[24] “Resource availability is a problem with uranium as long as we depend on conventional reactors. However, if countries move to a new generation of breeder reactors, which can use a wider range of fuels, availability will cease to be an important issue. For the United States, for example, on a heat-equivalent basis, if they are used in conventional reactors, domestic uranium resources are 4.2 times as great as domestic oil and gas resources. With breeder reactors, however, the U.S. uranium base is 252 times the size of its oil and gas base.” Tietenberg (2005, 148).

[25] “However, considerable exploration, innovative techniques and timely investment will be required to turn these resouces into refined uranum ready for nuclear fuel production and to facilitate the deployment of prmising nuclear technologies.” (IAEA and NEA 2020, 14).

consumption, leading to significant price fluctuations. Trieu, et al. (1994) confirm this by distinguishing spot market prices from long-term prices. Monnet, et al. (2017) identify dynamic constraints and the role of market competition as major drivers of prices, suggesting that "long-term availability of uranium depends on demand scenarios and more on market dynamics than on ultimate resources." Some recent literature explores how turning points could be better identified, e.g. price increases, or the role of technical innovation (Pedregal 2020; Landajo, Presno, and Fernández González 2021).

Figure 8 and Figure 9 show price developments since the early years of nuclear power. In periods of high expectancy and limited supply, prices have gone up (early 1970s, 2000s). However, they have also come down, both as a result of changing demand expectations, and rising mining supply. Contrary to expectations, the supply-demand balance for uranium has not shifted significantly over the last decade. At the end of the 2010s, prices were lower than in 1950 and in 1980, respectively.[26]

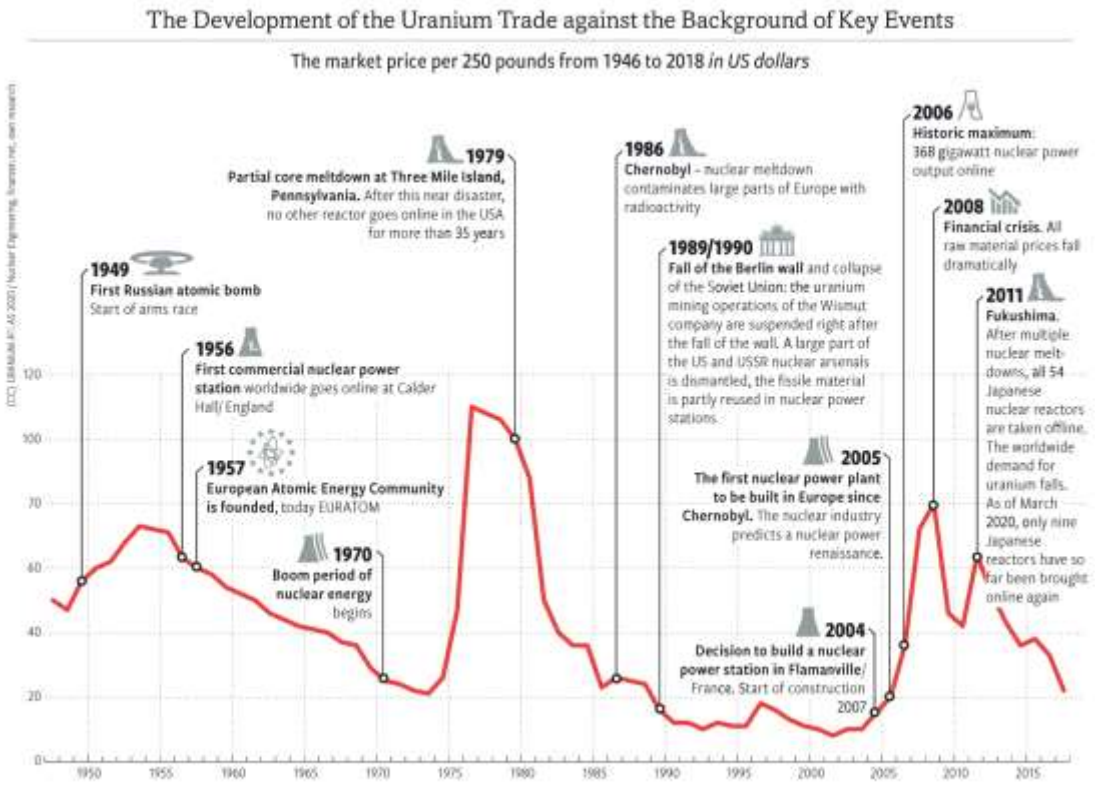


Figure 8: Uranium prices and key events since the 1950s

Source: https://www.nuclear-free.com/uranium-atlas-article/articles/uranium-industry-i-successful-resistance.html.

[26] In July 2022, the US spot price was about $ 40s/pound.

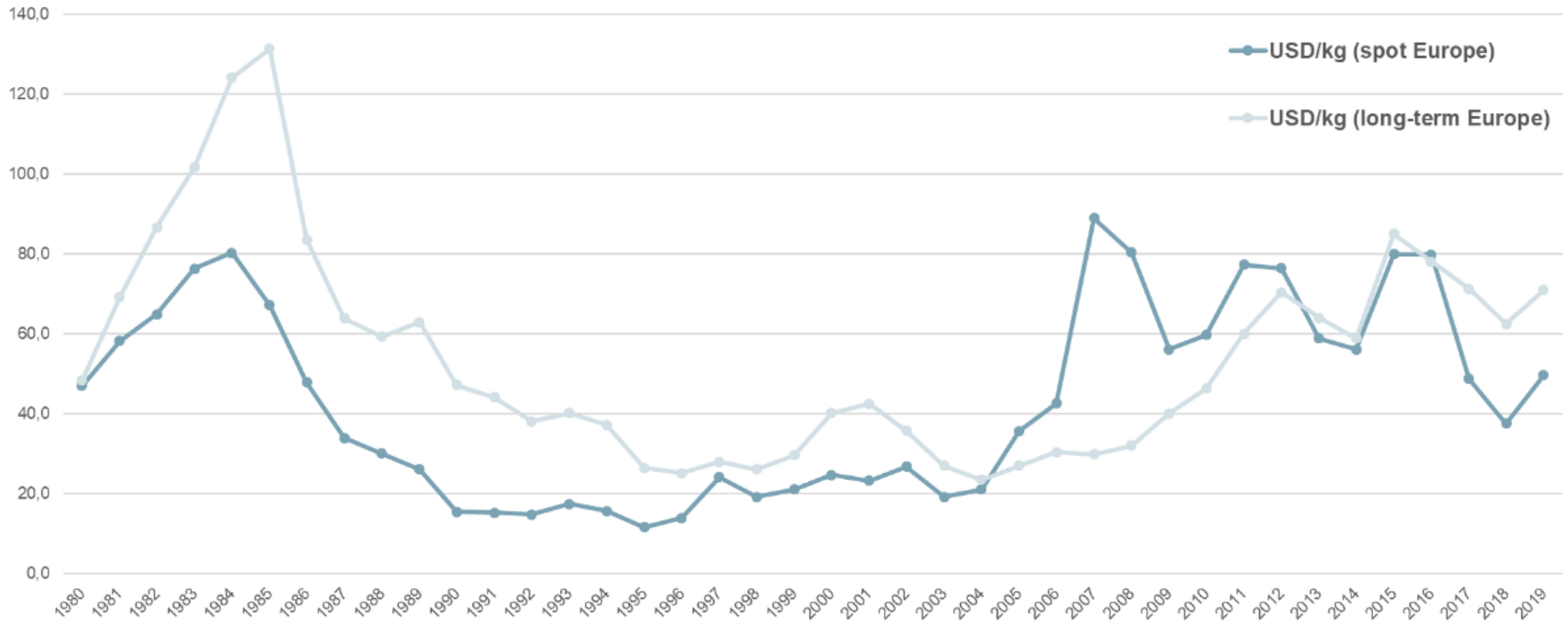


Figure 9: Long-term uranium prices (1980 – 2019): Spot and long-term

Source: ESA.

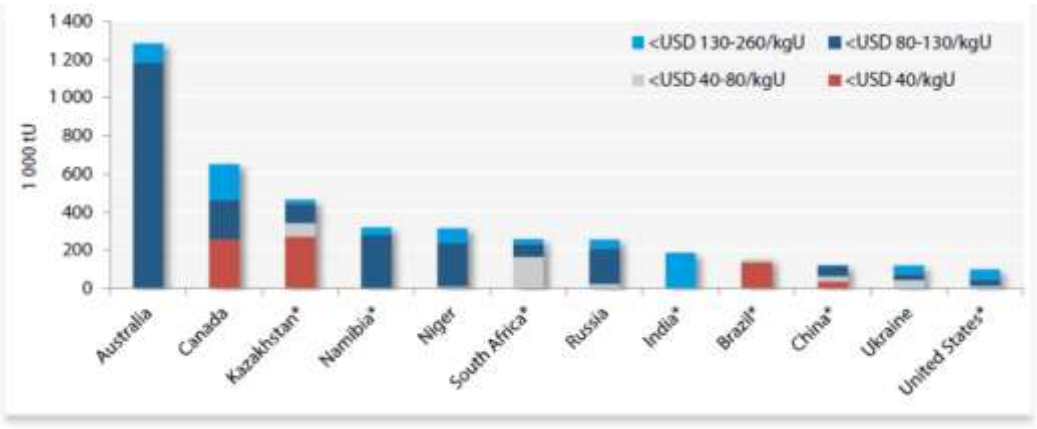
4.3 … and long-term resource availability

While short-run trends are quite diverse, evidence on the longer-term resource availability is somewhat clearer, although the literature is not fully conclusive. In this subsection, we identify the longer-term trends and explain that from an economic perspective, the resource availability seems to be assured: although the market is not fully competitive, there are no indications of market power abuse. But foremost, reserve and resource availability are large and can react flexibly to potential shortages. A comprehensive discussion of issues is provided by Bunn et al. (2003, 109 sq), which is still valid today; see also a critical assessment in (Hall and Coleman 2013), and a dynamic model of the global uranium market and the nuclear fuel cycle (Rooney, Nuttall, and Kazantzis 2015).

4.3.1 Market structure

Although the market is somewhat concentrated, the probability of oligopolistic behavior by a high concentration of supply is modest. About 15 countries or more are active in the market. The countries with the highest shares of identified resources are Australia (28% of resources), Kazakhstan (15%), Canada (9%), Russia (8%), Namibia (7%), South Africa and Brazil (5%, respectively), and Niger (4%) (IAEA and NEA 2020, 16) (Figure 10). The Hirschmann-Herfindahl Index (HHI, sum of squared market shares) is relatively high for uranium production in 2019 (2196).[27] There is a relatively high degree of vertical integration in the industry, including long-term contracts (Mendelevitch and Thien Dang 2016).

However, contrary to other resource markets, e.g. oil, the large producers are not those with the highest resources. Thus, Australia has by far the largest resources, but they are more expensive to mine than others are. The US, currently producing hardly any uranium, could become a producer with rising prices, or by imposing import quotas (Considine 2019). The concentration with respect to resources (mined below $ 130/kg) is significantly lower with an HHI of 1478 (own calculation based on IAEA and NEA (2020).



* Secretariat estimate or partial estimate.

[27] According to a generic interpretation of the Hirschman-Herfindahl Index, values of the HHI below 1,000 are considered unconcetrated, 1,000 – 1,800 moderately concentrated, and above 1,800 highly concentrated (Viscusi, Harrington, and Vernon 2005, 227).

Figure 10: Distribution of reasonably assured resources (RAR) among countries with a significant share of resources

Source: (IAEA and NEA 2020, 17).

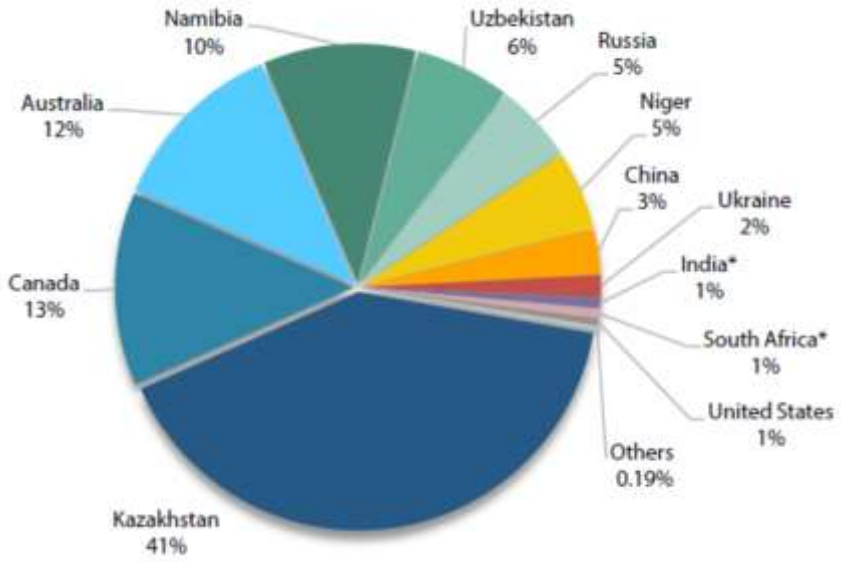


Figure 11: Uranium production worldwide (2018)

Source: (IAEA and NEA 2020, 57).

4.3.2 Current reserve and resource estimates

The available reserves ("economically minable") and resources ("physical potential") depend on market prices. The industry provides staggered reserve and resource estimates, currently split in four cost categories: < $ 40/kg, < $ 80/kg, < $ 130/kg, and, since 2010, < $ 260/kg. Within these categories, current uranium availability is as follows (IAEA and NEA 2020):

~ Recoverable resources at costs below $ 260/kg uranium are 8,070 kt, of which 4,723 kt are "reasonable assured resources" (RAR, Figure 10), and the rest are inferred resources.

~ In addition, undiscovered resources include prognosticated resources (PR) and speculative resources (SR). Together, they amount to 7,200 kt, consisting of 5,300 kt prognosticated resources (below $ 260/kg U) and another 1,878 kt of speculative resources (with an unassigned cost range).

Beyond conventional resources, uranium can be extracted from phosphate resources, if this was economically profitable. Also, it is theoretically possible to derive uranium from seawater (3-4 parts per billion), but this is technically unproven outside the laboratory setting, and elusively expensive (IAEA

and NEA 2020, 38). Last but not least, secondary resources are available, and were used to 10% of world reactor requirements in 2019 (IAEA and NEA 2020, 13).[28]

4.3.3 Dynamics of resource availability

As in other metal resource markets (like copper), the physical resource base has significantly grown since the 1960s, from about 1.5 Mt in 1965 to about 8 Mt of assured and inferred resources today (Figure 12).[29] At current production levels (~ 60.000 tons per year) and price levels (~ $ 40-60/t), it is not profitable to invest and obtain better resource estimates, or invest in additional exploration. Nonetheless, a further increase in the resource base is likely once prices would increase significantly.

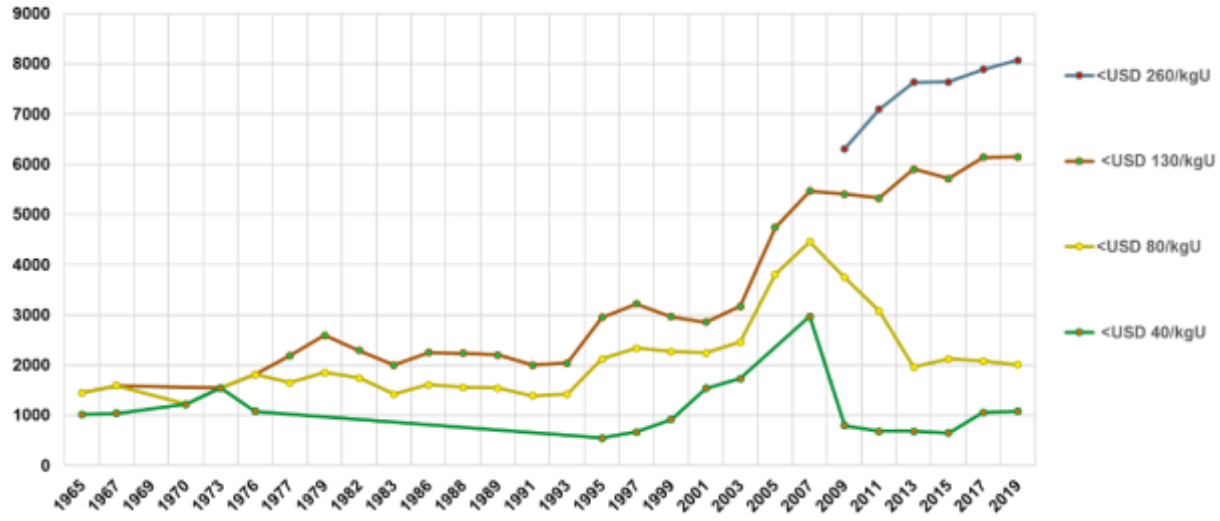


Figure 12: Uranium reserve development from 1965-2019 (kt)

Sources: IAEA-NEA Uranium yearbooks, various issues.

In essence, the question boils down to the supply elasticity of uranium, i.e. the long-term resource potential as a function of prices. Bunn, et al. (2003, 111) suggested the following relation between resources and prices:

$$R = 2.1\ (p/40)^{\varepsilon} \qquad (7)$$

where R is the total uranium resource (in Mt U) recoverable at price p ($/kgU) and ε is the long-term price elasticity of supply. The estimated supply elasticities at the time (the early 2000) of 2.3 – 3.2 are certainly on the optimistic side, suggesting resources between 34 – 105 Mt at prices below $ 130/kg.

[28] "Secondary supply includes excess government and commercial inventories, spent fuel reprocessing, underfeeding and uranium produced by the re-enrichment of depleted uranium tails, as well as low-enriched uranium (LEU) produced by blending down highly enriched uranium (HEU) (IAEA and NEA 2020, 13).

[29] IAEA-NEA (2020, 15) and previous editions of the "red book" on uranium resources, production, and demand, e.g. (OECD NEA 2006; NEA/IAEA 2018; OECD NEA and IAEA 2014). Cost categories are not inflation adjusted.

However, even with significantly lower elasticities it is reasonable to assume a significantly expanded resource base beyond the current cost categories.

Figure 13 shows the resource-price relation for 2019. While the function is rather linear, there are increases in resource availability to be expected for prices beyond $ 260/kg, increasing the amount of recoverable resources, i.e. turning undiscovered resources into the reasonably assured or inferred resources. Also, it is likely that within the reasonable resources, volumes move from higher-cost to lower-cost categories.

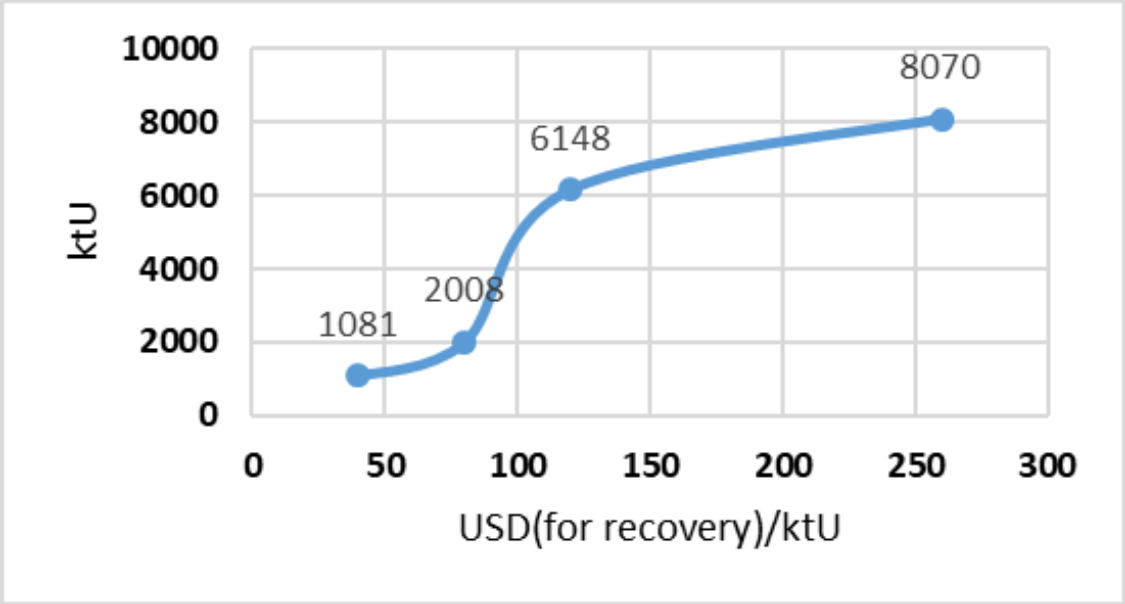


Figure 13: Recoverable uranium resources by cost category (2019)

Source: Own calculation, based on (IAEA and NEA 2020, 15).

4.4 Intermediate conclusion

The uranium market is characterized by shorter-term price fluctuations, but longer-term stability at relatively low prices. Estimates of the recoverable resource base have gone up from 1.5 Mt (1965) to 8 Mt (2019) at prices below $ 260/kg (in July 2021, the US spot price was in the $ 30s/kg). In addition, about 7.2 Mt undiscovered resources remain to be mined, should prices go up significantly. Given this evidence, it is very unlikely that uranium supply will be constrained even in the longer-term future, such that the plutonium route becomes economic, say, with uranium prices in the four-digit range.

5 Can reactors become competitive through standardized mass production (“SMR”-reactors)

In this section, we assess the potential for cost reduction for breeder reactors, and more generally other types of reactors of small power output, through standardized production. This is an expectation that some industry observer connect with so-called SMR reactors (“small modular reactors”, i.e. of relatively low capacity (< 300 MWel). Fast reactors are an important element of the SMR-reactors, such as the Chinese CEFR (Chinese Experimental Fast Breeder), but other countries are also pursuing R&D in the

field (Russia, South Korea, USA). We report on recent trends in the SMR reactor segment, and derive a methodology to benchmark their potential costs, compared to reactors with higher capacity.[30]

5.1 Non-conventional SMR-reactors

Closely related to the Generation IV activities is an R&D stream on so-called "SMR-reactors", that has emerged over the last one or two decades. Some industry observers consider this to become a competitive source of nuclear energy in the medium-term future (Locatelli, Bingham, and Mancini 2014; Rothwell 2016; Lloyd, Lyons, and Roulstone 2020a; WNA 2020b). In fact, the International Atomic Energy Agency (IAEA) has developed a new research&development field dedicated to SMR-concepts, accompanied by bi-annual reviews of the most advanced concepts from the IAEA database on "Advanced Reactors Information System (ARIS)" (IAEA 2018, 2020).

Even though there is no commonly agreed definition, SMRs are often defined as "reactors in which a single reactor has an electrical power output of less than 300 MW_{el} (or a thermal power output of less than 1000 MW_{th})" (Pistner et al. 2021, 24). The modularity of production and the possibility of standardized, industrial production of individual reactor module plays a particular role. SMR research takes as point of inception that traditional nuclear power plants with high electric power (up to 1,600 MW_{el}) have become too expensive, due to their long construction times, and lack of standardization (Lloyd, Lyons, and Roulstone 2020b; Boarin et al. 2021). Moving towards highly standardized, mass produced modules should reverse this trend.

Pistner, et al. (2021) provide a very detailed overview of SMR concepts. In many cases, these date back to developments in the 1950s, in particular the attempt to use nuclear power as a propulsion technology for military submarines. Today, a wide variety of theoretical concepts and demonstrators for SMR are discussed, but the majority only exist at the concept level. Very few SMRs are already in operation, among them two Russian floating nuclear power plant types (KLT-40, and RITM). "Other plants already in operation, such as the Chinese Experimental Fast Neutron Reactor (CEFR) and the Indian Heavy Water Reactor (PHWR-220), are also classified as SMRs in some places" (Pistner et al. 2021, 24), even though strictly speaking they are not designed to be produced in a modular way.[31]

There is a controversial discussion about the potential effects of SMR concepts in future energy systems (Locatelli, Bingham, and Mancini 2014; Lloyd, Lyons, and Roulstone 2020b; Pistner et al. 2021). In addition, it seems that the SMR optimism focusses mainly on light-water moderated technologies, which have a certain established record of development and implementation (Ramana and Ahmad 2016; Pistner et al. 2021). In the US, the term SMR is even sometimes limited to light water reactors,[32] for which more experience with scaling also exists, going back to the first SMR put in operation, the Nautilus Nuclear Navy submarine (officially called S2W), back in 1954. Therefore, the subsequent discussion

[30] The section largely relies on a study on SMR concepts by Pistner et al. (2021), a review of the literature and own calculations.

[31] Other reactor types are under construction, most advanced are the Chinese High-Temperature Reactor (HTR-PM) or the Argentine light-water reactor (CAREM).

[32] See Chu, Steven Chu (2010) "America's New Nuclear Option: Small Modular Reactors Will Expand the Ways We Use Atomic Power."

focusses more generally on SMR concepts at large, and applies the production model to a light-water reactor (Westinghouse) and, subsequently, fast plutonium reactors.

Reactor	Type, coolant	Power thermal/elec (MW)	Fuel (future)	Company, country	Notes
PRISM	Demonstration, pool, sodium	840/311	metal	GEH, USA	From 2020s
ARC-100	Prototype, pool, sodium	260/100	metal	ARC+GEH, USA	
FMR	Demonstration, helium HTR	50	?	GA-EMS, USA	2035
EM2	Helium HTR	500/240	oxide?	GA, USA	With MHI
Westinghouse LFR	Pool, lead	950/450	LEU oxide/silicide	Westinghouse, USA	
Moltex SSR-U	MSR	750/300 (for 8 modules)	Pu+U chloride	Moltex UK	
Astrid	Prototype, pool, sodium	100-200	oxide	France, with Japan	Delayed, after 2050
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	Cancelled
Gen4 module	Lead-Bi	70/25	LEU nitride	Gen4, USA	
Sealer	Lead	3-10 MWe	LEU oxide/nitride	LeadCold, Sweden	By 2025
Aurora	Heatpipe	4/1.5	U-Zr metal	Oklo, USA	COL application
eVinci	Heatpipe	0.2-5.0 MWe	various	Westinghouse, USA	

Table 4: Fast neutron designs with low power ratings (< 300 MWel) according to the World Nuclear Association

Source: (WNA 2021).

5.2 Production economics

5.2.1 Trade offs

The narrative of the SMR reactors is built on the hypothesis that modularity and learning economies will overcompensate the penalty from the low power rating. Modularity can occur in the construction of reactors, using standardized elements, and modularity in the mass production of components (Rothwell 2016, 92). However, the small power rating implies a significant cost disadvantage at the outset, foregoing economies of scale. This has to be countered by mass production, leaning effects, and other effects (Boarin et al. 2021, 255 sq.), see Figure 14.

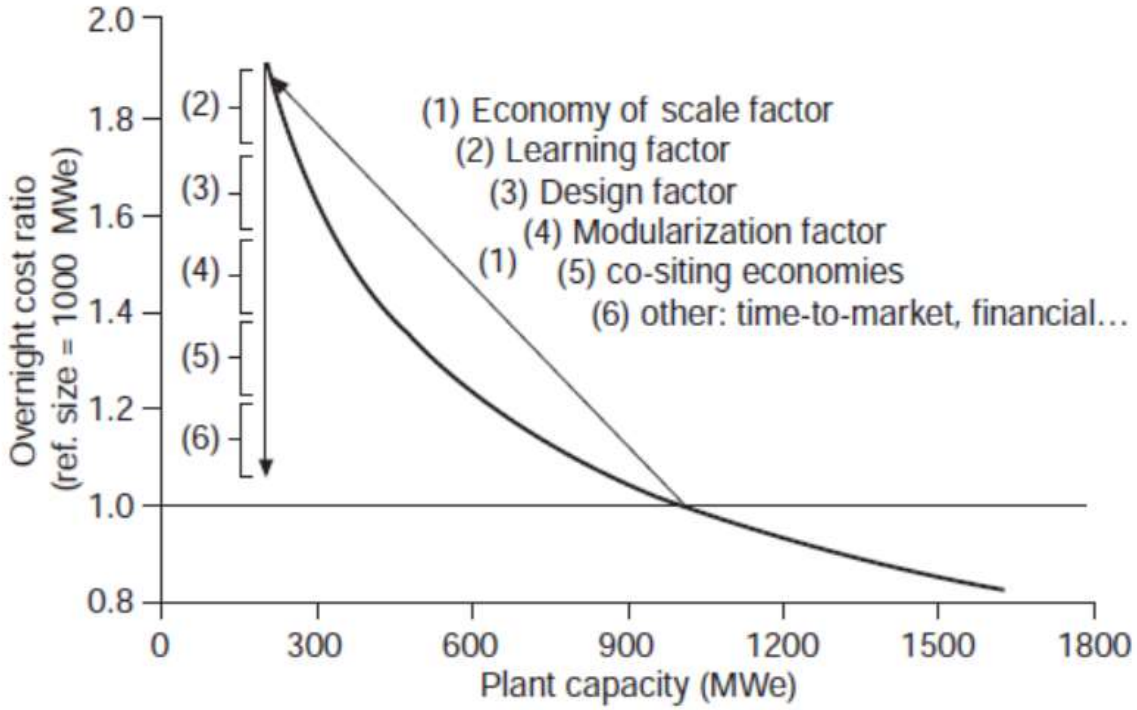


Figure 14: Production costs of SMR and other qualitative trends

Source: (Boarin et al. 2021, 253).

5.2.2 Scale economies …

Scale economies refer to a rule often observed, that the specific construction costs (e.g. in US-$/MWel) decrease as the size of the unit increases. They are rooted in fixed cost digression, volume effects, etc. Scale effects can be estimated in the following way (Ramana and Mian 2014, 119; Lloyd, Lyons, and Roulstone 2020b, 41):

$$\frac{C_{SMR}}{C_{LR}} = \left(\frac{S_{SMR}}{S_{LR}}\right)^b \Leftrightarrow C_{SMR} = C_{LR}\left(\frac{S_{SMR}}{S_{LR}}\right)^b \quad (8)$$

with $C_{SMR, LR}$ the total costs of the SMR reactor and the reference reactor of higher power (LR) with the similar technology in US-$, respectively, and $S_{SMR, LR}$ the electrical power of the two reactors in MWel, respectively; b is the scaling factor.[33] The general literature on production economics includes estimates of b in the range of 0.2 – 0.75 (OECD Nuclear Energy Agency 2000, 32). Based on observations in the nuclear industry, (Ramana and Mian 2014, 119) apply 0.5 – 0.6; for more references see (Pistner et al. 2021, 69).

[33] The higher b, the lower is the cost disadvantage of the reactor with lower power; for b = 1 the costs are proportional to power ratings.

5.2.3 … vs. learning effects and mass production …

Increasing the production of a standardized good should lead to falling construction costs, either through a better use of capital ("mass effects") and/or through higher productivity of labor ("learning effect", when moving from the "first-of-a-kind" (FAOK) to the n^{th}-of-a-kind (NOAK). The average costs can be defined as:

$$\frac{C_{SMR,n}}{C_{SMR,1}} = (1-x)^d \Leftrightarrow C_{SMRn} = C_{SMR,1} * (1-x)^d \quad (9)$$

with $C_{SMR1,\,n}$ are the construction costs ("overnight construction costs", OCC) of the first, resp. the n^{th} reactor, respectively, and x as the learning rate after the d^{th} doubling of output (e.g. 1 ➔ 2 ➔ 4 ➔ 8 corresponds to d = 3, n = 8). For "mass mass" products like microchips or solar modules, learning effects of 10-20% are common (VDMA 2020; Wirth 2020). In the French nuclear industry, a value of 3.2% was established on reactors with larger capacity (Berthélemy and Escobar Rangel 2015, 126), whereas SMR research suggests values of 3-5% (Lloyd, Lyons, and Roulstone 2020b), sometimes up to 10% (Mignacca and Locatelli 2020; Pistner et al. 2021, 71).

5.2.4 … combined

The two effects can be brought together to give

$$C_{SMR,n} = C_{SMR,1} * (1-x)^d = C_{LR} * \left(\frac{S_{SMR}}{S_{LR}}\right)^b * (1-x)^d \quad (10)$$

with the above definitions.

5.3 Some indicative evidence

Can SMR-reactors become cheaper than current reactors of high power? That depends on the learning and the mass production that can be generated. Given the absence of existing empirical evidence, we have to make simplifying assumptions to determine, for example, how many SMRs need to be produced to be competitive with the reactor of higher capacity.

Figure 15 shows the development of construction costs of a nuclear reactor as a function of the learning factor (x) and the number of units produced (represented by the doubling factor d). Clearly, a large number of units needs to be produced to achieve significant cost reduction. We use the example of an existing Westinghouse light water reactor with high capacity (AP1000, 1,117 MWel) and unit costs of $ 6,000/kWel and a (planned) Westinghouse SMR (225 MWel). Assuming a scale effect of 0.55 and an (optimistic) learning rate of 0.6, about 3,000 SMR 225 would need to be built to compensate for the size penalty. If, in addition, one assumes that the higher power reactor also achieves learning, this number would still go up.[34]

[34] Using an optimistic variant (specific costs: 6,000 USD/kW, b = 0.6, x = 0.1) would yield a value of 65, still above what Westinghouse was counting on ('Westinghouse Backs off Small Nuclear Plants' www.post-gazette.com/business/2014/02/02/Westinghouse-backs-off-small-nuclear-plants/stories/201402020074). On the contrary, using less optimistic values gives unbelievably high values, e.g. specific costs of 10.000 USD/kW, b = 0.5, x= 0.02: 666 billion.

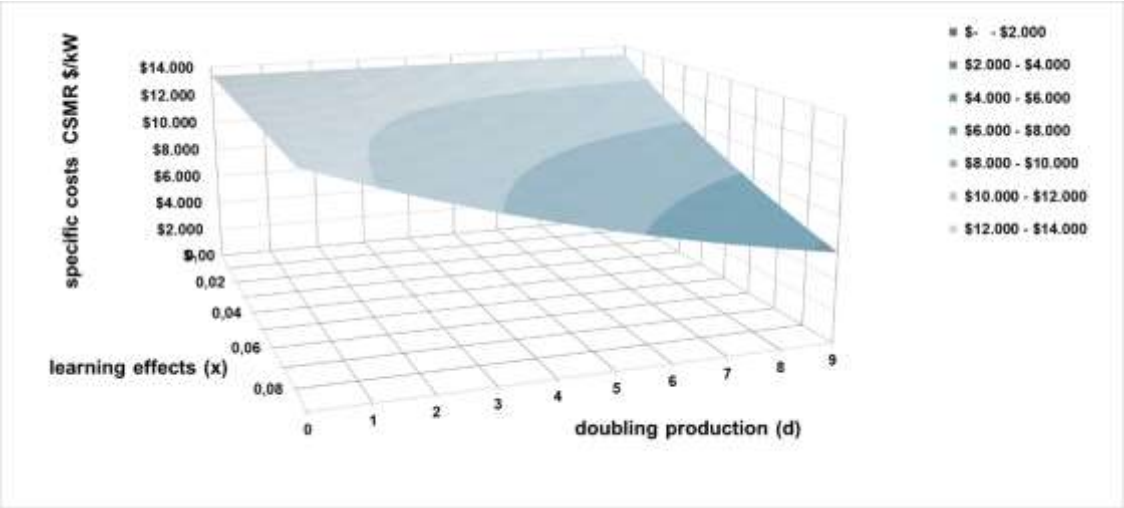


Figure 15: Costs of an SMR taking into account learning, and doubling of production

Source: Own calculations, based on Steigerwald et al. (2021).

It is even more difficult to benchmark fast reactors, due to a lack of representative models and reliable cost data. Table 4 shows a range of fast reactors characterized as SMRs by the World Nuclear Association. Currently, the Chinese Experimental Fast Reactor (CEFR) is only fast SMR already in operation. It's power output is low (20 MWel), but it is designed in the tradition of sodium fast reactors (SFRs), eventually using plutonium-uranium-oxide fuels (MOX).[35] Like other SMRs, the CEFR faced significant cost escalations. From the initial estimate of $ 8,000/kWel, these have increased to $ 23.000/kWel (Pistner et al. 2021, 73). Other fast reactors SMR concepts are under development, such as the PRISM (Power Reactor Innovative Small Module, 311 MWel), and the ARC-100 (Advanced Reactor Concept, 100 MWel).

A direct benchmark with fast breeder reactors of high capacity is not useful. However, transferring the approach from the light-water reactor suggests that a very large number of fast breeder reactors would need to be built to benefit from learning effects.[36]

5.4 Intermediate conclusion

High hopes are placed by some actors in the development of reactors of small capacity ("SMRs"), expected to become cost competitive after a period of learning and mass production. Assuming some basic production theory and parameters, this proposition is not convincing. This is shown using some production economics for the representative (Westinghouse) light water reactors. By analogy, there are

[35] The CEFR went critical for the first time in 2011, but has had major interruptions since. Although data on real utilization is not consistent between different sources, the CEFR has been developed further over the last years, as one of the founding pillars of an ambitious fast reactor program (Wang et al. 2013; Pistner and Englert 2017; Sokolski 2021).

[36] As a thought experiment, one could combine the costs of the CEFR with the power rating of the PRISM, benchmarked against the (optimistic) cost assumptionso of the Superphoenix demonstrator fast reactor ($ 4,580/kWel, Nature, Vol. 385, 9. Jan 1997, p. 104); assuming b = 0,5 and x = 5%, 9.168 reactors would need to be produced.

indications that similar results hold for fast reactors under development. Thus, we conclude that expectations of fast reactors becoming substantially more competitive in the medium-term future are unlikely to be fulfilled.

6 Can plutonium be efficiently abated?

If, as the last two sections suggested, plutonium is unlikely to become a valuable resource, can it be abated efficiently? Environmental economics assumes that harmful outputs should be abated as long as this is less costly than the harm they generate. Therefore, options need to be explored to reduce the amount of harmful plutonium, and, if possible, to provide economic analysis thereof, i.e. to check whether the aggregated costs of reducing the plutonium are lower than the avoided damage. In essence, there are two options to reduce the danger from plutonium: i/ Deep geological depository, and ii/ abatement. Attempts to place plutonium (and other radioactive waste) in long-term geological depositories is under way, though this is a very long-term and complex socio-technical process (Brunnengräber et al. 2015; Brunnengräber and Di Nucci 2019). If there was a way to get rid of plutonium more easily, this would be worthwhile exploring. In this section, we survey the literature on plutonium abatement, and discuss whether it could be done efficiently, i.e. at low cost and without creating other harm. The discussion focusses on fast metal cooed reactors, thus leaving aside other, still more hypothetical pathways;[37] neither does this section cover individual research reactors currently under development in the Generation IV and/or SMR programs, using similar processes of waste burning.[38]

6.1 Partitioning and transmutation (P&T)

Plutonium abatement ("burning") was addressed by physicists from the very beginning, e.g. Leo Szilard (Szilard 1947)[39], and it has become part of the narrative of plutonium as a large-scale source of energy (Gates 2021). Physically, it is indeed possible to significantly reduce the amount of plutonium in the final waste by a process called partitioning and transmutation (P&T). Research interest in P&T has grown again in the context of the "Generation IV" and SMR-reactor developments (National Research Council 1996; IAEA 2004; Kirchner et al. 2015; Pistner and Englert 2017). Transmutation relies heavily on the availability of fast reactors at large scale[40], and the reprocessing plutonium route in general (IAEA 2004).[41] A fast reactor can not only breed plutonium, but it can also burn it to reduce the burden of safe

[37] Such as accelerator-driven systems (ADS); and molten salt reactors (MSR). While the ADS-technology is not yet available (a demonstration reactor (MYRRAH) is planned in Belgium for the mid-2030s), the MSR requires pyrochemical separation that is far from being available, see (Frieß et al. 2021).

[38] For details on some of these projects, see (Locatelli, Mancini, and Todeschini 2013; Pistner and Englert 2017; IAEA 2020).

[39] "If plutonium is allowed to disintegrate, or let us again say if it is burned, heat is produced in much the same way as in the case of uranium 235. Heat is produced however not only when we burn plutonium, but also when we manufacture it. As a matter of fact more heat is produced in the process of making plutonium than in the process of burning it. So if we consider the atomic fuel plutonium for purposes of power production we must keep in mind that we produce heat as a by-product at the time we manufacture plutonium and that we also produce heat again later when we decide to burn a certain quantity of it." (Szilard 1947, 3).

[40] "Recycling of plutonium in LWR MOX reactors is an intermediate strategy to reduce separated plutonium stocks and to partially use its fissile content. However, full recycling and burning of plutonium is only possible when FRs become operational on the industrial scale." (IAEA 2004).

[41] "P&T is an alternative waste management strategy that aims to reduce the very long term radiological burden of nuclear energy. It relies on the nearly quantitative recycling of long lived and highly radiotoxic nuclides. It is therefore

disposal and have lower safe disposal requirements than the parent nuclides, in particular less plutonium. In the event, some nuclides can even be reused as nuclear fuel. Figure 16 summarizes the process.

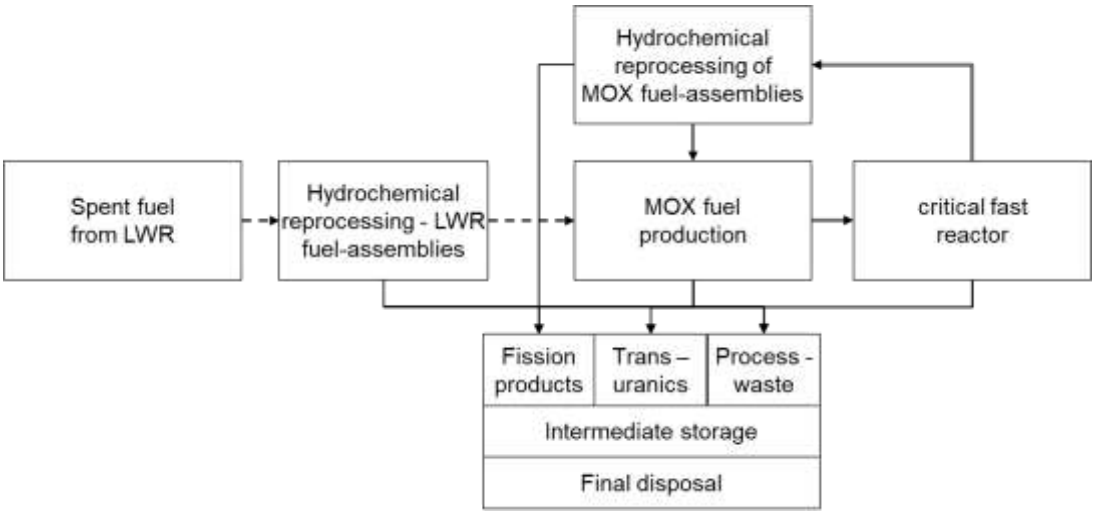


Figure 16: Partitioning and transmutation using a fast reactor

Source: Translated from (Frieß et al. 2021, 190).

In a first step, radioactive waste is partitioned into different wave streams (“partitioning”), the objective being to reduce the amount of transuranic waste, not only the plutonium, but also other minor actinides such as neptunium, americium, and curium. Partitioning involves at least the separation of transuranic elements into plutonium (so-called major actinide) and the minor actinides. Currently, the only established technology is hydrochemical separation, relying on a repetitive process of separating the heavy metals by solution, extraction, precipitation or adsorption in aqueous and organic solutions. The so-called hydrochemical PUREX process (plutonium – uranium – recovery by extraction) is used for fast neutron fuels (Frieß et al. 2021).

The second step, called transmutation, involves the conversion of radionuclides into other nuclides through nuclear physical transformations, particularly nuclear fission (Frieß et al. 2021, 25). Although transmutation is understood in theory, it has not been applied outside the laboratory context. Significant research and industrial development would still be required: Even though the principle of fast metal-cooled reactors is applied, special forms of reactors would have to be developed, amongst others significantly increasing the proportion of minor actinides in the fuel. This requires significant modification to reactor designs, and longer R&D periods (Kirchner et al. 2015).

Further challenges of P&T are the choice of the appropriate fuel, and the related danger of proliferation. For P&T with fast reactors, plutonium-uranium mixed oxide (MOX) fuels are the most obvious choice, though they would require a different composition than those used for light-water reactors, in particular

very important to stress the crucial role of reprocessing technologies in any further P&T development. For P&T to be a viable option it will be necessary for reprocessing expertise to be preserved either in existing industrial plants or by keeping R&D projects in this field alive.” (IAEA 2004).

with respect to the inclusion of minor actinides (Frieß et al. 2021, 29). Proliferation would be facilitated, because large amounts of weapon grade material would become available, without any radiation barrier.

6.2 Trade-offs in large-scale P&T scenarios

Research on "plutonium abatement" indicates trade-offs: The amounts of plutonium can indeed be reduced, but other products, mainly fission products, are generated in large quantities, so that the overall balance is unclear. Clearly this process is not "Pareto-efficient", because while some plutonium problems diminish (though they do not disappear), other problems appear.

Frieß et al. (2021) provide one of the most detailed analysis to-date of large-scale P&T scenarios, using the fast metal-cooled reactor, applied to the volumes available in Germany. On the one hand, they show that abating plutonium is possible: Provided technical solutions for MOX-elements with minor actinides, and a new fast reactor, are found in the coming decades, the scenario leads to a significant reduction of plutonium, i.e. for Germany from 130 tons to about 17 tons (Figure 17).[42] However, this would not only be very expensive and take a long time, but it would also generate significant amounts of additional waste:

~ A total of 23 new reactors would have to be constructed and operated over a period of about 300 years, to exhaust the possibility of transuranium reduction (Frieß et al. 2021, 34). In addition, a reprocessing facility for LWR-fuel and 18 reprocessing plant for FR-MOX fuel would be required, plus seven fuel fabrication plants (Table 5).

~ The amount of three long-lived fission products, technecium-99, iodine-129, and cesium-135, which serve as guide isotopes for evaluating the long-term safety of repositories, would increase significantly (48 – 71%).

~ In the course of the process, large quantities of low-and intermediate-level waste would be generated, mainly by the reprocessing and the dismantling of all the facilities (Frieß et al. 2021, 34) (Table 5). The volume would exceed 300,000 m^3, which is the size of the Konrad depository in Germany for medium- and low-level waste.[43]

[42] Americium would also be reduced (by over 50%), while neptunium would stay more or less constant. About 7 tons of Curim would be produced, which decay relatively quickly (in weeks) to another 6.5 tons of plutonium.

[43] Planning of this mine started in the 1970s, it is currently expected to open in the mid-2020s.

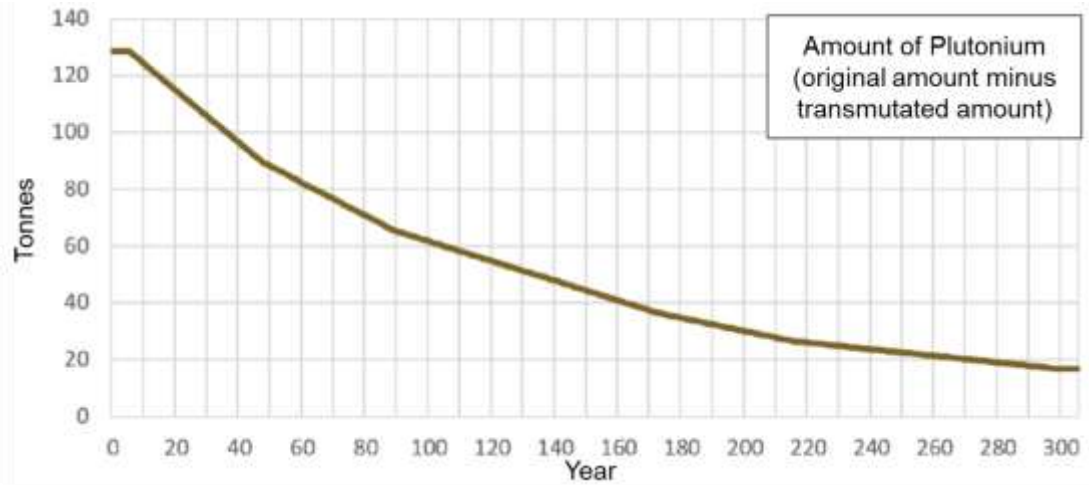


Figure 17: Abatement of plutonium through transmutation in a fast reactor (FR)

Source: Translated from (Frieß et al. 2021, 197).

The figure shows the initial amount minus the transmuted amount of plutonium in a fast breeder scenario. At the end of the scenario (after 300 years), at least 21.8 tons of plutonium remain, of which 2.3 t are in reprocessing and fuel fabrication.

	Amount	Comment	Total
Reactors			
Decomissioning	23 installations	5,000 m^3/installation	115,000 m^3
Operation	23 installations, 42 years each	42 years * 45 m^3/year	43,500 m^3
Reprocessing plant for light-water fuel			
Decomissioning	1	36,000 m^3	36,000 m^3
Operation	10,113 t HM	6.59 m^3/t HM	66,600 m^3
Reprocessing plant (reactor MOX-fuel)			
Decomissioning	18	1,500 m^3	27,000 m^3
Operation	2,710 t HM	6.59 m^3/t HM	17,900 m^3
Fuel fabrication			
Decomissioning	7	1,000 m^3	7,000 m^3
Operation	2,945 t HM	1.2 m^3/t HM	3,500 m^3
Total			**316,500 m^3**

Table 5: Infrastructure requirements for the P&T scenario with fast reactors[44]

Source: (Frieß et al. 2021, 201).

Clearly abating plutonium comes at very high costs. Even without having precise figures, the analysis suggests that the benefit-cost-ratio of a hypothetical large-scale abatement of plutonium by partitioning and transmutation is low. In addition, P&T for a couple of centuries is at odds with the institutional setting

[44] HM ~ heavy metal.

in many countries.[45] Last but not least, abatement of plutonium in spent fuels would not resolve the requirement to develop a long-term depository: First, because not all plutonium can be abated, and, second, because about 40% of highly-radioactive waste has been already vitrified and cannot be treated anymore (Frieß et al. 2021, 237).

6.3 Intermediate conclusion

Theoretical research on laboratory and pilot scale applications indicate that partitioning and transmutation can succeed in reducing the amount of plutonium. However, this requires significant amounts of new reactors, and generates additional amounts of other radioactive elements, mainly fission products and large amounts of medium- and low-level waste. Because it is very difficult to provide concrete figures and monetary values, in particular the danger of proliferation, in this section we discuss the trade-offs quantitatively, leaving the quantification to later research. No precise economic quantification is available on the cost and the benefits of abating plutonium, but the available evidence suggests that partitioning and transmutation are no promising neither secure route to support the plutonium economy. P&T programs require a large number of nuclear facilities, and very long-term operation of up to several centuries (including the decades of R&D before a possible realization of the P&T program). The nuclear facilities needed for P&T are not available at commercial scale, and it is highly unclear whether it will be technically possible. Not only would the amount of low-and intermediate-level secondary waste increase significantly, but also the amount of high-level long-lived fission products would increase significantly. To this, a high level of institutional uncertainty is added: The conditions for granting a license for novel facilities in Germany (or elsewhere) is currently not given, and unclear in the longer term (Frieß et al. 2021, 39).[46] Therefore, plutonium abatement is no alternative for the consequent implementation of a final depository.

7 Conclusion

In this paper, we have highlighted specific economic aspects of plutonium. Interest in the topic is increasing recently, due to the lack of competitiveness of light-water nuclear power, and various attempts to re-focus on the plutonium route using fast reactors, that once were expected to become the foundation of commercial nuclear energy. Due to its high radioactivity and potential for military use, the treatment of plutonium is highly regulated and there is no “market” to define its prices; neither are models of optimal resource depletion available to provide guidance on estimating the value of plutonium. Therefore, we report a simple analytical framework, and apply it to the different sub-questions, having to do with resources, construction costs, and plutonium abatement.

We find no evidence that the historical trend, i.e. a negative value of plutonium, is likely to be reversed in the future: In the long term, uranium resources are sufficiently abundant to prevent extremely high uranium prices. Current research on “SMR-reactors” is unlikely to generate a new generation of fast

[45] In Germany, the 13th Amendment of the Nuclear Power Law (Atomgesetz) defines an end for commercial nuclear power in 2022, and the final depository act (Standortauswahlgesetz), obliges the government to site a final depository until 2031, and then to proceed with filling this depository rapidly.

[46] At present, any P&T is clearly at odds with the German legislative situation, requiring the identification of a site until 2031, and subsequent filling of the depository.

reactors that would be cheaper. Abating plutonium is no economically efficient way to deal with the problem of waste.

Further research should update the available analysis. Arguments also need to be developed whether research in fast reactor technologies should continue, after seven unsuccessful decades. A full environmental economic assessment of the risks of fast reactors and plutonium, including proliferation, is still lacking in the literature. Last but not least, we need to better understand the implication of these findings for the process of identifying depositories for nuclear waste.

References

Acheson-Lilienthal Report. 1946. “A Report on the International Control of Atomic Energy.” Prepared for the Secretary of State’s Committee on Atomic Energy. Washington, D.C.

Baade, Fritz. 1958. *Welt-Energiewirtschaft: Atomenergie - Sofortprogramm oder Zukunftsplanung*. Hamburg: Rowohlt.

Berthélemy, Michel, and Lina Escobar Rangel. 2015. “Nuclear Reactors’ Construction Costs: The Role of Lead-Time, Standardization and Technological Progress.” *Energy Policy* 82 (July): 118–130.

Besnard, Manon, Marcos Buser, Ian Fairlie, Gordon MacKerron, Allison Macfarlane, Eszter Matyas, Yves Marignac, Edvard Sequens, Johan Swahn, and Ben Wealer. 2019. “The World Nuclear Waste Report. Focus Europe.” Berlin, Brussels.

Boarin, S., M. Mancini, M. Ricotti, and G. Locatelli. 2021. “Economics and Financing of Small Modular Reactors (SMRs).” In *Handbook of Small Modular Reactors*, 2nd ed., 241–278. Kidlington (UK) and Cambridge (USA): Elsevier.

Brunnengräber, Achim, and Maria Rosaria Di Nucci. 2019. *Conflicts, Participation and Acceptability in Nuclear Waste Governance: An International Comparison. Volume III*. Wiesbaden: Springer VS.

Brunnengräber, Achim, Maria Rosaria Di Nucci, Ana María Isidoro Losada, Lutz Mez, and Miranda A. Schreurs, eds. 2015. *Nuclear Waste Governance. An International Comparison*. Wiesbaden: Springer VS.

Bunn, Matthew, Steve Fetter, John P. Holdren, and Bob van der Zwaan. 2003. “The Economics of Reprocessing Versus Direct Disposal of Spent Nuclear Fuel.” Project on Managing the Atom. Belfer Center for Science and International Affairs, Harvard Kennedy School.

Bunn, Matthew, Hui Zhang, and Li Kang. 2016. “The Cost of Reprocessing in China.” Cambridge MA (USA): Belfer Center for Science and International Affairs Harvard Kennedy School.

Chu, Steven. 2010. “America’s New Nuclear Option: Small Modular Reactors Will Expand the Ways We Use Atomic Power.” *Wall Street Journal*, March 23, 2010.

Commissariat Général du Plan. 2000. “Report to the Prime Minister [of France]: Economic Forecast Study of the Nuclear Power Option.” Paris, France.

Considine, Timothy J. 2019. “The Market Impacts of US Uranium Import Quotas.” *Resources Policy* 63 (October): 101445.

Davis, Lucas W. 2012. “Prospects for Nuclear Power.” *Journal of Economic Perspectives* 26 (1): 49–66.

De Roo, Guillaume, and John E. Parsons. 2011. “A Methodology for Calculating the Levelized Cost of Electricity in Nuclear Power Systems with Fuel Recycling.” *Energy Economics* 33 (5): 826–839.

Eisenbart, Constanze, Christoph Pistner, and et al. 2004. “Wohin mit dem Plutonium? Optionen und Entscheidungskriterien.” Band 31. Heidelberg: Forschungsstätte der Evangelischen Studiengemeinschaft (FEST).

Frieß, Friederike, Nikolaus Arnold, Wolfgang Liebert, and Nikolaus Müllner. 2021. “Sicherheitstechnische Analyse und Risikobewertung von Konzepten zu Partitionierungs- und Transmutationsanlagen für hochradioaktive Abfälle.” Wissenschaftliches Gutachten im Auftrag des Bundesamtes für die Sicherheit der nuklearen Entsorgung (BASE) urn:nbn:de:0221-2021030826033. Berlin; Wien: Institut für Sicherheits- und Risikowissenschaften Universität für Bodenkultur (BOKU).

Gates, Bill. 2021. *How to Avoid a Climate Disaster - The Solutions We Have and the Breakthroughs We Need*. New York, NY: Alfred A. Knopf.

GIF. 2018. “GIF Annual Report 2017.” GEN IV International Forum.

Hall, S., and M. Coleman. 2013. “Critical Analysis of World Uranium Resources.” Scientific Investigations Report 2012–5239. US Geologicsl Survey, prepared in cooperation with the U.S. Energy Information Administration.

Holdren, John P. 1975. “Uranium Availability and the Breeder Decision.” *Energy Systems and Policy* 1 (3).

IAEA. 2004. “Implications of Partitioning and Transmutation in Radioactive Waste Management.” Technical Report Series 435. Vienna, Austria: IAEA.

———. 2017. “Nuclear Power for a Clean-Energy Future.” IAEA Bulletin.

———. 2018. “Advances in Small Modular Reactor Technology Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS).” Vienna, Austria: International Atomic Energy Agency.

———. 2020. “Advances in Small Modular Reactor Developments. A Supplement to: IAEA Advanced Reactors Information System (ARIS).” IAEA Booklet. Vienna, Austria: International Atomic Energy Agency.

IAEA and NEA. 2020. “Uranium 2020: Resources, Production and Demand.” Paris: Nuclear Energy Agency / Organisation for Economic Co-operation and Development.

JAEC. 2011. “Estimation of Nuclear Fuel Cycle Cost.” Tokyo, Japan: Technical Subcommittee on Nuclear Power, Nuclear Fuel Cycle, etc.

Jukes, J.A. 1956. “The Cost of Power and the Value of Plutonium from Early Nuclear Power Stations.” In *The Economics of Nuclear Power*, 1:185 ff. London.

Kirchner, Gerald, Matthias Englert, Christoph Pistner, Beate Kallenbach-Herbert, and Julia Mareike Neles. 2015. “Gutachten „Transmutation“.” K-MAT 48. Kommission Lagerung hoch radioaktiver Abfallstoffe. Hamburg, Darmstadt: Öko-Institut, Universität Hamburg, ZNF.

Landajo, Manuel, María José Presno, and Paula Fernández González. 2021. “Stationarity in the Prices of Energy Commodities. A Nonparametric Approach.” *Energies* 14 (11): 3324.

Lévêque, François. 2014. *The Economics and Uncertainties of Nuclear Power*. Cambridge, MA, USA: Cambridge University Press.

Liebert, Wolfgang, and Matthias Englert. 2015. “Risiken der Uranproduktion und der Urannutzung - Risiken für die Nutzung der Kernenergie.” Wien, Austria.

Lloyd, Clara, Robbie Lyons, and Tony Roulstone. 2020a. “Expanding Nuclear’s Contribution to Climate Change with SMRs.” *Nuclear Future*, November, 39.

———. 2020b. “Expanding Nuclear’s Contribution to Climate Change with SMRs.” *Nuclear Future*, November, 39.

Löbl, O. 1956. “Wirtschaftlichkeit der Atomenergie.” *Elektrotechnische Zeitschrift (ETZ)* 77 (13): 460 ff.

Locatelli, Giorgio, Chris Bingham, and Mauro Mancini. 2014. “Small Modular Reactors: A Comprehensive Overview of Their Economics and Strategic Aspects.” *Progress in Nuclear Energy* 73 (May): 75–85.

Locatelli, Giorgio, Mauro Mancini, and Nicola Todeschini. 2013. “Generation IV Nuclear Reactors: Current Status and Future Prospects.” *Energy Policy* 61 (October): 1503–1520.

Lucas, Larry L., James R. Noyce, and Bert M. Coursey. 1978. “The Half Life of Plutonium-239.” *The International Journal of Applied Radiation and Isotopes* 29 (8): 501–503.

Mendelevitch, Roman, and Thanh Thien Dang. 2016. “Nuclear Power and the Uranium Market: Are Reserves and Resources Sufficient?” DIW Roundup 98. Berlin, Deutschland: DIW Berlin - Deutsches Institut für Wirtschaftsforschung.

Midttun, Atle, and Thomas Baumgartner. 1986. “Negotiating Energy Futures: The Politics of Energy Forecasting.” *Energy Policy* 14 (3): 219–241.

Mignacca, Benito, and Giorgio Locatelli. 2020. “Economics and Finance of Small Modular Reactors: A Systematic Review and Research Agenda.” *Renewable and Sustainable Energy Reviews* 118 (February): 109519.

MIT. 2003. “The Future of Nuclear Power.” Cambridge, MA: Massachusetts Institute of Technology.

———. 2018. “The Future of Nuclear Energy in a Carbon-Constrained World.” Cambridge, MA: Massachusetts Institue of Technology.

Monnet, Antoine, Sophie Gabriel, and Jacques Percebois. 2017. “Analysis of the Long-Term Availability of Uranium: The Influence of Dynamic Constraints and Market Competition.” *Energy Policy* 105 (June): 98–107.

Morss, Lester R., Norman M. Edelstein, J. Fuger, and Joseph J. Katz, eds. 2006. *The Chemistry of the Actinide and Transactinide Elements*. 3rd ed. Dordrecht: Springer.

Muellner, Nikolaus, Nikolaus Arnold, Klaus Gufler, Wolfgang Kromp, Wolfgang Renneberg, and Wolfgang Liebert. 2021. "Nuclear Energy - The Solution to Climate Change?" *Energy Policy* 155 (August): 112363.

Murakami, Tomoko. 2021. "A Historical Review and Analysis on the Selection of Nuclear Reactor Types and Implications to Development Programs for Advanced Reactors; A Japanese Study." *Energy Reports* 7 (November): 3428–3436.

National Research Council. 1996. *Nuclear Wastes - Technologies for Separations and Transmutation*. Washington, DC: The National Academies Press.

NEA/IAEA. 2018. "Uranium 2018: Resources, Production and Demand." NEA No. 7413.

Neles, Julia Mareike, and Christoph Pistner, eds. 2012. *Kernenergie: eine Technik für die Zukunft?* Technik im Fokus. Berlin: Springer Vieweg.

Nelson, Andrew T. 2012. "Thorium: Not a near-Term Commercial Nuclear Fuel." *Bulletin of the Atomic Scientists* 68 (5): 33–44.

OECD NEA. 2006. "Forty Years of Uranium Resources, Production and Demand in Perspective." Paris.

OECD NEA, and IAEA. 2014. *Uranium 2014: Resources, Production and Demand*. NEA 7209. Paris, Vienna: Organisation for Economic Co-operation and Development (OECD).

OECD Nuclear Energy Agency, ed. 2000. *Reduction of Capital Costs of Nuclear Power Plants*. Nuclear Development. Paris: Nuclear Energy Agency, Organisation for Economic Co-operation and Development.

Owen, A.D. 1983. "The Economics of Uranium Demand." *Resource Policy* 9 (2): 110–121.

Pedregal, Diego J. 2020. "Forecasting Uranium Prices: Some Empirical Results." *Nuclear Engineering and Technology* 52 (6): 1334–1339.

Pistner, Christoph, and Matthias Englert. 2017. "Neue Reaktorkonzepte. Eine Analyse des aktuellen Forschungsstands." Darmstadt: Öko - Institut e.V.

Pistner, Christoph, Matthias Englert, Christian Küppers, Ben Wealer, Björn Steigerwald, Christian von Hirschhausen, and Richard Donderer. 2021. "Sicherheitstechnische Analyse und Risikobewertung einer Anwendung von SMR-Konzepten (Small Modular Reactors)." Wissenschaftliches Gutachten im Auftrag des Bundesamtes für die Sicherheit der nuklearen Entsorgung (BASE) urn:nbn:de:0221-2021030826028. Darmstadt: Öko-Institut e.V.

Radkau, Joachim. 1983. *Aufstieg und Krise der deutschen Atomwirtschaft 1945-1975: Verdrängte Alternativen in der Kerntechnik und der Ursprung der nuklearen Kontroverse*. Reinbek bei Hamburg, Germany: Rowohlt.

Ramana, M. V., and Zia Mian. 2014. "One Size Doesn't Fit All: Social Priorities and Technical Conflicts for Small Modular Reactors." *Energy Research & Social Science* 2 (June): 115–124.

Ramana, M.V., and Ali Ahmad. 2016. "Wishful Thinking and Real Problems: Small Modular Reactors, Planning Constraints, and Nuclear Power in Jordan." *Energy Policy* 93 (June): 236–245.

Ramana, M.V., and J.Y. Suchitra. 2007. "Costing Plutonium: Economics of Reprocessing in India." *International Journal of Global Energy Issues* 27 (4): 454.

Rooney, Matthew, William J. Nuttall, and Nikolaos Kazantzis. 2015. "A Dynamic Model of the Global Uranium Market and the Nuclear Fuel Cycle." *Resources Policy* 43 (March): 50–60.

Rothwell, Geoffrey. 2016. *Economics of Nuclear Power*. London, UK: Routledge.

Salin, Edgar. 1955. *Ökonomik der Atomkraft – Vor einer neuen Etappe der industriellen Revolution*. Cologne, Germany: Sigillum-Verlag.

Seaborg, Glenn T. 1970. "The Plutonium Economy of the Future." presented at the Fourth International Conference on Plutonium and Other Actinides (5 October 1970), Santa Fe, New Mexico.

Sokolski, Henry D. 2021. "China's Civil Nuclear Sector: Plowshares to Swords?" Occasional Paper 2102. Arlington, VA: Nonproliferation Policy Education Cente.

Strauss, Lewis. 1954. "Remarks Prepared by Lewis. L. Strauss, Chairman, United States Atomic Energy Commission, For Delivery at the Founders' Day Dinner, National Association of Science Writers, on Thursday, September 16, 1954, New York, New York." Washington D.C.: Atomic Energy Commission.

Suchitra, J.Y., and M.V. Ramana. 2011. "The Costs of Power: Plutonium and the Economics of India's Prototype Fast Breeder Reactor." *International Journal of Global Energy Issues* 35 (1): 1.

Szilard, Leo. 1945. “Liquid Metal Cooled Fast Neutron Breeders.” In *The Collected Works of Leo Szilard, (Vol. 1), Scientific Papers (6 March 1945)*, edited by Bernard T. Feld and Gertrud Weiss-Szilard, 369–375. Cambridge MA (USA): MIT Press.

———. 1947. “Atomic Energy, a Source of Power or a Source of Trouble (Speech given April 23 in Spokane, WA).” Leo Szilard Papers. MSS 32. Special Collections & Archives, UC San Diego Library, Spokane, WA.

Tietenberg, Thomas H. 2005. *Environmental and Natural Resource Economics*. 7 edition. Boston: Addison Wesley.

Tietenberg, Thomas H., and Lynne Y. Lewis. 2016. *Environmental and Natural Resource Economics*. 11th edition, International student edition. London New York.

Trieu, Luan Ho, Eric Savage, and Gavan Dwyer. 1994. “A Model of the World Uranium Market.” *Energy Policy* 22 (4): 317–329.

U.S. Department of Energy. 2003. “Report to Congress on Advanced Fuel Cycle Initiative: The Future Path for Advanced Spent Fuel Treatment and Transmutation Research.” Washington DC, USA: Office of Nuclear Energy, Science, and Technology.

VDMA. 2020. “International Technology Roadmap for Photovoltaic.” 11 Edition.

Viscusi, W. Kip, Joseph Emmett Harrington, and John M. Vernon. 2005. *Economics of Regulation and Antitrust*. 4th ed. Cambridge, Mass, USA: MIT Press.

von Hippel, Frank, Masafumi Takubo, and Jungmin Kang. 2019. *Plutonium: How Nuclear Power’s Dream Fuel Became a Nightmare*. Singapore: Springer.

von Hirschhausen, Christian. 2017. “Nuclear Power in the Twenty-First Century – An Assessment (Part I).” DIW Discussion Paper 1700. Berlin, Germany: DIW Berlin.

Wang, Bo, Fudong Liu, Chunming Zhang, Yahua Qiao, Yongye Liu, Yang Yang, Yichuan Wang, Zhaorong Shang, and Qiang Shi. 2013. “Site Selection Considerations of Spent Nuclear Fuel Reprocessing Plant in China.” *Energy Procedia*, The 3rd International Conference on Asian Nuclear Prospects (ANUP2012), 39 (January): 382–386.

Wealer, Ben, Simon Bauer, Christian von Hirschhausen, Claudia Kemfert, and Leonard Göke. 2021. “Investing into Third Generation Nuclear Power Plants - Review of Recent Trends and Analysis of Future Investments Using Monte Carlo Simulation.” *Renewable and Sustainable Energy Reviews* 143.

Wealer, Ben, and Christian von Hirschhausen. 2020. “Nuclear Power as a System Good. Organizational Models for Production Along the Value- Added Chain.” DIW Discussion Paper 1883. Berlin, Germany: DIW Berlin.

Wirth, Harry. 2020. “Aktuelle Fakten zur Photovoltaik in Deutschland.” Ise Frauenhofer.

WNA. 2020a. “Generation IV Nuclear Reactors (Update December 2020).” https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors.aspx.

———. 2020b. “Small Nuclear Power Reactors.” 2020.

———. 2021. “Fast Neutron Reactors (Update June 2021).” https://world-nuclear.org/information-library/current-and-future-generation/fast-neutron-reactors.aspx.

Zhang, Hui. 2020. “China Is Speeding up Its Plutonium Recycling Programs.” *Bulletin of the Atomic Scientists* 76 (4): 210–216.