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Adam Smith, Publick Works, and Nuclear Policy

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Abstract

Since the Treaty on the Nonproliferation of Nuclear Weapons entered into force in 1970, the peaceful uses of nuclear technology in electricity generation and medicine have been incorporated into international markets. However, nuclear markets are imperfect. This paper focuses on the properties of the nuclear industry that lead to "market failure", where markets do not necessarily result in socially efficient outcomes. These properties in the production or consumption of a good or service are (1) public goods, such as advances in science; (2) positive or negative externalities, such as nuclear weapons technology proliferation; (3) asymmetric information and uncertainty, where an insurer or financier cannot determine whether the client is acting with due care and due diligence; and (4) increasing returns to scale, such that a "natural" monopoly could be established. Because of these properties, the nuclear industry is a quintessential "publick institution" providing "publick works", as identified by Adam Smith in 1776. Furthermore, exploding demand for non-fossil generated electricity and declining access to medical radioisotopes requires a review of the public-private boundaries in international nuclear markets while continuing to uphold nonproliferation standards. For these standards to be effective, every nation and firm must adhere to nonproliferation agreements.

Keywords

Public Goods, Monopoly, Market Failure, Nonproliferation, Dual-Use Technologies

1. Introduction

This paper examines the characteristics of the international nuclear industrial complex marketplace and identifies economic properties that have had a profound impact on its evolution. We differentiate between private (market) forces and those originating in the national and supranational spheres. We trace the balance of private, national, and supranational interests in the formation of UN and US policy around nuclear technology and nuclear nonproliferation (On nuclear power policy in Europe, see Jorges, 2012).

Our investigation focuses on those characteristics of the nuclear marketplace that lead to "market failure", as identified in microeconomics. In an efficient market, economists expect to see market prices equal to the (marginal) cost of production, including a competitive profit, given the risks in an industry. The primary characteristics leading to inefficient production or consumption of a good or service are (1) public goods properties, (2) positive or negative externalities in production or consumption, (3) asymmetric information, and (4) increasing returns to scale. The nuclear power industry produces private and public goods at increasing returns to scale with both positive and negative externalities in an atmosphere of incomplete information. Because of the emergence of these properties, we conclude that the nuclear industry is a quintessential "publick institution" providing "publick works", as identified by Smith (1776: p. 452).

2. Market Failure in Nuclear Power Technologies

Economics distinguishes between private and public interests in markets. Private interests come from consumers (or households) and producers (or firms). (In more general contexts, consumers, households, producers, and firms are referred to as "agents" or "actors"; Section 4 discusses the State as an agent.) Several axioms of rational economic behavior model consumers' actions as if they seek to maximize their welfare subject to budget constraints (Varian, 1992: pp. 94-98). Firms are assumed to be cost minimizers or profit maximizers, subject to constraints imposed by technology, the legal environment, and the actions of other firms (Varian, 1992: pp. 341-348).

A central theme in classical economics (Smith, Bentham, Ricardo, and others) is that rational ("selfish") maximizing behavior on the part of producers and consumers can lead to desirable social outcomes. An essential theme in neoclassical economics (Marshall, Pareto, Walras, and others) is that markets will lead to efficient resource allocation when prices equal (marginal) costs.[1]

2.1. Markets with Public Goods Characteristics

Goods and services can be divided into "private" and "public". A private good is one for which increased consumption by one household or firm requires a reduction in consumption by others (rival consumption). On the other hand, a public good is one for which increased consumption does not diminish consumption by anyone else; goods of this type are described as "non-rival" or "shared" (Samuelson, 1954; SEP, 2021). Also, other consumers cannot be excluded from consuming

[1]Marginal cost is the sum of all resources required to produce the last unit of output. Average cost (equal to average fixed cost plus average variable cost) is the sum of all resources divided by the total output. Because marginal cost is difficult to measure, economic efficiency can be estimated as the difference between price and average variable cost, Leary (2001). Average variable cost is used to determine if a firm is engaged in predatory pricing.

public goods; therefore, these consumers are "non-excludable". For example, national defense is a public good with shared consumption where citizens cannot be excluded from national defense from external threats.

Scientific discoveries published in publicly available journals are another case in point. Consider, for example, the discovery of nuclear fission. As described by Sime (1998: p. 81),

> "Physicist Lise Meitner and two chemists, Otto Hahn and Fritz Strassmann, conducted a four-year-long investigation that resulted in the discovery of fission in their laboratory in Berlin. Meitner fled Nazi Germany in 1938 to escape the persecution of Jews, and soon after, Hahn and Strassmann reported the discovery. Meitner and her nephew, Otto R. Frisch, published the correct theoretical interpretation of fission a few weeks later."

Once these two papers were published, the discovery was non-rival and non-excludable—the discovery led to both nuclear weapons and peaceful uses of nuclear fission, such as nuclear medicine.

Because of these characteristics, it is difficult to charge consumers a price; in fact, most of the time, consumers would prefer to "free ride" on the contributions of others. Because everyone is better off with public goods like scientific discoveries and national defense, non-market interventions are required. Economic theory recognizes a spectrum of goods displaying varying degrees of "publicness". Many of the goods and services provided by the nuclear industry could be considered hybrid private-public goods requiring various systems of prescriptions, proscriptions, taxes, and subsidies. The primary public good produced by the nuclear industry has been nuclear science R&D (Dalrymple, 2003). For example, dozens of technologies were developed by General Atomics (General Atomics, 2024) with US federal support.

Regarding the theory of public goods, in classical economics, for example, in Smith (1776, Book V, Chapter 1, Part III, p. 452), governments had four responsibilities: national defense, administration of justice, public works, and education:

> "The third duty of the sovereign or commonwealth is that of erecting and maintaining those publick institutions and those publick works, which, though they *may be in the highest degree advantageous to a great society*, are, however, of such a nature that the profit could never repay the expence to any individual or small number of individuals, and which it, therefore, cannot be expected that any individual or small group of individuals should erect or maintain. The performance of this duty requires two very different degrees of expence in the different periods of society." (*emphasis added*)

While Smith was unable to articulate all forms of market failure, he points to problems associated with the properties of public goods, externalities, the effects of uncertainty on "rational" behavior, and monopolies.

2.2. Markets with Positive and Negative Externalities

Another source of failing markets is the existence of either positive or negative externalities associated with production or consumption. Externalities are, by definition, external to a particular market transaction between the buyer and seller; they might be "internalized" by creating a tradable market for them. Negative externalities, such as mine tailings, proliferation risk, and radioactive waste, will, in an unregulated market, lead to higher than socially optimal levels of production. In an unregulated market, a positive externality, such as low carbon emissions, will, other things equal, result in a lower than socially optimal level of production.[2] Coase (1960) discusses the problem of internalizing externalities under specific conditions. (Pasqualetti & Rothwell, 1993, examines these conditions in NPP, Nuclear Power Plant, decommissioning.)

Perhaps the paradigmatic negative externality in the nuclear sector is radioactive waste, or at least one on which the public focuses. To minimize the generation of radioactive waste, nations have implemented "the polluter pays principle", as discussed in Saab (2022):

> "The declaration issued by the United Nations Conference on the Human Environment in Stockholm in 1972, … embraced the principle of holding polluters responsible for their actions. It called for the inclusion of robust provisions in international environmental law that identify responsibilities and specify compensation to victims of pollution… But this general principle has not, in most cases, been translated into laws and regulations despite all environmental laws."

Although Adam Smith did not discuss externalities directly, he did consider the impacts of selfishness in his moral philosophy. In particular, he was concerned about the effects of coal on the environment (for example, from coal mine fires) and the treatment of miners. Smith wrote in his *Lectures on Jurisprudence* (Smith, 1763: p. 184) that coal mine owners, beyond the low wages paid, also generated negative employment externalities, i.e., workplace violence (Waters et al., 2012):

> "the love of domination and authority over others, which I am afraid is natural to mankind, a certain desire of having others below one, and the pleasure it gives one to have some persons whom he can order to do his work rather than be obliged to persuade others to bargain with him, will for ever hinder this from taking place."

Each of the nuclear sectors produces positive and negative externalities, requiring regulations limiting the production of the negative externality, such as nuclear weapons proliferation (US DOE-NNSA, 2024), or government subsidies to increase the output of positive externalities, such as the cleanup of hazardous and radioactive waste sites. This poses the question of the industry's net benefit. We

[2]Some positive externalities are non-rival and non-exclusive. For example, Carbon (Dioxide, CO_2) Capture and Storage (CCS) can produce *positive externalities* when used for enhanced oil and gas recovery. One policy that encourages CCS is to sell "carbon offsets" in "carbon markets". On the other hand, capturing CO_2 for the purpose of combatting climate change would be a *public good with positive externalities*. However, public goods are not produced for sale to individual agents.

conjecture that the avoided greenhouse gas benefits from NPPs would show the net benefit to be large, possibly larger than the real costs of the industry's negative externalities (not including the incalculable consequences of nuclear weapons use).

2.3. Markets with Asymmetric Information

A third type of market failure involves "asymmetric information", where one side of a transaction necessarily has more information than the other side. For example, one party to a transaction might have a set of "known knowns" and "known unknowns" that might be "unknown unknowns" to the other side of the transaction. Because of the safety issues associated with all nuclear power industry sectors, investors and insurance providers cannot determine whether agents are acting with due care and due diligence.

Therefore, it is more efficient to have an independent (extra-market) agency regulating safety behavior, given the statement by IAEA Director General (1997 to 2009) Dr. Mohamed ElBaradei, "A [nuclear] accident anywhere is an accident everywhere" (ElBaradei, 2005). Further, it is also more efficient to provide an active safety net should an accident occur in the nuclear sector (Aoki & Rothwell, 2013). To give rapid-response insurance to the US nuclear industry, the *Price-Anderson Act of 1957*, which added Section 170 to the *Atomic Energy Act of 1954* (42 USC 2210), and its extensions through 2025, provides multiple levels of insurance coverage (Rothwell, 2016, Appendix 3B). More recently,

> "[F]ederal Courts of Appeal issued decisions affirming a broad interpretation of the *Price-Anderson Act*, and in particular, a broad interpretation of the Act's primacy over state law and jurisdiction. First, in October 2021, the Sixth Circuit issued its decision in *Matthews v. Centrus Energy Corporation*. It held that the Price-Anderson Act provides the exclusive avenue for asserting liability arising from a nuclear incident, thereby preempting state and tort law claims… In January 2022, the Eighth Circuit issued its decision in *Banks v. Cotter Corp.* The Court applied a plain meaning of the term nuclear "occurrence," which is undefined, in supporting its broad grant of federal jurisdiction under the *Price-Anderson Act*. Under this interpretation, *Banks* held that the Act gives federal courts original jurisdiction over claims arising from nuclear incidents even in the absence of an applicable license or indemnity agreement." (Fork & Fowler, 2022: p. 1)

While Adam Smith did not discuss how "asymmetric information" plagued markets, he did discuss the underestimation of uncertainty by both consumers and producers and the power of uncertainty in influencing behavior (Smith, 1776, Book 1, Ch. X, p. 110). According to Brady (2015)[3],

[3]Brady (2015: p. 26) believes, "Bentham dominated all of England's political, social, economic, and institutional issues and debates from 1790 till 1830. David Ricardo, James Mill, J. B. Say, Nassau Senior, and the early John Stuart Mill were all Bentham students. Thus, Smith's use of the term 'uncertainty' was interpreted to mean risk. Smith was then misinterpreted as being some sort of utilitarian himself by misinterpreting his use of the terms self-interest and self-love. Smith came to be viewed as some sort of egoist, libertarian, utilitarian, or combination of the three."

"Adam Smith was the first academic in history to make an explicit, detailed Uncertainty-Risk distinction and apply it clearly in a number of worked-out examples and applications consistently in his analysis of decision-making in the *Wealth of Nations* on occupational choice, businesses such as mining, fishing, taxation, and foreign trade."

On mining, Smith (1776, Book 1, Ch. XI, pp. 200-201) wrote,

"In increasing the quantity of the different minerals and metals which are drawn from the bowels of the earth, that of the more precious ones particularly, the efficacy of human industry seems not to be limited, but to be altogether uncertain… The discovery of new mines, however, as the old ones come to be gradually exhausted, is a matter of the greatest uncertainty and such as no human skill or industry can insure."

2.4. Markets with "Natural" Monopoly Characteristics

In markets where average costs are continuously falling with increases in output (see **Figure 1**; these industries generally have high fixed costs and low variable costs), competition does not necessarily lead to efficient market outcomes, such as a socially optimal level of output. These are situations in which a "natural" monopoly can develop where the largest firms undercut the prices of smaller firms, driving them out of business until there is a single firm or a multi-firm cartel (Rothwell, 1980) that can increase profit by raising prices or cutting output. Consider the 19th-century histories of US Steel and Standard Oil. The traditional economic policy response to the exercise of monopoly power has been to institute government regulation of the monopolized industry, e.g., the *Sherman Antitrust Act of 1890* (codified at 15 USC 1-38), or nationalize and operate the monopoly as a State-Owned Enterprise (e.g., Amtrak in the US), or, more ambitiously, as a multi-state owned enterprise (as in the international uranium enrichment industry). The decreasing average cost characteristics of nuclear technologies create incentives that can lead to increasing levels of concentration within an industry. For example, consider decreasing average costs in the MOX (Mixed Uranium and Plutonium Oxide) fuel fabrication industry; Rothwell (2016: p. 187):

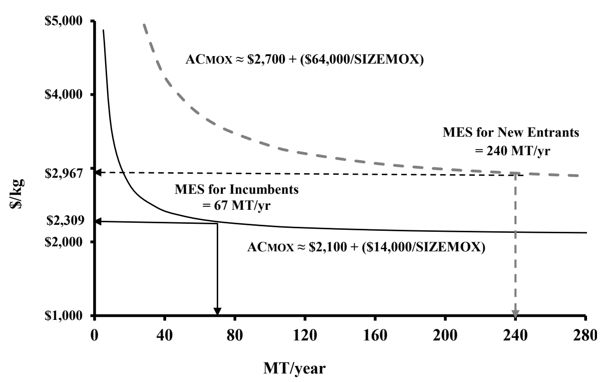

Figure 1. Costs for incumbents and new entrants in the MOX fuel fabrication market. Source: Rothwell (2016, Figure 4A.4, p. 187).

> "New entrants face high entry costs and increasing returns to scale… It is the costs of designing, licensing, and testing that increase the MES [minimum efficient scale] of new MOX plants. Simultaneously, increasing these costs also increases commercial entry barriers, thus increasing nonproliferation protection: if a facility is not commercial, then it is being done for non-commercial reasons."

Consider **Figure 1**, which suggests that the MES (with an error band of ±10% in its calculation, MES x 1.10) for a MOX industry new entrant is 240 metric tonnes, MT, per year, with a cost of $2,967/kg. In contrast, due to economies of scale and previously spent fixed costs, the MES for incumbents in the industry is 67 MT per year at a cost of $2,309/kg.

Because he supported free markets, Adam Smith opposed monopolies. He did support temporary monopolies, not "perpetual" ones (1776, Book V, Chapter 1, Part III, Article I, p. 459):

> "A temporary monopoly of this kind may be vindicated upon the same principles upon which a like monopoly of a new machine is granted to its inventor, and that of a new book to its author… By a perpetual monopoly, all the other subjects of the state are taxed very absurdly in two different ways: first, by the high price of goods, which, in the case of free trade, they could buy much cheaper; and, secondly, by their total exclusion from a branch of business which it might be both convenient and profitable for many of them to carry on. It is for the most worthless of all purposes, too, that they are taxed in this manner."

Because of natural monopolies in electricity generation and distribution, electricity utilities were some of the first monopolies to be state-owned or rate-regulated. In return for monopoly rights to sell electricity in a specific territory, the monopoly submits itself to rate-of-return regulation (Rothwell & Gómez, 2003). Under state ownership, the electric utility becomes a cost-of-service provider for missions such as economic development, e.g., rural electrification by the Tennessee Valley Authority.

While many countries built NPPs with a State-Owned Enterprise model, in the US, NPPs were constructed in a rate-regulated environment during the 1960s and 1970s. The peaceful use of nuclear technology for electricity grew out of US military R&D. According to the US AEC-DOJ (1968: p. 116) in a study of competition in nuclear power supply chains:

> "Much of the early work on light water reactors was directed at developing a submarine propulsion system… The program not only furnished the driving force for early reactor R&D but also trained people and provided industry with valuable experience in the rigorous quality control environment of the nuclear age… Westinghouse, which… had been instrumental in the submarine reactor work, designed the pressurized water reactor [PWR], and the Duquesne Light Company cooperated by supplying the generating facilities."

See the discussion of the implications of promoting the Westinghouse PWR in Cowan (1990).

Many sectors of the nuclear industry are paradigmatic "natural monopolies", with decreasing average costs as scale increases due to high fixed costs, as in **Figure 1**. These technology sectors include (compare with the sectors articulated in NEA, 2008),

(1) national advanced nuclear science R&D infrastructures (NASEM, 2007),

(2) an international uranium mining and milling industry (Rothwell, 1980),

(3) an international uranium conversion and enrichment industry (Rothwell, 2009),

(4) an international nuclear fuel fabrication industry (Rothwell, 2010),

(5) an international NPP construction industry and supply chain (Rothwell, 2016: pp. 2-5),

(6) national NPP electricity generating industries (Rothwell, 2022),

(7) an international medical radioisotope industry (NEA, 2019),

(8) national spent nuclear fuel management industries (Rothwell, 2021),

(9) national nuclear decommissioning industries (NEA, 2016),

(10) national low-level radioactive waste management industries (GAO, 2023), and

(11) a monopolized used fuel reprocessing and MOX fabrication industry (Rothwell, 2016, Section 4A.1).

These internationally concentrated industries can function as national monopolies. Even when operating as privately held companies in countries where there is fair and transparent competition, international producers can provide limits on national price increases and output restrictions (Kindleberger, 1986). Here, the global market serves as a "price regulator".

3. Market Failures in Nuclear Power Industry Sectors

Table 1 outlines the four types of market failure characteristics of nuclear industry sectors. First, some sectors could be national monopolies yet be subject to international competition: Is a sector a monopoly in a single country, or is it a monopoly internationally? These differences are pointed out in **Table 1**, columns 1 and 2.

Regarding externalities, there are two primary *negative* externalities across the nuclear industry: the proliferation of dual-use technologies for weapons and radioactive/hazardous waste. Proliferation risks exist at all stages of the nuclear fuel cycle. Some of the most significant proliferation risks are concentrated in knowledge and technology transfers, uranium enrichment, and fuel reprocessing activities. There is radioactive and/or hazardous waste produced in uranium mining, NPP generation, medical radioisotope production, Spent Nuclear Fuel (SNF) management (before geological disposal), and nuclear facility decommissioning that involves the decontamination and dismantling of the structures and equipment at a site. Depleted uranium from enrichment, as well as mixed

Table 1. Nuclear sector market failures.

Nuclear Market Failures	Natural Monopoly (National)	Natural Monopoly (Interntl.)	Negative Externality ("Bads")	Positive Externality ("Goods")	Public Goods (Non-rival)	Asymmetric Information (Safety)
(1) Advanced Nuclear Science R & D	No	No	Prolif.	Yes	Science	Release
(2) Uranium Mining and Milling	No	No	Waste	Few	Few	Hazards
(3) Uranium Conversion and Enrichment	Yes	Yes	Prolif.	Defense	Defense	Release
(4) Nuclear Fuel Fabrication	Yes	No	Few	Few	Few	Failure
(5) NPP manufacture and construction	Yes	No	Prolif.	Growth	Learning	Finance
(6) NPP electricity generation	Yes	No	Waste	Ancillary	Few	Accident
(7) Radioisotope generation and distribution	No	No	Waste	Health	Health	Release
(8) Spent Nuclear Fuel management	Yes	No	Waste	Few	Health	Myopia
(9) Nuclear Facilities Decommissioning	No	No	Waste	Site	Health	Release
(10) Low-Level Waste Management Facilities	No	No	Waste	Growth	Health	Release
(11) Spent Fuel Reprocessing and MOX	Yes	Yes	Prolif.	Few	Defense	Myopia

Accident: International Nuclear and Radiological Event Scale (INES) 4+; **Ancillary**: Provision of transmission services, such as grid stability; **Climate:** CO_2 emissions abatement; **Defense:** Provides for the defense of the nation; **Failure:** Failure of nuclear fuel; **Few**: Little to none; **Finance:** Asymmetric data in assessing financial risk; **Growth:** Economic and employment growth; **Hazards:** Hazardous waste produced, e.g., water pollution; **Health:** Use of nuclear medicine; **Learning**: Decline in construction cost and/or time; **Myopia:** Short-term discounting; **No**: No tendency toward monopoly; **Prolif.:** Proliferation risk of dual-use technologies; **Release:** Radioisotope release; **Science:** Basic science discoveries; **Site:** Release of the site for reuse; **Technology:** development of nuclear technologies based on nuclear science; **Waste:** Production of radioactive waste; and **Yes**: Tendency toward monopoly.

radioactive waste from reprocessing, can also pose a proliferation risk. However, it is more challenging to internalize (by determining a price for) proliferation externalities than to internalize (by creating a market for) waste externalities.

For example, the knowledge that a nuclear weapon was possible occurred with the first detonation in the US of a nuclear device on 16 July 1945 (AJLabs, 2023). The USSR detonated its first nuclear weapon on 29 August 1949. The UK detonated on 3 October 1952, France on 13 February 1960, China on 16 October 1964, India on 18 May 1974, Pakistan on 28 May 1998, and North Korea on 9 October 2006. It is possible that Israel, with the aid of South Africa, detonated a device ("Vela Incident") on 22 September 1979. India, Israel, and Pakistan have not signed the NPT. North Korea withdrew from the NPT in 2003.

There are also *positive* externalities such as (1) spinoffs from nuclear R&D into other industries, (2) strategic uses of advanced enrichment technology (e.g., lasers) in national defense, (3) economic growth from the expansion of NPP equipment manufacturing and construction (NEA/IAEA, 2018), (4) abatement of CO_2 emissions generated by fossil power plants by substitution of nuclear generation, and (5) health benefits discovered through the application of medical radioisotopes.

The public goods aspects of these sectors are similar to positive externalities.

However, again, positive externalities are *spinoffs* of a primary activity where there is a possibility of internalizing the externality by establishing a market. Parallel to these positive externalities, public goods characteristics abound in the nuclear sector: (1) advanced nuclear research provides for the discovery of fundamental laws of physics, and once these discoveries are known, their use is non-rival and non-exclusive, (2) enrichment and reprocessing capacity is a measure of a nation's independence to produce its nuclear fuel and avoid trade negotiations with political adversaries, a form of national defense, (3) the mitigation of climate effects due to carbon emissions abatement is global and non-rival, and (4) health benefits to radioisotope generation and distribution, safe disposal of radioactive waste, and health benefits by cleaning surrounding areas that were once nuclear production facilities; consider the East Tennessee Technology Park on the site of the decommissioned Oak Ridge Gaseous Diffusion Enrichment Plant.

Other examples of the public goods aspects of nuclear power are R&D programs, many of which began in the 1960s and 1970s, contributing (1) to diagnostic techniques using medical radioisotopes, (2) to radiation protection standards, and (3) to technologies for assessing the environmental impacts of nuclear industries. In the US, medical uses were pioneered within the system of national laboratories under contract with the US Atomic Energy Commission (AEC), the Energy Research and Development Administration (ERDA), or the US Department of Energy (DOE) as a part of federal investment in science to bring the benefits of nuclear applications to the public. Other medical applications have contributed to the treatment of Parkinson's disease, the preservation of blood cells for transfusion, and the introduction of small accelerators to produce short-lived radioisotopes for use in patients. US national laboratories produced many of these radioisotopes. However, the US AEC gradually transferred production to commercial suppliers while continuing to support research on new applications (US AEC, 1974: pp. 24-26).

Asymmetric information in nuclear industries heightens the importance of safety and security in every nuclear industrial sector. No national authority can monitor all the behaviors of its nation's nuclear actors (in particular, those engaged in international activities). The potential diversion of nuclear material poses one of the gravest threats to both physical safety and national security, and this can occur at multiple points throughout the life cycle of nuclear materials; for instance, material can be diverted from uranium enrichment processes, from devices that use radioisotopes, and from nuclear facilities.

Another aspect of asymmetric information applies to evaluating decisions that have costs and benefits beyond current generations (Thaler et al., 1997) because of the short-sightedness of our methodology for discounting future cash flows (i.e., we generally assume a 30-year time horizon because of 30-year mortgages and bond markets) when some radioactive waste requires sequestration and management for hundreds of years. As noted by Adam Smith (1776: p. 452), "The performance of this duty requires *two very different degrees of expence in the* *different periods of society*" (*emphasis added*). This myopia restricts markets from selecting optimal long-term disposal options. As with all aspects of the nuclear fuel cycle, there is an asymmetry of information between the present and the future in nuclear fuel management. It is difficult to imagine a market-based SNF management and disposal system. One reason is that current economic and financial reasoning is myopic when compared to the 10,000-year periods required to monitor SNF disposal. This myopia extends to national policies restricting the reuse of used nuclear fuel.

Regarding attempted monopolization in the nuclear power sectors, while many countries have centralized low-level radioactive waste (LLRW) facilities, the US Congress (1986) allowed the States to divide themselves into "Regional Compacts". See US NRC (2020). EnergySolutions, the owner of an LLRW facility in Utah (and the largest NPP decommissioning contractor in the US), attempted to merge with WCS (Waste Control Specialists), the owner of a facility in Texas. McDermott & McDermott (2017) summarize,

> "The US Department of Justice (DOJ) filed suit in November 2016 to enjoin the proposed acquisition of WCS by EnergySolutions, arguing that the merger would lead to a substantial lessening of competition in the LLRW disposal industry. DOJ alleged that EnergySolutions and WCS are the only significant competitors in this industry for the relevant geographic market… Judge Robinson identified two product markets: the disposal of higher-activity LLRW and the disposal of lower-activity LLRW. In both markets, she found that the relevant measures of concentration 'blow past the presumptive barriers' for harm to competition, especially in regard to higher-activity LLRW where the transaction would result in a 'merger to monopoly'."

Under modern economic policy, each one of these failures should be corrected to optimize social welfare. For example, recent efforts to eradicate global carbon emissions by 2050, paired with growing global energy demand, have increased international interest in low-carbon energy sources like nuclear power. To incentivize a shift to low-carbon energy sources, governments can levy taxes on greenhouse gas emissions, or if the electric utilities are state-owned, these utilities can subsidize the expansion of low-carbon generating assets financed by raising tariffs to customers. Also, under rate-of-return regulation, utilities can be issued certificates of public convenience and necessity to build low-carbon assets to enter their rate bases. Under a deregulated electricity market, there is no long-run guarantee that market prices will cover the cost of low-carbon generating assets, such as NPPs.

Hence, there needs to be more investment in nuclear assets that have public benefits. The problem of underinvesting in public assets was recognized in Smith (1776). Further, "It is essential to approach nuclear power in a political economy framework—the original discipline practiced by Adam Smith." (Cooper, 2017). In the context of these market failures, nuclear technologies are intrinsically *public works*, as defined by Adam Smith.

4. Role of the State in Nuclear Power Markets and the Nonproliferation of Nuclear Weapons

The question of explaining the motivations of a State as an *economic agent* has received less attention than explaining the motives of consumers or producers. An early tradition in welfare economics treated the State as if it had a welfare function on behalf of its citizens. However, there is no method of aggregating the preferences of individuals into an aggregate social welfare function that conforms to accepted neoclassical economic standards of rational individual choice (see "The General Impossibility Theorem" in Arrow, 1951). After Arrow, economists have tried to explain the behavior of the State as an economic agent independent of its citizens.

Economic theory does not explain motivations but seeks to explain behavior and social outcomes as functions of motives. When it comes to showing that a national policy was the result of an economic or a geopolitical motive, economics is useful only if the policy prescriptions arising from diverse private and public motivations can be shown to differ. In many cases of nuclear commerce and diplomacy, economic and political motives are aligned. In these cases, only historical research can shed light on policy motivations. A more recent example of this is the consummation of the US-India nuclear cooperation agreement (Mannully, 2008; Tellis, 2023). Both US economic interests and geopolitical alignment considerations favored this agreement, but which set of motivations was determinant? The legislative record is convoluted, involving extensive testimony and many votes on amendments to US Congressional bills. Hence, it is challenging to determine primary public and private motivations.

Regarding the economic theory of the State, in classical economics, for example, in Smith (1776: p. 452), the State had four responsibilities, as stated in Section 2 above. In neoclassical economics, the role of the State was extended such that it would assist the economy in achieving optimal resource allocation. With the development of macroeconomics (Keynes, Leontief, Friedman, and others), the management of the national economy has been added to the State's functions: to encourage business-cycle stability, to promote economic growth, and to manage the money supply and national debt. More recently, under the responsibility of optimal resource allocation, some regulatory functions in some countries have been given over to markets, but as NEA (2004: pp. 8-9) points out,

> "In privatizing and opening markets to competition, governments should make sure that they respect some basic principles. For markets, they have an ongoing responsibility to ensure fairness, access, transparency and effective regulation and to provide the public goods that markets may not otherwise deliver. Governments should ensure the security of supply through incentives or other means, guaranteeing that generating and transmission capacity and reserve margins are adequate and that the grid is effectively regulated to avoid blackouts."

On the other hand, at the foundation of preventing the negative externality of nuclear weapons proliferation is the right of all nations to pursue the peaceful use of atomic energy. According to the US State Department (2024),

> "The Treaty on the Non-Proliferation of Nuclear Weapons, more commonly known as the Non-Proliferation Treaty (NPT), has made the world safer and more prosperous for over fifty years. The NPT, with its three pillars of non-proliferation, disarmament, and peaceful uses of nuclear energy, is the cornerstone of the global nuclear nonproliferation regime."

Both national and supranational regulation is required to manage the proliferation risks of nuclear technologies. (As an example of supranational regulation, see Radavoi & Bian, 2014.) However, all signatories to the NPT have the right to engage in peaceful nuclear activities, provided they maintain nonproliferation standards. Trying to regulate nonproliferation with national institutions in a world of global nuclear markets is the economic reason behind the nonproliferation policy movement toward increasingly multi-lateral platforms for the formulation, execution, and enforcement of nonproliferation policy (Cupitt, 2021).

The NPT is not codified in international law but enforced through a set of safeguards (IAEA, 2024b) maintained by the inspection regime of the International Atomic Energy Agency (IAEA). Unfortunately, international law regarding the use of nuclear weapons is ambiguous. According to the "Advisory Opinion" of the International Court of Justice (ICJ, 1996) based on its interpretation of UN (1945), using or threatening to use nuclear weapons in "self-defense" is not against international law:

> "The Court then considered the question of the legality or illegality of the use of nuclear weapons in the light of the provisions of the [UN] Charter relating to the threat or use of force… at the same time, a use of force that was proportionate under the law of self-defence had, in order to be lawful, to meet the requirements of the law applicable in armed conflict, including, in particular, the principles and rules of humanitarian law. It pointed out that the notions of a 'threat' and 'use' of force within the meaning of Article 2, paragraph 4, of the Charter stood together in the sense that if the use of force itself in a given case was illegal—for whatever reason—the threat to use such force would likewise be illegal."

Articles I, II, III, and IV of the NPT (UN, 1968) read,

> "Article I: Each *nuclear-weapon* State Party to the Treaty undertakes not to transfer to any recipient whatsoever nuclear weapons or other nuclear explosive devices or control over such weapons or explosive devices directly or indirectly…"

> "Article II: Each *non-nuclear-weapon* State Party to the Treaty undertakes not to receive the transfer from any transferor whatsoever of nuclear weapons or other nuclear explosive devices or of control over such weapons or explosive devices directly or indirectly…"

"Article III. Each *non-nuclear-weapon* State Party to the Treaty undertakes to accept *safeguards*, as set forth in an agreement to be negotiated and concluded with the [IAEA] in accordance with the Statute of the [IAEA] and the Agency's *safeguards* system…"

"Article IV: Nothing in this Treaty shall be interpreted as affecting the inalienable right of all the Parties to the Treaty to develop research, production, and use of nuclear energy for peaceful purposes without discrimination and in conformity with Articles I and II of this Treaty." (*emphasis added*)

According to the IAEA (2024b),

"Safeguards are based on assessments of the correctness and completeness of a State's declared nuclear material and nuclear-related activities. Verification measures include on-site inspections, visits, and ongoing monitoring and evaluation. Basically, two sets of measures are carried out… One set relates to verifying State reports of declared nuclear material and activities… Another set adds measures to strengthen the IAEA's inspection capabilities. They include those incorporated in what is known as an 'Additional Protocol'—this is a legal document complementing comprehensive safeguards agreements."

Given these agreements, Moffatt (2019: p. 7) observed regarding the ICJ "Advisory Opinion",

"Viewed against the backdrop of the [ICJ] opinion on the legality of the threat or use of nuclear weapons, there is little reason to take measures directed towards complete nuclear disarmament, i.e., elimination, lightly. If it is international law itself and the 'stability of the international order' that are at stake, every initiative designed to 'end ... this state of affairs' deserves careful consideration."

President Eisenhower initiated the current state of affairs in his *Atoms for Peace* initiative in 1953, providing for the founding of the International Atomic Energy Agency to promote peaceful nuclear applications while facilitating international nuclear commerce with an accompanying system of controlled nuclear assistance and cooperation (Eisenhower, 1953). This expanded nuclear commerce also created opportunities to expand US influence through negotiations with recipients of Nuclear Cooperation Agreements with peaceful use assurances. Under US leadership, an international system to promote proliferation-resistant nuclear commerce evolved through many programs, including the IAEA Technical Cooperation Programme.

5. Evolution of Nuclear Power Technologies in the Context of International Treaties

After WWII, nuclear military applications were national efforts, leading to the development and demonstration of military technologies with State-Owned

Enterprises. The US made a deliberate decision to privatize civilian nuclear technology in the 1950s (WNA, 2020), but most other countries did not. Nationalized nuclear industries remain the standard model for much of the world. For instance, China, France, Russia, and South Korea together dominate NPP construction markets today, and they are all majority-owned by a government. One spillover of these free markets was the development of the nuclear power industry in the United Arab Emirates; see Rothwell & Wood (2024).

This poses one of the core questions for managing privatized nuclear technologies (Simeone, 2017): Can the privately held US nuclear industries compete with state-held competitors in international markets? Should the US government consolidate or nationalize nuclear sectors to address "chicken-and-egg" problems in nuclear investment (investment in high capital cost facilities before acquiring orders)?

Higher market concentration is often achieved by consolidating existing firms within a market segment (vertical integration in the supply chain) or across market segments (horizontal integration across the supply chain). These mechanisms have operated across national boundaries for over 75 years.

Table 2 shows how member countries of the OECD (Organisation for Economic Cooperation and Development), including South Korea, have done in the new NPP market with a mix of privately-owned and joint-stock NPP suppliers since 1995 (when there was no new construction started) compared to State Owned Enterprises in non-OECD countries (China, India, and Russia). Before 1995, the US Nuclear Steam Supply System manufacturers sold 112.6 GWs in Light Water Reactor (LWR) capacity to US electric utilities, 35.4 GWs to other OECD member countries, 5.9 GWs to non-OECD countries, and 500 Megawatts (MW) of Non-LWR capacity to all users. Other OECD and Non-OECD suppliers sold no capacity to the US before or after 1995. After 1995, US suppliers sold 11.8

Table 2. New nuclear power plant gigawatts (GWs) of capacity before and after 1995.

before 1995	US	Other OECD	Non-OECD*	Non-LWR	Total	Share
US	112.6	35.4	5.9	0.5	154.5	38.0%
Other OECD	0.0	144.1	7.3	35.5	186.9	45.9%
Non-OECD	0.0	12.4	34.1	19.0	65.5	16.1%
Total	112.60	191.93	47.35	55.01	406.88	100%
after 1995						
US	3.4	3.8	4.7	0.0	11.8	9.5%
Other OECD	0.0	26.7	11.9	0.0	38.6	31.0%
Non-OECD	0.0	0.0	68.0	6.4	74.4	59.6%
Total	3.40	30.46	84.55	6.40	124.80	100%

*Non-OECD is primarily the USSR/Russia before 1995 and Russia and China after 1995. Note: This includes units for construction, operation, and retirement. *Source*: IAEA (2024a).

GWs to US and foreign electric utilities (primarily Westinghouse AP1000s in the US and China). Non-OECD countries, such as China, India, and Russia, built 74.4 GWs of capacity worldwide. Although this is not a complete comparison of private-sector versus state-led nuclear programs, one can judge which group is now the most successful.

Traditional political economy and public choice theory treated a firm as an element of a *national* economy. Transnational linkages among private firms (joint ventures, acquisitions, and consolidation) have become increasingly common among North American, European, and Northeast Asian (Japan and South Korean) firms (Seward et al., 2013). A national government cannot adequately regulate consolidated firms. While some private firms continue operating their *production* within single countries, this is no longer the standard model for the nuclear industry outside China and Russia. Increasingly, transnational product markets and supply chains subject these firms to influence outside of the control of their host nations.

One solution to regulating multinational nuclear firms has been the Nuclear Suppliers Group (NSG), which shaped the existing international nuclear marketplace by setting supply conditions. With India's nuclear explosion in 1974 and growing concerns over planned transfers of sensitive fuel cycle technologies, the US and its allies led an effort to bring technology holders together to agree on guidelines for the supply of nuclear items and also to limit transfers of sensitive technologies.

Much of the nonproliferation policy revolves around the distinction between nuclear suppliers and buyers (in a transnational system of exporters and importers). This distinction is important from the perspective of describing requirements for managing proliferation risks from transfers of technology. However, it fails as a dichotomy for categorizing the roles of countries in international commerce. From the outset, the NSG has included suppliers and recipients, helping to enable nuclear commerce. As international nuclear commerce expanded with the energy crises in the 1970s, so did the expansion of political influence and economic benefits of the NSG. Many countries launched nuclear programs, some extremely ambitious: France and South Korea. According to Enia (2020: p. 385),

> "In a particular light, the Nuclear Suppliers Group (NSG) is a remarkable institution. Since 1974, member countries have voluntarily agreed to change their domestic laws, regulations, and procedures for exporting and/or importing nuclear materials and related dual-use technologies. These changes are not based on a specific NSG treaty nor a single set of procedures but instead on agreed-upon sets of guidelines and product lists. Countries change their own domestic institutions in order to meet the guidelines. The NSG has no enforcement mechanism… Why has this worked? In the trade of nuclear and dual-use technologies, countries have powerful economic incentives that would seem to push against voluntarily changing domestic regulations based on a relatively informal set of guidelines. The most obvious is the incentive

> to 'undercut' those abiding by the NSG guidelines and capture the market by selling and/or buying without concern for proliferation."

Efforts to strengthen restraints on sensitive nuclear exports have required a balance between nonproliferation and safeguards obligations and countries' efforts to exercise their NPT Article IV rights to access peaceful nuclear applications. One example of exercising Article IV rights was Brazil enriching uranium for its submarine program with limited IAEA inspections to guard Brazilian intellectual property (Cabrera-Palmer & Rothwell, 2008).

A clear case of divergent public and private interests is found in the uranium enrichment industry, which is not yet healthy enough to justify private investment either in new facilities, e.g., to manufacture high assay low-enriched uranium, HALEU. However, US reactors (and the US nuclear weapons manufacturing industry) have been the world's largest markets for enrichment. US energy security could benefit from US ownership of enrichment assets (with private operators under contract). Consider the US utilities conflicted situation (Rothwell, 2009: p. 141),

> "American electric utility demand can be supplied by Americans working at [the Urenco plant in New Mexico] and by the Russians through the extension of current contracts. Therefore, while it is not in the American electric utilities' interest to support USEC's high prices, it could be in their interest to support the existence of the USEC as a hedge against dependence on one or two suppliers."

The *Energy Policy Act of 1992* (EPAct, Public Law No. 102-486) established the US Enrichment Corporation (USEC) as a federally owned enterprise to enrich uranium for NPPs (NRRI, 1993):

> "EPAct provides strong support for nuclear power technologies. First, it authorizes funding for developing advanced nuclear reactors and streamlines the nuclear power plant licensing process. Second, the Act attempts to expedite the resolution of the contentious issue of high-level nuclear waste disposal… other provisions that affect the nuclear industry include the creation of a new corporation to operate uranium enrichment facilities, the establishment of a fund to finance the decommissioning of existing nuclear plants, and support for domestic uranium mining and export."[4]

The gaseous diffusion plants, previously owned by the State-Owned Enterprise, US Uranium Enrichment Enterprise, began operations under USEC management in 1993. These aging enrichment assets were fully privatized by 1998. Unable to compete with centrifuge enrichment, USEC gaseous diffusion plants slowly

[4]Compare with Sidley (2024), "On June 18, 2024, the U.S. Senate passed the *Accelerating Deployment of Versatile, Advanced Nuclear for Clean Energy* (ADVANCE) *Act* to accelerate the deployment of nuclear energy capacity, including by accelerating the licensing and creating new incentives for advanced nuclear reactor technologies, among them small modular reactors." Thus, after 32 years, the issues of licensing advanced reactors and SNF disposal remain.

became technically obsolete with increases in the electricity prices to power them. USEC announced its bankruptcy in 2014. Uranium enrichment is now dominated by national firms (Russia and France) and a transnational firm, Urenco, which is owned and managed by the Netherlands, the UK, and two German electric utilities hold the German share of Urenco. Urenco owns the only operating enrichment plant in the US.

The company that emerged from the USEC bankruptcy was Centrus Energy Corporation, which had the primary mission of producing HALEU fuel with the next generation of American centrifuge technology for the next generation of American advanced reactors. If Centrus can produce HALEU, Framatome is willing to fabricate fuel for advanced reactors, such as for the Terra Power plant in Wyoming, provided they can commit the necessary capital (WNN, 2024a):

> "A HALEU fuel cycle will need new enrichment facilities, transportation solutions, and conversion and deconversion facilities, but without a clear demand signal, private fuel cycle companies cannot commit the required capital to build out the necessary infrastructure. This led to what has been described as a 'chicken and egg' problem, threatening to delay the deployment of advanced reactors and small modular reactors."

HALEU is central to the deployment of advanced nuclear technologies. Given the previous US Uranium Enrichment Enterprise, one could conclude that a primary public duty of the US DOE is to assure HALEU capacity, including the possibility of direct federal government investment in supplying HALEU. WNN (2024b) announced that DOE had selected six potential HALEU enrichment providers. Currently, the only commercial producer of HALEU is TENEX, a Rosatom (Russian State-Owned Enterprise) subsidiary. Regarding late 2024 US DOE LEU and HALEU contracts, Daton (2024) writes,

> "The US Department of Energy said on 10 December it is offering initial contracts to six companies to produce low-enriched uranium (LEU) fuel for conventional nuclear plants to generate electricity… The move is part of US efforts to kick-start a domestic uranium fuel supply chain to reduce dependence on Russia, from which US reactors have been getting about 25% of their enriched uranium in recent years… Four of the six companies were awarded initial contracts in October to produce… HALEU to be used in advanced reactors. The four were American Centrifuge Operating, General Matter, Louisiana Energy Services, and Orano Federal Services… Funds to make the fuel domestically in the US were included in a May 2024 law to ban uranium shipments from Russia by 2028 [Public Law No: 118-62]."

6. Conclusion

The distinction between private and public interests is critical in characterizing progress in nuclear technology and the evolution of markets in which these technologies are traded. Both civilian nuclear power technology and technology for peaceful uses began in national research institutes and national defense programs. This origin was common to all countries in which the technology developed.

Based on the history of economic thought, nuclear technology is *intrinsically public* in that its average production costs are continuously declining, its use generates both positive and negative externalities, there are public goods properties in most sectors, and safety is always an issue. It is possible to produce aspects of this technology for civilian use in the private sector. The US made a deliberate decision to adopt this private industry model in the early phases of nuclear technology development, and private firms have been in the US-dominated global markets for decades. By sharing the Westinghouse PWR technology, first with France (with the 3-steam generator reactors in the *Contrat Programme CP0*, *CP1*, and *CP2* series) and later with others, e.g., China (first through France, then with the Westinghouse Advanced Passive AP1000) and South Korea (with the Combustion Engineering System 80, then owned by Westinghouse, to design and build the "Optimized Power Reactor", OPR1000, and the Advanced PWR APR1400), US firms enabled the transfer of peaceful nuclear goods and services while also enabling the birth and growth of international competitors.

The current circumstances for the US nuclear industry reflect competition from nationalized industries in Russia and China. Rothwell (2024) shows how China absorbed and enhanced Western reactor technology. Russia focused on updating its low-cost pressurized water reactor inherited from the Soviet Union. US firms (including branches of Westinghouse and General Electric) have no market power to increase their profits in reactor markets based on plants under construction. On the other hand, many of the NPPs in operation use US maintenance services and/or nuclear fuel services. US firms hold patents for world-class nuclear technologies for light-water reactor systems, but these are no longer exclusive to the US when these technologies have been sold or licensed to foreign suppliers by private firms. State-Owned Enterprises and research institutes in China and South Korea (Smith's "publick works" and "publick institutions") have aggressively developed, demonstrated, and deployed technologies to replace US patents.

While US firms do hold significant shares of the fuel and services markets and hold leading technologies in nuclear medicine and other peaceful uses, these markets are also becoming more competitive. Further, the US nuclear industry needs to have the required profits to reinvest in the US reactor supply chain (Kimani, 2024). The return on new investments carries substantial risk. If US reactor suppliers are going to be globally competitive and influential in the nonproliferation policy debate, public investment in the nuclear power industry is required, particularly in the US and Western Europe.

Even if market incentives are not sufficient to restore the US nuclear industry to a position of global leadership as a reactor supplier, public investment in the US industry, if aggressive in magnitude and timing, could do much to build US credibility as a supplier. Beyond the reactor supply market, other opportunities for leadership and continued nonproliferation influence exist. Leadership as a fuel supplier gives significant leverage in terms of control of fissile materials. Leadership in the use of nuclear medical and industrial technologies involves an extensive network of international contacts and contracts, providing a source of influence. Funding elements of the nonproliferation regime, especially extraordinary contributions that recognize the value of nonproliferation to all nations, is a direct source of international influence.

The US nuclear power industry is facing an aging crisis. Privatization of many sectors of the industry led to rapid growth before the Three Mile Island-Unit 2 accident in 1979. However, with privatization came sales of nuclear technologies to foreign State-Owned Enterprises, which are now undercutting prices of US suppliers: the Chinese Hualong One NPP is much cheaper than the AP1000 NPP. Demand for low-carbon electricity will grow dramatically with the introduction of artificial intelligent data centers (IEA, 2024) and the electrification of transportation. It is time to rethink the structure of the US nuclear power industry to prepare for a massive demand increase in no-carbon electricity while maintaining strong nuclear safety, security, and nonproliferation standards. This is a clear example of a public good that "*may be in the highest degree advantageous to a great society*" (Smith, 1776: p. 452).

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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