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Nuclear Power in the Twenty-first Century – An Assessment (Part I)

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Nuclear Power in the Twenty-first Century – An Assessment (Part I)

Christian von Hirschhausen*

Abstract

Nuclear power was one of the most important discoveries of the twentieth century, and it continues to play an important role in twenty-first century discussions about the future energy mix, climate change, innovation, proliferation, geopolitics, and many other crucial policy topics. This paper addresses some key issues around the emergence of nuclear power in the twentieth century and perspectives going forward in the twenty-first, including questions of economics and competitiveness, the strategic choices of the nuclear superpowers and countries that plan to either phase out or start using nuclear power, to the diffusion of nuclear technologies and the emergence of regional nuclear conflicts in the "second nuclear age". The starting point for our hypothesis is the observation that nuclear power was originally developed for military purposes as the "daughter of science and warfare" (Lévêque 2014, 212), whereas civilian uses such as medical applications and electricity generation emerged later as by-products. Based upon this observation, we interpret the nuclear industry in terms of "economies of scope", where strategies, costs, and benefits must be assessed in the multiproduct context of military and civilian uses of nuclear power. We propose a classification of different economic perspectives on nuclear electricity generation, and confirm the consensus of the literature that on its own, nuclear power has never been an economic method of producing electricity: not a single reactor in existence today was constructed by a private investor in a competitive, market economic framework. The economics-of-scope perspective is a useful heuristic to interpret countries' strategic choices regarding the use of nuclear power. The paper provides a survey of strategies used by the nuclear superpowers (United States, Russia, China), by countries phasing out nuclear power because they cannot benefit from economies of scope (e.g., Italy, Spain, Germany, Sweden, Switzerland), and by potential newcomers who may expect synergies between military and civilian uses (e.g., Iran, the United Arab Emirates, Egypt, perhaps one day also Japan). We conclude that the future of nuclear power in the twenty-first century must be assessed in terms of economies of scope, and that a purely "economic" analysis of nuclear electricity is insufficient to grasp the complexity of the issue; this also raises conceptual challenges for energy modelers. The paper leaves out some important questions to be addressed in a future Part II of the assessment, such as economic and technical issues of plant decommissioning, long-term storage of waste, and the potential role of nuclear energy in climate policies.

Keywords: Nuclear power, technology, competitiveness, economies of scope, geopolitics

JEL-codes: L52, L95, N7, Q48, Q54

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Figures

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"The bomb has returned for a second act.
And it shows no sign of exiting the stage anytime soon."

Bracken, Paul (2012, 271): The Second Nuclear Age.

"This technology is a lousy choice."

Henry Cordes, Director of Energiewerke Nord (German nuclear utility), on public television.[1]

1 Introduction

Nuclear power was one of the most important discoveries of the twentieth century, and it continues to play an important role in twenty-first century discussions around the future energy mix, climate change, innovation, proliferation, geopolitics, and numerous other crucial policy topics. The breadth of military and civilian applications—from the nuclear bomb to medical therapies, electricity generation, and others—could not have been predicted. Nuclear energy still plays an important role today and will continue to do so beyond the twenty-first century. In fact, few technologies in history have had such "explosive" effects on research as the quest for nuclear power and its consequences, going back as far as the late 1800s and early 1900s. The controversies about the role of nuclear power in climate mitigation and international cooperation are more heated today, in the twenty-first century, than they were in the "good old days" of the cold war (the "first nuclear age"). Nuclear power has again become a topic of daily concern.

There are two important lines of research on nuclear power, which have been largely disconnected up to now:

- On the one hand, there is a literature on the economics of civilian nuclear power (e.g., Rothwell (2016) that has investigated the competitiveness of this technology—or lack thereof—in detail. In a broad survey, Davis (2012, 68) summarizes the consensus of this literature: namely, that even seven decades after the discovery of nuclear electricity, the industry is still not competitive with conventional fuels such as natural gas and coal. This literature pays little to no attention, however, to the military use of nuclear power.
- On the other hand, there is a literature on the strategic and military importance of nuclear power, the arms race, and nuclear conflicts in the twentieth and twenty-first centuries, for instance in the period since the end of the Second World War, or today in countries of the Middle East, South Asia, and East Asia. The rise of game theory since the 1940s was fueled largely by the first nuclear age, that is, by the discovery and use of the nuclear bomb by the United States and the subsequent Cold War. Nobel Prizes in Economics awarded to John Nash (1994) and Thomas Schelling and Robert Auman (2005) attest to the importance of this

[1] Source: German broadcaster ARD, author's translation of original citation at: http://www.infosperber.ch/Umwelt/die-wahren-Kosten-der-Atomenergie-Atomdeal-Endlagerung, accessed August 29, 2016.

line of research. The present-day reality of not two but ten or more countries owning the bomb also poses new challenges to simplistic analyses of nuclear conflicts from parts of this literature (Bracken 2012). Yet none of these authors seems to have reflected on the "economics" of nuclear electricity generation.

This paper combines both lines of research and seeks a better understanding of some of the important issues of nuclear power in the twenty-first century (others will be addressed in Part II of this paper). We use a simple concept to combine the analysis of military and civilian uses of nuclear power: economies of scope. In any multi-output industry, the existence of economies of scope implies that the co-production of different goods costs less than the separate production by different firms. We claim in this paper that economies of scope are a useful heuristic to interpret developments in the industry and perspectives of the industry going forward, and that a single-output analysis cannot fully capture.

The next section sets out the "economies-of-scope" approach, and embeds it in the historic context. We rely here on the understanding of nuclear power as the "daughter of science and warfare", coined by Francois Lévêque (2014, 212) in reference to the groundbreaking research that led to the first nuclear experiments and subsequent "race to the bomb" in the 1940s. Looking back at the discovery and development of nuclear power, one is struck by the primacy of military and strategic considerations over economic objectives. After the Second World War and the dropping of two nuclear bombs on Hiroshima and Nagasaki, "civilian" applications, such as electricity and heat generation, emerged as by-products of military-oriented research, but strategic considerations remained the driving force. A typical case was the "Atoms for Peace" program launched by US President Eisenhower (1953) that tried to promote world-wide civilian use of nuclear power in exchange for the return of fissile material. We identify economies of scope in the strategies of reactor technologies that linked the need for weapon-grade fissile material (mainly plutonium) to the desire to co-produce electricity, for instance, in the gas-cooled, graphite-moderated reactors in the UK, France, and the Soviet Union. National innovation systems and the search for small modular reactors (SMRs; see Schneider, 2015, Special Section on SMRs, 68-76)—a focus of efforts into the 1950s that has recently returned to center stage—are also motivated by economies of scope.

The economies-of-scope approach is also helpful in better understanding debates about the lack of an economic case for nuclear power, as discussed in Section 3. A survey of the literature reveals that few arguments can be made to explain the development of nuclear electricity on purely economic grounds. Again following Lévêque (2014), we introduce a distinction between different time horizons (very long-run, long-run, short-run) and perspectives (social welfare, national, and private investor/operator), yielding a matrix of 3x3 economic metrics. We provide numerical evidence from the literature suggesting that from a social welfare perspective, nuclear energy is welfare reducing, and that from a national system perspective, the production of "just electricity" might not justify the high costs. We also report research findings on the purely private costs leading to the consensus in the literature that nuclear power plant investments are not something any private investor would pursue; worse, recent market and technological developments create a situation in which many nuclear power plants do not even recover their incremental costs and have to be shut down. Along these lines, we also address what we describe as the "nuclear power modeling paradox": the use of constant or even increasing shares of nuclear power for electricity generation in some energy system models, a contradiction to the observed facts.

The dismal economic prospects of civilian nuclear power do not, however, imply that nuclear power will disappear, and the economies-of-scope approach is useful here, too, in interpreting recent trends. When looking at national nuclear strategies, economies of scope become evident that combine military and civilian uses: All three nuclear superpowers—the United States, Russia, and China—continue to build nuclear power plants and expand their nuclear military forces, with a clear prioritization of military over civilian uses. Countries that cannot benefit from economies of scope, such as Italy, Spain, Germany, Sweden, and Switzerland, are discontinuing civilian nuclear activities. Nuclear newcomers such as Iran, the United Arab Emirates, Turkey, Egypt, and Sudan, in contrast, pursue strategies based on hopes of generating synergies in the context of highly competitive "nuclear diplomacy" between the superpowers. Even the strategy of Japan, which has been demilitarized since World War II, can be better understood in this context. Overall, the nuclear landscape is changing, and nuclear conflicts are becoming more decentralized and regionalized, in line with what Paul Bracken (2012) has referred to as the "second nuclear age" (the twenty-first century).

We can conclude on a conceptual note that nuclear power is a complex phenomenon that cannot be fully understood by focusing the analysis too narrowly on economic considerations. Nuclear power has never been seen primarily as a means of generating electricity economically, and current technological trends such as thorium reactors and small modular reactors will not change this. On the other hand, the idea that nuclear power will just "go away" because it is not economically competitive is unrealistic, because it reduces the analysis to a single, purely economic aspect. The hypothesis of economies of scope between civilian and military uses is useful in explaining current trends, looking at the future of nuclear strategies, informing the debate in the energy and climate modeling community, and identifying the real issues inherited from the last century—both for the present century and for those to come.[2]

2 Economies of Scope between Military and Civilian Applications

2.1 Nuclear power in the twentieth century

2.1.1 The origins of nuclear power: Science and warfare

Nuclear fission energy is released when an atom of uranium is split, producing several new chemical products, radioactivity (alpha, beta, and gamma rays) plus a large amount of energy (heat); the fast

[2] This paper is the outcome of a research project on nuclear power carried out jointly by DIW Berlin (German Institute for Economic Research), and Berlin University of Technology (TU Berlin); selected sections of the paper were written in the context of the EU SET-Nav project ("Navigating the Strategic Energy Technology Plan", HORIZON 2020 project, Work Package 7.5). The author is grateful for research assistance and/or comments and suggestions from Astrid Cullmann, Clemens Gerbaulet, Franziska Holz, Manuel Holz, Claudia Kemfert, Nicolas Landry, Casimir Lorenz, Pao-Yu Oei, Julia Rechlitz, Tim Scherwath, Ben Wealer, Alexander Weber, and Jan Zepter, as well as discussions with seminar participants at the International Association for Energy Economics (June 2016, Bergen, Norway), the European Association of Environmental and Resource Economists (June 2016, Zurich, Switzerland), and the US Association of Energy Economics (November 2017, Houston (Texas); the usual disclaimer applies.

neutrons cause a chain reaction as they hit other uranium atoms.[3] The speed of this chain reaction can be controlled by a "moderator" that slows down the neutrons; moderators include graphite, heavy water (deuterium), or light water. The spent fuel contains a large portion of unused fuel (uranium$_{238}$ and uranium$_{235}$), plutonium$_{239,\ 240}$, and other products such as barium, strontium, and cesium. Some of these isotopes of plutonium can be treated chemically (called "reprocessing"), and all need to be stored safely, for at least a million years, due to continued emissions of radioactivity that are dangerous to humans, animals, and the environment. Nuclear bombs can be produced from both highly enriched uranium and plutonium.

Scientific interest in atoms goes back to the ancient Greeks, who considered the "atom" to be the smallest element of the universe: in Greek, the word "atomos" stands for "that which cannot be split". Research on the atom in the fields of physics and chemistry surged around the end of the nineteenth century. An intense search for military applications of atomic power took place in the context of the Second World War, resulting in the "Project Manhattan", the successful US effort to develop a nuclear bomb.

In his book *The Economics and Uncertainties of Nuclear Power,* Francois Lévêque of the Paris School of Mines formulated a trenchant description of the drivers behind nuclear power:

"Nuclear power is the child of science and warfare"[4]

Lévêque refers to the development of nuclear power in the first half of the twentieth century, when basic research paved the way for the first nuclear experiments, leading to the "race to the bomb" between the United States and Germany in the 1940s. The scientific developments that made nuclear power possible include the research on radioactivity carried out by Edmond Becquerel and by Marie Sklodowska Curie and her husband Pierre Curie around the turn of the twentieth century; the identification of alpha, beta, and gamma rays, as well as uranium as the heaviest of all natural elements by Rutherford in 1905;[5] the development of relativity theory by Albert Einstein (1905); and the work of many other scientists in the first half of the twentieth century. In 1933, Leo Szilard published the first theory of a nuclear chain reaction. Experiments indicating the described chain reaction of uranium were carried out by Otto Hahn and Fritz Strassmann (in Berlin) in collaboration with Lise Meitner (in Stockholm), by Irène and Frédéric Joliot-Curie in Paris, and in Italy (Fermi), in the second half of the 1930s.[6]

The year 1939 marks the shift from basic research to the search for military applications. Motivated by nuclear scientists like Leo Szilard, Albert Einstein—then resident of Princeton, New Jersey—penned a letter to US President Theodore Roosevelt, warning of the danger of falling behind Germany, which

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[3] Another fissile element is thorium, but to date experience with splitting thorium is very limited.

[4] Lévêque (2014, 212).

[5] Elements containing more than 92 protons are called "transuranic" and have to be generated artificially.

[6] See Nelson (2014, Chapter 2) for historical details.

was thought to be pushing ahead with the development of the nuclear bomb. The USA entered into this race, first, by increasing support for applied research, and second, by handing over control of the sector to the military. Fermi, Szilard, and others succeeded in producing a sustained chain reaction (0.5 W) at the University of Chicago, in 1942, and Project Manhattan became a gigantic nationwide effort, in which massive economic resources were invested, to produce the nuclear bomb, under the leadership of science (Robert Oppenheimer) and the military (General Leslie Groves). The Trinity Test, the first large-scale experiment with nuclear power, was carried out on July 16, 1945, in the southwestern United States, followed by the nuclear bombings of Hiroshima and Nagasaki, in August 1945, at the end of the Second World War.

2.1.2 After the Second World War: Military considerations prevail and electricity emerges as a by-product

After the Second World War, the race for military power intensified among the four former Allies, with the United States on the one side and the Soviet Union on the other. While maintaining ties with the United States, the United Kingdom and France sought military independence as well. Both pursued ambitious research, development, and demonstration (RD&D) plans targeted at the large-scale rollout of nuclear weaponry. Their choice of technology is indicative of the fact that the “civilian” use of nuclear power—for instance, in electricity generation—was not a critical issue at the time and not pursued as an end in itself. Instead, electricity was seen as a side benefit when produced in significant quantities.[7]

- In the United Kingdom, all efforts were focused on developing the gas-cooled, graphite-moderated reactor, which was considered to be the simplest route to producing and extracting large quantities of plutonium. In fact, the United Kingdom opened the first series at scale—four 50 MW gas-cooled, graphite-moderated reactors at Calder Hall—as early as 1954, thus taking the lead in this area worldwide. In contrast to France and the United States, the United Kingdom maintained graphite moderation as the dominant technology until the 1980s. Later, the United Kingdom replaced the first-generation gas-cooled plants with the advanced gas-cooled reactor (AGR), an improved second-generation reactor. The United Kingdom pursued close synergies between military and civilian objectives. As a result, the graphite-moderated reactors made the co-production of plutonium and electricity particularly easy. The United Kingdom example also showed, however, that large-scale commercialization was difficult due to permanent technical problems.
- France followed suit with its own program of graphite-moderated reactors, the first three of which were installed at Marcoule (1 x 5 MW, 2 x 43 MW) in the late 1950s, followed by another six gas-graphite reactors later on (total of 540 MW). Its initial cooperation with the United Kingdom on the joint development of this technology was only partially successful, however, and each country maintained significant national RD&D capacities that placed a heavy financial burden on their respective national economies. France became the first country to give up

[7] This section is based on draft versions of data documentation by Wealer et al. (in progress) and of a research paper by Seifert, et al. (in progress).

independence in nuclear technology when Georges Pompidou became President in 1969, and turned to imports of light water reactors from the United States.

Very different strategies emerged between the two countries that would become the nuclear superpowers for the second half of the century.

- The Soviet Union was forced to start its nuclear program from scratch and take the difficult path of graphite moderation to accumulate weapons-grade plutonium. Its first experimental reactors at Obinsk in 1951, as well as the series of RBMK[8] graphite-moderated reactors could be used simultaneously for plutonium extraction and electricity generation.
- By contrast, the United States was in the comfortable position of not having to depend on a new technology to coproduce plutonium. Its plutonium supply was produced at the Project Manhattan facility in Hanford, Washington, which had been set up in 1943 to provide the plutonium for the first nuclear bombs. In December of 1951, the United States started the first experimental reactor to generate nuclear power: the Experimental Breeder Reactor I (EBR-I), in Arco, Idaho, which was 4 x 200 W strong. Given that a large supply of plutonium was available, the United States could afford the "luxury" of experimenting with new reactor designs such as the light water reactor (LWR), which had initially been developed for use in submarines ("Nautilus" research programme).

Although all four countries began running electricity generating units in the 1950s, electricity remained solely a by-product. The technologies used around nuclear power were driven predominantly by military priorities, such as the production of large quantities of fissile material (mainly plutonium), and the availability and national supply security of fuel (uranium). The production of electricity was not a key priority, and it only emerged as a consideration in the 1960s. In no country was economic electricity generation considered seriously by public, let alone by private utilities. In the United Kingdom, the Calder Hall nuclear power plant was a "disguised plutonium factory" (Radkau 1983), and the entire sector remained under state ownership. In France, it was only in the context of switching technologies that the national operator EdF decided to invest in large-scale capacities for light-water reactors in the 1960s. In the United States, too, commercial nuclear electricity had to be pushed significantly in the early 1960s to force utilities to take the step from demonstration to full-fledged commercial plants, the first being the Oyster Creek NPP (New Jersey), which went online in 1969.

2.1.3 "Atoms for Peace" (1953): An attempt to push civilian rather than military applications of nuclear technologies

Economies of scope between military and civilian uses of nuclear power also explain the "Atoms for Peace" initiative launched by the United States in 1953[9]. Arguments in favor of civilian use of nuclear power were needed, and the program aimed at convincing potential nuclear countries to focus their efforts in similar directions. The rhetoric of "economic" civilian nuclear power that emerged from this program—although in stark contrast to the high, real-world costs of the technology—inspired some of

[8] Russian standard design: "Reaktor Bolschoi Moschtschnosti Kanalny".

[9] This section is based in parts on Hirschhausen and Reitz (2015).

the leading engineering and business elites around the world to follow suit. The common misconception of "cheap" nuclear power is not based on empirical evidence but rather driven by the political objectives of this period of the 1950s. In his historic "Atoms for Peace" Speech to the United Nations General Assembly on December 8, 1953, then President Dwight D. Eisenhower (1953) proposed the concept of collective management of radioactive material under the supervision of an international authority. The International Atomic Energy Agency (IAEA) in Vienna was subsequently founded to prevent the misuse of fissionable material to build nuclear bombs. Thus, Eisenhower established the now common notion of "cost-effective" nuclear power as a basis for fruitful cooperation.[10] Similar rhetoric was used around the establishment of the European nuclear coordination organization, the EURATOM Treaty, which was signed in Rome in 1957 and intended to promote international cooperation on nuclear energy as a basis for modernization and industrialization. The signatories even wrote in the preamble of the contract that it had been concluded "…recognizing that nuclear energy represents an essential resource for the development and invigoration of industry and will permit the advancement of the cause of peace (...)".[11]

The political rhetoric was accompanied by a similar wave of enthusiasm in the business sector and among potential users of this "cheap" electricity. The promise of low-cost nuclear electricity led to a variety of nuclear applications ranging from nuclear cars to small nuclear home reactors, and prompted enthusiastic public interest. The general belief that the "civilian" use of nuclear power might become an economic activity prevailed in the Western world into the early 1960s. In 1954, Lewis Strauss, Chairman of the United States Atomic Energy Commission suggested in a speech to the National Association of Science Writers, "our children will enjoy in their homes electrical energy too cheap to meter..."[12]

Only a few economists shared the exuberant optimism displayed by large parts of government and industry, which was based on "core private beliefs" rather than economic reasoning. Edgard Salin, a post-Keynesian economist who was generally viewed as representing the "left" of the political spectrum, hailed the promise of the new industrial nuclear revolution, in which nuclear technology would take over the role of "God creator" (Salin 1955).

2.1.4 From the 1960s on: Expectations of economic civilian nuclear power vanish

However, the Atoms for Peace program soon showed visible signs of failure, since neither the Soviet Union nor emerging nuclear countries intended to comply with the proposed division of labor. Along

[10] See Lévêque, Nucléarie On/Off, 172; the first reference to cost-efficient nuclear power is made in Eisenhower's speech: "Who can doubt, if the entire body of the world's scientists and engineers had adequate amounts of fissionable material with which to test and develop their ideas, that this capability would rapidly be transformed into universal, efficient, and economic usage," web.archive.org/web/20070524054513/http://www.eisenhower.archives.gov/atoms.htm, accessed on February 19, 2014.

[11] and "…desiring to associate other countries with their work and to cooperate with international organizations concerned with the peaceful development of atomic energy…", see the 1957 EURATOM Treaty, http://europa.eu/eu-law/decision-making/treaties/pdf/consolidated_version_of_the_treaty_establishing_the_european_atomic_energy_community/consolidated_version_of_the_treaty_establishing_the_european_atomic_energy_community_en.pdf., last accessed March 20, 2016. See Hirschhausen and Reitz (2014) for an earlier interpretation in a similar sense.

[12] Quoted by Alley and Alley (2013, xiii), with reference to an article on in The New York Times (1954) (September, 17th).

with the UK and France, which forged ahead with both military and civilian applications parallel to the United States, the Soviet Union launched its own nuclear program and made steady progress during the Cold War. Other countries also introduced the military and civilian use of nuclear power, such as China, India, and Pakistan.

At the same time, at the latest in the 1960s (if not the late 1950s), hopes of making an economic case for civilian nuclear power vanished. This was evident in the United States, where private investors were expected to take over as promoters of civilian nuclear power. However, neither the step from experimental to demonstrator reactors nor the subsequent step to commercial plants succeeded. After the Experimental Breeder Reactors I (EBR I in Idaho), three demonstration plants were developed, in Shippingport (PA, 60 MW, PWR), Dresden 1 (IL, ordered in 1956, online in 1960 (Exelon), and Yankee Row (MA, 168 MW PWR, ordered in 1956, online in 1961, consortium of MA utilities). However, the costs of electricity from these plants escalated significantly, and no cost digression potentials were observable. Citing US sources, Radkau (1983) reports growing disenchantment over the dismal economic prospects of civilian nuclear power as early as the late 1950s and the perceived need for a resounding success story to save the industry, such as the commercial diffusion of light water reactors.[13]

The commercial rollout of nuclear power plants did not materialize, however, and private industry had to be lured into nuclear technologies with significant support and guarantee schemes. The first commercial NPP, Oyster Creek (NJ), was ordered by a cost-of-service regulated public utility (Jersey Central Power & Lights) that could roll over all costs into their customers' rate base. It is generally acknowledged that the equipment provider (General Electric) also subsidized the offer strategically in order to kick-start the rollout of commercial plants.[14] A further element of subsidy was inherent in the Price-Anderson Act on liability, capping the responsibility of the operator at a minimum amount.[15]

In the United Kingdom and France, the state-owned character of the utilities prevented private, economically based decision-making. The case is similar in Germany, where nuclear power never became a commercial success. The first experimental reactors (Kahl, Karlsruhe) were entirely state-financed. The first three demonstration plants[16] also relied on public financing, being constructed following the "Gundremmingen model", where the responsibility of the private investor and operator was reduced to a small share of total costs (in Gundremmingen: < 100 mn. DM, see below for details). When the first commercial plants were ordered in the second half of the 1960s[17], hopes of one day having an economic means of generating electricity had almost vanished.

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[13] See Hertsgaard (1983) for details.

[14] Oyster Creek was ordered in 1963 by GE and went online in 1969. It was a 636 MW pressurized water reactor. The installation is now owned by Exelon, which is also responsible for the decommissioning.

[15] US$560 mn., see Alley and Alley (2013, 160).

[16] Gundremmingen A (237, BWR, online 1966, RWE); Lingen (250 MW, BWR, online 1968, VEW), and Obrigheim (357 MW, PWR, online 1968, Westinghouse license, Siemens).

[17] Stade (672 MW, ordered in 1967, online in 1972, Nordwestdeutsche Kraftwerke AG); and Würgassen (640 MW, BWR (AEG, pre 69 series), ordered in 1967, online in 1972, to PreussenElektra (1975)).

2.2 “Economies of scope”: A useful heuristic

2.2.1 Economies of scope

Based on the arguments presented above, it seems reasonable to combine the two approaches and consider the nuclear industry simultaneously from a military and a civilian perspective. We refer to this, using a term from economics, as the “economies-of-scope” approach. Rather than focusing on just one of the aspects—as most of the literature to date has done—we suggest broadening the perspective and approaching the nuclear industry from an “economies-of-scope” perspective. We rely on a simple definition based on those laid out in Sharkey (1982) and Viscusi et al. (2005):

Economies of scope in any multi-output industry imply that the co-production of different goods costs less than the separate production by different firms, or

$$C(X + Y) < C(X) + C(Y)$$

where C ~ total costs, X,Y: different products.

Nuclear co-production includes military goods and services, such as nuclear bombs and fissile material, as well as civilian goods and services, such as electricity and medical services. This subsection focuses on three indices for economies of scope: the choice of reactor technology since the end of the Second World War, national systems of innovation, and recent discussions about small modular reactors (SMRs).[18]

2.2.2 Choice of reactor technologies

Nuclear technologies developed after World War II had to pursue multiple objectives, and this is still the case today for many countries. In this subsection we show that the choice of reactor technologies was long driven by economy-of-scope considerations, and this is likely to be still the case in many countries (such as Iran, Pakistan, India). There is some research on the issue by historians of technology, such as Radkau (1983) and Radkau and Hahn (2013) for the post-war period, or Bracken (2012). However, these rather technology-oriented perspectives were not placed in the broader economic context, for instance, by linking the choice of technology with the prevailing incentive structures, relative costs of technologies, and expected energy economic conditions for refinancing the investment.

2.2.2.1 Reactor types and scope economies

2.2.2.1.1 Overview of reactor types

Nuclear reactor technologies can be distinguished by the fuel used (either natural uranium$_{238}$ with approx. 1% of fissile U_{235}, or enriched uranium, U_{238} with about 3-5% U_{235}), three basic combinations of moderators (that is, elements steering the chain reaction), and different coolants (that is, elements

[18] Some of the political science literature refers to the interdependence as “dual use“, also implying a joint production of civilian and military nuclear power technologies, see Cox et al. (2016) for a recent interpretation of UK nuclear policy.

transporting the heat to be used for electricity production). Table 1 provides an overview of the possible combinations.

		Coolant		
		Gas	Heavy water	Light water
Moderator (fuel used)	Graphite (natural uranium)	GCR		LWGR
	Heavy water (natural uranium)		PHWR	
	Light water (enriched uranium)			BWR PWR

BWR ~ boiling water reactor; GCR ~ gas-cooled, graphite moderator reactor; LWGR ~ light water cooled, graphite-moderator reactor; PHWR ~ pressurized heavy water reactor; PWR ~ light water cooled, pressurized water reactor; FBR ~ fast breeder reactor (not shown in table).

Table 1: Major reactor types and fuel used

Source: own depiction based on IAEA nomenclature.

The choice of reactors implies different capabilities to combine the generation of energy and weapons-grade material, as in the case of plutonium and electricity generation. Roughly, one can distinguish reactor types with which it is relatively easy to combine the two, which are graphite- and heavy water-moderated reactors, and those where the combination is more complicated (although still possible), for instance, light water reactors.

2.2.2.1.2 Graphite-moderated reactors

In this setting, the neutron flow is moderated by graphite, and the reactor is composed of a large number of steel pipes (“channels”) in which gas (e.g., helium) captures and transports the heat. Alternatively, light water can be used as a coolant (as in the Soviet-type RBMK reactors). The reaction of the graphite with the uranium neutrons rapidly produces—among other things—a large quantity of plutonium$_{239}$. Graphite moderated reactors can be run with natural uranium, and are constructed such that the scope economies of nuclear power, that is, the production of military weaponry (here: plutonium) and electricity, can be carried out easily. The reactor is not under high pressure (as is a pressurized light water reactor, for example), so that the fuel rods containing the uranium elements can be shifted and loaded or unloaded in continuous mode. This facilitates the outtake of plutonium in real time and at the desired densities.

2.2.2.1.3 Heavy water reactors

In the early 1940s, the first tests of larger-scale nuclear power were carried out in a “heavy water” reactor; heavy water is used as a moderator and usually also as a coolant.[19] Thanks to the efficient moderation with low neutron absorption, the HWR is able to use natural uranium oxide as a fuel. As with the graphite-moderated reactor, the heavy water reactor can also produce an element for use in nuclear bombs: Tritium, which is radioactive and can also be used to produce nuclear bomb material. Tritium is 3H produced when the deuterium (2H) captures an additional hydrogen neutron. A heavy water reactor requires significantly more space and material, and thus has higher capital costs.

2.2.2.1.4 Light water reactors

Light water reactors (LWRs) were not part of the initial technology set of the late 1940s/early 1950s, because they require enriched uranium (U_{235}, at least 3-5%), which is complicated and very expensive to produce and was not readily available in the 1940/1950s. With Project Manhattan, the United States developed the first large-scale enrichment facility in Oak Ridge (Tennessee). Few other countries have been able to take that route up to today. The extraction of plutonium from light water reactors is more complicated: it is possible in batch mode only, and it requires premature extraction of Pu_{239} from the process before it converts to Pu_{240}, which prevents the plutonium from being used in bombs due to the danger of self-ignition.[20]

2.2.2.2 Early phase of nuclear power dominated by graphite and heavy water reactors

After World War II, all nuclear countries except the United States developed technologies based on an economies-of-scope approach, that is, simultaneous production of plutonium and electricity. The Soviet Union developed the AM-1 reactor, a gas-cooled, graphite-moderated reactor, that later evolved into the RBMK, the workhorse for the Soviet Union and many of its satellite countries. The first “economies-of-scope” power plant was Obinsk in 1951, and the first successful nuclear test occurred shortly thereafter.

The United Kingdom and France followed technically similar, but organizationally separated routes, both also using gas-cooled graphite-moderated reactors (UK: Calder Hall, 1956, 4 x 50 MW, first bomb test in 1952 (“Operation Hurricane”), France: Marcoule (1957), first bomb test in 1960 (Gerboise Bleue, or "blue jerboa"). Canada chose the heavy water reactor, partially based on the UGX experimental reactor (first plant: 1958). All the countries mentioned could therefore base their independent national nuclear strategies on natural uranium (U_{238}).

Based on the heritage of Project Manhattan, the United States was in the comfortable position of having both enriched uranium and plutonium at its disposal; it could thus satisfy the strategic needs of the military sector without having to engage into the dual-reactor technologies mentioned above

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[19] Heavy water is also called “deuterium”, D_20. This corresponds to H_20 plus an additional neutron, $2H_20$; heavy water contains the hydrogen isotope deuterium (D, or 2H), with the mass-number of 2 (H: 1).

[20] Two types of LWRs must be distinguished. First, the boiling water reactor (BWR) has only one circuit that transports the steam from the reactor into the turbine, and then back, which spreads radioactivity to the thermodynamic process, and requires more protection; the BWR is less capital-intensive, but more complex to manage in operations. Second, the pressurized water reactor (PWR) has two separate circuits and therefore higher capital costs, but is easier to manage in operations. A comprehensive Data Documentation on nuclear power plants is under preparation.

(graphite, heavy water). Project Manhattan gave birth to the first large-scale uranium enrichment facility (Oak Ridge, Tennessee), as well as a dedicated site for plutonium at Hanford (Washington State). Thus, when the engineering firm Westinghouse developed the first light water reactor for the United States Navy, which was considered to have the potential for low-cost electricity, it was decided to base the United States civilian nuclear development on this reactor type as well—much to the surprise of the international nuclear community. Ultimately, the Soviet Union also developed a light-water reactor (VVER), and through the licensing to their respective partner countries, the light water technology spread and became dominant in electricity generation. A recent example of this is the development of "small modular reactors" (see below).

2.2.3 National innovation systems and small modular reactors (SMRs)

Economies of scope also exist between military and civilian R&D and in the larger integration of these activities into the respective national innovation systems. The synergies start with the education and preparation of a trained workforce: significant synergies can be reaped through the large scale and high level of permeability between the military and civilian job market. Universities and other forms of higher education have an easier time attracting students if a healthy job market and a diversity of jobs—in industry, research, the military, and so on—await students at the end of their studies. Both segments (military and civilian) require a similar basic understanding of nuclear power, so that a combined effort of the two subsectors strengthens a qualified workforce.

In terms of R&D, too, economies of scope prevail. This is evident in the development of new technologies such as fast breeder technologies (in the 1950s/1960s), high-temperature thorium-reactors, and so on, aiming at both military and civilian applications.

2.2.3.1 SMRs as the future of the nuclear industry?

The growing debate around "small modular reactors" (SMRs), considered a new type of reactor, must also be considered in the context of economies of scope. There is an increasing literature, and a growing number of research projects, assessing the potential of this new technology. SMRs are defined as reactors of relatively modest size, between 25 and 300 MW, the components of which are mass-produced centrally but then transported to the plan sites, where they are assembled in a decentralized way. Economies of scale achieved through mass production and lower assembly costs achieved through the smaller scale are considered potential drivers of increased competitiveness. A study by the University of Cambridge assesses the economic potential of SMRs to be in the range of UK 65/MWh (Roulstone 2016), whereas that of the Hinkley Point C reactors is estimated at UKP 93/MWh; however, to achieve this low value, true mass production is required at the level of 300-500 pieces.

The traditional nuclear states (United States, Russia, China, United Kingdom, France) are actively pursuing R&D on SMRs: Russia is currently testing the construction of two SMRs as "swimming NPPs" (40 MW each, named "Academic Lomonossov"), Argentina is building a 27 MW SMR reactor, and India and Jordan have expressed particular interest in this technology as well. A literature review reveals 39 ongoing or planned projects, and the World Nuclear Organization even estimates that 96 SMRs could be functioning by the year 2030 (World Nuclear Association 2016).

2.2.3.2 The absence of economic cases …

However, based on current estimates, there is no reason to believe that civilian SMRs producing electricity only (and perhaps heat as a by-product) can become competitive in the near future. In fact, current and future cost projections are not only many times the costs of conventional power plants, but also more than double the costs of electricity generated by third-generation, "large-scale" NPPs (which, as shown below, are far from being competitive). The EU Joint Research Center's "Strategic Energy Technology Information System" (JRC – SETIS) quotes expected average costs of a generic SMR in the range of €11,000/kW by the 2020s, falling only gradually thereafter.

Previous experience with "modularizing" the production of smaller or larger NPPs has not been promising thus far. This is the case for a number of similar plants in France (see Rangel and Lévêque, 2015), but also, more recently for the Westinghouse AP-1000 nuclear power plant, which was conceived in a modular way and expected to benefit from scale economies by using a standard design. However, although six of these reactors were started to be built recently (four in the United States and two in China), no economies of scale could be reaped; among the reasons are differing security standards, a lack of knowledge transfer between the sites, and bad project management (K. Rhodes 2016).

Other "small modular reactor" projects are not truly modular, and most of them are small but not new. The Argentinian project CAREM was launched in 1984 but later abandoned before being revived again in 2006; the Russian icebreaker SMRs (KTL-40) had been used in previous designs since 1957. The Pebble Breed Reactor, currently developed by China under the heading of "SMR", is just an experimental plant with little likelihood of being modularized (see Special Sections "Small Modular Reactors" in Schneider et al. (2015, 2017)).

In sum, the economic viability of SMRs is not clear, and they are no option any private investor would seek. Potential scale economies in production and assembly must be weighed against technical risks (e.g., failure of one mass-produced piece) and higher proliferation risks. At present, "small is beautiful" is a far from being a recipe for success in the construction of nuclear reactors.

2.2.3.3 … calls for scope economies

If current SMR projects are not viable from the sales of electricity as such, a plausible explanation for the ongoing "SMR hype" comes from its potential scope economies. When looking at the current technical developments of SMRs and the applications envisaged, one realizes that the idea is not at all new and that it corresponds to the "economies-of-scope" logic laid out above. In fact, the first larger-scale reactors developed in the late 1940s/1950s were … small and produced in a modular fashion. An example is the Nautilus, the United States' first light-water reactor (LWR) installed in a submarine, a technology that used less space than graphite-moderated reactors. The first small reactor developed in the Soviet Union was also used on a submarine, as was the case for an SMR developed by the West German nuclear research center in Geesthacht, installed on the submarine

“Otto Hahn”. Russian icebreakers, too, have been in use since 1957 and are now coming back (with a new design, of course) under the heading of SMRs: Russian SMRs are to be installed on a navy ship and will supply “civilian” electricity to a region of Eastern Siberia.[21] Thus, as early as the 1950s, SMRs were already expected to be one future direction of nuclear power that could be mass-produced and used interchangeably by the military and the civilian sector.

In the United States, the UK, and France, research is being carried out with a view to both military and civilian applications. The US company NuScale is expected to develop twelve 50 MW SMRs (light water) for an NPP in Intermountain (Idaho) but is receiving considerable research funding from the Department of Energy. In the United Kingdom, some economics of SMR are expected (Roulstone 2016), but the military-civilian nexus is the main force keeping the ideas alive (Cox, Johnstone, and Stirling 2016). In France, the Commissariat de l’Enérgie Atomique (CEA), the centralized research center for military and civilian nuclear power, has developed a large project for SMRs. The European Union is also supporting SMR development through a small pilot project, called Allegro-reactor, a helium-cooled plant that will reportedly be installed in a Central European country.

3 Some Economics of Nuclear Power

3.1 Classification of different economic perspectives

The economies-of-scope approach is also helpful in understanding the discussion about the economics of nuclear power and in structuring some of the arguments in the debate. In particular, it provides some perspective in the discussion about the economic justification of civilian nuclear power. In fact, if the nuclear industry does have multiple benefits—that is, scope economies—then its lack of competitiveness does not necessarily imply that it has no “raison d’être” at all. Before turning to concrete numbers, we propose a matrix to differentiate different types of economic analysis: Following Lévêque (2014, Chapter 1), we differentiate the analysis of nuclear power by time horizon and also by the actors’ perspectives (see Table 2).

3.1.1 Different time horizons

- The very long-run analysis covers the lifetime not only of the plant and the decommissioning process (lasting another several decades), but also of the radioactive waste, that is, at least a million years. This perspective is rate in (energy) economics and introduces fundamental choices (e.g., the discount rate) and ethical questions into the analysis.
- The long-run analysis adopts the dynamic perspective in which investment in new NPP capacity is possible, thus covering a range of about 35-45 years (up to 50-60 years for some US plants with lifetime extensions), and hence addressing the question of whether a nuclear power plant “pays off” from the respective perspective.
- The short-run analysis focuses on the question of whether, given their capacities, plants should continue to generate electricity or be closed down because revenues do not cover

[21] Other examples include the Argentinian, Chinese, and Indian SMRs.

short-term costs (variable fuel costs, operation and maintenance, capital additions due to necessary repair work, life extension, etc.). The typical short-run perspective is 1-5 years.

3.1.2 Different perspectives

- The social welfare perspective takes into account the negative and positive externalities of the nuclear activity, such as the risk of accidents and potential environmental and health damage. The sum of the private and social costs and benefits provides insight into the social justification of nuclear power.
- The national perspective includes considerations about the nuclear energy system as a whole, including the innovation system, the fuel cycle, and the necessary infrastructure to operate nuclear power. Depending on what elements of the nuclear system a country has invested in, the national perspective can yield quite different results when compared to a private operator or investor's perspective.
- Finally yet importantly, the private operator or investor is interested in the private costs and revenues and whether she can recover the short-term expenses and/or long-term investments. As discussed below, it is difficult to attach a very long-term perspective to private investors, since their existence a million years hence is very unlikely.

Table 2 provides an overview of the different perspectives of analysis, by sketching out nine different approaches one might adopt (I through IX). In the following subsections, some of these perspectives are analyzed in more detail.

	Very long-run (million years, "eternity" costs)	Long-run (investment possible, ~ 30-50 years)	Short-run (capacities fix, ~ 1-5 years)
(1) External costs	I: $C_{E\text{-}VLR}$	II: $C_{E\text{-}LR}$	III: $C_{E\text{-}SR}$
(2) National system costs	IV: $C_{N\text{-}VLR}$	V: $C_{N\text{-}LR}$	VI: $C_{N\text{-}SR}$
(3) Private costs for operator/investor	VII: $C_{O\text{-}VLR}$	VIII: $C_{O\text{-}LR}$	IX: $C_{O\text{-}SR}$
(4) Total (e.g. (1) + (2) or: (1) + (3)	…	…	…

Table 2: Different categories of the economics of nuclear power: Time horizon and perspective

3.2 The social welfare perspective

3.2.1 The very long-run costs of nuclear energy (box I: $C_{E\text{-}VLR}$)

The assessment of very long-run external costs of nuclear power from a social welfare perspective raises interesting economic issues, in particular with respect to the discount rate applied, as well as the ethical question of whether a society should be allowed to produce nuclear power at all and leave the negative externalities (radioactive waste) to later generations.

This discussion goes back at least to the 1970s and the attempts of the US government to license a site for storing highly radioactive waste in Carlsbad, New Mexico. In a detailed analysis of the approach and the expected externalities, Schulze, et al. (1981) explore economic and ethical arguments based on different principles:

- From a libertarian perspective, creating risks (nuclear waste, etc.) that will be inherited by future generations is unethical since a long-term compensation of future generations over hundreds of thousands of years is deemed impossible.
- From a utilitarian perspective, the benefits of using nuclear power accruing to generation I (early users) can compensate for the risks to future generations, which depend largely on the chosen social rate of discount.

Whereas traditional cost-benefit analysis would assume a social rate of discount in the range of 2-4%, Schulze, et al. (1981, 832) argue that "assuming future generations are unlikely to be compensated for risk of nuclear waste storage, rejection of nuclear waste storage, a zero percent rate of discount may be appropriate from a consequentialist ethical perspective." In that case, future potential costs are not discounted away, and thus the social welfare case for "economic" nuclear power is significantly weakened.

Another issue raised by the very long-term perspective is that the "polluter pays principle", which plays an important role in economic and legal daily life, breaks down and has to be replaced by more complex, but also more realistic rules. In the very long term, it is impossible to attribute the responsibility for the pollution created to the polluter since the legal entity is very unlikely to exist at that time. Alternative organizational models for sharing financial and operational risks of operating nuclear installations still have to be found.

3.2.2 External costs, long run (box II: $C_{E\text{-}LR}$)

Numerous estimates are available on the long-run external costs of nuclear energy, depending on the assumed probability of an accident, the expected damage, and the implied social costs thereof. It is difficult to compare these figures, as they are based on different approaches, assumptions, and calculations. Figure 1 provides different estimates of the external costs of nuclear power in the long run to illuminate some of the issues at stake. The fact that they range from below 1 €cent/kWh to 34 €cents/kWh shows not only the large variance but also the importance of assumptions about inputs that drive the output.

Friedrich and Voss (1993) and the suite of ExternE project reports (e.g., EC 2003) provide by far the lowest estimate, but one that does not take into account the issue of insurance and risk. Ewers and Renning (1992) use a higher estimate for the costs of a meltdown (€8.5 bn.$_{2015}$). Meyer (2012) introduces a "regular" damage value, which is then adjusted for risk adversity of the population to reach more than double the value.

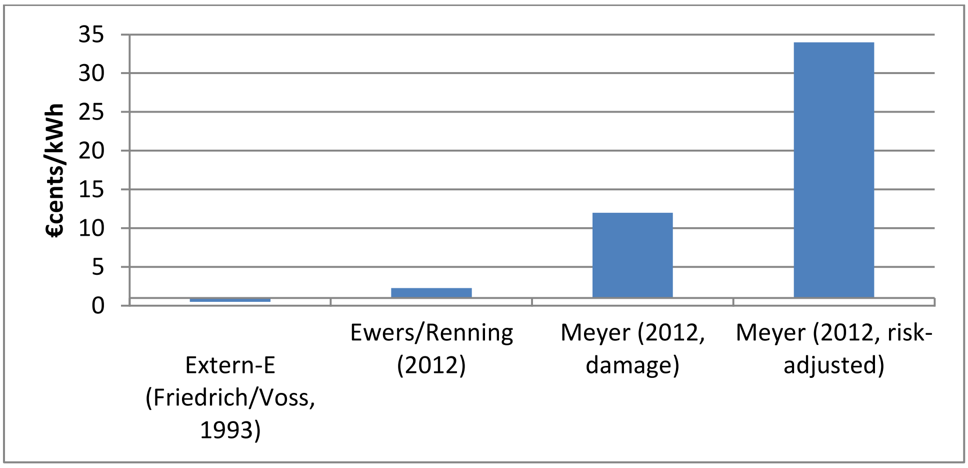

Figure 1: Estimates of the long-run social external costs of nuclear power

Sources: Own compilation, based on the cited literature[22]

Note that he above estimates do not take into account the costs of risk insurance by the operator, and thus all underestimate the true costs significantly. A study by a German insurance association is interesting in that respect, in that it introduces the social costs of liability under different assumptions about the sharing of the risk (VFL 2011). In general, social costs are higher the less the risk can be pooled, and the higher the expected effects on individual and society are.[23] From an economic point of view, note that none of the risks are appropriately covered by any insurance scheme. Thus, an objective assessment of the risks, for instance, in terms of an insurance premium, is not possible.

3.3 The national perspective

3.3.1 A complex web of organizations and institutions (box IV: $C_{N\text{-}VLR}$, box IV: $C_{N\text{-}LR}$)

The national perspective addresses the costs and potential benefits of developing nuclear power in a specific country. In essence, it provides information about who has what kind of costs along the complex value-added chain of producing nuclear power, both for military and civilian purposes. Nuclear power requires an upstream system of a knowledge base, institutional and physical infrastructure (sites, transportation, waste storage, etc.), as well as a legal and institutional infrastructure; it is a “system good” that cannot be produced without this complex web (in contrast to goods like mineral water or pet food). Thus, the economics of the nuclear power vertical value-added chain look very different when taking the entire chain into account, as opposed to a situation where the entire infrastructure is sourced out to a (foreign) provider like the United States (General Electric,

[22] Friedrich and Voss (1993) derive a rather low value (0.1 – 0.7 US$ $cents_{1993}$/kWh); however, they cover routine operation only, without taking into account the risks of accident; likewise, the ExternE project in 2005 published an average value of 0.4 €$cents_{2005}$/kWh (averaged from BE: 0.5, DE: 0.2, FR: 0.3, NL: 0.7, UK: 0.25) (source: http://www.externe.info/externe_2006/, accessed November 15, 2016).

[23] VFL (2011) contains three different cases, combinations of damage (€340 billion vs. €6,090 billion), and possibilities of pooling the risk: i/ liability provision, 10 years, €340 billion, pooled; ii/ liability provision, 10 years, €340 billion, individually; and iii/ liability provision, 10 years, €6,090 billion, individually.

Westinghouse) as supplier. Also, the question of whether radioactive waste can be exported to some other country ("pollution haven") or has to be disposed of nationally plays an important role.

There are no precise estimates on the costs of national systems of nuclear power, but historical analyses suggest that these are rather high. The most remarkable exercise is of course Project Manhattan, the installation of an entire nuclear system from the ground up in the United States, between 1943 and 1946.[24] Although the national system costs have come down over time (in relative terms), they still represent a large part of GDP.

There is an alternative path: "outsourcing" the entire national system of innovation and buying just the "service" of nuclear power and/or nuclear weaponry. This may be a strategy of follower countries such as Egypt or Sudan, which have been offered the entire chain by Russia and China, respectively. "Second movers do not need to stand up against a giant R&D enterprise to discover original technical solutions; they only need clever people and a reasonable competent set of scientific and engineering institutions." (Bracken 2012, 119).

3.3.2 The importance of institutional design

Another "new" but in reality very old issue that falls under the heading of a "national perspective" has gained attention with the large-scale closure of the nuclear power plants in the 1970/80s: the challenges of scrapping the plants and storing the radioactive waste for the long term. While this "wicked problem" (in the parlance of political scientists; see Brunnengräber and Schreurs 2015, 47–78) was well known from the start, it was easier to ignore it rather than to address it early on. As a result, not a single site for long-term storage exists as of today, and few countries have accumulated sufficient funds to finance this activity, lasting at least a century and requiring safe storage for at least a million years.[25]

The national costs also depend heavily on how responsibilities are divided up and framed along the value-added chain—in particular the downstream part, where issues of decommissioning and long-term storage of radioactive waste arise. Questions include: Is trading nuclear waste allowed? Who carries the technical and financial risks for the decommissioning and storage process? The national perspective is indeed the relevant level to analyze very long-run costs as well, bringing boxes IV $C_{NS\text{-}VLR}$ and VII $C_{O\text{-}VLR}$ together. In fact, it seems very difficult to make a private operator/investor responsible for the very long-term costs of waste storage: contrary to the "polluter pays" principle, which is enshrined in environmental economic theory, private operators seem to be exempt from that obligation around the world.[26] A variety of organizational models has evolved in which the national authorities more or less take over technical and financial responsibility for managing the very long-term issues.

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[24] See Jänsch and Herrmann (2015), with reference to other literature on Project Manhattan, such as Groves (1983) and Rhodes (2012).

[25] See Thomas, "50 ways to lose your money", for a striking case study of the UK, Brunnengraeber, et al. (2015) for an international survey

[26] The US federal government takes responsibility for storing the waste, charging companies a small amount for later costs (see Diekmann 2011). In Germany, the long-term liability for waste storage has been taken on by the government, even though operators were initially in charge of making provisions for this (see Hirschhausen et al. 2015).

With respect to the long-run horizon, the national perspective becomes somewhat blurred with the investor perspective: it is unlikely that a private investor is able to calculate, or even carry on his balance sheets, risks extending beyond one million years, the time required for safe storage of nuclear waste. Therefore, a conflict arises between the “polluter pays principle” embedded in many countries’ legislation (e.g., §9 of the German Atomic Energy Act), and the implementation in reality. These long-term costs and risks are instead socialized, whereas the private investor may be required to contribute to the financing of the long-term costs (which is the case in most countries; see Seidel and Wealer, 2016).

3.4 The private operator/investor perspective

3.4.1 The long-run perspective (box VIII: $C_{O\text{-}LR}$)

The majority of the literature adopts the perspective of an operator and/or an investor interested in recovering operating and/or investment expenses; this corresponds to a “private costs” approach (independently of whether the operator/investor is a private company or publicly owned; see, e.g., the approaches suggested by Rothwell, 2015, and d’Haesseler, 2013). This perspective ignores the social welfare costs of nuclear power, but can be justified by an interest in “real business” decisions with respect to nuclear power, mainly whether one might expect future investment into NPPs (long-run perspective), and whether existing plants should be maintained or closed down (short-run perspective).

With respect to the long-run investor’s perspective, an interesting finding in the literature is that at no point in time were investments in nuclear power plants profitable and forthcoming in a competitive market environment. In the long-running discussion about nuclear power, there is a surprisingly wide consensus in the literature that civilian nuclear power is not a technology private investors like to, or have ever chosen to put their money into. As explained above, the scope economies approach is helpful in digesting this finding.

3.4.1.1 Historical overview: Absence of an economic case for competitive nuclear power

Going back over the long history of civilian nuclear power, one discovers that not a single plant was ever built by a private investor under free-market, competitive circumstances. This observation has been noted previously, for instance in the survey by Rosenkranz (2010), but it has not always been reflected in the discussion about nuclear power. It is evident that the first reactors generating electricity after the Second World War were designed entirely based on previous military research, and, hence, could not possibly have been financed by private investors. This was the case of the first NPPs generating significant amounts of electricity, such as Calder Hall (UK, 4 x 50 MW), Marcoule (France, 2, 39, and 40 MW), or the first light-water reactors in the United States, which were based on the US Navy project for submarine propulsion, the US Nautilus, launched and commissioned in 1954.

After the R&D phase, demonstration plants were built to familiarize future operators with the technology and to induce the industry to develop larger-scale demonstration plants. These demonstrators were still financed almost exclusively by public subsidies, such as the first three demonstrators in the United States (Shippingport, PA, Dresden 1, IL, and Yankee Rowe, MA), or the 250 MW fleet of demonstrators in Germany (Gundremmingen A, Obrigheim, Lingen), ordered in the early 1960s.[27] The production costs of these demonstrators was by no means competitive, an extreme example being the Shippingport demonstration plant in the United States, whose costs exploded in the 1960s: instead of reaching the expected costs level (similar to coal) of ~ 2-3 US$cents/kWh, average costs were five to seven times higher.[28]

In most countries pursing nuclear development, the sector remained under full state control, without attempts to attract private capital. Thus, in the UK and in France, the pursuit of an independent, national route for military and civilian uses of nuclear power, through graphite-moderator reactors, was carried out entirely by state-owned companies (United Kingdom Atomic Energy Authority, and Electricité de France and the Commissariat l'Enérgie Atomique, respectively), as was the case in Canada with the development of the CANDU heavy-water reactor through Atomic Energy of Canada Ltd. (AECL).[29]

On the other hand, the United States and Germany attempted to attract private investors through complex risk-sharing agreements. However, it became clear quite rapidly that no private investor would put money into an NPP without being shielded from the technical and economic risks. Both in the United States and in Germany, the expected rush of private investment into the industry did not take place in the 1960s given the technical, financial, and security challenges of civilian nuclear power (see Cohn, 1990, and Hertsegaard, 1983, for the United States and Radkau, 1983, as well as Radkau and Hahn, 2013, for Germany). In the United States, a way to induce investment in commercial plants was to assure full cost recovery for the regulated utility, to exempt companies from insurance (except a nominal fee foreseen in the Price-Anderson Act of 1957), and to relieve them from future obligations of decommissioning and waste storage, as was done for the first commercial plant at Oyster Creek (NJ) and subsequent plants. A similar, comprehensive approach was applied in Germany, where the big utilities saw no business case for nuclear power and required substantial support to go forward with industry-scale investments, such as Stade and Würgassen, in the late 1960s (~ 670 MW each; see the detailed account by Radkau, 1983, Chapters 2 and 3).[30]

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[27] Radkau (1986, Chapter 2) summarizes the main elements of the "Gundremmingen-model" of financing: a cap on the "private" contribution of DM 100 mill. (< 1/3 of total costs); further subsidized financing conditions through EPR credits (DM 50 mill., + DM 19 mill. for Berlin-contracts; preferential credit of the US EXIM-Bank: DM 80 mill., guaranteed by the German Federal government, a cap on operational losses ("Betriebsverluste") of 10%, up to the maximum of DM 100 mn.; inclusion into the U.S.-Euratom-program, leading to a delay of payment for imported enriched uranium (for DM 42 mn.) for 10 years.

[28] Data provided by Radkau (1983), using historical exchange rates.

[29] Canada was one of the founding nations of the International Atomic Energy Agency (IAEA), and quickly developed a national program after the war: the CANDU (CANada Deuterium Uranium) was a heavy-water reactor using natural uranium as a fuel and deuterium as moderator. The first CANDU was ordered in 1955 (Ralphton, Ontario, 22 MW). To this day, Canada has maintained the CANDU route, running 19 reactors in the country, and has exported the technology to India, South Korea, Romania, Argentina, and China.

[30] Direct and indirect support for these plants included a 90% state funding for "industrial research", preferential credits, degressive depreciation ("Vorzugskredite und degressive Abschreibungsmöglichkeiten, Radkau and Hahn, 2013, 139, own translation); the take-over of the risk of (inexistent or expensive) storage (so-called "Verwertungsnachweise" provided free of charge). In addition, the leading utility, RWE, requested further general political support for its large-scale engagement into nuclear power, as specified in the "RWE-Termsheet" of 1967, developed in the context of investment in two Biblis reactors (Radkau, 1983, 212, own translation): The government thus aimed to ensure significant growth of electricity consumption in industry and household sectors (to absorb existing overcapacities, mainly cheap lignite, and to end the aggressive marketing of

3.4.1.2 … confirmed by the economic literature …

The more recent economic literature largely confirms the absence of an economic case for nuclear electricity, and has rejected the hypothesis of nuclear power becoming competitive thanks to rapid diffusion, economies of scale, and positive learning, among other factors. The two campus-wide studies by MIT (2003) and the University of Chicago (2004) both agree that in the first decade of this century, nuclear power was not cost competitive with coal and natural gas,[31] an assessment that remains valid to this day. Note that at the time of these studies, investment costs for new builds were estimated in the range of 2,000 US$/kW, less than a third of current capital costs. More recently, Parsons and Joskow (2012)[32] and D'haeseleer (2013)[33] have confirmed the lack of competitiveness of nuclear power.

High and rising capital costs are one of the explanations for the lack of competitiveness of nuclear power. The escalation of capital costs was observed early on and has been shown regularly for several decades now, for instance, in papers by Joskow (1982) for the United States, Grubler (2010) and Rangel/Lévêque (2012) for France, and Schneider, et al. (2016) for the third-generation European Pressurized Reactor (EPR in Finland, France, and the UK plans for Hinkley Point C).

Civilian nuclear power has never been an economical way of producing electricity. In a comprehensive survey of the history of nuclear power, Davis (2012) stresses the public welfare perspective and the potential negative externalities, such as the risk of nuclear accidents and subsequent health and other damage, the unresolved issue of nuclear waste storage, and "perhaps hardest of all to measure, the risk associated with the proliferation of nuclear weapons" (Davis 2012, 61). With regard to the social welfare perspective, Davis (2012, 61) notes that an "important priority for future work is to refine measures of these external costs and incorporate them explicitly into levelized cost analyses". The paper also focuses on cost issues related to nuclear power, including a historical analysis of construction costs, capital costs, levelized costs and learning-by-doing effects. Davis (2012) concludes that despite "a certain confluence of factors that could make nuclear power a viable economic option" (p. 50), there is still an absence of an economic case for nuclear power:

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natural gas ("natural gas psychosis"), fueling consumers' hopes of a cheap substitute for natural gas for use in cooking and heating, which led to the prohibition of natural gas-fueled power plants (Verstromungsgesetze, valid until 1992).

[31] See MIT (2003, ix): "In deregulated markets, nuclear power is not now cost competitive with coal and natural gas." The University of Chicago study (2004, 6) concludes: "A case can be made that the nuclear industry will start near the bottom of its learning rate when new nuclear construction occurs. (p. 4-1) "The nuclear LCOE for the most favorable case, $47 per MWh, is close but still above the highest coal cost of $41 per MWh and gas cost of $45 per MWh." (p. 5-1).

[32] "The new construction projects in the U.S. that are moving forward with serious investments being made all had one or both of the following characteristics: (a) they are slated to receive federal loan guarantees and/or (b) they are in states where the plants would be subject to cost of service regulation and were supported by state regulatory commissions rather than competitive wholesale market prices. Both attributes shift risk to taxpayers or to consumers paying regulated prices that pass through actual construction and operating costs." Joskow and Parsons (2012).

[33] D'haeseleer (2013, Synthesis on the Economics of Nuclear Energy) concludes: "Nuclear new build is highly capital intensive and currently not cheap, … it is up to the nuclear sector itself to demonstrate on the ground that cost-effective construction is possible." (p. 3)

"In 1942, with a shoestring budget in an abandoned squash court at the University of Chicago, Enrico Fermi demonstrated that electricity could be generated using a self-sustaining nuclear reaction. Seventy years later the industry is still trying to demonstrate how this can be scaled up cheaply enough to compete with coal and natural gas."[34]

3.4.1.3 … and some recent estimates

Davis based his results on a comparison of the long-run costs of nuclear (~10.5 US$cents/kWh) with those of the competing fossil fuels coal and natural gas: even in the presence of a US$25/t CO2 carbon tax, nuclear is not competitive with coal (~ 9.6 US$cents/kWh) or natural gas (~ 6.2 US$cents/kWh) (Davis 2012, 59, Table 3). Applying a similar approach, we have updated the analysis for the European context, and compare new-build projects in nuclear power plants, coal, and natural gas plants, respectively. Table 3 summarizes this modeling exercise, in addition to a baseline with no climate policy, we also run two cases for carbon pricing: 25 €/t and 100 €/t, respectively.

New-build nuclear is by far the most expensive technology in the absence of a CO_2 price, but it remains uncompetitive even at a CO_2 price as high as €100/t. The main reason is the high capital cost of a new plant (evaluated at €6,000/kW, i.e., about €5,100/kW, plus an additional €900/kW for decommissioning and storage), but also the relatively low costs of fossil fuels (mainly natural gas). The private long-run costs of nuclear power are about 10.2 €cents/kWh, significantly higher than coal (5.1 €cents/kWh) and natural gas (5.0 €cents/kWh). Cost differences remain even when introducing a carbon price of € 100/ton of CO_2, which clearly is an implausibly high value at this point in time. The 10.2 €cents/kWh for nuclear then compare with 10.0 €cents/kWh for coal, and 7.9 €cents/kWh for natural gas.

	Levelized costs in €cents/kWh		
	Nuclear	Coal	Natural Gas
Baseline (2016) (no CO_2-price)	10.2	5.1	5.0
CO_2-price: 25 €/t	10.2	6.3	5.7
CO_2-price: 100 €/t	10.2	10.0	7.9

Table 3: Levelized costs for electricity generation in Europe (2016)

Source: own calculations (carried out by Clemens Gerbaulet); cost assumptions according to DIW Data Documentation (Schroeder et al. 2013), Lorenz, et al. (2016), and Kemfert, et al. (2017).

[34] Davis (2012, 61).

3.4.2 The short-run perspective (box IX: $C_{O\text{-}SR}$)

Another perspective of a private operator of a nuclear power plant that has traditionally played a minor role in the discussions is the short-run perspective. The short-run perspective takes the generation capacity as given, and asks whether a profit-oriented operator would want to continue to produce if, for instance, the price were higher than the short-run costs.

Traditionally this question has not been given much attention since nuclear power plants usually have the lowest incremental costs and are built under cost-of-service regulation. However, even after restructuring of some power markets in some regions, NPPs are still considered to be sources of income. Thus, in the "old world" of fossil-dominated electricity markets, nuclear power plants benefitted from ample infra-marginal rent, because the incremental costs were regularly below the wholesale market prices.

As we move further into the second decade of the twenty-first century, however, the situation has changed. In fact, with the shale gas revolution ongoing in the United States and lower wholesale electricity prices prevailing in most markets around the world, a new phenomenon is gaining ground: the loss of operational competitiveness of nuclear power plants. Two opposing trends have challenged the comfortable situation of nuclear power recently:

~ Wholesale prices have fallen, from the previous range of 40-60 US$/MWh to a range of 20-40 US$/MWh.[35] In Europe, too, the forward price for 2018 electricity averages 25–30 €/MWh (~ 28–33 US$/MWh) at the Paris/Leipzig energy exchange, about half of the value three to five years ago. Several trends have contributed to the price decline, such as weak electricity demand, low natural gas prices (mainly in the United States), low CO_2 prices, and an increasing share of renewable energies with low incremental costs.

~ On the other hand, the costs of running and maintaining aging NPPs have risen in recent years, and they are accompanied in some countries by fuel taxes and other levies. The short-run costs include fuel, operation & maintenance, in some (few) cases waste management and decommissioning, and also capital additions for aging plants, safety requirements, and/or lifetime extensions (e.g., from 40 to 50 or even 60 years in the United States). Depending on the age of the plant, the quality of O&M, and the required capital additions, the short-run costs of maintaining a NPP in operation can be as high as 3-6 US$cents/kWh (Lovins 2013), which is above the wholesale price.[36] Given the low or even falling costs of competing fuels (mainly natural gas), it is difficult to see scenarios in which nuclear electricity might become profitable in the medium-term.

Empirical evidence from this decade shows that the loss of operational competitiveness is not a hypothetical construct, but has become reality for the utilities concerned. In such a situation, the question of premature closure of NPPs arises, and this trend is accelerating as prices continue to fall and costs continue to rise. In France, the government has announced the closure of the oldest plants

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[35] The average day-ahead in the Californian wholesale market in 2015 was about US$30/MWh.

[36] Lovins (2013, 5) provides a detailed account of industry proprietory data, indicating a range of average U.S. nuclear generating costs between 24 – 60 US$/MWh for 2009 – 2011; thus, roughly half of the plants had higher incremental production costs than the average wholesale prices of 36 US$/MWh.

(Fessenheim, Cattenom), and similar discussions are ongoing in Belgium (Tihange, Doel), Sweden (Ringhals 2), all also before the expiration of the respective license. In Germany, the Grafenrheinfeld NPP was closed in June 2015, six months before the end of its license (closure in June 2015), and many other NPPs slated for closure until 2022 are likely to turn off electricity production before these dates. The most striking evidence of the loss of competitiveness, however, comes from the United States, where 16 (sixteen) GW of nuclear capacity has already been closed down prematurely, or is threatened to do so in the near future (see Table 4).

It is natural that bankruptcy-threatened nuclear power plants try to influence market design such that the chances for their survival increase. Thus, nuclear utilities are lobbying regulators at the federal and state level on both sides of the Atlantic in favor of a specific incentive for consumers of nuclear power, or quota for nuclear power in the respective energy mix. An example is the New York "low-carbon electricity" scheme, another one the Department of Energy's notice of proposed rulemaking entitled "Grid resilience pricing rule", designed to provide nuclear power (and other conventional fuels) a "just and reasonable" rate for wholesale electricity sales.[37]

	Plant	State	Investor	Capacity (MWnet)	Date of closure
realized	Crystal River-3	Florida	Duke Entergy	860	2013
	San Onofre-2	California	Southern California Edison	1070	2013
	San Onofre-3	California	Southern California Edison	1080	2013
	Kewaunee	Wisconsin	Dominion Generation	556	2013
	Vermont Yankee	Vermont	Entergy	620	2014
	Fort Calhoun-1	Nebraska	Omaha Public Power District	478	2016
			SUM of closed plants:	4664	
announced	Fitzpatrick	New York	Entergy	855	2017
	Clinton	Illinois	Exelon	1065	2017
	Quad Cities	Illinois	Exelon	1880	2018
	Pilgrim	Mass.	Entergy	685	2019
	Diablo-Canyon-1	California	PG&E	1122	2024
	Diablo-Canyon-2	California	PG&E	1118	2025
			SUM of announced closures:	6725	
under discussion	Oyster Creek	New Jersey	Exelon	615	
	Prairie Island	Minnesota	Xcel Energy	1100	
	Palisades	Michigan	Entergy	778	
	Davis Bessie	Ohio	First Entergy	894	
	Ginna	New York	Exelon	581	
	Indian Point	New York	Entergy	1022	
			SUM of closures currently discussed:	4990	
		SUM of plants closed, announced or discussed closures		16379	

Table 4: Recent closure decisions of nuclear power plants in the United States

Source: Website of operators, WSNIR, 2016.

[37] "Grid Reliability and Resilience Pricing", DOE Docket Nos. RM18-1-000.

3.5 The nuclear power modeling paradox

3.5.1 The paradox: reality and modeling results contradictory

Given the broad consensus on civilian nuclear power not being an economic option, how can we explain that different model families such as energy system models and Integrated Assessment Models (IAMs) still include large shares of nuclear power in the future low-carbon electricity mix? The paradox we want to address in this section of the paper is simple: on the one hand, as we have shown above, civilian nuclear electricity generation is just a by-product, and, taken by itself, the civilian nuclear industry has never been able to build plants under competitive market environments ("economically"). On the other hand, most electricity sector models and energy system models come up with "competitive nuclear power" as a strong pillar of the low-carbon energy mix. In this context, we will focus on the models used by the European Commission to establish long-term reference scenarios.

This section addresses a critical implication from top-down modeling approaches, which systematically result in high shares of nuclear energy, such as the European Reference Scenario (EC 2013, 2016), the International Energy Agency (IEA 2015), or the community of Integrated Assessment Models (IAM, see Kim, et al. (2014)). The economies-of-scope approach to nuclear energy may once again be useful in resolving the apparent paradox of electricity sector models and energy system models: if nuclear power is nothing but a valuable by-product of the nuclear military system, less effort should be invested into giving nuclear power an "economic" competitiveness that it simply does not have. Or, in other words, the conversation about the cost calculations used in models, or the models themselves, can give rise to a pragmatic and enlightened debate about the role of nuclear power in the energy mix.

3.5.2 The modeling-policy interface

In a conceptual piece on the "Science–Policy Interface", motivated by political discussion about the IPCC Assessment Reports and their scientific foundations, Edenhofer and Korwasch (2012) reject the simplistic vision of the Weberian "decisionist model" and the Schmollerian "technocratic model" of the policymaking process, to suggest a "pragmatic-enlightened" model of the policymaking process. In their model, different institutions "compete" for political attention, among them the "modeling–data–scenario" groups. Instead of providing decision makers with "the" correct results ("decisionist model") or even providing relevant research questions and policy implications ("technocratic model"), these policy advisors should, the authors argue, describe alternative pathways to the public debate and continue to participate in the policy process following on the political discussions.

Energy system models run the danger of following the "decisionist" path, by engaging in an intimate relationship with data providers and advisees, the famous "iron triangle", and cut off access to models, data, and interpretation through complex mathematical and institutional procedures. In a piece on the political economy of modeling, Midthun and Baumgartner (1986, 223) describe this process of "negotiating energy futures", implicitly criticizing the decisionist approach used in energy system models. Midthun and Baumgartner also provide a very concrete example of the "scientific" debate about the future of nuclear power led by IIASA's world energy model in the 1970s: while predicting a very bright future for nuclear energy between 1980 and 2030 (77% of total electricity generation), minor changes in assumptions or other rigidities cause this figure to collapse to 0%. Such changes include elasticities (GDP-related, demand-related, and cross-price elasticities, etc.), cost assumptions, and pre-defined market shares.[38]

The texts by Edenhofer and Korwasch (2012) and Midthun and Baumgartner (1986) suggest to define some rules to keep the science-policy interface fluid, including a high level of transparency, sufficient data, the representation of all relevant societal interests, clear and open statement of basic assumptions, and impartiality of the implementation system with respect to alternative energy futures. According to the authors, any modeling exercise, be it on nuclear energy or other issues should adhere to these principles.

3.5.3 The paradox: "competitive" nuclear in the European Union's Reference Scenarios

The current debate about the future role of nuclear in a lower-carbon energy system to 2050 somewhat resembles the negotiation of energy futures in the 1970s. Both energy system models and IAMs have evolved in their technical complexity, but they play a similar role with respect to the socio-economic institutional framework. In addition, it seems that—independently of the economic context and technological developments elsewhere—nuclear power is carved in stone as a central pillar of decarbonization. Thus, in the Stanford Energy Modeling Forum on "Global Technology and Climate Policy Strategies" (EMF 27), all 16 models (except for one, MESSAGE) see nuclear electricity rising up to the horizon 2100, and more than half of the models see at least a doubling of nuclear electricity generation (from currently 10 EJ/yr to over 20 EJ/yr); three models even predict a six-fold growth of output, to 60 EJ/yr (Kim et al. 2014). Likewise, the International Energy Agency's "Energy Technology Perspective" reserves an important wedge for nuclear energy in combatting climate change (12% of decarbonization efforts by 2050, see (IEA 2016).[39]

In the following, we address a concrete nuclear power modeling paradox that we observe in the scenarios underlying the EU's energy and climate policy. For over a decade, these have relied on a complex modeling tool, called PRIMES, developed by the Technical University of Athens. Contrary to the consensus in the literature about the absence of competitive nuclear power, the PRIMES model used by the European Union to quantify its "Reference Scenario" derives opposing results of an increasing net capacity of nuclear power in Europe up to 2050 (Figure 3).[40] Figure 2 shows the newly

[38] „A 16% increase in nuclear power costs greatly alters the modal split. Coal-based power now accounts for most of the electricity production, reaching 85% in 2030 (instead of 8% in the original scenario). LWRs (light-water reactors) not only do not increase their present contribution to electricity production substantially, but are actually phased out over the 50-year time horizon. FBRs (fast breeder reactors) are not introduced at all. Thus, the nuclear contribution disappears entirely (compared to a 77% contribution in the original scenario).

The interesting point here is that the electricity models are the most detailed energy models in the IIASA study. And the 16% uncertainty range in the future nuclear costs seems quite reasonable when one looks at actual cost developments since the IIASE study was prepared, and when one knows that IIASE failed to include decommissioning costs of reactors in its cost assumptions." (Midttun and Baumgartner 1986, 227).

[39] Metayer, et al. (2015) criticize conventional energy system models (focusing on the International Energy Agency, IEA) for underestimating the cost breakthroughs, and derived exponential quantity increases, of the solar industry for over a decade, an assessment now widely shared in the scientific community, see (Creutzig et al. 2017).

[40] Not a single scenario is presented without nuclear power.

built nuclear power plants in the reference scenario, which increase massively between 2025 and 2035; overall, a total of 119 new NPPs are built during that period according to model calculations (EC 2013). Results of the 2016 exercise are similar (Figure 3).

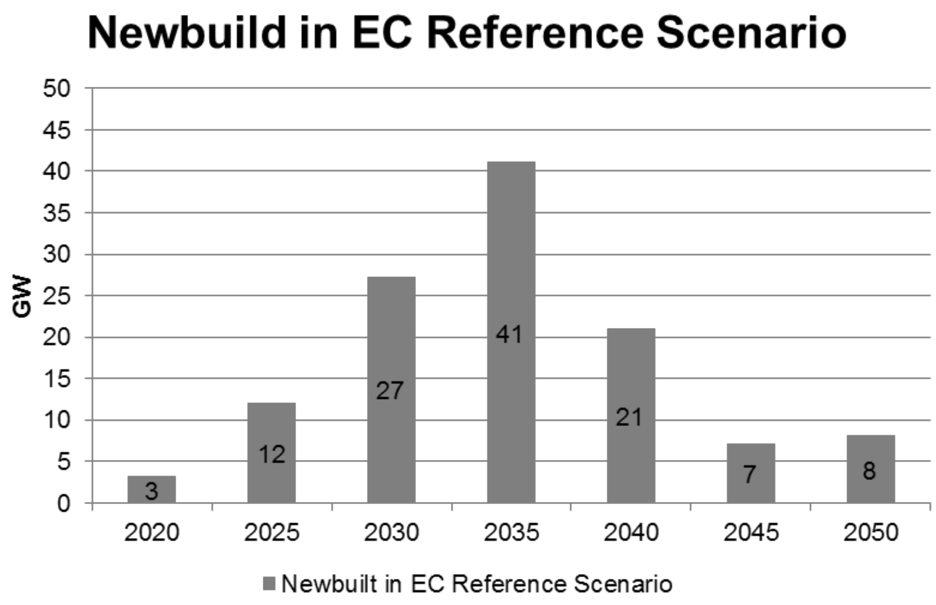

Figure 2: Construction of new nuclear power plants in the EU, according to the (2013) Reference Scenario

Source: EC (2013).

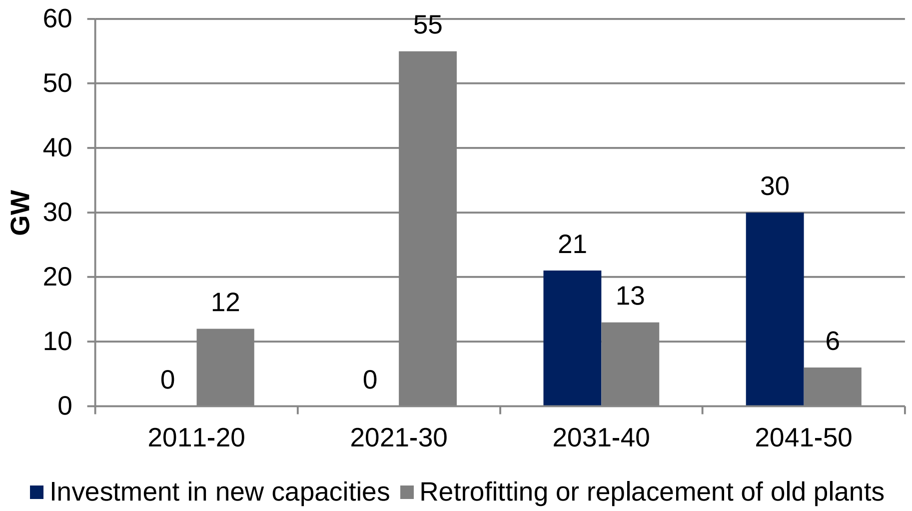

Figure 3: New-built and retrofit nuclear power plants in the EU 2016 Reference Scenario

Source: EC (2016).

3.5.4 Explanations: Diverging cost estimates and a bias for baseload nuclear

As discussed in the previous section on the private costs of nuclear power, these have continuously increased over the least decades, leading to "negative learning" and rising capital costs (Grubler 2010; Escobar Rangel and Leveque 2015). The trend is maintained in the first projects for the "generation III" reactors, the European Pressurized Reactor (EPR), the construction costs of which are estimated in the range of 6,000 – 10,000 €/kW, excluding decommissioning and waste storage.

The model underlying the EU Reference Scenario adopts an inverse perspective: not only the estimate for a new nuclear power plants is significantly lower (4,350 €/kW in 2020), but also, instead of increasing capital costs over time, the model assumes gradually decreasing costs, towards 3,949 €/kW in 2050. This leads to a significant decrease in life-cycle costs: when applying our simple Excel spreadsheet model used above, LCOEs would fall from 10.2 €cents/kWh to 8.5 €cents/kWh in 2020, and to 8.0 €cents/kWh in 2050.

The PRIMES model is not available for expert consultation, and both the programming code and the interfaces between sub-models are not made public. However, judging from the available data (input costs, output of nuclear EU-wide aggregate, as well as country-specific capacities and electricity generation), and the available bits and pieces of model information (Pantelis Capros et al. 1998; P. Capros 2011), it can be assessed that a second idiosyncrasy of the PRIMES model consists in the segregation of electricity market shares in "baseload", other loads, and "intermittent" generation technologies, and that nuclear has a comfort zone reserved for it in the baseload segment. Instead of an economic optimization program, which would yield coal or natural gas as a "corner solution", the model is probably calibrated such that it largely reproduces the status quo observed in 2010 in each of the EU member states, which of course implies a high share of nuclear energy—higher than would correspond to a purely economic calculation. By projecting the past electricity mix into the future to at least some extent, a base share of electricity is "reserved" for nuclear power, independent of the fixed or the variable costs.

4 Military use of nuclear power in the second nuclear age

The previous section has shown that no economic incentives exist to manage a nuclear power sector for civilian electricity generation only. But that does not mean that all countries are giving up nuclear. In fact, the economics-of-scope hypothesis is helpful in interpreting what is going on in the nuclear industry in many countries around the world by highlighting the combination of civilian and military activities. In particular, one observes significant movements away from the civilian use of nuclear electricity, for instance in some European countries, whereas other countries are considering entering the nuclear power sector, mainly in the Middle East and Asia. A third group of countries, the "nuclear superpowers" (United States, Russia, China) are pursuing different combinations of civilian–military strategies: The United States is almost abandoning the civilian route; Russia is hesitant due to financial and technical obstacles, and China alone has undertaken a large civilian expansion program world-wide. All three are investing massively in the modernization of their nuclear military equipment and engaging in "nuclear diplomacy". In this section, we try to identify logic within these movements, by applying our understanding of the industry in terms of "economies of scope" between civilian and military aspects.

4.1 The context of the second nuclear age (or: "twenty-first century")

The economies-of-scope approach is very useful in interpreting different strategies of countries discontinuing the civilian use of nuclear power, or conversely, working to build a nuclear industry in the "second nuclear age". The latter term was coined by Bracken (2012), and it describes the world of today, as distinguished from the "first nuclear age", characterized by a duopoly of nuclear superpowers, the United States and the Soviet Union in the twentieth century. The second nuclear age is above all a multiplayer game with "many independent nuclear decision-making centers" (whereas the first nuclear age essentially had two)." (Bracken 2012, 106).

In strategic terms, the main difference between the first and the second nuclear age is the decentralization of decision-making centers and the significant increase in the number of countries and additional players that have or are close to having a nuclear bomb at their disposal: among them are major powers with nuclear forces (such as the United States, Russia, China, and India), secondary nuclear forces (such as Pakistan, North Korea, Israel), non-nuclear countries that are trying to go nuclear (Iran), and subnational groups, all strategically interlinked through an "interplay of conflict, cooperation, manipulation, collusion, and compromise" (Bracken 2012, 231). While in the first nuclear age, the two superpowers were able to maintain some control over tertiary nuclear powers and control the proliferation of nuclear power as part of economies of scope (e.g., through the "Atoms for Peace" initiative), this process has spiraled out of control in the second.[41]

4.2 Strategic choices of nuclear strategies

4.2.1 The nuclear superpowers: United States, Russia, and China

The economies-of-scope approach suggests that the nuclear superpowers, the United States, Russia, and new entrant to the group China will continue to seek synergies between military and civilian uses of nuclear power, although with different focal points. The United States seems to focus on military use, but is seeking to maintain a foothold in the civilian sector as well. Russia is trying to halt the decline of its technological base by shifting significant resources to both military and civilian uses at the risk of a further erosion of its macroeconomic situation. To date, China is pursuing the clearest ambitions to harvest economies of scope: it is emerging as the world market leader in civilian nuclear power generation and engineering, while at the same time developing its nuclear military forces. All

[41] Bracken (2012) suggests that "the economics of nuclear power in the second nuclear age also have a very destabilizing potential. The possibility that poor countries could find the means to go nuclear and get the bomb is no longer inconceiveable. Low-budget civilian entry into nuclear technology is an easy step to going nuclear in the military sphere, all the more so, as this can be greatly facilitated through nuclear diplomacy of the superpowers".

three countries are also deploying a dual strategy in foreign relations, trying to establish or reinforce strategic alliances through dual “nuclear diplomacy”.[42]

4.2.1.1 Economies of scope …

The United States has traditionally maintained the strictest separation between the military and the civilian sector. As outlined above, Project Manhattan provided the country with independent, full-fledged military capabilities, from the upstream resource supply, enriched $uranium_{235}$ and plutonium production all the way to different bomb designs. Therefore, the United States was the only country worldwide where the civilian sector was not a mere “appendix” of the military sector after World War II, and in the 1950s; later on, this separation was maintained.[43] Nonetheless, the United States continues to provide substantial support to next - or third-generation civilian nuclear power. Edward Moniz, former U.S. Secretary of Energy serving under U.S. President Obama (2013-2017), emphasizes that it is essential that policymakers recognize that the civilian nuclear power sector and its associated supply chain are intimately connected and key enablers for national security (Energy Futures Initiative 2017).

The Energy Policy Act (EPAct) of 2005 included significant subsidies designed to incentivize the first new-builds in decades, including loan guarantees, production tax credits, and the reimbursement of costs due to regulatory delay (Moniz 2011). Currently, two reactors are still under construction at Vogtle, Units 3 and 4 (Georgia), expected to go online in the early 2020s, whereas the other two hopefuls from 2013, VC Summer, Units 2 and 3 (South Carolina), have been abandoned; none of the four would have been developed without the EPAct provisions (K. Rhodes 2016). But the major activity of the United States under the Obama administration’s Nuclear Weapon Strategy is the modernization of its nuclear weapons arsenal, including the construction of a new generation of ship-submersible ballistic nuclear (SSBN), air-launched cruise missiles (AlCM), intercontinental ballistic missiles (ICBM), and nuclear-capable aircraft fighters (SIPRI 2015). The expenses involved dwarf subsidies for nuclear power plants around the world: the US federal budget has earmarked no less than US$ 348 bn. for the period 2015-2025 (SIPRI, 2015), and expenditures for the next three decades are estimated above US$ 1 trn. (SIPRI 2016).

The Soviet Union had traditionally sought to maintain a very close relationship between military and civilian nuclear activities. The very choice of the graphite route for the first-generation reactors linked the need for plutonium to the aim of increasing electricity generation. The organizational structures of the nuclear industry were kept under joint control, and R&D activities were coordinated closely. After the fall of the Soviet Union, Russia re-established almost all of the former activities within its territory and maintained close ties with users of its technology in the former Soviet countries as well as former allies or satellites such as Hungary or Mongolia. Even amid economic crises and an unprecedented

[42] The latter criterion, active nuclear diplomacy, excludes India from the group of nuclear superpowers, that other observers such as Bracken (2012) would include in this group: With the spread of nuclear technologies beyond the United States, the superpowers, and the five permanent members of the UN Security Council, the dual use of nuclear power, too, has spread worldwide, accompanied by “nuclear diplomacy”.

[43] The United States maintains two different sites for storing nuclear waste: the waste from the military is stocked at the Carlsbad, New Mexico, facility, whereas waste from civilian use is supposed to be stored long-term in Yucca Mountain, Nevada.

downturn, Russia maintained and even expanded its nuclear activities: it has granted 15-year life extensions to the fleet of RMBK and VVER-440 reactors, and has developed a new, generation III$^+$-design rector, the VVER-TOI (1,200 MW, see Schneider, et al., (2016, 209)). Russia has eight reactors under construction, two of which are "floating reactors" on the submarine Akademik Lomonossov (so-called SMRs), and one fast breeder reactor (Beloyarks-4). The target for nuclear power for 2020 is 30.5 GW (in 2014, capacity was 24 GW, see Schneider, et al (2016): "Russia", 208-211). In parallel, Russia is spending significant resources to upgrade its nuclear military equipment (SIPRI 2015).

China has declared the ambition of becoming the leading nuclear state in the world, and is pursuing a unique expansion program. With 34 reactors already operating (29 GW), there are as many as 21 units under construction (22 GW). The China National Nuclear Corporation (CNNC) has set out a target for the sector of 58 GW (WNISR, 2016). China has pursued a consistent strategy of importing different reactor types (AP 1000, VVER, EPR), including substantial technology transfer, and on this basis has developed its own reactor type, the Hualong One (1,000 MW), which is currently being built for the first time at the Fuqing site (Fuqing-5 and -6). China has also intensified its research efforts on fast breeders, high-temperature reactors, and small modular reactors.[44]

4.2.1.2 … and nuclear diplomacy

In addition to domestic activities, the three nuclear superpowers are also engaged in sustained nuclear diplomacy aimed at building or strengthening international relationships involving nuclear technology transfers. Nuclear diplomacy can work in both directions: diplomatic channels can be used to sell nuclear technology (reactors, weapons, etc.), but the more or less free supply of nuclear technology can also serve as a means to increase diplomatic reputations and power. After the tough competition for commercial deals in the preceding period, the current period appears to be dominated by the second approach of competition for diplomatic influence at the risk of economic benefits ("nuclear technology dumping"). By proposing favorable financial conditions and massive technology transfers, the nuclear superpowers are trying to expand their influence on emerging countries in what seems to become a global competition for strategic technology.

In the spirit of the "Atoms for Peace" program of 1953, the United States continues to offer third countries a supply of highly enriched uranium for research reactors in the framework of bilateral agreements, e.g., with South Korea, Japan, and Germany. The absence of a domestic repository for high-level nuclear waste, even seven decades after the discovery of nuclear power, somewhat weakens the US position, as former Secretary of Energy Ernest Moniz (2011) has acknowledged.[45]

[44] In addition to its ambitious expansion plans for civil nuclear power, China has developed a comprehensive retaliation arsenal, and seems to have abandoned its promise not to proceed with a nuclear first strike, see discussion by Bracken (2012).

[45] Moniz (2011) concluded his argument in favor of sustained nuclear activity: "The United States already runs a similar program on a smaller scale, having provided fuel, often highly enriched uranium, to about 30 countries for small research reactors. But with no functioning commercial waste management system in place, the program cannot be extended to accommodate waste from commercial reactors. Instead, Washington is trying to use diplomacy to impose constraints on a country-by-country basis, in the futile hope that countries will agree to give up enrichment and reprocessing in exchange for nuclear cooperation with the United States. This ad hoc approach might have worked when the United States was the dominant supplier of nuclear technology and fuel, but it no longer is, and other major suppliers, such as France and Russia, appear uninterested in imposing

With respect to reactor technology, too, US competitiveness seems to have declined: Westinghouse, which created the “mother” of all pressurized water reactors, is still offering its equipment to countries worldwide, but its market position has been weakened by increasing international competition and technical problems with its AP 1000 reactor, both in the United States and abroad.[46]

Russia is currently the champion of nuclear diplomacy, as it sets out to compensate for a lack of economic strength with military power, not only at home but also abroad. Russian state-owned company Atomstroyexport and other subsidiaries of Rosatom are currently building NPPs in Belarus, China, and India; negotiations are underway with a large number of other countries, including Armenia, Bangladesh, Finland, Hungary, Iran, Jordan, South Africa, Turkey, Ukraine, and Vietnam (Lévêque, (2014), Schneider, et al., (2016, 210)). Most of these cases are driven by geopolitical, not economic, considerations, since Russia is not only providing technology but also financial support.[47] It is unclear, though, how long Russia can sustain such “dumping” practices, given the macroeconomic weakness of the country and growing budgetary imbalances.

Starting from behind, but now headed for world primacy, China is pursuing a particularly aggressive strategy, with respect to both civilian applications and its military nuclear arsenal. As one of the permanent members of the United States Security Council since the end of the Second World War, China is a nuclear latecomer but has pursued an ambitious follower policy. Its nuclear diplomacy is built both on a newly developed domestic reactor technology (Hualong One) and the pursuit of own interests. China seeks export markets as diverse as the UK, Pakistan, and even Sudan, a country that has been plagued by civilian war and terrorism for the last decades.[48]

4.2.2 Europe: Leaving the nuclear sector, with two exceptions

In Europe, once the heartland of nuclear power research, one observes segregation between countries that benefit from scope economies and are therefore pushing towards the continued use of civilian power, and others that do not and are therefore likely to abandon the (non-economic) purely civilian use of nuclear power. The current situation closely resembles that just after the end of the Second World War, with two countries active in both civilian and military uses of nuclear power: the UK and France, both of which are permanent members of the UN Security Council. Both had chosen to pursue independent nuclear technological development as early as the 1940s by taking the graphite-moderated route, which was particularly suitable for simultaneous plutonium production and electricity generation. Both countries have maintained a state-governed nuclear industry to this day,

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such restrictions on commercial transactions. Putting together a coherent waste management program would give the United States a leg to stand on when it comes to setting up a proliferation-resistant international fuel-cycle program.“

[46] Delays and cost escalation of the four AP 1000 reactors under construction have further weakened Westinghouse’s competitive position, see (K. Rhodes 2016), and eventually lead to bankruptcy in 2017.

[47] See Lévêque (2014) for a survey of the Russian nuclear diplomacy and an insightful case study of its “dumping” strategy toward Egypt.

[48] See Bloomberg (2016): China’s CNNC Seeking to Build Sudan’s First Nuclear Reactor, http://www.bloomberg.com/news/articles/2016-05-24/china-s-cnnc-seeking-to-build-sudan-s-first-nuclear-reactor, accessed August 29, 2016. The President of Sudan, al-Baschir, is sued by the International Tribunal in Den Haag because of violence committed in the civil war in the Dafour provinces.

even though they had to abandon aspirations of technological autarchy.[49] Today, they remain the only countries actively engaged in nuclear activities in both the military and the civilian sector, and the only countries in Europe to pursue a long-run new-build program for NPPs, despite highly unfavorable financial conditions:

~ The UK is pursuing a new-build program to replace the second-generation Advanced Gas-cooled Reactors (AGRs), a legacy of the post-war period. The flagship project is the construction of two large units at the Hinkley Point site, of 1,600 MW each. The project is politically sensitive, because the consortium consists of two foreign companies, the French EdF (67%) and the China National Nuclear Corporation (CNNC, 33%), proposing the EPR. Other projects include the construction of three AP 1000 near Sellafield (now called Mooreside) by a consortium of equipment supplier Toshiba–Westinghouse, and the French-Belgian utility Engie. Last but not least, the China General Nuclear Power Corporation (CGN) is actively pursuing construction of its own creation, the Hualong One reactor (HPR 1000), at a site to be determined. Having given up its own civilian nuclear program, the United Kingdom therefore has to choose among three different technological options (EPR, AP 1000, HPR 1000), or not go forward at all;

~ France is also counting on economics of scope between civilian and military nuclear uses, including a relatively high share of nuclear electricity, currently supplying over 75%. EdF is currently installing the first EPR plant in Flammanville (Normandy), to be operational in the early 2020s. The project was considered to be the first of a large number of plants replacing the aging nuclear fleet of the 1970s/1980s. Yet, due to unfavorable technical and commercial circumstances, no follow-up decisions have been made so far. Instead, EdF is seeking lifetime extensions for about 25 GW of its plants (mainly plutonium-uranium MOX reactors, see Schneider, et al., 2016, “France Focus”). The French law on the energy transition prescribes a reduction of the nuclear share of electricity to 50% by 2025; subsequently, further reductions are currently being discussed, going down as low as 0% nuclear energy by 2050 (Criqui, Hourcade, and Mathy 2015).[50]

None of the other European countries can benefit from such scope economies, and it is likely that they will give up attempting to generate economical nuclear electricity. Italy, Belgium, and Spain had already announced that they would not pursue new-builds before the 2011 accident in Fukushima, and Germany and Switzerland joined immediately thereafter in 2011. Finland, where another European EPR is currently under construction, cancelled its plans for a second EPR reactor in 2015. Lithuania and Bulgaria held referenda in which the population voted against new nuclear projects. The Czech Republic, Slovakia, and Hungary are pondering the modernization of their respective nuclear fleets, but are unlikely to go ahead given the immense costs of the projects. Last but not least, Poland is considering entering the group of nuclear electricity countries, but has not followed suit on ambitious projects for a 6 GW new-build program thus far (WNISR, 2016, 53/54). According to our approach, it is

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[49] France abandoned the graphite route in the 1960s, and turned to imports of Westinghouse-licensed pressurized water reactors; in the UK, the last graphite reactor closed down in 2013, and the new-build program now relies on the EPR and other imported technologies.

[50] In addition to the construction of “generation III” reactors, both the UK and France are also engaging in R&D of “generation IV” reactors of different types, mainly small modular reactors (SMRs), as well as breeder technologies.

unlikely that Poland would make that step, because chances are very low that the country would seek economies of scope with a large-scale build-up of military capabilities.

4.2.3 Potential “newbies” with mixed intentions in the Middle East and Asia

On the receiving side of the nuclear diplomacy, one observes a relatively large number of countries, mainly in the Middle East and in Asia have stated that they plan to pursue entry into the nuclear industry. It is not always clear what strategies these countries are pursuing, but clearly economies-of-scope considerations play a key role: As outlined by Bracken (2012) and Thränert (2010), the regional conflicts in the Middle East and Asia therefore now also have a concrete nuclear context. Clearly, while the potential newcomers may consider nuclear electricity a useful addition to their energy mix, there are also military and strategic considerations involved.

Most countries consider entering the nuclear sector by purchasing reactors for electricity generation, but none of these decisions is based on the idea of adding an economic source of electricity to the power mix. The United Arab Emirates have launched the construction of a large plant (four reactors). The allocation of the contract was highly politicized, and it was ultimately awarded to KEPCO of South Korea).[51] Turkey, Saudi Arabia, Egypt, Jordan, Bangladesh, Vietnam, Thailand, and Kazakhstan have also developed plans to establish nuclear facilities, in many cases with support from one of the nuclear superpowers (see Schneider, et al., 2016, for a survey). None of these countries has either the technical competence or the technical and institutional infrastructure to launch nuclear power on its own, and therefore all rely on substantial technology transfer and in most cases financial support as well. The following section focuses on the military aspects of nuclear development by taking a regional focus, looking at both potential “newbies” and established nuclear powers.

4.3 The changing nuclear landscape and the regionalization of conflicts

The scope economies approach is helpful in understanding the dynamics of nuclear power, especially in those regions where potential newcomer countries are particularly numerous, such as South Asia, East Asia, and the Middle East. According to Bracken (2012, 2), “the bomb is a fundamental part of foreign and defense policies in the Middle East, South Asia, and East Asia, and has become deeply embedded in those regions.” Most countries in these regions are already deploying an economies-of-scope strategy or are attempting to join the club in the near future. In both groups of countries, there is a close interdependency between the military role of nuclear power and attempts to reap side benefits from existing nuclear infrastructure, for instance, in electricity generation. This subsection describes the nuclear strategies of (potential) nuclear powers, examining them in the context of the regionalization of nuclear and other conflicts.

[51] The second newcomer country at present is Belarus, which is importing two reactors from Russia in the Ostrovets plant (Belarussian-1 and -2), supplied and financed by Atomstroyexport (Schneider et al. 2016, 40).

4.3.1 South Asia

In South Asia, the conflict between India and Pakistan has an important nuclear ingredient. Other failed or uncertain states in the region play an important role as well, such as Afghanistan and the Central Asian countries. Nuclear weapons became part of the arms race between India and Pakistan, with India obtaining technology through Canada and the Soviet Union, and Pakistan through Canada, the United States, and China. The first nuclear tests were carried out in India in 1974 and in Pakistan in the early 1980s. Further nuclear tests followed in 1998, at a time when the test ban treaty was respected elsewhere. Thanks to its economic superiority, India seems to have surpassed Pakistan, and is now on its way to challenging the role of China as an emerging superpower. While India is presently focusing on its conflict with its Western neighbor, Pakistan, it is also using nuclear developments to bolster its position as a challenger of China (in addition to other instruments such as IT technology for cyberwarfare; see Bracken (2012)).

In addition to about 20 existing reactors (5 GW), India is currently constructing another six reactors with a capacity of 4 GW, including a second VVER reactor from Russia, and a Prototype Fast Breeder Reactor (PFBR, see Schneider, et al. (2016, 144 sq.)). The nuclear strategy of India is not without problems, however: most of the civilian power plant projects are significantly behind schedule, and Western equipment suppliers (such as EdF/Areva, Westinghouse, GE) are hesitant due to India's nuclear liability law and the uncertainty of being paid once commercial contracts are closed (Schneider, et al., 2016, 146). With respect to its nuclear weapon arsenal, India is developing its Agni arsenal of land-based rockets with a range of 5,000 km ("Agni-V"), and has been successful in installing its first submarine-based nuclear warhead[52]. The construction of a nuclear reactor in Khushab (Rawalpidi) is part of intensified efforts to develop a nuclear strategy, as is the increasing focus on plutonium-based nuclear weapons.[53]

Pakistan is also pursuing a dual-use strategy, closely supported by its strategic ally (and India's competitor), China. China has already supplied two of the three reactors operating in Pakistan (total of 690 MW), and is currently constructing the first two Chinese export reactors (Hualong One), close to the megacity of Karachi. Parallel to the civilian use of nuclear energy, Pakistan produces its own highly enriched uranium, as well as plutonium, for nuclear weapons (Schneider, et al., 2016, 163). Pakistan is actively pursuing the development of its land-, sea- and air-based arsenal, increasing its potential to enter into combat on Indian territory with battlefield missiles, nuclear cruise missiles aboard ships, and possibly nuclear demolition weapons (Bracken, 2012, 166).

In other countries in the region, too, nuclear power plays a role. Bangladesh is said to have concluded an agreement with Russia, whereby it will receive two VVER-1200 reactors and the right to return the spent fuel to Russia for US$ 13.5 bn. (Schneider, et al., 2016, 43/44); it is unclear, however, if the Russian credit would ever be paid back in case of delivery. With respect to South and Central Asian

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[52] The Economist 2015, 19; SIPRI 2015.

[53] Bracken (2012, 166) calls this strategy "more bang for the buck."

states such as Afghanistan and others (Uzbekistan, Tajikistan, etc.), there are concrete risks of proliferation.

4.3.2 East Asia

In East Asia, several important nuclear powers come together to form another “hot spot” of regional conflict with a nuclear flavor.[54] The region also positions itself in a change of era, where the previous bilateral, Europe-centered conflict between the United States and the Soviet Union is replaced by several decentral, regionally focused conflicts. While the Pacific used to be an “American lake… in the future, it could be a contested zone of rivalry” (Bracken 2012, 209). In particular, the flexibility of the United States in the region is challenged by China’s expansion policy, based on progress with both nuclear and conventional military equipment, as well as progress in IT- and cyber-war technology.

A very peculiar nuclear power, North Korea, has pursued a quite effective scope economy strategy, having initially been supported by the United States, South Korea, China, and even Japan at different points in history (Bracken 2012, 192). Given the failure of subsequent governments to provide reasonable living conditions to the population, the only viable survival strategy for the government is to increase its domestic and foreign military power, including its nuclear arsenal, with respect to South Korea, Japan, the United States, and other countries.[55] North Korea has constructed between 10-12 nuclear warheads, and is currently expanding its capacity for uranium enrichment and civilian nuclear power. North Korea has developed a comprehensive rocket arsenal capable of reaching South Korea, Japan, United States, and perhaps even Europe.

The strategies of Japan and South Korea could also be considered in the light of the civil-military interaction. Even though they have been officially demilitarized since 1945, both countries have emerged as champions of civilian nuclear energy, with 58 (Japan) and 25 (Korea) reactors constructed, respectively, and very strong domestic engineering firms. Japan has recently set up an energy program that calls for a 20-22% share of nuclear power in the electricity mix. One of the two reactors currently under construction, the Ohma-1 plant, is designed to operate with a 100% plutonium MOX core (Schneider, et al., 2016, 162), which would strengthen the fuel cycle and the country’s ability to produce plutonium.

By contrast, some of the countries in the region seem to be diverging from the “normal” dual-use approach. The situation in South Korea has changed recently: In 2017, new President Moon Jae-in announced a nuclear phase-out over the next decades to ultimately eliminate nuclear weapons. The previous target for nuclear power in the electricity mix (29%) has been reduced to 20% by 2020, and should further decrease thereafter.[56] Along similar lines, Taiwan plans to close down its civilian capacities by 2025, and Indonesia has shelved previous plans for large-scale nuclear entry. Thailand

[54] This subsection is based on Bracken (2012, Chapter 7, “East Asia“, 189 – 211).

[55] Bracken (2012, 192) calls this strategy “suicide in your neighbor’s living room.“

[56] South Korea has obtained some relief of the previous prohibition to export spent fuel for reprocessing. Although the agreement signed with the U.S. does not (yet) give South Korea the right to indigenous development of enrichment or reprocessing, it allows the country to export spent fuel for reprocessing, and to receive plutonium mixed oxide fuel (MOX) with U.S. approval (Schneider, 2016, 167).

has only formulated vague ideas about potential capacities to come online in the late 2030s (see Schneider, 2016, for details).

4.3.3 The Middle East

The situation in the Middle East is peculiar as well: Whereas not a single country is officially pursuing military nuclear strategies, and only one small nuclear power plant exists in the region (Busher, Iran), thinking of countries both within and outside the region is dominated by the "nuclear Middle East". Previously, the conflict between Israel, which has the nuclear bomb without acknowledging it, and Iran, which is believed to be working towards the bomb without acknowledging it, has been the focus of much of this strategic thinking.[57] However, in recent years, the process has begun to include many more countries such as Saudi Arabia, the United Arab Emirates, Iraq, Jordan, and Turkey. In addition, with the Arab Spring having turned into an Arab nightmare, not only countries but also smaller groups and terrorist organizations such as Al Qaeda and the Islamic State may be striving to obtain nuclear weapons. Thus, the nuclear Middle East has gone from being a well-defined conflict to becoming a "dynamic system of mutually coupled actors." (Bracken 2012, 160).

Israel has chosen a very particular way to go nuclear, and it was one of the few countries that did not benefit from economies of scope itself. However, it obtained nuclear power from an economies-of-scope country, France, and handed it on to what would become a scope-economies country as well, South Africa.[58] After its own first nuclear test in the Sahara in 1960, France gave Israel nuclear "research" reactors and detonator technology. This lead to Israel's plutonium facility at Dimona, and eventually a nuclear weapon." (Bracken, 2012, 102).[59] On the receiving end, South Africa, which had started a bomb program in the 1970s, collaborated with Israel on a neutron bomb test in the Indian Ocean, 1,600 miles southeast of Cape Town.[60] South Africa produced its first nuclear bomb in 1982, and five more in the following years; in parallel, it expanded its nuclear industry with the construction two 900 MW reactors, located at Koeburg (close to Cape Town), delivered by French Framatome (now Areva, 1980s).

Iran is another example of a country building up a nuclear industry based on the expectations of economies of scope. It acquired a nuclear power plant (Bushehr, VVER-1000-446, 1000 MW) while in the process of developing its own significant nuclear research capabilities and uranium enrichment

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[57] The section on the Middle East in Bracken (2012, 127-161) almost exclusively focuses on Israeli-Iranian relations.

[58] Bracken (2012, 160) suggests that the "second nuclear age", i.e., the era beyond the bilateral nuclear conflict between the USA and the Soviet Union during the Cold War, began with the nuclear bombs of Israel and South Africa, two countries that "used the Cold War to conceal what they were doing and tried to manipulate cold war countries for their own purpose." (Bracken 2012, 101).

[59] "Israel went nuclear in 1966, not with a test but with a reliable design judged certain to explode. The country had two atom bombs primed for hitting Cairo and Damascus in the June 1967 war. Israel going nuclear can't be forced into the cold war story line at al. The United States learned of the Israeli program but decided to remain quiet about it. Not having good labels for what was taking place, yet alone policies for preventing it, the U.S. government pushed the Israeli nuclear program to the side. There is still controversy about this. A top-secret memo in 1969 discussing the Israeli bomb, from Henry Kissinger to Richard Nixon, has now been declassified. It shows the United States wanted to keep the Israeli bomb secret as much as the Israelis did. …" (Bracken 2012, 102), the original source is Kissinger (1969).

[60] "Israel promised South Africa a primitive weapon design, and in return received uranium and testing rights." (Bracken 2012, 105).

facilities;[61] Iran's "research" reactor at Arak is capable of producing 1 kg plutonium per month (Economist, 2015, 18). In addition, in 2015, the time to centrifuge weapon-grade material to make a bomb was estimated to be three months only (The Economist 2015, 18). Even though an agreement was struck between Iran and the group of 5+1 (five permanent members of the UN Security Council, plus Germany), restraining Iran's military capabilities for ten years, the danger of a nuclear conflict remains.

Beyond this conflict, the nuclear context is changing the Middle East on a large scale. Saudi Arabia stands out here as an economic powerhouse that could easily afford a large nuclear industry. The country has set up the "King Abdullah City for Atomic and Renewable Energy", (KA-CARE) that has produced a plan to construct 16 nuclear power reactors (Schneider, et al., 2016, 57). Saudi Arabia has also negotiated cooperation agreements with several nuclear countries (France, Russia, China, and South Korea), the most advanced being the building of two small modular reactors by South Korea, under the pretext of combatting water scarcity. The United Arab Emirates is the only country in the region that is currently building nuclear power plants: it purchased four reactors from the Korean Electric Power Corporation (KEPC, 1,400 MW each), at costs estimated between US$ 20-32 bn. (~ US$ 5,000-8,000/kW), that will come online between 2018 and 2020 (Schneider, et al., 2016, 42). Although the UAE have negotiated a non-proliferation treaty with the United States, the deal is not without risks, the country being a traditional hub for nuclear technology, which is transferred, amongst others, towards Iran, Libya, and North Korea. The UAE owns Scud missiles (purchased from North Korea) as well as advanced conventional weaponry and defense systems from Western partners (SIPRI 2015).

Increasingly active in the region, Turkey is also considering going nuclear, with three NPP projects under development: Akkuyu is the most advanced, with a BOO (build–own–operate) contract struck with Rosatom for four VVER-1200 reactors, at estimated costs of US$ 20-25 bn. (4.8 GW, ~ US$ 4,200 – 5,200/kW, Schneider, et al., 2016, 46). In parallel, Turkey has started an intensive research program, including civilian and military elements (Jewell and Ates 2015).

A nuclear Middle East may also include some more or less politically unstable second-tier countries that have expressed an interest in becoming part of the "club". Egypt and Jordan have made plans to develop nuclear power plants, both benefiting from active nuclear diplomacy by Russia and China. Egypt signed an intergovernmental agreement with Russia for the construction of four VVER-1200 reactors at Dabaa, estimated at € 20-22 bn., of which Russia would provide 90% of the finance (Schneider, et al., 2016, 50). Jordan, too, had initially signed an agreement with Rosatom for the construction of two VVER reactors, with Russian financing 49.9% of the plant and taking back the spent fuel. However, since Jordan had difficulties raising the remaining financing, the China National

[61] The original contract for Bushehr was struck with Siemens for two PWRs of the Biblis type (1,300 MW). However, Siemens withdrew from the contract, and Iran subsequently turned to Atomstroyexport, which modified the plans to construct one VVER-1000/446 that went online in 2011.

Nuclear Corporation (CNNC) entered into the negotiations, with the option of financing an even larger share (Schneider, et al., 2016, 51), implying that Chinese reactors might replace the Russian ones.[62]

Last but not least, in light of current developments in fragile or failed states such as Syria and Iran, a nuclear Middle East also raises the specter of "old issues that plague the Middle East and have not gone away: Israel settlements, Gaza, Hezbollah, and Lebanon." (Bracken 2012, 136). According to some sources, Al Qaeda and the Islamic State have been seeking nuclear weapons, too, in what is another characteristic of the second nuclear age (not only in the Middle East): nuclear terrorism. Just as in South and East Asia, the effects of a nuclear Middle East driven by scope economies extend far beyond the Middle East. Europe and South Asia are already part of the "great game", both as partners but also as potential targets of the Middle East.[63]

5 Conclusions

Nuclear power plays an important role in international politics and in the energy sector, but the economic literature has treated these two fields separately so far. In this paper, we develop a model of the nuclear industry as driven by the search for economies of scope between military and civilian uses. We show that this approach is useful to identify trends in the industry that seem illogical when considered solely from the military or the civilian perspective.

Several decades after the introduction of commercial nuclear power, the industry has still not succeeded in making a case for being an "economic" source of electricity. In fact, the gap between the per-unit costs of nuclear and other energy sources, as identified by Davis (2012), has widened over the last years. Furthermore, the investment cost increase of nuclear new-builds identified in the United States and France for the period 1970-1990s (Rangel and Lévêque, 2012, Grubler, 2010), is continuing, and the specific costs for the new EPR of the third generation are also much higher than anticipated. Thus, the dynamics of nuclear power new-builds have slowed in the western world; an exception to this rule is China and some other emerging countries.

Clearly there is a contradiction between the low economic competitiveness of nuclear power and the important role it plays in many of the longer-term energy system projections, such as the Reference Scenario by the European Commission (European Commission, 2013) and the World Energy Outlook (IEA, 2015). In a sensitivity analysis of our dynamic investment model, dynELMOD, for the European level (Gerbaulet et al. 2014), we found that the results are highly sensitive to the estimation of capital costs: a value between € 3,000-4,000/kW, usually adopted in international comparisons, yields a high share of nuclear power, whereas the historical and recently observed values of € 5,000-7,000 yield much lower shares.

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[62] A historical perspective shows that countries in the region tried to go nuclear before. Iraq developed a nuclear reactor (Osirak) in the 1970s, and Syria did likewise in 2002. Israel bombed and destroyed both of these—in 1981 and 2007, respectively—in limited moves in the second nuclear age in the Middle East (Bracken, et al., 2012, 157).

[63] Israel is cooperating with India on satellite intelligence, North Korea or Pakistan may offer a nuclear reactor to Syria or Saudi Arabia, and the US is in the boat, too, via missile defense systems protecting Europe. "The military dynamics are spilling outside the region", and "they are reaching a level of geographic scale and intensity that may well swamp the confident predictions that the Middle East has always been troubled and that not much has changed." (Bracken 2012, 161).

"Atomic weapons have returned for a second act (…) in what I call the second nuclear age", writes strategist Paul Bracken (2012) in his book on "The Second Nuclear Age: Strategy, Danger, and the New Power Politics". Clearly, the dynamics of the nuclear industry cannot be reasonably analyzed outside the economies-of-scope framework, e.g. with a purely economic focus only. Nuclear power has emerged as the "daughter of science and warfare" (Lévêque 2014, 212), and has essentially remained a strategic investment in the second half of the twentieth century, which Bracken calls the "first nuclear age". From a purely economic perspective, nuclear power has never been competitive, and not a single reactor has been constructed with private investment under market competitive conditions. Nowadays, with low natural gas prices and falling costs of renewables, even the short-run operational profitability of existing nuclear power plants is no longer assured, as indicated by the wave of premature plant closures in the United States and elsewhere. Treating this technology as an "economic" one in energy system models therefore makes no sense, and distorts our understanding rather than enlightening us about the future of energy development and climate policy. Also, the assessment of the costs of civilian nuclear power requires important economic and ethical assumptions that are rarely made explicit in the analysis. It would be scientifically more honest, and much easier, to assign the full social costs to nuclear power, and to state the assumptions about nuclear power capacities expected in the future exogenously.

The dismal economic performance of civilian nuclear power does not imply, however, that this technology will go away. On the contrary, we observe long-term plans by the nuclear superpowers (United States, Russia, China) to expand their respective nuclear arsenals, and to back up the military activity with some civilian capacities including new-builds of nuclear power plants (to varying degrees): China is pursuing both aspects particularly actively. Some countries are leaving the sector because they cannot benefit from scope economies (e.g., Italy, Spain, Germany, Switzerland), while potential newcomers are counting on synergies between military and civilian uses (e.g., Iran, the United Arab Emirates, Egypt, perhaps one day also Japan). This paper has left out some important aspects that will be dealt with in Part II of this assessment, such as decommissioning of nuclear power plants and the search for a long-term storage, as well as an analysis of the "second nuclear age" from the perspective of game theory.

The economies-of-scope approach used in this paper may not be entirely original and is certainly insufficient to explain all the complexities of this sector. On the one hand, historians of technology insist on the military origins of the application of nuclear energy in the context of the Second World War and its aftermath, when the first nuclear power plants built were nothing but "plutonium factories, disguised as power plans" (quoted in Radkau (1983, 53) with reference to the first UK plant, Calder Hall). Likewise, strategy analysts would refer to the Iranian nuclear program as a military threat without considering its potential economic benefits. On the other hand, present-day economists often treat nuclear power as just another generation technology, without referring to its military origins. While the economies-of-scope approach will certainly not resolve all the controversies, it is useful in explaining some of the trends in the industry, and it also helps to focus the perspective on the future.

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