2021

Evaluating Nuclear Energy as a Component of U.S. Energy Innovation Systems

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Evaluating Nuclear Energy as a Component of U.S. Energy Innovation Systems

A Thesis

Presented to

the Faculty of the College of Arts, Humanities and Social Sciences

University of Denver

In Partial Fulfillment

of the Requirements for the Degree

Master of Arts

by

Bryce Jones

August 2021

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Title: Evaluating Nuclear Energy as a Component of U.S. Energy Innovation Systems
Advisor: Henning Schwardt
Degree Date: August 2021

Abstract

Nuclear energy is contentious in policy discussions that evaluate its role in the current U.S. clean energy innovation system. OECD nations, on average, have begun to reduce their dependence on nuclear energy. However, the United States has remained invested in its nuclear energy infrastructure and the role that it plays within federal research and development. This thesis examines the Neo-Schumpeterian perspective and the National Innovation System's approach, the economic history of nuclear energy in the United States, and given insight from these factors, discusses the current role of nuclear energy in the U.S. energy innovation system. The objective is to determine if omitting nuclear energy's role in U.S. energy from policy analysis is beneficial in the national innovation systems evaluation of the green industrial revolution or if its exclusion ignores potential path developments for a low carbon future.

Acknowledgments

The amount of support and care from my wife and my parents while I have been in graduate school has been immeasurable. I must also thank my advisor, Dr. Schwardt, for the guidance he has provided me through coursework and through reviews of drafts for the thesis. My gratitude also extends to my committee as I must thank Dr. Piovani and Dr. Schneider for their time and insight. The entirety of the DU Economics Faculty and staff have been crucial mentors to me throughout my academic journey, and I deeply appreciate the amount of support and opportunities provided to me through this program.

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Chapter One: Introduction

Climate change is a grand issue facing modern society, and to address it “The current global industrial system must be radically transformed into one that is environmentally sustainable. Sustainability will require an energy transition that places non-polluting clean energy technologies at the fore. It moves us away from dependence on finite fossil and nuclear fuels and favors ‘infinite’ sources of fuel.” (Mazucatto, 2015) This definite exclusion of nuclear energy initially surprised me upon reading “The Entrepreneurial State” as most climate policy discussions almost solely consider emissions instead of including other environmental issues. Mazucatto later states that “It [Climate Change] is also an issue that can be partially ‘solved’ with the aid of non-renewable technologies like nuclear… is that really what we want?” (Mazucatto, 2015).

But is excluding nuclear from analysis of the U.S. energy innovation system and its response to climate change beneficial, or are we missing out on better understanding a potential path development outcome? The objective here is not to definitively state that nuclear energy is the “winner” of future low-carbon energy. Instead, the focus here is to evaluate nuclear energy as a component of clean energy that has a lot of unique characteristics. Identifying potential possibilities and valuing variety in production are defining characteristics of the National Innovation Systems approach. Arguably, an abrupt and blatant exclusion of nuclear energy from the U.S. energy innovation system is counterintuitive to an evolutionary approach as under fundamental uncertainty, it is impossible to pick sole winners and losers. Rather, the question to ask is if nuclear energy is a variety in energy production that is justified if de-carbonization is the prime objective.

To answer if excluding nuclear from innovation policy analysis is justified, Chapter Two will examine the traditional economic approach to technology and the traditional role of government. Understanding these features is critical, as it will become apparent the policy suggestions of this approach have little to nothing to offer in guiding policy making. Chapter Three will introduce the neo-Schumpeterian perspective and the National Innovation Systems approach, which will provide an alternative framework to the neoclassical models which permit innovative mission-based policy to be placed at the forefront. Chapter Four provided a brief overview of the economic history of nuclear energy in the United States, which is foundational to analyzing its current role in the U.S. National Energy Innovation System as it permits us to see past technological lock-ins that have pushed nuclear onto a sub-optimal path. Chapter Five will then analyze the current nuclear energy technological innovation system and will evaluate the nuclear programs within ARPA-E to determine if the current mission-based approach to pursue low-carbon technologies in the DOE is truly pursuing potentially radically innovative approaches, or if nuclear is being included as an appeal to ceremony.

Chapter Two: The Neo-Schumpeterian Perspective and the National Innovation Systems Approach; an Overview

An Introduction to Neo-Schumpeterian Approaches

While the Neoclassical approach has included technology exogenously and has attempted to endogenize technology, an alternative approach is needed. Solow’s neoclassical growth models simply interpret the error term of growth as technological progress. This is problematic as it fails to remove technology from the black box and offers no answer to what makes one society more technologically creative than another. These models identify that total factor productivity (their interpretation of technological growth) is the greatest driver of growth. But this leaves little to nothing for the role of policy, as the long-run government action only creates distortions in the equilibrium path of GDP growth.

In contrast, Schumpeter’s viewpoint places technological progress at the dynamic center of economics. Technological change's unique aspects, its unevenness and discontinuity across space and time, and its lack of predictability made innovation the primary factor of disequilibrium in the economic system. However, the way Schumpeter evaluated technological progress changed drastically throughout his life. These changes are substantial enough to warrant analyzing his earlier work and later work as being written by almost entirely different authors (often referred to as Schumpeter Mark-1 and Schumpeter Mark-2 in neo-Schumpeterian literature). In Schumpeter's original work, such as Business Cycles, innovation takes a rather romantic formulation that he contrasted with the neoclassical perfectly informed, rational representative agents that were able to make Pareto efficient decisions on the rate of return on their future investments with his own two forms of agents. The first form of agent, being the entrepreneur, doesn't have a crystal ball to see into the future but is capable and willing to engage the challenges of innovation as an 'act of will.' The second form of agent, being a large group called imitators, were simply managers that appealed to ceremonies (whether they be production methods, management structures, or some other form of institution) established by the entrepreneurs of society (Freeman 1995).

The Schumpeterian perspective that inspired an evolutionary economic approach that places technological change and innovation at the forefront began to gain momentum during the 1970s and 1980s as the growth of Information and Communications Technologies brought a significant increase in technological and scientific change that was enhanced by the emergence and diffusion of ICT technologies. Bringing innovation and technology to the center of economic analysis and theory allows the Neo-Schumpeterian approach to fill a critical gap left behind from orthodox economic theory. For the first time within economics, it gives a range of systematic analyses, theories, and evidence about the multifaceted complexity revolving around technological change. Christopher Freeman, Nathan Rosenberg, Richard Nelson, Sidney Winter, alongside numerous other influential economists, established research institutes such as the Science Policy Research Unit and the Maastricht Economic Research on Innovation and Technology that provided a bedrock for this approach. The Neo-Schumpeterian research area has exponentially expanded over the last few decades. It primarily seeks to: remove technology from the "black box" by investigating the procedures, identify sources that are conducive to innovative activities, and finding technological and innovation data that can provide appropriate indicators necessary for empirical research and policy analysis, evaluating how technology and innovation affect the performance of economic variables at various levels of aggregation, utilizing the empirical contributions and lessons gained from the above approaches to guide practical policymaking (Lundvall, 2007).

Within the Neo-Schumpeterian approach, technology and innovation are the actual substance of economic and structural change and drive the beginning and end of firms, markets, and industries. Technology and innovation are also the factors that primarily drive economic growth. However, the approach differentiates from Schumpeter in conceptualizing and analyzing creative destruction by dissolving analysis into the micro, meso, and macro levels; introducing differentiation across time by discerning short- and long-term processes of technological change; and placing greater weight on the forms of actors such as firms, industries, and national systems of innovation.

National Innovation Systems: An Overview

Innovation Systems emphasizes the systemic nature of technological change and highlights the linkages and interaction across various actors involved in the creation and diffusion of new technologies. Within this framework, innovation is an outcome that arises from the systemic interactions, knowledge flows, and reliance upon similar technology within and between various actors, firms, industries, and public/private technological and scientific institutions. This viewpoint generates a National Systems of Innovation approach that identifies that nations each adopt their own unique institutional mixes for creating environments conducive to innovation and that each of these mixes has different historically determined industrial structures and cultural contexts (Evangelista, 2018).

An innovation systems framework can be thought of as a practical method for describing and mapping innovation programs and agencies at the regional and national levels. Creativity does not appear out of the blue or from the imagination of a single entrepreneur. Instead, innovation is described as a series of interactions in which various organizations and individuals pool their resources to create, disseminate, and apply information. The diffusion of specific competencies among agents and organizations, as well as the institutions that shape competition, communication, and cooperation, will be reflected in the division of labor and the form of collaboration.

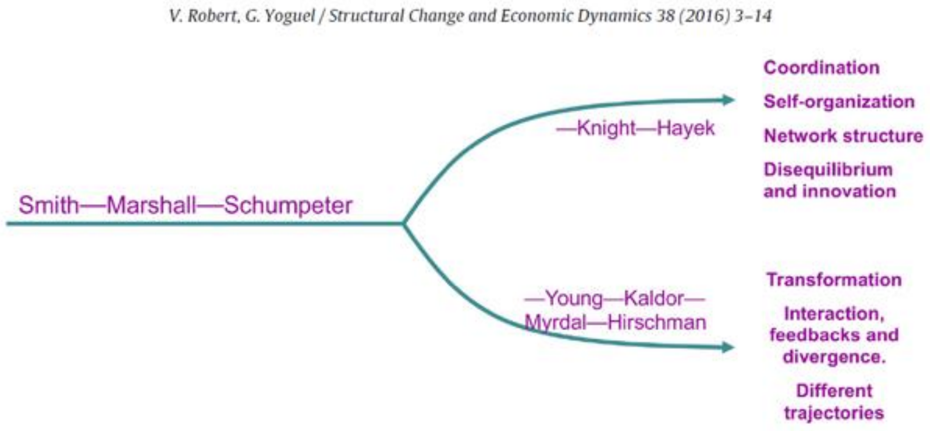
V. Robert, G. Yoguel / Structural Change and Economic Dynamics 38 (2016) 3–14

Figure 1: Two Alternative Paths of Complexity in Economic Thinking Source: Yoguel, Robert (2016)

. The systemic nature of innovation and the learning process generates a historically embedded, interdisciplinary approach that emphasizes the centrality of institutions, interdependence, and non-linearity. Since innovation systems emphasizes the differences between systems and how they generate divergent paths, they also explain the mechanisms to which systems at different degrees of aggregation can diverge. How firms interact within their institutional environment creates different dynamics within economic aggregates, which naturally generates research interests in structural change and development policies since productive and trade specializations generate dynamics in technological learning across various levels of aggregation. Innovation systems is not a cookbook for picking winning innovation policies but is rather a methodology that recognizes and explains the heterogeneity and divergence between different institutional mixes and innovation systems. Innovation Systems inspired policy focuses on generating feedbacks and interactions between components of the system (I.e., ensuring that learning can be extended from the local to regional level and regional to local level) (Robert, Yoguel, 2016).

The evolutionary approach diverges from the dull, static unique equilibrium of the neoclassical models by abandoning the presumption of diminishing returns by instead introducing dynamic increasing returns to scale. What enables increasing returns to scales are learning dynamics, specifically the capacity for agents to learn by doing. History is another factor permitting increasing returns to scale, as past choices influence paths taken in technological development. The rightful abandonment of the representative agents permits divergence in processes adopted by firms, which do not disappear in the long run. Therefore, with these factors, it doesn’t necessitate that the strongest firms necessarily survive since first move advantages on increasing returns technologies and the effects of policies that enable certain forms of technologies and firms over others can create a technological lock-in (Mazzucato, 2015).

Evaluating innovation within a system is useful since it transcends placing research and development as the start of the causal chain that generates increasing productivity, with the level of productivity gain being dependent upon innovation and diffusion. It is important to note that specific elements of systems of innovation are deliberately established by an actor, such as the state. Nuclear energy is a clear example since, as will become apparent in the next chapter, it is highly unlikely that nuclear energy would have become an industry at all without the state.

The approach diverges from the neoclassical tradition's linear innovation process, in which science leads to technology that meets consumer needs. The linear approach suggests that commercial R&D is applied science, with a gradual and unidirectional transition from basic research to commercial implementation. Feedback has no role within the neoclassical interpretation of the innovation process, which is clearly counterfactual to the real world. The linear innovation interpretation exists to create justifications for public support of industrial R&D and to justify subsidies and basic research investment in an externality correcting context. This methodology fails to define the amount of government intervention required to correct an externality, let alone the sort of intervention required for the specific fields of the innovation process that must be addressed to fix the externality. The linear perspective ignores the flaws and failures that occur throughout learning that create radical and incremental innovations. Because basic research does not always lead to commercial innovation, the linear viewpoint equating commercial R&D to applied science is problematic. When issues occur during the testing and design phase of a new product, new processes are often developed, which leads to new research and, in some cases, new mathematical disciplines. The potential for disconnect between technological progression and science, as well as the equation of commercial R&D and applied science, identify clear divergences from the linear neoclassical approach and the necessity of an evolutionary system-oriented perspective (Edquist, 1999).

Innovation systems can be viewed as the result of a different type of abstraction than that employed by neoclassical economics. The most fundamental distinction is a dual change in emphasis from allocation to creativity, as well as from rational choice to learning. Innovation is critical for economic performance in the global economy at both the firm and regional levels. Firms that allocate in a Pareto-efficient manner but continue to produce the same commodity using the same process technologies year after year are doomed to fail. As a result, focusing on creativity is almost as legitimate as focusing on allocation. Agents in this form of a learning economy are continuously exposed to quick and frequent changes where the capability of institutions and agents to learn and shift to ever-changing conditions becomes the condition for success. Processes such as production, development, and trade are arenas where agents have the capacity to learn and increase their competencies in decision making (Edquist, 1999).

The primary factor for why neo-classical economics fails to give attention to innovation and instead favors allocation is that their mathematical models and tools are applied with the most efficacy to allocation. They ignore the differences in competence across agents and favor representative agents with rational expectations since the introduction of learning strains the static tools they hark determine our profession's “scientific” quality. But this view of what is treated as scientific gets conflated with what instead can be numericized, which leads to the acceptance of “arithmo-morphic” ideas as scientific but rejecting those that are dialectic (Roegen, 1971). Certainly, this is not to say that allocation and decision making do not have importance, but rather focusing on innovation and learning permits us to utilize a different lens, the innovation system, to unveil what remains hidden within the neo-classical tradition (Lundvall, 2007).

Four Different Perspectives in Economic Analysis		
Perspective	**Allocation**	**Innovation**
Choice Making	Standard Neo-Classical	Management of Innovation
Learning	Austrian Economics	Innovation Systems

Table 1: Four Different Perspectives in Economic Analysis Lundvall(2007)

In summary, the innovation system approach has nine broad characteristics. First, innovation and learning processes are at the heart of the analysis because technological process is a learning process in the broadest sense. Innovation is a practice of creating new knowledge or combining existing aspects of knowledge in new ways, technological innovation can be thought of as a learning process. The holistic and interdisciplinary nature of the approach is also noteworthy. It is holistic to attempt to identify a broad range of all determinants of innovation and it is interdisciplinary in the sense that each determinant can include both economic and non-economic factors such as organizational, social, and political characteristics. The evolutionary influence and the influence of feedback processes create historical roots for the Innovation Systems approach. Understanding path dependencies and technological lock-ins necessitate an evaluation of the evolution of innovation, institutions, knowledge, and organizations. In addition, rather than comparing real systems to ideal systems, innovation systems compare existing systems to each other in order to gain understanding of the sources of successful innovation policy. Interdependence and non-linearity within the innovation process is heavily emphasized since firms often work closely with other institutions through a complex set of relations that are characterized by numerous feedback loops and by reciprocity. These interactions take place within unique institutional mixes characterized by unique laws, norms, and cultural habits, implying that technological advancement is influenced not just by the elements within a system but also by the relationships between them. Since it is important to create a distinct idea of innovation rather than a neoclassical assessment that is primarily focused on process developments of a technological nature, product technologies and organizational innovation are included in the systems of innovation approach. Also, institutions are crucial in this context because they are required to comprehend the social patterns of innovation activity, especially its path-dependent characteristics, as well as the roles played by law, norms, and other factors. (Edquist, 1999)

National Innovation Systems and Policy Making

The systems of innovation approach's evolutionary design places organizations and learning processes at the center of attention, which has important policy implications. The level detail required to establish a public policy that is conducive to creativity is far higher than in the neoclassical linear model. Policy must create cooperative interactions within a framework capable of accurately detecting emerging technical or economic opportunities while also allowing for the emergence of new ones. As a result, the approach of assessing a policy's effectiveness changes to the degree to which the policy can generate creative opportunities. Due to the potential for feedbacks and multiple equilibria, alternative directions for innovation have to be assessed in order to avoid singularly locking into one technology or indiscriminately supporting every technology. Criteria such as the impacts that a given technology's innovation has on economic growth and employment while aiding the formation of novelty need to be made explicit in their economic and technological dimensions in fostering innovation to begin a trend toward better-informed innovation policy-making (Edquist, 1999).

Figure 3 located five of the evolutionary neo-Schumpeterian groups, as defined by Robert and Yoguel (2016), onto a graph where the Y-axis is a categorical variable where each strand is either part of the 1st path or 2nd path of the graph in figure one. The X-axis describes whether each group emphasizes top-down or bottom-up policy designs. From a theoretical perspective, this graph identifies tensions such as the debate between vertical and horizontal policies, mission-based versus diffusion-oriented policies, and public good

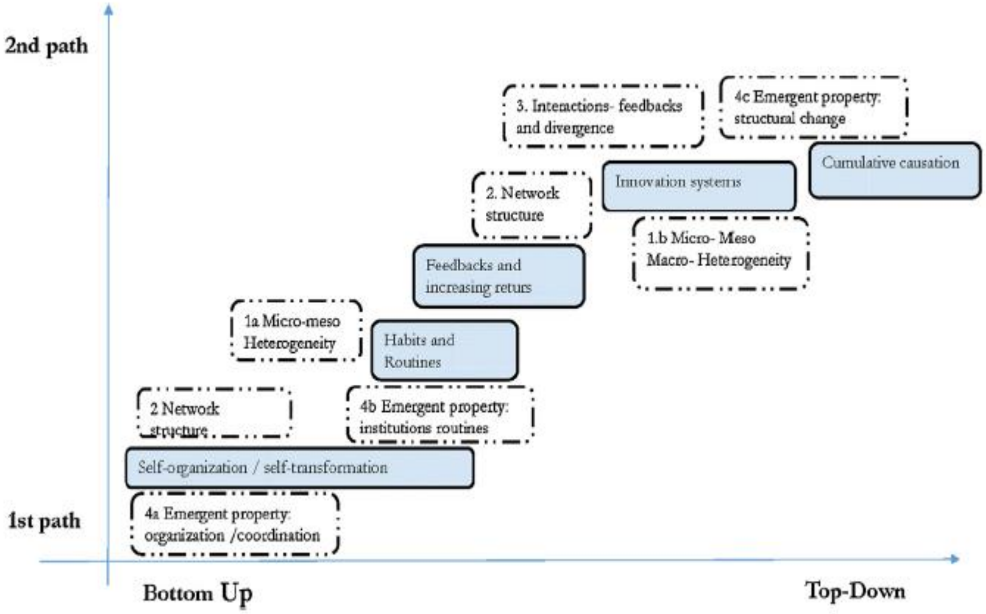

Figure 2 The relationship between the two traditions of complexity in economic history and the five groups of evolutionary economics. Source: (Robert and Yoguel, 2016)

provision vs. externality correcting interventions. Top-Down policies as those that are mission-oriented that are not aimed at solving a unique market failure but instead create variety within the productive structure. This is not to say that top-down policies cannot generate public goods, as policies such as massive professional training programs fit the bill of being a top-down policy aimed at public good provision. Top-down policies induce processes that create structural change while bottom-up policies aim to solve a market failure or provide a public good.

Top-down policies recognize that the currently emerging structure is not guaranteed to be favorable to economic development. Consequently, interventions should not only be viewed from a bottom-up aspect but primarily through top-down policies whose concentration is on defining current technological and productive specialization factors and identifying the potential driver sectors for the form of economic development desired. The identification process for potential driver sectors ranges within the literature base, from "finding windows of opportunity (Pérez, 2010; Dosi, 1982), choosing sectors with increasing returns (Dosi et al., 1990; Reinert, 2007), focusing on short cycle technologies (Lee, 2013), to prioritizing the manufacture and production of capital goods (Rosenberg, 1963; Pisano and Shih, 2009), among others"(Robert and Yoguel, 2016). And while the NSI approach with its historical tradition often aims to discuss specializations in modes of production, they also identify the role of evolutionary dynamism in structural change (Robert and Yoguel, 2016).

Chris Freeman, one of the founders of the National Innovation Systems approach, recognized that "the policies promoted by List in his development of the concept of National System of Innovation advocated not only for the protection of infant industries but a broad range of policies designed to accelerate, or to make possible, industrialization and economic growth"(Robert and Yoguel, 2016). This places value in a policy's ability to facilitate learning about new technologies and the best way to apply them. Borrowing from Latin American Structuralism, Robert and Yoguel make it clear that

> structural change is, by definition, a process of qualitative change, which does not emerge spontaneously from the smooth accumulation of factors of production. In this sense the evidence confirms what the literature on comparative development has already pointed out, namely the key role played by the industrial and technological policies in picking up a dynamic growth path among the various alternative paths.

These top-down policies promote mission-oriented interventions have a goal of a specialization profile that is conducive to economic development by promoting policies that promote sector selection (Robert and Yoguel, 2016).

The focus upon top-down policies here is not to entirely discredit the role of bottom-down policy solutions. The evolutionary dynamic is generated from the interactions of individual agents, but those actions are impacted by macro and meso structural conditions and institutions that can limit their behaviors and capacities to learn. An example of this is when "intervention is necessary to change specialization trade profile in order to avoid lock-in situations while simultaneously developing capacities to increase the generation of variety, which in turn improves the innovative capacity of the system."(Robert and Yoguel, 2016). Structural change policy is able to be enhanced if we no longer solely focus on improvements in the firm's competitive processes but by also introducing a focus on the selection process of technologically progressive sectors (Robert, Yoguel, 2016).

It would be false to state that there is a direct antinomy between mission and diffusion-oriented policies. However, the remainder of policy focus within this thesis will focus upon mission-oriented policies**.** To evaluate the conduciveness of mission-based policy, Mazucatto (2020) creates a policy framework for public sector actions that aim to shape market activities by seeing if they answer R.O.A.R:

1. Route of directionality: A policy's capacity to set the market onto the objective (objectivity here as a coherence to a defined mission statement) direction and route of change, which answers if a policy is engaging in market creation or merely market tinkering.
2. Organizations: To ensure that public organizations are capable of addressing contemporary challenges, we must identify how public entities are structured regarding their capacity to manage risk-taking and to engage in exploration.
3. Assessment: Instead of solely relying on static cost/benefit analyses, what new dynamic indicators and evaluation tools can be used to assess policy making?
4. Risks and Rewards: This criterion focuses on ensuring that the evaluation framework generates inclusive growth by asking if a public investment into the innovation chain doesn't just socialize risk but socializes reward.

In chapter four, I will more discretely apply this framework to ARPA-E and its nuclear projects in order to evaluate if nuclear energy is a valuable variety of production if de-carbonization is a primary goal for the U.S. energy innovation system.

Chapter Three: An Economic History of U.S. Nuclear Energy and Path Dependency

Nuclear Energy's Inception: Atomic Energy Commission and the Navy

Nuclear Power is a technology that, without substantial military and defense-related research, would not exist. The Manhattan Project was created to produce the atomic bomb and was a major institutional innovation during WWII as it marked a change from the public armory system to the private contractor system in the creation ofweapons and created a switch to "big science" in the mobilization of scientific resources into mission-based research and development policy. The project's divergence in the scope of the government's role in technology and science was not the only thing radical about the project, as the cost by July of 1945 had grown to approximately two billion dollars (about thirty billion dollars valued in 2020). To properly evaluate the level of complexity and depth of the project and its results would necessitate a book. But, for the purposes of this chapter, the policies and institutions created after the project serve as the primary focus.

After WWII, the U.S. Atomic Energy Commission was given the authority to regulate and promote the creation of military and non-military nuclear technology, meaning that the infrastructure utilized to initially support the work of the Manhattan Project were now under their supervision. There was initially a lack of enthusiasm from the AEC and the power industry on the prospects of nuclear power environment. In 1951, the director of Reactor Development at the AEC wrote “the cost of a nuclear power plant is essentially unknown. We have never designed, much less built and operated, a reactor intended to deliver significant amounts of power economically.” (Cowan, 1990).

Initially, most of the AEC’s labs' focus was on the development of weapons, and firms were concerned about the long-run potential of access to an adequate uranium supply and the relative level of secrecy constraints imposed by the government. However, the AEC was able to diminish concerns on uranium supply by initiating a uranium exploration and procurement program that, by the early 1950s, alleviated concerns on the availability of uranium for power. Subsequently, Dwight D. Eisenhower gave a pivotal “Atoms for Peace” speech that inevitably committed the United States to a more engaged role in commercial nuclear power.

The pre-commercialization era of nuclear energy in the United States marked a period of several different reactor designs. How nuclear reactors are classified is by the coolant that is used to transfer heat from the core of the reactor and the moderator used to control neutron energy levels in the reactor core. There was the light-water reactor that used water as both the moderator and coolant for the reactor. There is a heavy water reactor where both the coolant and moderator are heavy water D20. There was also the graphite reactor where gaseous helium or carbon dioxide is used as a coolant while graphite is the moderator (Cowan, 1990). But the early developments for nuclear power were like a multiarmed bandit, where many arms seem feasible, but there is uncertainty about the payoffs of any of them, and resources can be allocated to reduce this uncertainty. The AEC in the forties and early fifties were engaged in numerous reactor projects. While the only project aimed specifically at civilian power was GE’s intermediate breeder reactor, the light water, liquid-metal-cooled, graphite-moderated, aqueous homogenous, and fast breeder reactors each were important to the development of the commercial reactor. Between 1951 and 1953, a group of firms chose four of the AEC reactor technologies to analyze for further development. What was determined is that economically competitive nuclear electricity was a way off, but that under the current development process of the various reactor designs, the light water reactor was argued to be the cheapest to produce electricity. These cost estimates, however, differed from cost estimates presented at the first Geneva conference in 1955. At this conference, it was concluded that the gas graphite reactors were by far the cheapest method to produce electricity at 4.7 mills per kWh, whereas the lowest cost estimate for the light water reactor design was 14.7 mills per kWh.

The light-water cooling and enriched uranium design prevailed in the United States, primarily due to influence from naval research. Britain and France initially used gas graphite reactors, and Canada opted into using heavy water and natural uranium. By the mid-1960s, the world's major industrial nations were making significant nuclear energy investments. Construction experience from past military research led to improved reactor designs, which embedded the industry onto a light-water technological development path in the United States. Specifically, a driving factor in the light-water reactor development path was the existence of uranium-enrichment facilities left over from atomic weapons programs. Without these enriched-uranium facilities, it is very doubtful that the light water reactor design would have been the design of choice or a serious contender compared to other reactor designs that utilized natural uranium (Pool, 1997). It is clear in this situation that in regard to path dependency, economic factors were being treated as a secondary concern of strategic considerations.

Eisenhower's "Atoms for Peace" speech inspired congress to pass the Atomic Energy Act of 1954 which established statute for private sector development of nuclear technology as well as the ability to cooperate with other nations on creating "peaceful uses" of nuclear technology. By January 1955, the AEC announced its first round of the Power Reactor Demonstration program with the hope of generating R&D information and increasing commercial interest in creating nuclear power plants. The government offered funding to four projects, the Yankee pressurized water reactor, the Fermi fast breeder reactor, the Hallam sodium cool reactor, the graphite-moderated reactor, and (through private funding) the Dresden boiling water reactor. In 1962 there were seven commercial nuclear power prototypes in operation, each with the objective of generating enthusiasm in the general public, power industry, and Congress about the potential of nuclear power. At the time, nuclear power fanatics hyped that nuclear energy would soon make power so inexpensive "that it would become too cheap to meter" (Pool, 1997). But, of the three projects, only the Yankee light water reactor could be deemed a success, drawing largely from the previous extensive development and testing within the Navy's submarine propulsion programs. Furthermore, at the time the Power Demonstration Project was announced, the AEC had already begun cooperation with Westinghouse and Duquesne Light and power to build a light water reactor in Shippingport, Pennsylvania. The Fermi and Hallam reactors were still in too early of development stages, being experimentally feasible but not commercially for the United States (Ruttan, 2006).

By the mid-1970s, restrictions by the AEC on uranium enrichment facilities were the only primary exception of private ownership of the nuclear energy supply system. The concerns of nuclear fuel availability of the mid-1960s had been greatly relaxed. There was further hope for the nuclear power industry as the oil crisis in the early 1970s was anticipated to increase nuclear power demand. However, a combination of public safety, health, and environmental concerns brought expansionary hopes to a halt by the end of a decade. The AEC in the 1960s indicated that the capital costs of nuclear power would be substantially greater than large coal plants but that investors would be compensated through low operating costs due to the limited amount of fuel necessary to generate power in the reactors. However, the level of cost reductions from learning by doing and learning by using as well as the projected economies of scale were never realized. Instead, they were further offset by the increases in reactor complexity driven by increasingly stringent safety standards. It was often found that final costs exceeded initial estimates by over a hundred percent. The mid-1970s made it clear that the relatively simple and comparatively inexpensive light water reactors of the 1960s were no longer commercially viable.

Public safety concerns during the 1970s led to continually tightening safety requirements for nuclear power plants by the agency that succeeded the AEC, the Nuclear Regulatory Commission (NRC). It is unclear if the new NRC requirements resulted in significant improvements in nuclear power safety, nevertheless often changing safety standards made engineers frequently enact design changes during construction, which increased construction costs and construction time. In the 1980s, average U.S. commercial reactor construction time grew to over ten years, and (adjusted for inflation) the costs of new nuclear plants of comparable size to their 1970s predecessors quadrupled. Nuclear power plants, due to high capital costs, began to experience higher electricity production costs more expensive than coal-burning plants. Exacerbating the cost problems, electrical shortages that began to emerge in the 1980s pushed electrical utility firms to turn to natural gas as their primary energy source since natural gas plants were quick to bring online despite the relatively higher per kilowatt-hour costs compared to coal and nuclear power (Ruttan, 2001). There have been expansions onto current plants in recent years, with “The newest reactor to enter service is Tennessee’s Watts Bar Unit 2, which began operation in June 2016. The next-youngest operating reactor is Watts Bar Unit 1, also in Tennessee, which entered service in May 1996.” (EIA, 2020)

The National Lab System: An Overview

Understanding the National Lab system operated by the United States is important to understanding ARPA-E, given that many ARPA-E nuclear energy products occur at national laboratories or through private-public partnerships housed at national laboratories. Frankly, the National Energy Laboratories operated by the DOE are some of the least-understood parts of our national innovation system. The statute creating these institutions was the 1946 legislation that created the AEC, which became the entity that operated the plants, equipment, and personnel that were previously being utilized to build the atomic bomb. The main consideration for the AEC’s creation was to avoid military control of nuclear energy and nuclear technology. The AEC was established with two key goals: to provide the large-scale infrastructure needed for research and to secure facilities needed to develop technologies for national security. It was also responsible for watching the use of nuclear materials for the civilian and military development of nuclear technology and expanded and maintained many of the weapons laboratories, which were inherited from the Manhattan Project. Initially, national laboratories only included multiprogram laboratories that were involved in basic research, such as Oak Ridge, and laboratories that were initially at first focused on nuclear weapons and weapons material (such as the Hanford site) were not covered by the term “national laboratories.” However, as research scope increased over time, the national laboratory scope widened. The AEC and the laboratories during the 1950s faced significant administrative issues, specifically on how they could ensure program autonomy in a way that is compatible with scientific viability and the level of secrecy needed for national security concerns. In this time period, laboratory budgets increased substantially as they were given improved equipment and infrastructure needed to engage in the basic research needed for subatomic and high-energy physics. Some of these developments created controversy, as Alvin Weinberg (1961 director of the Oak Ridge Laboratory) states, “First, is Big Science ruining science?; second, is Big Science ruining us financially?’ and third, should we divert a larger part of our effort toward scientific issues which bear more directly on human wellbeing?”(Ruttan, 2006).

Many of these concerns became a reality by the early 1970s as financial pressures from the Vietnam War decreased the productivity growth of the economy and created an energy shock in the early 1970s. In response, laboratories expanded their areas of research. The Lawrence Radiation Laboratory created the Energy and Environment, Earth Sciences, Materials, and Molecular Research divisions. Oak Ridge National Laboratory created desalinization, natural resource, alternative-energy research, and civil defense programs while also expanding upon its large-scale biology program. When the AEC was Disbanded in 1975, its infrastructure and staff were transferred to the Energy Research and Development Administration, which eventually became the Department of Energy. For twenty years after the initial deformation of the AEC and its inclusion into the Department of Energy, it took over twenty task forces and major commissions for the department to address the questions and expectations it had from its national energy laboratory system. Nevertheless, by the eighties, the Department of Energy laboratories converged on four broad missions: a national security mission, a science mission, an energy mission, and an environmental mission.

The national security mission was to decrease the risk of nuclear proliferation and to maintain current nuclear deterrents. The science mission was to allow universities and industry access to their large-scale scientific infrastructure. These efforts support the nation's federally funded research programs and aid the nation's environmental sciences, life sciences, and mathematics programs. The energy mission aids the creation of new energy production technologies that have economic, environmental, and safety concerns embedded. This mission’s main objective is to decrease oil dependence on the Persian Gulf region and to decrease climate change risks associated with carbon fuels. Finally, the environmental mission aims to increase nuclear waste control efforts. Stabilizing, safely storing, and disposing waste alongside deactivating, decontaminating, and decommissioning support facilities are among the chief environmental concerns following cold war practices. The final objective is to remediate the contamination caused by the DOEs' energy and nuclear weapons programs.

In this time period, the economic growth mission was superimposed on the DOE, much like other institutions. These economic growth missions applied a set of institutional innovations over property rights from the new technology generated from the federally funded research and development. Specifically, the Stevenson-Wydler Technology Innovation act, the Bayh-Doyle act, and the Federal Technology Transfer Act each played a key role in this economizing of the national labs' bureaucratic structure. Technology transfer became a mission for all federal laboratories under the Stevenson-Wydler act. Passed in the same year as the Stevenson-Wydler Technology Innovation Act, the Bayh-Dole act granted title to technologies that were created from federal funding to the agents of the research and development. Six years later, the Federal Technology Transfer Act granted incentives to the nationally owned and operated laboratories to commercialize their creations, and in 1989 the National Competitiveness Technology Transfer Act was passed and further extended the incentives for commercialization under the Federal Technology Transfer Act to federally funded, but contractor-operated laboratories. The National Competitiveness Technology Transfer Act of 1989 and the Federal Technology Transfer Act of 1986 were important pieces of legislation in encouraging federal laboratories to engage in cooperative research and development agreements with industrial partners.

There was initial skepticism from the science and technology community on the potential efficiency of these sets of institutional innovations over the 1980s. After all, international public-private partnerships were not the norm. In France and the U.S.S.R., research and development were publicly funded and operated at the national level, and historically in the United States, the government had been centerfold in all nuclear matters. Nevertheless, after many empirical studies, it was clear that the cooperative research and development agreements were more impactful than originally predicted in increasing industrial patents and increasing company-financed research and development. By the mid-1990s, in spite of the successes of the cooperative research and development agreements, concerns grew against the dual-use and cooperative programs that increased technology transfers to the private sector. Pessimists were not against the efficiency of these programs but rather, in an Austerian fashion, argued that it was pressing the federal budget thin to support these programs and that they were shifting effort away from traditional energy and defense missions (Ruttan, 2006).

While these programs of the 1980s increased some technology transfer from the national laboratories to industry, they are not leading to a substantial development in general-purpose technologies. These policies are also rooted in generating incremental technological innovations rather than radical innovations. The policies have not been able to gain substantial political support. A national commitment to the development of carbon-free alternative energies could focus on the creation of new environmentally compatible general-purpose technologies through the national laboratory system. ARPA-E can serve to partially fill this gap. Investing in radically innovative areas of reactor design and fuels research in projects housed at the national labs can give directionality to basic research needed to substantially reduce the carbon intensity of our energy systems. Extending the ROAR format here is not fully possible as the national lab system is not inherently a top-down policy. However, the national lab is a locus of innovation for the DOE as innovations in organizational structure through the focus of public-private partnerships has created some of the most robust organizational capacities for the public sector. These innovations in organizational structure are a primary factor for why so many of the ARPA-E nuclear projects are conducted by national labs and through public-private partnerships. The variety of input into basic science is critical as it provides directionality to the progression of research and development that is necessary for later technological applications for commercial purposes. This organizational innovation is a critical institutional shift that drastically enhances learning capacities for public and private actors, which eases translating codified knowledge into tacit knowledge, a critical factor to novelty generation.

Path Dependency for Increasing Returns Technologies:

To contextualize path dependency to nuclear reactor development, exploring the dynamics of allocation under increasing returns is a necessary first step since these allocation choices establish path dependencies. New, complex technologies such as nuclear in the late 1940s and early 1950s exhibit a high capacity for ‘learning by using,’ meaning as the technology is increasingly adopted and experienced continues to be gained, which drives further improvements to the technology. When we see that there are two or more increasing returns technologies competing for a market of potential adopters, there is an increasing propensity for seemingly insignificant events to give a technology an incremental advantage in adoptions. These seemingly insignificant events can be political situations, unexpected successes in prototypes, or other unexpected events.

Nevertheless, incremental advantages can snowball the technology to become further adapted and improved. This snowballing can cause a technology that gains an early lead in an increasing returns market to block out other technologies. The variety of potential incremental advantages within markets of increasing returns technologies generates multiple equilibria, and while static neoclassical analyses can identify these locations, it cannot tell us which outcome will be ‘selected.’ However, Arthur employs a dynamic approach that allows for the chance of a likelihood of a ‘random event’ occurring while a new technology is being implemented, which allows us to examine how these forms of events influence outcome selection. This approach also shows how chance events during the adoption of increasing returns technologies occur more frequently, which means that ex-ante adopter’s preferences and perceptions of a technology’s possibilities cannot suffice in anticipating the market outcome. The dynamic approach also identifies that increasing returns can push the adoption process into developing technologies that have comparatively long-run inferior potentials. Inflexibility is another characteristic for increasing returns technologies in that once a dominant technology emerges, it becomes progressively more locked in as more agents adopt the technology. Non-ergodicity is the final unique trait for these forms of technologies since historically, small events cannot be averaged away by the dynamics but rather are deterministic in the market’s outcome.

Figure 4 identifies the dynamic model characterized by increasing returns adoption. Here, new R-type Agents that have an innate preference for technology A will switch to adopting B if a chance event pushes B far enough ahead of A in payoffs and number of adopters. So, R-agents will switch technologies when

$$d_n = n_A(n) - n_B(n) < \Delta_R = \frac{(b_R - a_R)}{r}$$

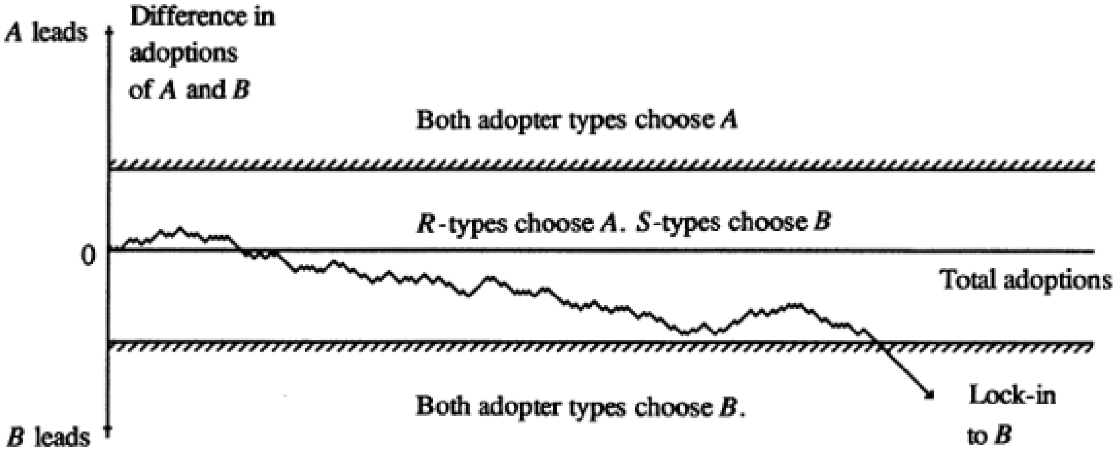

Figure 3: Increasing Returns Adoption: A Random Walk with Absorbing Barriers. Source: Arthur (1989)

Where $n_A(n)$ and $n_B(n)$ are defined as the number of choices of A and B respectively, r is a positive constant denoting increasing returns to adoption and b_R and a_R represent the payoffs of each technology for R-type agents.

Similarly, S-type agents that have an innate preference for technology B will switch to adopting A if a chance event pushes A far enough ahead of B in terms of payoffs and number of adopters. So, S-agents will switch technologies when

$$d_n = n_A(n) - n_B(n) > \Delta_S = \frac{(b_S - a_S)}{s}$$

where b_S and a_S represent the payoffs of each technology for S-type agents. We can now identify regions choice in the d_n, n plane as seen in the figure with the upper boundary being equation one and the lower boundary being equation two. As soon as a region beyond one of the equations is entered, both agents will choose the same technology. Therefore, in the d_n, n plane, the equations are barriers that absorb the adoption process. That is, once either equation is reached by a random movement of d_n we see a complete adoption of a technology as it becomes locked in. This makes the adoption process under increasing returns characterized as a random walk with absorbing barriers.

It is clear that predictability under increasing returns is lost. While the agent is able to predict if one technology will take the market and can predict that it will be technology A with probability,

$$\frac{s(a_R - b_R)}{[s(a_R - b_R) + r(b_s - a_s)]}$$

they still cannot predict what the actual market share outcome will be with any degree of accuracy despite knowing the supply and demand conditions. Flexibility is also lost in the case of increasing returns because, once the adoption process is absorbed into one of the two technologies, the limit of taxation and subsidization adjustments necessary to shift the choice barriers to a point where the policies influence adoptions go to infinity. Increasing returns are clearly non-ergodistic as small events can adjust the payoffs of each technology which decides the paths of market shares. Path efficiency does not hold over increasing returns as we cannot expect the best technology to win like we can for constant and diminishing returns technologies. This is because, under increasing returns, market lock-ins can occur for technologies that are inefficient in the long run if the competing technologies improve at different rates. Initially lucrative but slow-to-improve technologies are attractive to agents in situations where hasty development is viewed as a necessity (Arthur, 1989).

Extending the varieties of capitalism can provide insights into disparities in technological lock-in across different institutional mixes. Namely, the patient capital necessitated by coordinated market economy (CME) style economies would suggest a lower degree of lock-in for increasing returns technologies within a system since capitalists in these systems are less focused on short-term profits. By being reliant on their own reserves or on bank capital (instead of stock market funds in liberal market economy (LME) systems), CME firms are going to be timelier in their decision-making processes when adopting different technologies. In contrast, LME firms are going to be more concerned with maximizing shareholder value which puts greater pressure on maximizing their short-term profits. Short-term profit maximization necessitates hasty decision making, which pushes capitalists to adopt technologies that are initially lucrative despite them being slow to improve over the long run (Hall and Soskice, 2001). Nuclear reactor technologies are a prime empirical case that reflects lock-in through learning, and it is not a coincidence that the institutional mix where the LWR lock-in occurred is within the liberal market economy. There exist other historical events leading to lock-in, such as the adoption of alternating current and of the QWERTY keyboard, which are similar cases of increasing returns technologies that experienced lock-in based on early adoption choices taken within an LME.

Comparative Nuclear Energy Systems

Not all developed nations during the seventies and eighties were gradually swaying away from nuclear energy. France, through the end of the twentieth century, appeared to be committing more so to nuclear energy. During an oil crisis in 1973, France was importing oil for two-thirds of its total energy production, which fueled a political push for energy independence. Following an oil embargo, the French state ordered the creation of six 900-MW reactors. Given France’s resources, the state at the time believed that nuclear energy could be the only power system that could be internally developed. France invested and developed all aspects of the nuclear power cycle, including reactor design and construction to fuels and waste research. By the end of the nineties, about seventy percent of electric power production in France was generated by nuclear power. Nuclear energy plant construction times in France were halved compared to the United States, which decreased capital costs to a point where French electricity rates were the lowest in Europe.

A nation that twenty years earlier was importing oil for two-thirds of its oil consumption was now exporting power to nearly all of its neighboring states. This success was not a product purely of private ingenuity but rather can (in part) be attributed to substantial nuclear research and development subsidies provided by the state. Other factors of this include plant design and construction standardization, increased aversion to oil dependence, and “the competence and sophistication needed to manage a technology with high-risk potential. This success also reflects a political system in which important technical decisions are made by a bureaucratic-technical elite and the public is excluded from effective participation in such decisions” (Ruttan, 2001).

The oil shocks of the 1970s and concerns about health and environmental implications of fossil fuel and nuclear-based power generation have created a debate about energy futures. In the early 1970s, 67% of federal energy research and development funds were invested into nuclear power, with 42% on the liquid metal fast breeder reactor alone. Energy conservation was seen as a potential factor that could be used to decrease the growth rates of energy use and that renewable energy could become a significant proportion of incremental growth in renewable energy production. However, what was recognized is that the shift from fossil fuel and nuclear sources to renewable energy could only be achieved by innovation in the technology of electric power generation which would require the creation if incentives to producers and consumers (Ruttan, 2001)

The Safety and Sustainability of Nuclear Energy

A proper evaluation of the safety of nuclear energy necessitates considering not just the physical characteristics that determine the safety of a complex system but the people and organizations that operate them. High degrees of complexity breeds uncertainty and can be highly susceptible to even small changes, which can allow a minor malfunction to snowball into a catastrophe. This creates an impossibility in creating a playbook that outlines a procedural response to every potential situation. There is plenty of room for human error in operation as there is always a potential for an operator to freeze up when facing an unexpected situation. Clearly, organizational reliability is a necessity if we want to generate a system around a technology that enables its physical reliability. Some would argue that it is fundamentally impossible to create such a high-reliability organization, but that is not entirely accurate. For instance, the U.S. air traffic control system has handled managing thousands of daily flights around the country with remarkable success. The intricate dance of planes bouncing between airports and crisscrossing each other’s paths at incredible speeds creates ample opportunity for error, and yet it is not extremely good luck as to why air traffic control has been able to manage this web but through proper management.

For nuclear power, Diablo Canyon is an interesting case of organizational structure similar to what can be found on Navy aircraft carriers in that they practice a layered bureaucratic structure. By this, I mean that there exists an underlying typical hierarchal structure in which the director is the head, and then there are diminishing levels of authority from engineers to technicians. But there exists a second bureaucratic structure, one that de-emphasizes rank or position and instead puts a greater emphasis on expertise which creates a greater weight upon communication and cooperation among units. With respect to Diablo Canyon, it was clear that a system as complex as a nuclear power plant is impossible to create a specific playbook for everything in advance, so employees must do more than follow policy blindly. Agents have to be constantly thinking about what they're doing to avoid creating a potential catastrophe. This creates a management structure in which every employee is encouraged to make contributions. Procedures are treated as a living document, and employees consistently make contributions to them. The evolving form of procedures permits aids organizations in dealing with the demands generated from the uncertainty of the system, as it encourages a degree of continuous learning and improvement that would be impossible in a strictly hierarchical structure.

Constant communication and active learning are also necessary to make these forms of organizations successful. Constant communication decreases the potential for mistakes since it helps ensure that everyone is on the same page. For air traffic control, there is consistent communication with aircraft alongside the introduction of assistants in the control tower during peak travel hours to assist in direction. Continuous learning ensures that employees not only know the procedure but understand why they are written. This opens up the ability for employees to properly analyze current procedures so that they can also create recommendations for improvement.

High-reliability organizations offer a sort of “proof of principle” in that we are able to identify successful organizations that have been able to manage hazardous technology safely and efficiently. However, this sort of approach does not create a guarantee that every single nuclear site in the United States would be operated to the same level of success as previous high-reliability organizations. There is a definite potential for some to slip through the cracks. The financial system before 2008 was believed to be able to manage incredible risk within its organizational structure. However, the potential for information asymmetries brought the system to its knees and necessitated a bailout.

Another concern is that if the management of the system is successful over a long period of time, regulators can begin to take that performance for granted, which creates difficulty in the justification of the cost of eternal vigilance. In the case of Diablo Canyon, from the outside, it may seem unproductive and costly to have constant meetings about what could potentially go wrong and to be consistently adjusting their procedure. While constant vigilance is a defining characteristic of these organization’s success, it can become difficult for policymakers unfamiliar with the methodology to justify its costs over time, generating the risk of returning to a by-the-book typical hierarchal structure. In short, if we insist on taking this Faustian bargain of nuclear power, it will prove to be no bargain at all if we are unwilling to continuously invest in safety (Pool,1997).

In the current environmental movement, advocacy for nuclear power's role is unpopular, as many wish that nations transition to one hundred percent renewable energy sources for electricity generation (such as solar, wind, and geothermal). This is certainly the case with Germany, as the nation under the Energiewende program aims to achieve full decarbonization and denuclearization by 2050. The program, for example, is supported by economists such as Mariana Mazzucato, who appreciate the mission-based program and its capacity to address a grand challenge such as climate change. Specifically, Mazzucato approves of the way that it sets routes of directionality by clearly identifying renewable energy sources to be the electricity generating sources of power by the middle of the century. The approach of establishing renewable energies, she argues, doesn't fall into the pitfall of only considering decarbonization as an environmental concern since technologies such as wind and solar avoid the problems of waste that nuclear generates and avoids the concerns of safety that nuclear technologies have in energy generation.

However, while I agree with Marianna Mazzucato on the magnitude of the threat that climate change poses to humanity and on the capacity that top-down mission-based policies have on combatting these issues, I disagree with her exclusion of nuclear in mission-based policies responding to climate change. Mazzucato asks, " Is that really what we want?" (Mazzucato, 2015) in defending her exclusion of nuclear power in *The Entrepreneurial State* when arguing that while nuclear is "clean" in the sense that it is emission-free, that the safety and waste concerns that nuclear poses to the community and to the environment warrant exclusion from the green energy revolution. This assumption, I believe, gravely mischaracterizes the impacts and effects that nuclear energy has previously had on cleaning up energy for electricity generation and ignores the current capacities of next-generation reactor technologies.

Clean energy has grown in absolute terms, but the issue is that the share of electricity globally has fallen by 4.5%. Nuclear too has declined by about 7% since its peak in the mid-1990s but solar and wind haven't yet filled the gap of the loss in nuclear. This is under conditions where in the United States, renewables have received one hundred and fourteen times more in subsidies than nuclear per-terawatt hour of generation in 2016. What is astonishing is that over the eight-year span of 2008 to 2016, the sum of public and private expenditures into renewable energies equates the public and private investment into nuclear over its entire commercial history (1962-2016). Therefore, given this comparatively immense investment, why have solar, and wind nevertheless remained at the periphery of most nation's grid systems (Hansen and Shellenberger, 2017)?

Shellenberger conducted an analysis to identify how this investment into renewables has affected the quantity of carbon per unit of energy over 68 nations since 1965 and found that there was no correlation between the additions of solar and wind power and the overall carbon intensity of electricity generation. This implies that this significant investment into solar and wind hasn't generated a massive decrease in carbon intensity at national levels. Shellenberger noted that over a nation's energy life that there is a significant correlation between decarbonization and the establishment of nuclear energy and hydroelectric energy and no correlation with wind and solar. The initial answer to this lack of correlation is that the past energy generating capacities of solar and wind are comparatively low to other energy production counterparts. In terms of raw energy outputs over the last ten years, it is clear that more non-carbon power was added across nations from nuclear and hydro than wind and solar.

With respect to Germany, as of 2017, they invested $222 billion into renewables since 2000. And while Germany had installed 4% more solar panels in 2016, they generated 3% less electricity from solar overall due to the decreased sunshine in Germany over that year. The common counterargument to this is that if a year is less sunny, then the chances are that it is windier, but Germany installed eleven percent more wind turbines in 2016 but nevertheless generated two percent less electricity from wind in 2016. With respect to energy policy in Germany today, Mazzucato (2021) identifies that under Energiewende that the hasty de-nuclearization under Energiewende has caused the previous nuclear energy capacities to be replaced by coal-burning plants, which has made Germany a laggard among the Powering Past Coal Alliance. This replacement of previous nuclear capacities with coal is problematic. Before the current phaseout under Energiewende, forty percent of electricity was generated by coal, and thirteen percent was generated by nuclear (Hansen and Shellenberger, 2017). In addition, the phase-out of nuclear in Germany has pushed prices to be twice as expensive as French electricity. While some would argue that this price increase is justified since it does a lot for clean energy and overall climate, the price jump did not actually correlate with overall cleaner energy as with respect to France they get significantly more of their electricity from clean energy sources than Germany (Hansen and Shellenberger, 2017). In regard to emissions, German emissions have been increasing from 2006 to 2016 and are anticipated to continue to increase, as evidenced by the phase-out of nuclear causing an increase in coal-burning plants.

The counterargument provided to the adoption of solar and wind is that it will become cheaper the longer it is supported in the form of learning by doing. And while that is true for the costs of the solar panels and the wind turbines, it is not true with respect to the energy from solar and wind as the electricity actually becomes more expensive over time since its value actually declines. Shellenberger notes that Leon Hearth found that the value of wind to the electrical grid falls by forty percent when it accounts for thirty percent of electricity-generating capacities and finds that solar power's value falls by half when it becomes just fifteen percent of electricity generation. The diminishing value in each of these cases comes from the fact that these energy sources generate a lot of power when we do not necessarily need it and are not generating power when it is in demand (Hansen and Shellenberger, 2017).

Another factor of this cost story is that renewables necessitate a significant amount of materials such as steel, glass, and cement since the energy sources that renewables utilize (the sun, wind, etc.) are energy dilute. Being energy dilute necessitates spreading collectors across a larger physical landscape to collect those energy flows into useable electricity. Also, the quantity of materials needed to create power from renewables is inversely related to its energy return and energy invested. Consequently, this inverse relation means that solar panels create three hundred times more toxic waste per unit of energy than nuclear energy creates due to solar energy's immense material throughput. And unlike nuclear waste, which is safely contained in immense concrete casks in the depths of the earth, solar panel waste is coupled with the electronic waste stream. Being included in the electronic waste stream means that solar panels are very likely to be disassembled in poor communities where children are exposed to lead, chromium, cadmium, and other toxins whose toxicity never declines over time because they are elements (Hansen and Shellenberger, 2017).

In regard to storage capacities, there could be potential for breakthroughs on the horizon. But the breakthroughs are unlikely to be significant enough to make electricity generated from renewables consistently available. As of 2016, if all storage capacities in California were allocated to backing up the grid, we would only have twenty-three minutes of storage (and that includes every single car and truck battery which is completely impractical as people need them to drive after all). This means that storage capacities would have to dramatically improve if we are going to have the capacity to store energy from one sufficiently windy and sunny year to accommodate the decreased production in a low-wind low-sun year (Hansen and Shellenberger, 2017).

One of the main concerns surrounding nuclear is safety, as incidents like Chernobyl have created worries about nuclear accidents. But with respect to Chernobyl, the UN report found that twenty-eight deaths were caused by acute radiation syndrome. These deaths were the firefighters who got extremely close to the fire from the unshielded and uncontained reactor. The UN Report on Chernobyl found that fifteen deaths came from thyroid cancer triggered by the event over the last twenty-five years. And while tragic, it is nevertheless the form of cancer that is arguably the most manageable as the mortality rates of thyroid cancer are so low that as long as you have ample access to medical care, the likelihood of surviving is very high. Furthermore, there was no effect on fertility malformations or infant mortality and no effect on pregnancies. There were no heritable effects and no proven increases in any other cancer, including among the responders that put out the reactor fire (Hansen and Shellenberger, 2017).

With respect to Fukushima, it is astonishing that the plant was created only to withstand a three-meter tsunami since, at the time, it was well within the realm of possibility for a tsunami to exceed that size, and it was possible to accommodate safety measures for larger potential tsunamis even with the LWR design (Henson,). Nevertheless, the UN report indicated that there were no deaths from radiation, but there were 1,500 deaths from anti-nuclear radiophobia (deaths caused by radiophonic panic, evacuation, and stress). This is a rather peculiar outcome as the nuclear fearmongering actually created significantly more harm than the nuclear incident itself. The earthquake that triggered the tsunami, however, killed over 15,000 people. The UN also found that there was unlikely to be an increase in thyroid cancer and no impact on adverse pregnancy from the event (Hansen and Shellenberger, 2017).

Putting the safety of nuclear in terms of health, living in a big city actually increases your likelihood of death more than if you were putting out the Chernobyl fire as living in a megacity versus a small town increases your likelihood of death from pollution by 2.8% and living with someone who smokes increases your likelihood of death by 1.7% while exposure to 250mSv (Chernobyl Liquidator) increases your likelihood of death by 1.0% and exposure to 100mSv (Chernobyl Liquidator) increases your likelihood of death by 0.4%. With respect to Three Mile Island, the amount of radiation that nearby residents were exposed to was equivalent to the radiation one would receive from flying in a commercial aircraft across a continent and back, which really is not that dangerous (Hansen and Shellenberger, 2017).

With respect to accidents, the worst renewables accident comes from the Banqio Dam collapse in China, where 170,000 people were instantly killed. Similarly, natural gas is no stranger to danger as it can explode and kill people in the surrounding community. Furthermore, the World Health Organization found that annually seven million people die from air pollution. With respect to Germany, the World Wildlife Fund found that German pollution is killing about 2,500 people a year due to premature deaths triggered by air pollution at a particulate matter of mostly PM 2.5. Overall, more people die in a single day from air pollution than have died from nuclear energy over its fifty-year span. The figures above generate a difficult truth that the anti-nuclear community must face, which is that nuclear is currently the safest way to make reliable carbon-free power. Therefore, the pursuit of nuclear is actually saving lives. Hansen identifies that to date; nuclear energy has actually saved almost two million lives simply by offsetting the burning of fossil fuels. This figure doesn't even account for any impact on the climate. Rather the figure is based just on abating air pollution (Hansen and Shellenberger, 2017).

What is remarkable is that the preceding safety and efficiency figures come from light water reactor technologies, which we have known from the beginning of the nuclear age to be an inferior reactor design. There are new reactor designs that manage many of the issues that have been raised about nuclear power. New reactor designs are passively safe in that if there is an event like an earthquake or tsunami that the reactor will just such down and the reactors don't necessitate any power to cool them. This was not the case with the light water reactor technology that existed at the Fukushima plant because once they lost power the reactors couldn't be cooled. With respect to waste the next generation of reactors are much more efficient and produce less waste. The LWR design is a thermal reactor where the neutrons are slowed down and while it's one way to create energy from nuclear fuel, the thermal reactor only utilizes one percent of the energy in the nuclear fuel (Hansen and Shellenberger, 2017).

On the other hand, the more modern fast breeder reactor designs, which allow the neutrons within the reactor to move faster, allows for more than 99% of the energy in the fuel to be utilized in the energy generation process. The new reactors therefore generate a significantly smaller waste pile with a half-life measured in decades instead of millennia. But when U.S. scientists got to a point in the technological development process that a commercial reactor was around the corner, the program that was researching and developing fourth-generation power plants was terminated due to anti-nuclear dissent (Kahn, 2014).

Another aspect of safety is that individuals are concerned that nuclear energy and weapons are inherently connected, but a clear counterexample is that North Korea was denied nuclear energy capacities and developed weapons while South Korea was permitted nuclear energy. Just like all other nations that develop nuclear energy, South Korea had to agree not to get a nuclear weapon, and it has done just that. A key aspect of preventing the proliferation of nuclear weapons has been the establishment of nuclear power, which is a correlation backed up by over sixty years of data. This is rather simple to prove, as in the international community if you want to be a part of nuclear energy, you must agree not to create nuclear weapons (Hansen and Shellenberger, 2017).

This creates significant pressure on the Energiewende program to meet its decarbonization goals. The current transition has also created a challenge in regard to equitably distributing its costs. Renewable energy generation receives significant tariff subsidies (a policy established in 2008), which has caused Germans to face surcharges on their electricity bills, causing some of the highest electricity prices in Europe as electricity prices in Germany rose forty-seven percent from 2006 to 2016 (Hansen and Shellenberger, 2017).

While some energy-intensive energy industries are exempt, this nevertheless increases the burden faced by households which can diminish public support. Mazzucato(2021) argues that social missions are more difficult to fulfill than pure technological missions as the social missions incorporate political, regulatory, and behavioral changes. While growing pains are to be expected from any transition, what is critical is to ensure that they are short-lived. With respect to energy generation for electricity, for the Energiewende mission (and decarbonization goals like it), there must be significant advancements in ensuring the consistency of the energy generation cycle. And while fuel cell research has technologically come a long way in terms of raw storage capacity, the critical challenge to renewables is nevertheless ensuring that there is enough energy produced to accommodate the periods where energy generation is low, but demand is high. But given that current capacities indicate that if all energy storage capacities in California can only sustain 23 minutes of energy, it would be something short of a miracle if we are to anticipate that storage capacity can advance quickly and cheaply enough to succeed in fully sustaining an entire grid over a low-sun low-wind year.

Therefore, it is apparent that if a mission such as decarbonization of our electricity generation system is to be achieved that nuclear energy at the least can play an integral role in it. Because the only primary concern with nuclear that most environmentalists have is safety and storage. But with regard to safety, it has empirically been shown to be a relatively safe energy generation technology. With regard to storage, it is clear that next-generation reactors could have the capacity to utilize previous waste and generate significantly less waste with a much shorter half-life. Because as with airplanes, it is no debate that a crash is terrible. But a single airplane crash has never brought to earth the entire aviation industry. Instead, with respect to airplanes, engineers would evaluate the problematic model and would find out what the problem was to ensure that the next version was safer.

The environmental community needs to adopt a similar attitude to nuclear as it is very clear that in the case of nuclear technology that there currently exist approaches that are vastly superior to the light water design. Nevertheless, we should be pursuing these advanced designs because, at this moment, current renewable energies and storage technologies are not an alternative that can come close to competing in terms of cost and consistency to fossil fuels.

Chapter Four: The Role of Nuclear Energy in the U.S. Energy Innovation System

Introduction

The objectives of this chapter are to outline the current status of commercial nuclear energy in global energy markets, identify what makes mission-based policy unique, and determine if the ARPA-E nuclear programs are actually engaged in funding potentially radically innovative technologies or if they serve as an Ayersian "appeal to ceremony." To determine the current role of commercial nuclear energy evaluation at the industry level is necessary as the complexity of the nuclear system itself warrants its own analysis, and initially expanding into its role globally aids in identifying alternative growth patterns of commercial nuclear energy. The technological innovation systems (TIS) viewpoint is successful in doing this as it can identify if commercial nuclear is a technology in maturity or in decline.

With this information, the National Innovation Systems framework can be better utilized as the information from the TIS helps with ranking the technology in comparison to others for policymakers to pursue. However, adjustment to the national level also necessitates a further understanding of the role of mission-based policy as the NIS framework calls for top-down mission-based policies to influence systemic innovation as they are the most efficient at generating learning capacities. This, therefore, necessitates an evaluation of what makes a quality modern mission-based policy. After identifying why mission-based policies are unique and necessary in the NIS approach, I will further break down the ARPA-E program into its nuclear sub-programs to determine if these programs are engaging high-risk, high-reward technologies that have market-creating capacities. If these market-creating capacities do indeed fall in line with ARPA-E's mission, then it is problematic to exclude nuclear from the evaluation of the U.S. approach to creating a low carbon energy innovation system.

Technological Innovation Systems for Commercial Nuclear:

There is critical debate around the trajectory of commercial nuclear energy. Some view nuclear as a critical technology to address climate change as it produces few emissions, while others see nuclear energy as a system in decline. Using the technological innovation systems format, Markard et al. "examine a broad range of empirical indicators at the global scale to assess whether or not nuclear energy is in decline." Note the differing degree of aggregation in this analysis since the authors are evaluating nuclear energy through a global but sectoral lens as they compare it to other forms of energy production. This is useful to situate the current relative position of nuclear as an industry but does not provide direct insight into the role of nuclear energy in a nation's energy policy mix, which is tailored to their own opportunities. Particularly, there are nations like Russia, China, and to an extent France where the operation and creation of nuclear power are organized and operated by state-owned firms that receive substantial public support. For these nations, the institutional rigidity of nuclear power can be difficult to overcome. Nevertheless, these author's analysis aims to determine if nuclear power is in a stage of decline globally. If so, the range of technical options that can phase out CO2-intensive technologies at a large scale becomes limited. To determine if nuclear is in global decline, the authors evaluate if not just 'core firms' but if networks, skilled labor, legitimacy, suppliers, customers, and other complementary components of the nuclear value chains are being lost. If so, then the result is a vicious cycle of negative developments that occur, which doom a technology's fate. The following paragraphs will describe nuclear energy in the technological innovation systems in a manner that will encompass organizational, technological, institutional, and contextual developments within the industry (Markard et al., 2020).

Nuclear energy is characterized by the complexity of its products and systems. It necessitates significant upfront investments and long lead times as licensing, planning, and construction can take over ten years, and once operational, operate for forty years. Investment costs are high as they can take many decades to repay, but operational costs are low. The degree of uncertainty in cost is extremely high as there is uncertainty in construction and licensing as well as the state of electricity prices and capital costs. Nuclear also necessitates highly skilled labor and robust organizational systems, as identified by the el diablo case in the previous chapter. The success of a plant is dependent upon the involvement of numerous unique actors, including suppliers, regulators, policymakers, and investors.

The success of nuclear is also dependent upon the regulatory environment concerning the timeliness of licensing, safety standards, and waste handling. One positive regard for nuclear is the impact upon air pollution since nuclear energy is an extremely low carbon technology and is capable of providing more energy in a relatively invariable manner since it does not suffer the same variability to weather conditions as renewables do. And while the fuel cell research and innovation in batteries are radically changing the capacity to store energy from renewable sources, it is still the case as of now that there is substantial variability across months in the energy produced from renewables.

The low carbon portion of nuclear is crucial in current energy systems since most clean energy strategies that nations have pursued that aim to simultaneously pursue denuclearization fail to facilitate clean short-term transitions. After Japan halted the operation of its nuclear plants following the Fukushima accident, fossil fuel's share of electricity production leaped from 60% to over 80%. In California, after the San Onofre nuclear power plant was shut down in 2012, its electricity share was simply replaced by polluting natural gas (Markard et al., 2020). Similarly, in Germany, following the policy goals of Energiewende, the closure of nuclear plants was simply replaced by fossil fuels in the short term (Mazucatto, 2021).

Therefore, an aspect to keep in mind for mission-based policies pursuing to address grand challenges such as climate change is the short-term aspects of routes of directionality. Because while in twenty to thirty years the objective of policy like Energiewende to achieve full de-carbonization and de-nuclearization is certainly achievable, without proper short-term planning, hasty de-nuclearization can lead to short term increases in emissions which has negative repercussions on the current environment and current public health. This by no means de-legitimizes the rather bold endeavors of the policy, but rather it should be identified as a learning opportunity for future transitions. Long-term goals should remain the primary focus in a mission-based policy as it takes time to transform a market. Nevertheless, there exist significant dichotomies in growing pains for market transitions and ensuring that a transition adheres to the final goal to the best of its ability is favorable.

Despite these concerns of scaling back existing nuclear plants, climate justifications for new LWR commercial plants are particularly difficult to pursue and assess as the timeliness of a new nuclear plant is unfavorable compared to the more modular development processes of solar PV and wind. The age of the current fleet of nuclear actors will affect the level of nuclear power, capacity in the coming decades, considering that "of the 451 nuclear reactors operating in 2018 had been producing commercially for 32 years or more". (Markard et al., 2020). New constructions are occurring at much lower levels globally than the rate of closure of old plants.

The actor base for nuclear energy has been shrinking as all private North American firms, and the German firm Siemens have exited the market and the future of other firms such as Hitachi and Toshiba face an uncertain future in the market considering few projects are currently proposed, and ongoing constructions are facing challenges and delays. However, the state-run Russian (Rosatom), South Korean(KEPCO), and Chinese(CNNC) companies appear to be doing well. Rosatom has the most planned nuclear constructions, while KEPCO and CNCC have smaller, more domestic projects. Kepco, however, is building four reactors in the UAE and has submitted the design for approval in the United States to hope to expand here. Rosatom similarly is building reactors abroad. The actor base of the industry is currently characterized by the consolidation and exit of private firms in the West and the success and expansion of state-owned enterprises in the East. Particularly in the West, recent market developments show that plans for new nuclear power stations as well as ongoing constructions are being abandoned. For example, the VC Summer nuclear station was canceled due to delays, introductions of new module designs, a shortage of qualified labor, and manufacturing and production issues. In total, the project cost the utility and public over nine billion dollars. Similarly, in the UK, Hitachi withdrew from the Welsh Wylfa project in 2019 and Toshiba withdrew from their Cumbria project in 2018, with each company citing a lack of skilled labor force and, a declining TIS base, and a lack of new construction experience as warrants for withdrawing (Markard et al., 2020).

The regulatory environment has increased in complexity over time as safety regulations and licensing procedures have necessitated input from a vast range of stakeholders, which has ultimately increased planning and licensing costs and time. Similarly, public opposition to nuclear has increased as risks in all parts of the nuclear value chain. Accidents such as Chernobyl and Fukushima have roused public opposition to nuclear globally, with numerous nations outright suspending and banning the construction of new reactors as well as phasing out current operations. Over twenty-five percent of nations (Primarily OECD nations) who originally utilized nuclear energy have since abandoned it, with nations such as Ireland outlawing nuclear without ever implementing it. In contrast, nations such as the UAE, Bangladesh, Turkey, and Belarus have opened their energy systems to nuclear technologies (Markard et al., 2020).

Public research and development funding for nuclear technologies has been wavering in comparison to research spending on renewables and fossil fuel energy technologies. R&D spending is a crucial component of maintaining the highly skilled workforce that nuclear necessitates, which correlates with the overall loss of technological breakthroughs, industry jobs, and innovative business models required for a complex industry. Forecasted projections for nuclear power generation conducted by the International Atomic Energy Association identify a clear decline following the Fukushima accident in 2011 and that substantial new nuclear capacities would have to be developed to offset oncoming retirements caused by economic challenges and overall aging. These rather dismal expectations are telling for the prospects of nuclear technological innovation systems as these forecasts are being generated by organizations that have historically and currently are in favor of nuclear energy. Cost reductions due to learning failed to materialize between 1970 and 1990 due to the complexity of the technology and the increased system complexity for technological scale-ups. Resistance to the technology during this time period also created longer planning and licensing times (Markard et al., 2020).

Today, conditions on these fronts have not improved but worsened as new reactor constructions have been faltering recently, and network density is depreciating, making the system has been experiencing “learning by forgetting,” a tell-tale sign of an industry in decline. Time overruns on construction times have become more frequent and can quickly generate cost overruns as the increased construction time puts pressure on capital costs and human resources costs. Currently, for nuclear power, time overruns explain more than sixty percent of cost overruns for new projects. Decreasing variety is a telling indication of technology in the maturity stage, and for nuclear, it is clear that diversity of reactor types has decreased as the Pressurized Water Reactor (a variety of the light water reactor type) has become the dominant reactor design. There are variations in forms of PWRs indicating that commercial nuclear is continuing to incrementally innovative but is faltering in architecturally innovating. Furthermore, this market consolidation upon the PWR design has failed to actualize cost reductions (Markard et al., 2020).

In a wider context, nuclear energy has been facing challenges in the more liberalized and privatized energy markets of many developed nations today. This wave of market liberalization eroded the previous political structures and monopolies upon which nuclear depended, and the public legitimacy of nuclear energy has faltered as accidents from Three Mile Island to Fukushima have eroded public trust. These technological and institutional factors have created a trend of denuclearization in the west. However, in quickly growing economies in the East, such as China, India, and South Korea, nuclear has grown due to increasing electricity demands and existing infrastructures. There are also increasing geopolitical considerations that are positively impacting the industry as nations like the US, Russia, China, and South Korea are engaging in the creation of reactors abroad with geopolitical intentions. Rosatom is currently creating a reactor in Turkey and has been offered a license for another, which creates economic and political opportunities for engagement between Russia and Turkey (Markard et al., 2020).

Of course, these factors are not new to the industry. As identified in the last chapter, the AEC pushed for the Euratom project to compete with the Soviet Union on nuclear energy in order to guide the industry in Europe into adopting American technologies. The primary competitors to nuclear are fossil fuels and renewable technologies such as wind and solar. The primary competitive challenges that nuclear experiences are their high startup costs and the sociopolitical and environmental concerns of the technology. Renewables are such a critical competitor as technological learning is extremely high in these fields. Current trends of substantial cost reductions in renewable technologies have the potential to offset nuclear energy's economic competitiveness. Nuclear is also experiencing substantial pressure from natural gas as innovations in fracking and substantial subsidies in nations such as the United States have put gas-fired power plants into a favorable position compared to considerations of new nuclear plants. While small modular reactors are painted as a potential nuclear alternative to the large scale LWRs of the sixties and seventies due to their improved safety and reduced construction costs and times compared, there is a considerable need for research and development investment into sustained support for small modular reactors and environmental concerns of waste and thermal pollution still exist among policymakers (Markard et al., 2020).

Overall, based upon institutional and sectoral factors at a global level, the commercial nuclear technological innovation system since the 1990s has been experiencing a severe crisis and decline. Firms are withdrawing from projects due to costs, and many of the former key reactor players have left the industry or have essentially reorganized themselves. The regulatory and support network of nuclear has experienced deteriorating legitimacy as many nations have implemented phase-out policies, and the performance of the technology has faltered due to costs and construction uncertainties. Fierce competition from traditional fuel sources and renewables within liberalized electricity markets have further deteriorated the role of commercial nuclear. While this is characteristic of most OECD nations, there has been a wave of new constructions led by China and India since 2010, and these nations are developing geopolitical strategies to develop new nuclear technologies in developing nations. Overall, the status of nuclear as an industry is negative as many of the indicators present a state of deterioration in the functioning of the commercial nuclear technological innovation system. These results are in line with similar reports from the IEA and MIT, which also identify similar assessments and problems regarding the overall hopes for commercial nuclear energy.

This dismal state of the industry and its prospects, however, do not fully negate its potential for inclusion in the US energy innovation system. A primary factor for this is the broader issue of technological diversity. It is incredibly difficult to come back to nuclear technology once abandoned as recreating the highly qualified labor, specialized regulatory environment, and the complex network of sociopolitical and institutional support is difficult to recreate once lost. There is a serious question policymakers must ask when considering full de-nuclearization as they must identify what a “good” level of technological diversity is and if it is worth it as they manage the tradeoff between swift green transitions caused by the dire state of climate change and the potential challenges generated by renewable technological lock-in. Fundamental uncertainty plays a critical role here as well since this study does not account for the potential for radical innovation to disrupt the future commercial nuclear market. Therefore, a national innovation systems framework that focuses on the role of high-risk, high-reward nuclear energy research and development within the current mission-based policy framework that the DOE is implementing through ARPA-E to combat climate change is crucial.

Contrasting the neoclassical role of government with mission-based policy

The neoclassical tradition in welfare economics identifies that individuals who are pursuing their own endeavors within a competitive market will result in Pareto-efficient outcomes. If these conditions exist, then the state has a minimal role in the market as they are solely limited to addressing temporary deviations away from Pareto-efficient market outcomes. These deviations can arise under transaction costs, temporary, imperfect information through information asymmetries such as moral hazard, through the existence of non-competitive markets, or if externalities exist. Even given these conditions for the state to aid in nudging the market back to equilibrium, public choice theory hampered decision making. Since all agents, including government agents, are self-interested, policymaking is hampered as the interest of politicians will become captured by interest groups via financing. This can create “government failures” when the state attempts to tinker in the market as the policy response will become morphed away from the intentions of the public as policymakers cater to their own interests. This creates a peculiarity within the neoclassical tradition that analysis of policy action must be focused on justifying and measuring the lack of government project failure, as the default assumption is that markets are efficient and find the best outcome. Given this market fundamentalism, the prescription for policy is often dreadful inaction, as policymakers fear that interventions will only worsen the status quo (Mazucatto, 2020).

This fearmongering translates uniquely into the neoliberal policy practice regarding innovation, industrial policy, and structural change. Only certain elements of the technological development process, specifically early-stage R&D, are treated as a public good and, therefore, can have justifications for state aid. Market fundamentalism is pertinent, as it is viewed that the private sector is an exceptionally capable innovator whose entrepreneurial prowess and decreased risk aversion under competition define their aptitude. The state, in contrast, is treated as a risk-averse entity that is terrified of committing a government failure if it is too proactive in attempting to “pick a winner” in the research and development market. The only public goods that the state is justified to provide in the neoliberal context are regulatory public goods. Since markets are presumed to be efficient, the only tools that the state needs to apply are those that “set the table” for competition. The removal of market frictions (such as decreasing transaction costs or creating a legal system that clearly defines private property) being the primary regulatory public goods, with the exception being a justification for state programs that increase human capital and aid in labor market fluidity such as skills training programs. This minimalistic role generated discontent among policymakers and heterodox economists, as the suggested innovation policy portfolio was historically disembodied from the policy mix of technologically creative nations. As will be further described later, innovative mission-based policies such as DARPA are radically innovative and immensely successful as they have not existed to “fix” markets but to create them. Policymakers and heterodox economists wanted to shift the discussion on policy into one that evaluates policy in a framework that acknowledges the potential for both government failures and market failures and that under fundamental uncertainty, it is impossible to remove all failures and externalities at once, which necessitates “the need for policies that support scale economies, dynamic learning effects, and cross-sectoral spillovers.”(Mazucatto, 2020)

In a more macro-economic sense, market fundamentalism still plays a crucial role in determining the role of the state as monetary and fiscal policy is limited to being a countercyclical tool that balances out the adverse impacts of the business cycle. The state utilizes rules-based frameworks to avoid a government failure arising from intervention, which makes many discretionary interventions unfavorable. Fiscal policy in this context is reined in by budget deficit targets that aim to produce a "balanced budget" over time. That is not to say that deficits and surpluses cannot be run momentarily, but that for a healthy economy, they should average out to zero over the long haul. The stringency generated by welfare economics and public choice theory birthed a culture of impact analysis that relied upon cost-benefit analysis as the workhorse to gauge a given policy's effectiveness. The neoclassical viewpoint fails to embody any outright justification for the mission-oriented and market creation courses of directionality that exist in mission-based policies such as DARPA that created innovations as radial and creatively destructive as the Internet. This framework is a necessity to address the grand societal challenges we face today (Mazucatto, 2020).

The market tinkering approach ignores insights that can be gained from the analysis of the structure of public sector organizations that is necessary to properly utilize high-risk investments. Furthermore, the assessment criteria for public investments are inherently problematic in the neoclassical paradigm. Tools such as cost-benefit analysis are ahistorical and incapable of handling complexity and dynamism as a basis of success is blinded to anything other than allocation. Cost-benefit analysis attaches a probability to a given technological development outcome, but this is blind to fundamental uncertainty as there is no underlying probability distribution to the development process of every single technology. For example, it would be ridiculous for somebody in the 1990s who is attempting to map out potential technological developments of the cereal Captain Crunch in 2020 to include “Oops All Berries!” as a path development outcome for the cereal brand. Since the idea of such a cereal would not even occur to the individual since nothing like it existed at the point of analysis. But despite there being no clear underlying probability distribution of the cereal at a time, it was nevertheless still created, meaning that the ontological premise of every action having an underlying probability distribution function is flawed as it ignores fundamental uncertainty.

Application to Nuclear Energy’s role in the US energy innovation system:

Climate change is perhaps one of the greatest existential threats that modern governments have to address. Mission-based policies that are engaged in market-shaping are a popular answer, and for the United States addressing this issue within the energy sector is done through the ARPA-E program. Modeled after DARPA, this program aims to promote an independent energy system that decreases reliance upon traditional fossil fuels in favor of carbon-free systems of energy. What is unique in the US approach to a green answer to climate change via our energy systems is that unlike OECD nations such as Germany, nuclear is not blatantly excluded. Mazucatto states that “The current global industrial system must be radically transformed into one that is environmentally sustainable. Sustainability will require an energy transition that places non-polluting energy technologies at the fore. It moves us away from dependence on finite fossil and nuclear fuels and favors ‘infinite’ sources of fuels.” (Mazzucato, 2015). This is certainly the case with Energiewende in Germany, as the mission is to de-nuclearize and transition energy systems to renewables.

What is unique to ARPA-E is that nuclear is a part of its portfolio. Therefore, after a brief comparison between the DARPA and ARPA-E models, I will evaluate several of the nuclear projects within ARPA-E to determine if these projects are focused on the high-risk, high-reward aspects of nuclear energy that would normally not be invested in by private firms. Furthermore, are these projects in research areas that are potentially groundbreaking enough to increase nuclear power's viability in the context of a green energy revolution? Because as identified by the TIS analysis of commercial nuclear, it is clear that the current status of commercial nuclear is in decline and that it is forecasted to continue its downward spiral. But this doesn't identify the role of funding basic research in the current US national innovation system. Since radical innovations can have such a dramatic capacity for creative destruction and since the US DOE is institutionally embedded into nuclear research, what a primary question for nuclear energy's role should be isn't whether or not nuclear will be the next dominant form of energy production. Rather, the question should be if keeping the current complex institutional mix is "worth it," considering the promises that nuclear energy can have in offering consistent carbon-free energy and considering the difficulty of recreating the current institutional network if a future radical nuclear innovation occurred. Therefore, if ARPA-E is financing potentially radically innovative areas of research, then policymakers should be content. Keeping nuclear even at the periphery of investment would be worthwhile since recreating the institutional mix of regulation and research exhibited today would be almost impossible if we engaged in full de-nuclearization.

A key aspect of ARPA-E’s mission statement is to remain dominant in scientific energy research. Nuclear energy is certainly a component of this, and therefore deserves its role in ARPA-E if we want to remain at the cutting edge of energy in broad. Furthermore, it is truer to the evolutionary approach to accepting nuclear as a component because current experts identify that it has characteristics that are conducive to success in addressing decarbonization. The technological risk landscape is bumpy and uneven. If we simply exclude potential paths that can achieve the main objective based upon contentious concerns, we are blatantly limiting our capacity to succeed. Climate change poses such an incredible threat to every sphere of life, and industry experts identify that if we want to change our energy systems to combat this grand challenge, then nuclear can play a role (especially in creating consistent power).

The approach adopted by economists such as Mazzucato, who push for 100% renewables, is unknowingly solely relying on a dramatic and rapid development in current storage capacities to offset the variation of the renewable energy’s generation cycle. As Hansen previously indicated, if all the storage capacities in the state of California as of 2016 were utilized to store energy to power the grid, we could only power the grid for twenty-three minutes. How are we supposed to transition fully to renewables if current capacities for storage can only provide such a limited timeframe of energy? What are we to do when there are entire years of underproduction due to decreased wind or sunshine? This is why variety in production is so critical to the clean energy system. Nuclear, even in its inferior LWR form, has empirically been a variation in energy production that has proven to offset fossil fuels. Excluding nuclear energy from the current innovation system pushes us into a situation where, if we want full decarbonization, we must solely rely on a dramatic innovation in storage capacities. Is that really what we want? Or, do we want a low-carbon energy system that under fundamental uncertainty pursues multiple potentially fruitful paths that fall under the grand objective of decarbonization?

Additionally, as exhibited from the TIS study, many nations are choosing to opt into nuclear energy via contracts with state-owned enterprises such as Russia's Rosatom. In the past, fears of non-American international influence played a major role in the AEC's development of LWRs and their diffusion through programs such as Euratom. While it would certainly be a false equivalency to equate cold-war soviet fears to current US energy policy, a central question should nevertheless be if leaving nuclear energy in the international community is worthwhile? What is the opportunity cost of losing out on nuclear energy developments abroad?

It is useful to utilize Mazzucato's (2020) ROAR framework to analyze the usefulness of current mission-based policy in the DOE to answer the question of nuclear energy's role in the national innovation system. Specifically, contextualizing ROAR to ARPA-E's nuclear projects will aid in answering the question of nuclear energy's role in the U.S. Energy Innovation System.

Routes of directionality:

Establishing a clear direction for issues to be solved is a necessary key for a successful market-shaping innovation policy. These policies necessitate cross-sectoral investments and numerous bottom-up solutions, and while some fail, failure should be treated as a part of institutional learning necessary to direct future successful policies. Creating the correct mix of bottom-up and top-down solutions is crucial, as too much of a bottom-up focus will make technological progress dispersive with minimal effect, while too much of a top-down focus can stifle innovation. The primary difference between the old ‘Moon-shot’ sort of mission-oriented policies and new mission-oriented policies is that technological challenges alone are not the focus. Rather these missions focus on changes across many political and economic sectors. Energiewende, for example, is Germany’s energy policy aimed at combatting climate change, phasing out nuclear power, and improving energy security and independence by gradually eliminating imported fossil fuels and replacing them with renewable resources. This policy establishes the desired direction of technical change and encourages growth across different sectors. In this way, the policy is changing the direction of these sectors to a desired socio-economic objective. What is crucial is that it is not simply an objective statement to “go green” as it is mandating that traditional sectors such as steel and others alter their production, service, and energy consumption practices to be in line with the mission statement. This creates technological, social, and behavioral spillovers alongside clear economic aims (Mazucatto, 2020).

New age mission-based policies aim to tackle grand challenges, such as climate change, and therefore must be broad enough to create public engagement, enable discrete missions, and bring in cross-sectoral investment, all while ensuring that industry is involved and that measurable successes are achieved. Setting the direction for an answer to climate change is not the same as missions specifying how to precisely achieve success. Instead, missions kindle the creation of an array of unique solutions that have the capacity to achieve the objective. Mission selection criteria, therefore, play a critical role. Missions should be selected in a way that increases societal value, establishes clear targets, incorporates innovation and research, is cross-disciplinary, and incorporates several competing solutions and experimentation that is bottom-up (Mazucatto, 2020).

Take ARPA-E’s mission statement: “ARPA-E’s mission is to decrease our nation’s dependence on foreign energy sources, reduce greenhouse gas emissions, improve energy efficiency across the board, and maintain or reestablish U.S. scientific leadership in the energy sector.”. This statement can be broken down into several missions, such as a carbon-neutral energy system. This mission can then inspire research and innovation into improved reactor designs, fuel cell research, and other projects. This market-shaping mission-based approach surpasses the traditional market tinkering static state viewpoint, which prioritizes Pareto-efficiency and Jevonian value. Market shaping forms of policy do not just alter public investment strategies but also include a larger array of institutional features of markets, including creating demand for new products through procurement and establishing a robust regulatory framework through the establishment of environmental standards.

ARPA-E’s nuclear energy projects fit well into this route of directionality aspect of a successful mission-based policy as they clearly have the potential to improve the nation’s energy independence, reduce carbon emissions, maintain U.S. scientific leadership in the energy sector. With respect to ARPA-E, nuclear projects are sub-sects of the overall mission that have the capacity to fit the bill in achieving energy independence, reduced carbon leadership, and a continuance of scientific leadership. The nuclear projects each identify that the research conducted, whether advanced reactor projects or fusion projects, identify that the research within the project has the capacity to decrease carbon emissions. The projects specifically identify the necessity of the role nuclear will need to play in combatting climate change, which sets a clear route of directionality as it identifies that nuclear needs to be a component of the U.S. energy innovation system. The projects also have obvious benefits in ensuring U.S. energy independence as all portions of the energy production process are conducted domestically. With respect to setting a route of directionality to energy independence, the nuclear projects fall well within this line. After all, for France, the nation pursued its own energy independence for electricity generation via the creation of nuclear energy facilities. With respect to scientific leadership, the research conducted through ARPA-E's nuclear projects clearly seeks to maintain its role in scientific advance. The ALPHA project is a fantastic example of a pursuit of scientific leadership as the creation of the intermediate density fusion reactor. This was an approach never before pursued by private or public researchers and generated an entirely new form of fusion reactor that is more efficient than its peers.

Organizational Capacities in the Public Sector

Creating the skills, capacities, and structures that are capable of increasing the likelihood of a public organization's success at learning and creating symbiotic private sector relationships are critical to achieving success via mission-oriented policies. Successful public-private partnerships should rethink their relative roles as far too often, the public portion of engagement is limited to de-risking private capacities. This limitation of the public role ignores the capacities and challenges that are involved within assigning risk to the public sector as de-risking focuses upon minimizing potential risks associated with losing projects instead of maximizing t\he likelihood of picking winners, which necessitates a catalog approach to public investment. Within this approach, the gains generated from just a few successful projects have the capacity to not just cover losses from failed projects but also enable learning in the project selection process for investment decision-making. Failure in this context is acceptable as long as the institutional structure generates enough winning policies that have the capacity to cover losses and that losses are properly utilized as learning opportunities to improve and renew later projects. This falls well within the evolutionary framework set out by Nelson and Winter as "The design of a good policy is, to a considerable extent, the design of an organizational structure capable of learning and of adjusting behavior in response to what is learned." (Nelson and Winter, 1982).

The ARPA-E program and its nuclear projects are a prime example of a successful organizational capacity in the public sector as the public-private relationship is foundational. There are many examples of unique projects within these programs that are established as an explicit public-private partnership, one of which is the HolosGen-Transportable Modular Reactor project within the MEITNER program. Many of these projects are conducted in coordination with universities and with the national lab system, which fosters the research process. This emboldens learning capacities as the dynamic capabilities of the partnership can provide directionality to the basic science research conducted at the public level to generate technologies desired in the private sector.

Furthermore, the emphasis on generating learning capacities is a clear extension of the Aalborg school of national innovation systems as learning takes a dynamic center for economic analysis. Nevertheless, the application of the dynamic capabilities of the public sector is limited in the literature. However, developmental state literature identifies that the success story of generating strong public sector capacities for the Asian tigers can be attributed to "the by talent recruited and motivated via Weberian means of meritocratic recruitment and career management to make working for government either financially competitive and/or culturally even more rewarding/prestigious than working in the private sector." (Mazucatto, 2020) Merit-based recruitment and career systems as well as creating a policy orientation aimed at development supported by small and relatively cheap bureaucracy centered around an organization that has its own degree of autonomy, such as the Ministry of International Trade and Industry in Japan, is crucial to developing a Weberian framework of capacities.

However, challenge-driven public policy needs to be based on an evolutionary understanding of the capacity of the public sector. This pushes innovation policy to favor the lead-and-learn approach of creating and shaping markets with numerous policy tools that have open-ended impact horizons and that learn throughout their lifespans from coordination with private actors and engagement with society. This drive to create engagement with a wide collection of social actors and the ability for the public sector to show leadership in vision is vital to success. ARPA-E's nuclear programs achieve just this, as the directionality of the projects is influenced by both public and private institutions. This open and wide collection of institutions being coordinated by leadership in the public sector offer a significant role in guiding the research process in a manner that has the greatest capacity of novelty generation.

Too often, previous policies aimed at engagement create rigid top-down planning exercises and practices that are simply a continuation of the static quo. But the nuclear programs with ARPA-E are not this Ayersian form of an appeal to ceremony. Rather, the current projects seek to fund the highest risk of failure but highest potential reward efforts that private venture capital fails to fund. Whether it is the intermediate fusion reactor design under the ALPHA program or if it is via increasing the efficiency and safety of advanced reactor designs, the ARPA-E projects seek to advance current fusion research efforts and to increase the efficiency and safety of a potential commercial advanced nuclear reactor. Furthermore, missions are not just about generating technological solutions but about the expansion of experimentation capacities and therefore are evaluated by their ability to integrate research and system-level reflection.

Assessment and Evaluation:

Connecting the budgetary process to the application of a public-value-based policymaking forward is challenging as current public policy talks begin from current fiscal constraints rather than the desired outcomes of their policy goals. While governments typically aim to discipline their spending by establishing a ratio of borrowing to current GDP or last year’s borrowing, this fails to account for multiplier effects attached to spending. Also, since the US federal government is a currency issuer rather than a taker, there is not the same fear of bankruptcy that the private sector experiences. This allows public policy to focus upon achieving desired missions unconstrained by the relative size of the government deficit. This concern of the deficit will fluctuate across time, however, depending upon private sector confidence and the status of the business cycle. Inflation still is a consideration as it is obvious that sometimes an economy can face capacity constraints shown through rising prices which can necessitate contractionary fiscal policy. The point here is that budget deficits in a mission-based policy format have a less prominent role in decision making than it does in a market-tinkering approach.

It is important to criticize here the policy evaluation techniques offered by the market failure framework as they exhibit a blatant disregard for evolutionary capacities. Current policy evaluation is being placed within a constraint-driven budgetary process, and therefore policy appraisal techniques focus upon allocative efficiency and ex-ante cost-benefit analysis (CBA). Ceteris Paribus, costs are defined through their opportunity costs, and market prices are defined by the base year of analysis. CBAs typically apply various discount rates to reflect variations in the time preferences of users of the service for having money in the present rather than later. Upon completion, the results are adjusted for inflation, and the benefits and costs are summed to calculate a net present value for various policy options. Some analyses attempt to monetize social and ecological externalities upon realizing the potential for externalities. The hope that neoclassical economists have in this approach is that the establishment of an intervention's market price will allow policymakers to make informed decisions that maximize welfare. However, the foundation of these analyses is flawed as they just exist to prevent a failed policy, not to inform the public about the capacity for policy to be proactive in market shaping and creating. Under fundamental uncertainty, not all path developments can be foreseen, so it is unclear as to why the neoclassical tradition is so routed in the CBA approach to innovation. The very nature of innovation is change, and while CBA can somewhat describe a subject in motion, it fails to capture fundamental change in results.

For example, CBA would fail if utilized as an evaluation tool for DARPA as it was fundamentally uncertain that technologies such as ARPA-NET would become so creatively destructive. The over-reliance upon accounting costs alongside poor estimations of extra-economic costs and benefits fails to account for the very dynamism that makes mission-based policy evolutionary and unique. Missions’ primary purpose is to radically change the current availability and existence of goods and services by drastically accelerating innovation, which makes the static ceterus paribus assumption so problematic in traditional economic evaluation. Constantly comparing all policy options to the status quo too heavily emphasizes short-term risks as it encourages decision-makers to favor only marginal interventions. Yet, “there is considerable evidence that innovation systems exhibit increasing returns or an ‘S-curve’-type effect, where shifting incentives across multiple sectors may be more likely to achieve such increasing returns” (Mazzucato, 2020), which implies that, if anything, there should be a large-scale bias surrounding innovation policy. The optimization bias furthermore ignores the integral learning process of the innovation systems format that is integral to achieving critical technological advancements. CBA answers what the *current* optimal allocation of fixed resources is. It does not acknowledge a dynamic interpretation of efficiency that evaluates the best use of resources to reach a desired goal over time. This approach is concerned with shifting the technological frontier through the creation of new resources via innovation and investment. Dynamics, therefore, are much more crucial as an evaluation tool today, as while the ‘Moon-Shot’ policies of old had clear endpoints, current missions that address grand challenges are much more long-term and have foggier endings.

Dynamics within evaluation are critical in evaluating the potential usefulness of some of the ARPA-E nuclear programs due to their long-term time horizons and foggier endings. However, what is clear from industry input is that advanced reactor technologies (and nuclear in general) can serve as a critical answer to the grand challenge that is climate change. Hansen and other pro-nuclear environmentalists emphasize the role that nuclear must play in the green energy revolution. Specifically, nuclear fills the role of easing the renewables energy generation cycle when those technologies are under-producing. Advanced reactor designs are already at a point of research and development that a commercial reactor is technologically feasible. These reactors are much safer, smaller, and more efficient than the LWR design, which is exceptionally promising as the analysis provided by Hansen on the capacities of nuclear were on existing LWR designs. The ARPA-E nuclear projects, such as MEITNER, enhance the current capacities of the advanced nuclear reactors to improve their safety measures and to decrease their capital costs. Therefore, when we ask what forms of variety are useful to our clean energy system, the step once routes of directionality are established, and organizational capacities in the public sector are created is to assess and evaluate our options.

Upon assessment, we cannot ignore the productive and safety capacities of current (albeit inferior) LWR designs, as the next-generation reactors have the capacity to leapfrog the successes of the LWR. Dissenters of nuclear energy often neglect the empirical findings of those like Hansen and, upon evaluation, misuse analytical tools borrowed from neoclassical economics to discredit the capacities of nuclear. Or they identify a nuclear accident and express fear of the next accident if we continue to pursue nuclear and if it becomes locked in. With respect to the utilization of cost-benefit analysis style critiques, it is clear that under uncertainty, costs and benefits cannot be uniquely identified over large time horizons, especially if the object of analysis is undergoing innovation as innovation fundamentally changes potential costs and benefits over time.

This applies to current nuclear projects because current analyses often cite current cost overruns and safety concerns that originate from the LWRs of the seventies. This is obviously problematic as it ignores the innovative capacity that the nuclear industry has exhibited over the past fifty years to improve reactor designs in terms of productive capacity and safety. With respect to fear of an accident, Hansen well established the safety of nuclear with empirical findings suggesting nuclear energy has globally saved two million lives due to preventing emissions from fossil fuels. Findings in line with Hansen in the anti-nuclear approach are overlooked primarily because of the immediate effect of a nuclear incident and the fear it generates. But an airplane crash is similarly catastrophic, and yet you don’t see mass boycotts of commercial airliners. Rather, faulty designs go over heavy scrutiny and are treated as learning opportunities for future aviation technologies in order to create a better aviation system for the future. The same mentality needs to be adopted in attitudes to nuclear if we want to have an honest shot at the decarbonization of our energy systems. To properly evaluate the capacities that nuclear energy can offer to create true decarbonization, we must evaluate it in a manner that addresses safety in a clearer light and in a manner that asks if it is a variety of production that is worth pursuing given the results of current de-nuclearization efforts on energy production.

Risks and Rewards:

A question that needs to be more frequently asked among policymakers is: why do we publicize the risk of research and development but privatize all its rewards? Because it is common practice for a portion of the rewards of research and development financed through private venture capital to be distributed to investors. However, if the public finances innovation, the only reward we are expected to receive is just the creation of the product. But having the state earn even a minuscule return from successful projects could provide the finance to cover inevitable losses alongside the costs of future investments. The path-dependent cumulative nature of innovation feeds this need since returns from investments will come in slowly as it can take decades for firms to begin and build up to the potential of generating large profits. After Tesla took substantial public sector investment, it took until recently for the firm to receive profits. But the public sector had no equity attached to its investment. The public's only reward was returns generated via knowledge spillovers that were created through the tax system since the expansion of Tesla created new jobs and increased tax revenue from Tesla itself. However, since the patent system has evolved to a state where it is relatively simple to create patents on upstream research, the heavily reached benefit of knowledge dissemination is essentially blocked, which constrains knowledge spillovers.

Since innovation is cumulative and experiences dynamic returns to scale, countries can reap significant gains from being the first movers in developing new technologies. However, in a post-Breton Woods era that permits the free movement of capital, a particular nation funding initial investment into innovation is not guaranteed to receive the full economic benefits relating to innovation. Corporate tax avoidance and evasion are rising, and behemoths such as Apple and Google are the most egregious cases of receiving significant public support while continuing to abuse the tax system through international operations. This damages the capacity for policymakers to evaluate downstream innovation investments that are targeted at specific technologies as a portfolio. Evaluation as a portfolio is essential since, under fundamental uncertainty, some investments will fail, and therefore gains from upstream successes are needed to cover downstream risks. These factors provide a strong case for arguing that the state should reap some financial gains from the technological breakthroughs it has financed by retaining ownership of a small proportion of the intellectual property it aided in creating. Of course, no one is arguing that this should be some exclusive license or should be an ownership proportion large enough that it deters diffusion. The government certainly should not be run like a commercial enterprise. It instead should run in a method to spur innovation elsewhere. Retaining even a minuscule proportion of the value the state created from its investment can generate plenty of funds that can be reinvested into new projects. For example, imagine if the US government had even a sliver of equity in technologies it created through DARPA, such as GPS and the internet. The amount of revenue generated would be enough to finance such a broad array of future innovation policies that it could cover failed investments such as Solyndra ten times over.

This concept of equity in innovation investment is nothing new, as state-owned venture capital activity is commonplace in Finland through Sitra and in nations whose state-development banks attach equity to their investments, such as Brazil, Germany, and China. While certainly the idea of the state owning even a non-controlling stake in a private corporation would have capitalists like Rockefeller rolling in their graves, a non-controlling stake in the form of preferred stocks that receive priority in dividends doesn't alter the freedom of the firm to engage in its desired decision making. The traditional market tinkering approach has enabled the public to criticize policy too quickly for its failures and to appreciate success too slowly. Instead of losing sleep over solely attempting to pick winners, there needs to be more focus upon how the rewards of investment can be distributed in a manner that can cover eventual losses and raise funds for future projects. This necessitates a tax system that can effectively support innovation and mechanisms for the state to receive rewards when it makes specific investments into companies.

ARPA-E's Nuclear Energy Programs:

ALPHA

The Accelerating Low-Cost Plasma Heating and Assembly (ALPHA) program strives to empower development toward fusion energy through establishing an array of technological options that can be pursued with experiments that are smaller, with lower costs, experience short construction times, and exhibit high experimental throughput. Current orthodox fusion research utilizes either magnetically confined fusion or inertially confined fusion. Each methodology is difficult to recreate within the industry as they necessitate costly facilities. However, under ALPHA, the purpose was to increase research and development into a class of magneto-inertial fusion reactors. These reactor's fuel densities are a form of middle ground between the current magnetic and inertial fusion designs (Nehl, 2019).

The pursuit of fusion research within the DOE is not new. For decades, the DOE has pursued potentially transformational fusion opportunities. However, despite fusion often being delegated to the realm of “big science” (which is the opposite of most ARPA-E programs, which are typically small, targeted, and short-term), ARPA-E, until this program did not have a role in nuclear. Upon starting ALPHA, ARPA-E aimed to change the traditional dynamic by bringing in an assortment of smaller groups and private startups who are pursuing fusion development and by bringing in additional private sources of funding (Nehl, 2019). This is a clear enhancement of the organizational capacities in the public sector as fostering the relationship between smaller groups and private startups who are currently pursuing fusion development can offer additional private sources of funding and input into the basic research that needs to be pursued in order to generate fruitful technological applications.   The primary motivations for the ALPHA program were driven by an analysis signifying the potential for lower-cost technological development pathways for fuel densities in between the standard approaches. Furthermore, substantial experimental results from both orthodox methodologies alongside increasing private investment into fusion research opened up the chance for new approaches to fusion that can attain cost gains (Nehl, 2019).

Analyses show low-cost opportunities for fusion approaches utilizing intermediate density with very high magnetic fields that can achieve significantly lower costs than the traditional MCF or ICF approaches. These cost savings come from scientific developments in fusion research. However, increased private interest in fusion is also propelling this form of program. Tri Alpha Energy (TAE Technologies) here in the U.S., Tokamak Energy in the U.K., and General Fusion in Canada are the primary firms pursuing fusion interests. Considering the existence of private interest despite the extremely high technological risk and long timeframes of fusion, a program like ALPHA could serve as a perfect opportunity to act upon this interest. A central purpose of the program was an aim to expand the field of fusion by providing further options for fusion development that can perform at various levels of funding with private investments. Upon identifying the potential for low-cost pathways achieved through previous scientific research that is supported by experimental results, ARPA-E was able to identify this midway approach to fusion as a potentially transformational technology that had the capacity to change the directionality of fusion energy (Nehl, 2019).

Upon identifying these opportunities, ARPA-E launched the ALPHA program to investigate and expand upon the "intermediate-density" approach, which includes an array of approaches that share common attributes and are capable of achieving maximum ion densities between 10^{18} and 10^{23} cm^{-3}. The ALPHA program also specified cost goals, engineering gain goals, and shot rate goals of the proposed plasma systems in order to achieve experimental success soon while enabling the capacity for economically viable fusion reactors in the long run. Nine teams were awarded the opportunity to research under the ALPHA program. Each exhibited a diverse scientific methodology in order to achieve the density and cost goals. The ALPHA program also funded "Integrated Concept" teams whose exploratory efforts aimed to evaluate new components that could enable (in a broad sense) new paths for fusion. "Driver" teams that created technologies for the linear compression system that could then be utilized in MIF approaches. The "Applied Science" teams in the program engaged in experimental and simulation studies on the current orthodox approaches while the "Exploratory Concepts" team "developed novel plasma configurations and driver components." The list below identifies the institutions that can be categorized under these forms of teams. Due to the technological complexity of each research area, I have only placed them into the categories identified by the authors and have not provided an in-depth analysis of all nine team's research as that analysis is made explicit in Nehl 2019.

For the National Innovation System's analysis on nuclear energy's role in the ARPA-E program, what is particular to note is the variety of approaches and variety of actors engaged in meeting the objective set out by the ALPHA program (Nehl, 2019). Many of these projects exist in the form of public-private partnerships, which is an organizational capacity with proven success within other aspects of the DOE, such as within the national lab system. The national lab system has seen immense success due to aid in directionality that the private sector brings to the table, and it is a positive sign to see the ARPA-E program carrying this tradition.

Integrated Concept Teams:

- University of Washington/Lawrence Livermore National Lab: Sheared-Flow Z-Pinch for Fusion
- Helion Energy: Magnetic Compression of Field Reversed Configuration (FRC) Targets for Fusion
- Magneto-Inertial Fusion Technologies, Inc. (MIFTI)/ University of California, San Diego (UCSD)/University of Nevada, Reno (UNR): Staged Z-Pinch Target For Fusion

Drivers Teams:

- Los Alamos National Laboratory/HyperV Technologies: Plasma Liners For Fusion
- NumerEx. Stabilized Liner Compressor for Low-Cost Fusion

Applied Science Teams:

- Sandia National Lab/University of Rochester Laboratory for Laser Energetics: Magnetization and Heating Tools for Low-Cost Fusion
- California Institute of Technology/Los Alamos National Lab: Heating and Compression Mechanisms for Fusion

Exploratory Concepts Teams:

- Lawrence Berkeley National Laboratory/Cornell University: MEMS Based Drivers for Fusion
- Swarthmore College: Plasma Accelerator on the SSX

All teams operating in the ALPHA program under ARPA-E are mandated to allocate five percent of award funding to technology transfer and outreach activities. Research under ARPA-E is allocated to high technical risk but high reward technologies that are failed to be funded by private venture capital, and for fusion, this is particularly unique given the comparatively longer time horizons of fusion development which put the technology to market component of the program in a unique position. In addition to these technology transfer and outreach activities conducted by each program, ARPA-E also engaged in corresponding technology to market activities in order to continue momentum on further low-cost fusion efforts under the ALPHA program. Each team was asked to create a technology to market plan that outlines how their research could be implemented in a relatively quick and affordable way for commercial fusion energy while providing estimates for the estimated cost of development and phases of creation for their technologies. These deliverables aid ARPA-E in benchmarking the progression to end-of-project goals and expectations, which increases their understanding of future funding needs (Nehl, 2019).

ARPA-E provided the teams with an overview of intellectual property considerations and identified that with respect to global fusion energy patents, it was clear that the orthodox magnetic and inertial confinement approaches were dominant. This signified a clear opportunity for their "middle of the road" approach. Furthermore, more than half of the intellectual property assets for fusion have expired, suggesting "to ALPHA teams that they may wish to be judicious about the timing of filing given the 20 years of patent protection granted relative to the anticipated timeline to commercialization" (Nehl, 2019).

ARPA-E also engaged the teams with a large group of stakeholders interested in commercial energy, such as other government offices, several private investment interests, as well as electric-power and power-plant industry representatives. ARPA-E also commissioned a capital-cost study that generated an overnight-capital-cost estimate and a sensitivity analysis for four of the teams pursuing fusion-power-plant designs. Despite these estimates being conservative (since they were based on current nuclear plant technologies), the study concluded that the ALPHA concepts could achieve overnight capital costs of around one billion dollars. ARPA-E subsequently "commissioned an independent assessment of the prospects for low-cost fusion development by the JAON advisory group" (Nehl, 2019) and found that the middle of the road approach adopted by the ALPHA program is a plausible approach to controlled fusion and recommended further investment and research into making the technology feasible for commercial fusion power plants. The study also found that there was significant spin-off potential from their research (such as fusion space propulsion) and that “all promising approaches should be supported rather than focusing resources on early front-runners” (Nehl, 2019) While the results of ALPHA are promising, there is still “a great deal more development required before any of these concepts can be established as viable candidates for fusion energy.”(Nehl, 2019) Nevertheless, the successes generated from the program have generated interest in ARPA-E to generate a new fusion program that preserves the essence of ALPHA’s mission but is broader in scope.

With respect to utilizing the ROAR framework to analyze ALPHA as a component of the ARPA-E mission, it is clear that the program generates clear promise. Route of directionality is clearly established, and the organizational capacities are enhanced through the public-private partnerships and through the further technology to market steps that the ARPA-E program has teams undertake. These steps help accelerate basic science and research into technological applications that can be utilized within the commercial sector one day. Assessment and evaluation are also built into the ARPA-E program, and therefore each of these teams, upon completion, have assessed and evaluated the potentially marketable trajectories of their research. However, in regard to risk and reward, perhaps there is some room for improvement as these projects have not resulted in any form of equity for the public.

Under this framework, it is clear that the ALPHA programs meet the objectives of energy independence, de-carbonization, and especially scientific leadership. Fusion enhances energy independence as the materials, and other inputs are domestically available. And with respect to de-carbonization, it offers immense promise. While currently, a lot of progress must be made in terms of energy efficiency for fusion, it has that high-risk, high-reward aspect as it's the same methodology that our sun uses to generate energy. Fusion is the best textbook case of a technology that could potentially be incredibly radically innovative as it promises the potential for immense increasing returns if it reaches a commercially viable state. And as Robert and Yoguel 2016 identify, to succeed with mission-based policy in a national innovation systems format, one successful approach is to select sectors with increasing returns as they aid in novelty generation. Fusion is a technology that exhibits a high capacity to benefit from learning by using and can be a technology that, upon being increasingly adopted and experienced, can drive further improvements to the technology. These further improvements can build up incremental advantages to fusion which can potentially push the technology into a primary role over the current fossil fuel-dominated energy production techniques.

Nevertheless, if fusion becomes commercially viable, then fusion offers an energy production methodology with no carbon input (aside from plant construction). With respect to the objective of scientific leadership, it is clear that the ALPHA program and the intermediate density fusion reactor generated great successes in this regard. By definition, this is a high-risk, high-reward technology that was created in the public sector and was a research area that was previously unexplored with private venture capital. While necessitating further research and development, this new approach to fusion has the potential to be an increasing returns technology that is critical to the success of mission-based policy. Energy independence, de-carbonization, and scientific leadership are aspects critical to addressing the grand challenge of climate change and therefore make research and development into this aspect of nuclear energy a potential fruitful component of how our energy innovation system addresses climate change.

Current Nuclear Programs within ARPA-E

BETHE

The BETHE program aims to support the creation of timely and commercially viable fusion energy. The program builds upon recent progressions in fusion research and generates synergies with the developing private fusion industry as the program hopes to deliver an array of higher maturity and lower-cost fusion options through its three research categories. The first of which is the Concept Development category that seeks to further increase the performance standards of current lower cost but less mature fusion concepts. The Component Technology Development category aims to decrease the capital costs of the higher cost, but more mature fusion concepts and the capability teams aim to improve current existing methodologies and capabilities (such as machine learning) to better enhance the development of these concepts. The technology-to-market component of the project aims to enable a smooth fusion commercialization path through the incorporation of public-private partnerships. The program aims to bring the costs of controlled fusion down, “ARPA-E believes that a current commercial fusion power plant should target an overnight capital cost of <US$2B and <$5/W.” This target will help enable grid-ready fusion within twenty years, which is argued to aid in meeting the globally demanded cost-effective deep decarbonization energy goals by the latter half of this century.

The BETHE program follows the footsteps set out by its predecessor ALPHA since the ALPHA program aided in generating private interest, but “it is difficult for lower-cost fusion concept developers to secure enough funding to meet performance milestones, much less realize a grid-ready fusion demonstration. This unsustainable situation for lower-cost fusion concept development is a strong motivator for the BETHE program.” The potential impacts of the program are beneficial to the dimension of security, environment, and the economy as developing a commercially viable fusion energy system in a timely manner could ensure the U.S.’s lead in energy innovation and energy security. With respect to the environment, fusion drastically improves the likelihood of achieving global clean-energy demand and mid to late-century carbon goals. The economic benefit is a clear source of reliable, abundant, and highly dispatchable power that can enable a cheap transition to a low carbon economy.

The project listing for BETHE is larger than the other programs as there are fifteen total projects under BETHE. In appendix A, the Current BETHE projects list identifies the projects within the program and their descriptions. Nevertheless, it is clear that the expectations of these projects are aspirational and follow a similar trend as ALPHA and could even surpass the success of the ALPHA program given the project’s broader scope. This form of follow-up is incredibly fruitful to the generation of novelty as it follows up upon previous research under the ALPHA program. Following through is critical, as we cannot just generate potential routes forward and not see them through if the routes fall under the mission statement. Given the innovation need of the program, it is apparent that the work being pursued in the BETHE program falls well within ARPA-E’s mission statement and guidelines and pursues radically innovative fusion research that private capital is unable to foster (BETHE, n.d.). Within an evolutionary framework, we must continuously adapt our capacities and approaches to new information, and given that innovation is the dynamic center of the capitalist mode of production, it is imperative that the generation of basic science within mission-based policies is guided through the ROAR framework if we want to succeed in addressing grand challenges such as climate change.

GAMOW

GAMOW is a joint project between the DOE's ARPA-E and the Office of Science-Fusion Energy Sciences (SC-FES) that prioritizes "R&D in (1) technologies and subsystems between the fusion plasma and balance of plant, (2) cost-effective, high-efficiency, high-duty-cycle driver technologies, and (3) cross-cutting areas such as novel fusion materials and advanced and additive manufacturing for fusion-relevant materials and components" (GAMOW, n.d.). Current and past fusion research and development was fixated on creating the necessary fuel density, temperature, and energy confinement time that would be needed to create a feasible fusion energy system. As of now, investments have focused on creating technologies and materials that are necessary to generate a system of fusion energy that is commercially viable. Nevertheless, there needs to be more work done on this front as further innovations and advancements are needed for a technically and commercially viable fusion system. This program aims to aid projects that engage in research and development into fusion-energy subsystems and cross-cutting areas that can enable within the next few decades a commercially viable fusion energy reactor. Given that the program was released on February 13, 2020 there are currently no projects in the program (GAMOW, n.d.)

Nevertheless, while there are no current projects to analyze within the program, we can still utilize its innovation need statement to identify its role in a mission-based policy system. And based upon this innovation need, it is clear that the project aims to accelerate research and development into aspects of fusion energy that are not currently being pursued but nevertheless need development to generate a commercially viable fusion energy reactor. This has the potential to be radically innovative as pursuing the technological developments necessary for commercialization is vital if we want fusion to exhibit increasing returns. In my viewpoint, this pushes the project into the radically, rather than incrementally, innovative realm as we need non-carbon increasing returns technologies if we want de-carbonization policies to succeed in surmounting the fossil-fuels lock-in. Because while not necessarily altering the fundamental design, the engagement of research and development into fusion energy subsystems and cross-cutting areas is a component needed to bring down costs.

MEITNER

The innovation need for the MEITNER program is perhaps the most blatant link to the sub-optimal path that nuclear technologies followed through the light water reactor design. The innovation needs section states:

> Nuclear power provides about one-fifth of U.S. electricity generation, delivering reliable, low emission baseload power to the grid. These plants are all conventional light water reactors (LWR), the technology of which has evolved steadily over time. As utilities have begun retiring older plants, however, comparatively high costs have made it difficult to justify building new nuclear power plants. The low volume of new plant construction

> combined with expected retirements of existing plants is projected to reduce U.S. nuclear electricity capacity by 20.8 GW by 2050. For nuclear energy to contribute in the coming decades, the next generation of nuclear reactor plants need to simultaneously achieve “walkaway” safe and secure operation, extremely low construction capital costs, and dramatically shorter construction and commissioning times than currently available plants. To attain these goals, new, innovative, enabling technologies for advanced reactor designs are needed. The development of these enabling technologies requires an understanding of the interrelatedness of design choices. Thus, MEITNER encourages a rethinking of how pieces of the nuclear reactor system fit together when developing the technologies that will make these plants viable. In the building phase, cost savings may be realized through modular and advanced manufacturing techniques that bring most of the work to the factory instead to the construction site. Technologies that could reduce operational expenses include robotics, sophisticated sensing, model-based fault detection, and secure networks to enable substantially autonomous controls as well as a high degree of passive safety. (MEITNER, n.d.)

The clear need for a shift in directionality in reactor design has pushed ARPA-E to create the MEITNER program to find and create innovative technologies that lower the costs and increase the safety of advanced nuclear reactors in hopes to enable advanced reactors capable of creating a foundation for a modern, domestic nuclear supply chain. Advanced modeling and simulation tools will be utilized on the projects to improve them as project teams have access to input from an array of experts coming from nuclear and non-nuclear disciplines. ARPA-E itself, similarly to the ALPHA projects, provides a resource team that coordinated with the project teams on their techno-economic analysis and on modeling and simulation. If the MEITNER projects are successful, they can aid in future developments of secure, inexpensive, and safe advanced nuclear power plants. Nuclear is identified as security-enhancing as nuclear power plants provide needed grid stability through generating a reliable baseload power yearlong and “are among the most secure facilities in the country.” Nuclear also meets identified environmental goals as it has low lifecycle emissions and meets economic goals as it provides high-efficiency electricity generation for the U.S. grid. The primary challenge, however, is overcoming capital costs and construction times, a goal that advanced reactors can achieve given their decreased size and increased safety.

Unlike the ALPHA program, the MEITNER program is still ongoing as the project was only released on 06/04/2018. Therefore, industry experts have yet to engage in a retrospective “deep dive,” as Nehl 2019 provided for ALPHA. Therefore, for this project, Appendix List 2 provides the overview of the projects written by their respective teams for the project listings to provide an overview of the directionality of technological progress within the MEITNER program.

What is notable about the direction of advanced nuclear reactors is the departure from the LWR design that the industry is currently locked into. Specifically, six of these projects are working on technologies directly related to the molten salt reactor design or the high-pressure gas-cooled reactor design. The other projects concern cost reductions around advanced reactors in general. These considerations include better seismic alert systems to the integration of AI for operations suggestions (with the exemption of shutdowns, of course, as that requires an expert level of human input). What is remarkable about this is that this trajectory of research was somewhat identified in Ruttan (2006) as he mentioned that gas-cooled reactors appeared to be an interesting engineering endeavor of research into reactors but was not yet commercially viable. However, today it is clear that the commercial viability of advanced nuclear reactor designs within the ARPA-E program is becoming a primary area of focus in its nuclear-focused project areas. However, with respect to legislation, there is still a need for institutional regulatory innovation. While the nuclear regulatory council (NRC) continuously admits that they do not favor a specific reactor design, it is clear through legislative efforts that there is a significant need for the NRC to become prepared to regulate and license for commercial non-LWR style advanced reactor designs.

To meet this need, on January 14th, 2019, Congress passed the Nuclear Energy Innovation and Modernization Act. This bill " revises the budget and fee structure of the Nuclear Regulatory Commission (NRC) and requires the NRC to develop new processes for licensing nuclear reactors, including staged licensing of advanced nuclear reactors" (Barrasso, 2019). Section 103 of the bill is what is particularly applicable to the analysis here, as it establishes that "the NRC must (1) establish stages within the licensing process; (2) increase the use of risk-informed, performance-based licensing evaluation techniques and guidance; and (3) establish by the end of 2027 a technology-inclusive regulatory framework that encourages greater technological innovation" (Barrasso, 2019).

This timeframe is of particular concern as there are bipartisan efforts to expedite this regulatory preparation to be in line with commercial developments. Because as of now, there are over fifty advanced reactor designs across various stages of development within the United States, and several developers have even begun initial licensing activities. The first small modular reactor design certification was issued at the end of 2020, and two more are already in a pre-application phase. As of now, the NRC has identified over twenty advanced non-water reactor applicants with at least seven unique reactor designs that are almost prepared for the licensing application phase. Furthermore, the NRC received its first non-water reactor application in March, with three more novel designs being submitted by the end of 2020 (Barrasso, 2020). Alongside research projects within ARPA-E and other projects throughout academia and the DOE, it is clear that the area of advanced reactor technologies is rapidly innovating, which makes it imperative that the NRC's rulemaking can keep pace with industry if advanced commercial reactors are ever to be competitive on the market.

Therefore, the MEITNER program appears to be pursuing incremental innovations that are nevertheless important to ensuring commercialization success for advanced reactors. These projects are not aimed at fundamentally changing the current designs of molten salt or high-pressure gas reactors but instead are focused on augmenting them to achieve safety and cost objectives. For instance, the projects aimed at reducing building phase costs via advancements in modular and manufacturing techniques by bringing more of the work to the construction site do not fundamentally change the reactor design or the reactor creation process. Rather, they are focused on incrementally innovating these aspects of the nuclear reactor system in order to enhance safety aspects and decrease initial and operational cost concerns. These factors, I believe, do not justify a title of being radically innovative. The object of analysis (the reactor) does not fundamentally change. Nevertheless, while the projects are unlikely to be radically innovative, it does mean that they are unnecessary. These advancements are crucial to pushing the advanced reactor designs into a state of cost-reduction and safety that creates increasing returns. This is vital in an evolutionary framework if we want the advanced reactor designs to survive the selection and adoption process that fuels incremental advancements that are necessary to overthrow the lock-in of current fossil fuel dominance in energy generation for electricity.

GEMINA

The Generating Electricity Managed by Intelligent Nuclear Assets (GEMINA) program intends to create digital twin technology for advanced nuclear reactors and to change operation and maintenance systems for the next generation of nuclear power plants. This program aims to generate interdisciplinary teams that develop digital twin (similar) technologies for advanced reactor designs as the bedrock for their operations and management systems strategies. To do this, teams need to create tools that permit greater flexibilities in reactor systems, increased operational autonomy, and faster design iteration. The goal of the program is to generate a ten times operations and maintenance cost reduction at advanced nuclear reactors, which would substantially increase their economic competitiveness to conventional and renewable fuel sources. To achieve this edge in operations and maintenance systems cost reductions, teams will apply technologies such as artificial intelligence. The solutions these projects generate will focus upon cost reductions in operations and management at various levels of plant operation, from the reactor core to the entire plant system. Since advanced reactors are still within the design phase, the project teams will create cyber-physical simulations that simulate the operating dynamics of the advanced reactor core utilizing a combination of non-nuclear experimental facilities and software.

The innovation need for the program draws from anxieties of pre-mature nuclear reactor shutdowns in the United States. A primary reason for this is that, despite many considering nuclear power to be necessary to achieve a zero-carbon grid in the United States, current nuclear power plants are comparatively cost-intensive in some markets. Therefore, decreases in operations and maintenance costs could be significant in keeping plants competitive, as operations and maintenance costs consist of about eighty percent of a reactor's total generating cost. The nuclear energy industry has failed to deeply explore or to apply these forms of innovation, which generated a profound need to create effective, low-cost advanced reactor operations and maintenance methodologies. This is also an incredible opportunity for advanced reactor innovation, as learnings gained currently on existing nuclear reactors generate feedbacks into the design process of advanced reactors, which creates a bedrock for an optimal operations and maintenance structure. Overall, the innovative need for the program is clear as “GEMINA sets the stage for a future where advanced reactors operate with a staffing plan and fixed O&M costs more akin to those of a combined cycle natural gas plant than those of the legacy light-water reactor fleet. The program goal is to reduce fixed O&M costs from ~13 $/MWh in the current fleet to ~2 $/MWh in the advanced fleet.” (GEMINA, n.d.)

Similar to MEITNER, the GEMINA project is ongoing as it only started on October 2nd, 2019. Therefore, there has yet to be an in-depth analysis by industry experts analyzing the successes of the program. The Under Secretary of Energy Mark W. Menezes Identified that “As the United States’ largest provider of clean, emissions-free energy, nuclear power is an essential component of our Nation’s electricity supply. Investing in projects and R&D that will make our nuclear fleet more efficient and cost-effective is critical to ensuring this clean, reliable energy source continues to power our country for years to come”(Energy.gov, 2020). A similar sentiment is shared by the director of ARPA-E Lane Genatowski as they remark, “Advanced nuclear reactors have the potential to provide reliable and low-cost clean power to millions of American homes,” said ARPA-E Director Lane Genatowski. “These GEMINA teams are working to develop tools for the advanced reactors of tomorrow to improve operations and lower maintenance costs by designing more autonomous and efficient processes." (Energy.gov, 2020)

Therefore, similarly to what I provided for the MEITNER program, the intent was to provide an overview of the projects that were written by their respective teams for the projects and will provide an analysis of the directionality of the team's works within the GEMINA project to determine the directionality of technological progress within the GEMINA program. However, since the GEMINA is so relatively new compared to the MEITNER program none of the teams have yet to publish a written summary identifying the scope of their projects. Therefore, all there exists as of yet to analyze is the intent of the program. It is clear that the intent to decrease operating costs would aid in making current LWR facilities more competitive in markets where pressures from subsidized natural gas are decreasing their economic viability. The project's application of advanced technologies such as artificial intelligence has the capacity to be radically innovative to the management and operations structure of current and future reactors. Therefore, as of now, it appears that the direction and foundation of innovation need of the program appear to adhere to ARPA-E's mission statement and standards. Similar to the MEITNER Program, I would classify the GEMINA program as an incrementally innovative program in that the fundamental designs of the reactor technologies are not changing as they are simply being enhanced to be safer and cheaper via technologies such as artificial intelligence. These augmentations are necessary steps to ensure that advanced reactors are on a path to being increasing returns technologies with the capacity to overthrow the lock-in of fossil fuels in the U.S. energy system. However, it will take time for these projects to publish their scopes and to achieve their goals. So, for now, all that can be said is that the aspirations of the program appear somewhat hopeful.

Conclusion:

Mission-based policy provides a stark departure from the static, neoclassical-inspired policy tools offered within the market tinkering approach. ARPA-E, heralding much of its structure from the DOD's DARPA program, applies the market transformative mission-based approach to the nation's energy needs. While not directly acknowledged within *The Entrepreneurial State*, nuclear is a vital component of the ARPA-E program as it seeks to enhance energy security and push to a carbon-neutral energy system. Furthermore, many of the nuclear programs that ARPA-E hare are engaged in research and development that meet the "high technical risk-high reward" criterion. Fusion is particularly a radically innovative area, and the ARPA-E's ALPHA project stepped up by engaging in areas of fusion research that were not being pursued by existing organizations. As of now, we must wait and see what the MEITNER and GEMINA programs can produce, but in terms of expectations, their pursuits appear promising. Each program aims to simultaneously enhance the capacities of current advanced reactor designs while also offering potentially high cost-reductions to existing light water reactor designs.

Nevertheless, the innovation need declarations of each program make it blatantly clear that a primary desire is to overcome the technological lock-in of the light water reactor design and a secondary pursuit is to hedge against the current cost and operational constraints of these reactors. The innovation need sections, opinions of department leadership, and retrospective feedback from the industry all indicate that the nuclear programs of ARPA-E have the capacity to be radically innovative. Market creation through the generation of commercially viable next-generation today and the potential for future fusion reactors each have the capacity to alter current and future energy markets. And as Henson indicates, nuclear energy provides a key role in ensuring the stability of energy provision in a de-carbonized grid. While there are concerns other than emissions surrounding these technologies that negatively affect the environment, input from the DOE makes it clear that nuclear is a part of the U.S. approach to a low-carbon future. This also does not appear to be drastically sub-optimal in that the ARPA-E program is by definition a mission engaged in the simultaneous pursuit of growth and discovery. Projects within the nuclear programs are simultaneously engaged in discovering new production methodologies while enhancing current advanced reactor designs and enhancing legacy LWRs. This is a multi-faceted approach to address a blatantly in decline technological innovation system for commercial nuclear. While it is unlikely to be a complete remedy, pursuing radical innovations for nuclear technologies can nevertheless transform the landscape into something much less grim. Furthermore, if current projections of the TIS for commercial nuclear ring true in the future, it is not as if the U.S. has all of its eggs in the “nuclear” basket. After all, the ARPA-E program is engaged in numerous clean energy production methodologies such as solar and wind.

The funding and development of renewables research is a massive component of current research, especially within the ARPA-E program. Therefore, the “catch-all” approach of the U.S. energy policy criticized by Mazucatto; 2015 I would argue doesn’t lack directionality as it alluded. Rather, given the immense capacity of the U.S. DOE, the tradeoffs are not as dire as they are in other OECD nations. Furthermore, since the DOE is historically embedded in the pursuit of nuclear innovation, the capacities that the federal nuclear energy research and development system have within the United States is perhaps one of the most capable.

While satisfying the routes of directionality component of mission-based policy, the ARPA-E program, and its nuclear sub-programs also are clearly institutions that exhibit the organizational capacity to address modern problems and utilize assessment tools beyond cost-benefit analysis. While costs are certainly a concern many of the projects address, the basis of success is not on a static CBA criterion but rather, the criteria are much more concerned with innovative capacity. The nuclear programs evaluate success in terms of their capacity to radically change the technical capabilities alongside potential future economic efficiency concerns. Similar to DARPA, a key omitted factor to successful mission-based policy is the public reward component. This aspect could warrant future research as the variety of firms engaged in nuclear prospects, for example, are young in age compared to other current nuclear energy firms. Future research could also expand upon the component of the international relations of a modern U.S. nuclear energy research and development approach. Considering that most OECD nations are de-nuclearizing while other nations such as China and India are rapidly expanding their capabilities (and simultaneously these nation’s state nuclear entities are expanding abroad too), there is a clear potential for the U.S. to engage with not just China and India over energy but with many other nations that are seeking to develop energy independence and emissions goals through nuclear capabilities.

The evaluation of ARPA-E’s nuclear projects demonstrates not just that the state has the capacity to engage in nuclear in a market-creating sense as part of its response to climate change and the effort to de-carbonize our energy for electricity generation systems. Rather, these projects and commentary from ARPA-E leadership demonstrate that nuclear not just can play, but ought to play, a pivotal role in our national innovation system. The environmental input from Henson clearly identifies that with regard to consistency, costs, and safety than even the current LWR dominated industry has a role in addressing de-carbonization. And current nuclear phase-out policies such as Germany’s Energiewende show that de-nuclearization has simply resulted in nuclear plants being replaced by fossil fuels and has resulted in increased electricity imports originating from nuclear plants abroad. Therefore, it is beyond a shadow of a doubt that there is potential for nuclear in the clean energy technological risk landscape. And given the outcomes of current phase-out policies and concerns of storage for renewables, nuclear energy has a justified role in our national innovation system. Because again, this is not about directly selecting “winners and losers,” as under fundamental uncertainty, we cannot identify a clear “winner” in terms of all non-carbon energy production technologies. But rather, this study is about evaluating the inclusion of nuclear energy in our clean energy innovation system, which has recognized nuclear energy’s current potential to be a worthwhile source of variety in de-carbonized energy production.

Chapter Five: Conclusion

The technological risk landscape is bumpy, and under fundamental uncertainty, it is unclear what technologies will be the best paths to pursue. Despite this uncertainty and given the current state of the commercial nuclear energy technological innovation system, previous technological lock-ins, and growing social unrest concerning engaging the potential risk that nuclear energy entails, nuclear faces a challenge in being included as a path to pursue when facing the grand challenge of climate change. Nevertheless, the current difficulty felt by nuclear does not exclude it from being a worthwhile engagement in the national innovation system. While there have been advances in fuel cell research that have enhanced storage capacities and productivity gains which are continuing to make wind and solar more profitable, it is risky depending on these advances alone to push renewables into being the sole producer of energy for electricity that is consistent across time.

Because there will never be a policymaker that will push for an energy system that cannot guarantee that the lights will stay on. Consistency is the primary factor keeping nuclear within the clean energy innovation system as it offers a variety of production that is clean, safe and also offsets downturns of production in renewables when there are low-sun low-wind months, or even years. Current analyses on the consistency and safety that nuclear offers are still on the LWR design, and therefore the promise that advanced reactor projects can bring will exceed the efficiency and safety of current reactors. Alongside developments from mission-based policies such as ARPA-E, the advanced reactor design can relatively soon enter the market as an increasing-returns technology while current projects into fusion pursue perhaps in the truest sense, the high-risk, high reward research and development that private venture capital alone cannot facilitate.

Nevertheless, if we are to have a low-carbon energy system that is consistent enough and is inexpensive, solar and wind certainly play a role in energy production. But that is not to say that nuclear has no role in this innovation system. There are reasons beyond consistency and appeals to ceremony for why the DOE continues to pursue nuclear projects in its ARPA-E program. The promise of Advanced Nuclear Reactors in terms of safety, efficiency, and cost appears promising. Projects within ARPA-E have advanced fusion and advanced reactor technologies alongside other research within the national lab system. But the regulatory environment is still slowly but surely preparing for the U.S. commercial introduction of these technologies. Nevertheless, historically nuclear has been more successful in offsetting fossil fuel-powered energy plants than renewables ever have (Henson and Schellenberger) while simultaneously offering a non-carbon intensive and relatively safe option when compared to natural gas coal. Furthermore, there is always the promise that fusion has to offer if it ever becomes technologically and economically feasible at the commercial level.

Therefore, excluding nuclear from policy analysis in our energy innovation system is problematic as there are clear potential path dependencies that are worth evaluating. While current commercial nuclear currently looks bleak, the progress on the introduction of advanced commercial reactors alongside continued research in the high risk of failure, but high reward nuclear technologies can push advanced reactors into becoming increasing returns technologies that have the potential to offset the current fossil fuels lock-in. In addition, de-nuclearization would erode our current system's capacity to re-introduce nuclear if a radical innovation were to occur that pushes nuclear out of the periphery. Rebuilding these institutions is incredibly difficult and diminishes the system's capacity to turn codified knowledge of potentially radical nuclear developments into tacit knowledge. The opportunity cost of losing out on current nuclear energy projects abroad could also be great, as engaging now opens up a dialogue for future renewable energy projects. Therefore, despite the current decline in commercial nuclear energy, it is my belief that capacities for radical innovation, the consistency needed within the current variety of de-carbonized electricity production technologies, difficulty in re-building the current nuclear institutional network if said radical innovation was to occur, alongside current efforts to push advanced nuclear reactors into the commercial sphere should keep nuclear energy in our clean energy innovation system.

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Appendix

Current Meitner Programs

- HolosGen- Transportable Modular Reactor
    - "HolosGen is developing a transportable gas-cooled nuclear reactor with load following ability….HolosGen's reactor concept will provide low overnight cost, autonomous operations, rapid deployment, independence from environmental extremes, and easy electrical grid connection with near real-time load following capability….The project will improve the understanding of the turbine efficiencies and the coolant flow within the nuclear reactor." (MEITNER, n.d.)

- Moltex Energy – COST SSR (Composit Structural Technologies for SSR)
    - "Advanced reactors, including Moltex's stable salt reactor design, may be able to forgo large, expensive containment structures common in the current fleet of nuclear plants…. This new composite structural technology standardizes and expedites plant construction elements. In addition, this new technology presents an opportunity to accelerate construction for advanced reactors faster than solar, wind or combined-cycle power plants, significantly reducing the capital cost of next generation nuclear power." (MEITNER, n.d.)
- North Carolina State University (NC State) – Management and Control System for Advanced Reactors
    - "North Carolina State University (NC State) will develop a highly automated management and control system for advanced nuclear reactors. The system will provide operations recommendations to staff during all modes of plant operation except shutdown operations. Using an artificial-intelligence (AI) guided system enabling continuous extensive monitoring of plant status, knowledge of current component status, and plant parameter trends, the system will continuously predict near-term behavior within the plant and recommend a course of action to plant personnel. …. AI-guided models trained on data from plant monitoring instruments combined with expectations generated by advanced modeling and simulation can vastly improve the effectiveness of plant diagnosis and prognosis in plant management, as well as enable vulnerability search in safety analysis. In particular, the system will greatly increase the time available before operator action is required. This means that a significantly smaller operational staff—assisted by instrumentation, operator training, and smart procedures—is needed to manage the plant, reducing overall operational cost." (MEITNER, n.d.)

- Stony Brook University – Technology Enabling Zero-EPZ Micro Modular Reactors
    - "Stony Brook University will develop advanced technologies for gas-cooled reactors to increase their power density, enabling them to be smaller. The team seeks to develop a high-performance moderator—which slows down neutrons so they can cause fission—to enable a compact reactor with enhanced safety features. Shrinking the reactor size enables greater versatility in deployment and reduced construction times and costs, both of which are especially important for smaller modular reactor systems that may be constructed wherever heat and power are needed." (MEITNER, n.d.)
- The Research Foundation for the State University of New York (SUNY) – Reducing Overnight Capital Cost of Advanced Reactors
    - "The University at Buffalo, the State University of New York (SUNY) will develop seismic protective systems to safeguard essential and safety-class components inside nuclear power plants. Currently, these systems and components are custom-produced for each new plant, with multiple designs often needed for a given plant. Earthquake considerations may add up to 35% to the overnight capital cost for new plant designs in regions of moderate to high seismic hazard. This project will develop and implement modular systems to protect individual components from earthquake shaking effects. Because the systems can be implemented independent of reactor type, they will simplify plant design, facilitate economical reactor construction in regions of moderate and high seismic hazard, and enable efficient seismic protection of safety-grade equipment in reactor buildings. By focusing seismic protection on components that require it, the approach can facilitate reduced thickness of walls and slabs in other parts of the plant, further saving construction time and costs." (MEITNER, n.d.)
- University of Illinoi, Urbana Champaign(UIUC) – Enabling Load Following Capability in the Transatomic Power MSR
    - "The University of Illinois, Urbana-Champaign (UIUC) will develop a fuel processing system that enables load-following in molten salt reactors (MSRs), an important ability that allows nuclear power plants to ramp electricity production up or down to meet changing electricity demand. Nuclear reactions in MSRs produce unwanted byproducts (such as xenon and krypton) that can adversely affect power production. In steady, baseload operation, these byproducts form and decay at the same rate. When electricity production is ramped down, however, the byproducts start to be produced at a greater rate than they decay, leading to a buildup within the reactor. When power production must be once again increased, the response rate is slowed by the time needed for the byproducts to reach their equilibrium level (determined by the radioactive decay half-life,

    which is on the order of hours). Thus, buildup of these unwanted byproducts resulting from ramping down inhibit proper load following for molten salt reactors. Fortunately, MSRs transport fuel in a flowing molten salt fuel loop, which means that a section of the reactor, outside the core, can be leveraged for fuel processing and "cleanup." The team will determine the feasibility of removal of these unwanted byproducts and design a fuel reprocessing system, removing a major barrier to commercialization for molten salt reactors." (MEITNER, n.d.)

- University of Tennessee at Knoxville – Magnetically Suspended Canned Rotor Pumps for the Integral Molten Salt Reactor
    - "The University of Tennessee and Oak Ridge National Laboratory (ORNL) are developing and performance testing an innovative prototype pump for a small, modular, advanced molten salt nuclear reactor (MSR). The reliability of fuel salt circulation pumps is important to MSR commercial deployment since these pumps must operate leak-free for years at high temperature and in an extreme radiation environment. Present generation pumps are restricted to long vertical shafts with bearings located above the salt line, decreasing both pump lifetime and efficiency. This project will incorporate two innovations that will dramatically improve the reliability of molten salt pumps—magnetic bearings and canned rotor structure. This design will eliminate the need for shaft seals, a preferred approach identified in the MSR experiment at ORNL in the 1960s. The proposed pump will also employ advanced electromagnetic materials suited to MSR operating temperatures and radiation levels. Lastly, operating this fuel salt pump and monitoring its performance will require innovative sensors to remotely locate the control electronics. The resulting design will improve MSR plant performance and cost metrics." (MEITNER, n.d.)
- Westinghouse Electric Company – Self-regulating, Solid Core Block for an Inherently Safe Heat Pipe Reactor
    - "Westinghouse Electric Company will develop a self-regulating "solid core block" (SCB) that employs solid material (instead of bulk liquid flow or moving parts) to passively regulate the reaction rate in a micro-scale nuclear reactor. The project aims for the reactor to achieve safe shutdown without the need for additional controls, external power sources, or operator intervention, enabling highly autonomous operation. The SCB is key to the reactor design, which is comprised of a core (containing fuel, moderator, and axial reflectors) and primary and decay heat exchangers, all connected end to end by horizontal heat pipes. During off-normal conditions, the reactor will shut itself down and promptly dissipate the decay heat for an indefinite amount of time without any operator intervention or using any control systems, improving safety. The team will conduct modeling and simulations to predict the SCB's inherent self-

    - regulating ability. It will then fabricate and test several SCB samples to validate the modeling and simulation tools and confirm feasibility of advanced manufacturing techniques. The SCB will be the central component of the team's complete micro reactor concept, a robust product that aims to overcome many common challenges of current nuclear power plants, including complicated plant designs, uncertain construction times, high operating and financing costs, and load following limitations" (MEITNER, n.d.)
- Yellowstone Energy – Reactivity Control Device for Advanced Reactors
    - This project is currently canceled.

Current BETHE Programs

- CFS- Pulsed High Temperature Superconducting Central Solenoid For Revolutionizing Tokamaks
    - "The tokamak is the most scientifically mature fusion energy concept, which confines hot plasma in the shape of a torus (similar to a donut). This plasma is controlled in part by a central solenoid electromagnet. Using high-temperature superconductors (HTS) and an innovative design, Commonwealth Fusion Systems (CFS) and its partners aim to build a central solenoid capable of quickly changing ("fast ramping") its current and magnetic field, while also being robust enough to survive many thousands of cycles. This new HTS magnet will enable a new mode of tokamak operation, in which power output is repetitively pulsed. By comparison, traditional, steady-state tokamaks require expensive and complex external current-drive systems, and aggressive plasma physics with substantial scientific risk. The pulsed-tokamak power-plant pathway has the potential to reduce costs, speed timelines, and revolutionize the future of fusion power." (BETHE, n.d.)

- Los Alamos National Laboratory (LANL) – Electromagnetic and Particle Diagnostics for Transformative Fusion-Energy Concepts
    - "Los Alamos National Laboratory and its partner, the University of Nevada-Reno, will provide visible spectroscopy and soft x-ray imaging diagnostics to characterize the performance of a number of lower-cost, potentially transformative fusion-energy concepts. Multi-chord visible spectroscopy measurements will enable the identification of impurities and their spatial and temporal variation in the plasmas, which is essential for understanding plasma composition and plasma conditions. A state-of-the-art, solid-state X-ray imager, the Adaptive Gain Integrating Pixel Detector

    (AGIPD), will be used to make soft x-ray movies of the hot plasma core, enabling visualization of the evolution of instabilities of all but the shortest duration plasmas."(BETHE, n.d.)

- Los Alamos National Laboratory (LANL) – Target Formation and Integrated Experiments for Plasma-Jet Driven Magneto-Inertial Fusion
    - "Los Alamos National Laboratory (LANL) will lead a team that will test an innovative approach to controlled fusion energy production: plasma-jet driven magneto-inertial fusion (PJMIF). PJMIF uses a spherical array of plasma guns to produce an imploding supersonic plasma shell, or "liner," which inertially compresses and heats a pre-injected magnetized plasma "target" in a bid to access the conditions for thermonuclear fusion. LANL will develop a magnetized target plasma for the approach at a smaller scale than would be needed for a reactor. The team will perform first integrated liner-on-target compression experiments at the LANL Plasma Liner Experiment facility. Compression and heating will be studied and compared with computer simulations. The experimental results will illuminate the viability and scaling behavior of this class of fusion devices with energy, plasma jet parameters, and reactor size, informing the prospects for future development and energy scaleup of this concept."(BETHE, n.d.)

- Massachusetts Institute of Technology (MIT) – Radio Frequency tools for Breakthrough Fusion Concepts
    - "Fusion requires confining plasmas at extraordinarily high temperatures. One of the most promising ways to heat plasmas to these temperatures is with high-power radio-frequency (RF) waves. Beyond providing heating, RF waves can enable control of the radial current profile in a plasma, which can help improve confinement and control or mitigate plasma instabilities. Complex analytic theory and computer simulations are required to design effective and efficient plasma-heating scenarios, which must be tailored for various fusion concepts. MIT's Capability Team will apply established state-of-the-art theoretical and simulation tools, developed and tested by the fusion research community on more traditional concepts, to accelerate the development of potentially transformative, lower-cost fusion concepts. The computer simulations will use some of the largest supercomputers in the world, and the predictions from these codes will guide these high-risk, high-reward experiments for the best chance of success."(BETHE, n.d.)

- NK Labs – Conditions for High-Yield Muon Catalyzed Fusion
    - "A muon is a short-lived subatomic particle with the same charge as an electron but 206 times the mass. When bound to an atomic nucleus, it orbits much closer to the nucleus than an electron does. In the context of a

deuterium-tritium molecule, this screens the electric charge and reduces the “Coulomb barrier” that ordinarily prevents the nuclei from fusing. When a muon stops in a mixture of deuterium and tritium, even at ordinary temperatures, it causes nuclear fusion. In most cases, the muon is released following a fusion reaction and will catalyze additional fusions, but roughly 0.8% of the time it sticks to a resulting alpha particle and is removed from the catalytic cycle. This effect has hindered efforts to design a reactor based on muon-catalyzed fusion (µCF). Reducing this “sticking rate” by varying environmental conditions could open the door to a viable, cost-effective µCF reactor concept. Using modern experimental techniques from the field of high-pressure physics, the team will simultaneously heat, pressurize, and bombard a tiny volume of fusion fuel with muons, at pressures up to 100 times higher than what has been attempted previously, where it is hypothesized that the sticking rate will be reduced. They will measure the muon sticking fraction and cycling rate and other key parameters over a range of temperatures, pressures, and tritium concentrations. They will update publicly available computer models and databases based on their results, which, if favorable, may potentially lead to new µCF designs capable of net energy gain.” (BETHE, n.d.)

- Oak Ridge National Laboratory (ORNL) – Magnetic Field Vector Measurements Using Doppler-Free Saturation Spectroscopy
    - “Knowing the magnetic field inside a fusion device is essential for understanding and validating performance, but measuring the magnetic field without perturbing it is exceedingly challenging. This Capability Team will build a non-perturbative, portable diagnostic to measure the topology of the equilibrium magnetic field vector in potentially transformative, magnetically confined fusion devices. The technique to be used, Doppler-free saturation spectroscopy (DFSS), is a pump/probe laser-based technique that has demonstrated magnetic field measurement accuracy of <10 G in laboratory experiments. The new DFSS diagnostic will be built and tested during this project, and will be ready to deploy to multiple fusion experiments around the country through public-private partnerships such as DOE’s Innovation Network for Fusion Energy program. Directly comparing the topology of experimental and theoretical magnetic-field equilibria will provide critical information required to optimize and accelerate the development of lower-cost fusion concepts.” (BETHE, n.d.)

- Princeton Plasma Physics Laboratory - Stellarator Simplification using Permanent Magnets

    - "Princeton Plasma Physics Laboratory (PPPL) will design and build a prototype structure with an array of rare-earth permanent magnets to generate the precise shaping fields of an optimized, quasi-axisymmetric stellarator design. The stellarator is an attractive fusion-energy concept because it has minimal recycling power and auxiliary systems, and no-time dependent electro-magnet systems. Two challenges have delayed its progress: 1) obtaining adequate confinement in three-dimensional (3D) fields and 2) engineering the magnetic configuration with sufficient precision at low cost. Breakthroughs in calculating and optimizing confinement properties of 3D magnetic systems have addressed the first challenge. A recent concept proposes permanent magnets and simple planar coils for making the complex fields required by stellarators. Use of permanent magnets along with planar toroidal field coils could dramatically simplify stellarator construction, assembly, and maintenance, and place the stellarator on a compelling path toward lower-cost fusion energy."(BETHE,n.d)

- Sapientai - Data-enabled Fusion Technology
    - "Sapientai, LLC will form a team under the Data-enabled Fusion Technology (DeFT) project to provide state-of-the-art data-enabled modeling and simulation capabilities to accelerate the development and evaluation of lower-cost fusion concepts. The team will leverage machine learning (ML) and artificial intelligence (AI) capabilities to better understand and use the results of existing experimental data and models to accelerate the development of lower-cost fusion concepts toward higher fusion performance. The DeFT team includes not only experts in ML/AI but also fusion and plasma physics, uncertainty quantification, applied mathematics, and scientific computing. This combined experience is critical for enabling effective deployment of ADA/ML/AI methods in such physically complex systems. By project end, the DeFT team will have applied their ML/AI capabilities to at least three fusion concepts, helping accelerate each team's progress toward lower-cost fusion energy."(BETHE,n.d.)

- Type One Energy Group - Non-Planar Capability HTS Magnet Coil with Additive-Manufactured Components
    - "A stellarator is a fusion energy concept that uses magnetic fields to confine fusion fuel in the form of a plasma. International R&D is underway with a new class of stellarators setting performance records with the goal of generating stable and disruption-free power. Stellarators have been expensive and time consuming to build. Their large and complex electromagnets need to be shaped, supported, and positioned with precision. To overcome these challenges, two game-changing technologies hold great promise: advanced manufacturing (AM) to enable the complex shapes to be built accurately, rapidly, and economically; and high-

    temperature superconducting (HTS) magnets to reduce the size and weight of the reactor. This project will reduce the highest initial risks of building a non-planar HTS magnet by demonstrating whether HTS cable windings for an actual stellarator design maintain the needed tolerances and superconducting-current properties with three-dimensional bend radii as low as 10 cm. Success in this project will allow follow-on efforts to build a prototype non-planar HTS magnet coil to enable a stellarator development path to lower-cost fusion energy.” (BETHE, n.d.)

- U.S. Naval Research Laboratory - The Argon Fluoride laser as an enabler for low cost inertial fusion energy
    - “The U.S. Naval Research Laboratory (NRL) will advance the science and technologies of the electron-beam-pumped argon fluoride (ArF) laser as a potential method of improving laser-target coupling, a necessary (but not sufficient) condition for advancing low-cost inertial fusion energy (IFE). ArF’s deep UV light and capability to provide a wider bandwidth than other laser drivers improves the laser-target coupling efficiency and enables high gain at driver energies below 1 MJ. The ArF technology will use solid-state pulsed power and similar electron-beam pumping used by krypton fluoride lasers to achieve record-setting “wall-plug” efficiencies for deep UV lasers. These advantages could enable the development of smaller and lower-cost IFE power-plant modules. These factors could drastically change the current thinking that IFE is too expensive and the power-plant size too large to be competitive in contemporary power-generation markets.” (BETHE, n.d.)

- University of Maryland, Baltimore County (UMBC) - Centrifugal Mirror Fusion Experiment
    - “The University of Maryland, Baltimore County, will advance the performance of the centrifugal-mirror (CM) fusion concept, which has previously demonstrated stable plasmas with temperatures above 100 eV. The CM has a simple, axisymmetric geometry and provides a potential low-cost pathway to a breakeven experiment. The team will azimuthally rotate a mirror-shaped magnetized plasma to supersonic speeds using high-voltage biasing between a central rod and outer electrode rings. The rotation will stabilize, heat, and centrifugally confine the plasma, potentially eliminating the need for costly auxiliary heating systems requiring high recirculating power. Eliminating systems that require high recirculating power could potentially improve the economics of a fusion power plant. The project aims to overcome engineering challenges of the high-voltage biasing, and scientific challenges of achieving good stability and confinement while pushing into higher-temperature regimes. Performance, namely electron temperature, will be benchmarked in this project with assistance from BETHE Capability Teams. The project aims to achieve a fusion triple product exceeding 1017 keV s/m3. This

    represents an intermediate step towards the fusion-energy breakeven goal of T=10 keV and nTτ=1021 keV-sec/m3. Successful demonstration of the viability of CM fusion may potentially establish a more-economical scaling to a fusion power plant compared to that of mainline fusion approaches."(BETHE, ,n.d.)

- University of Rochester - Advanced Inertial Fusion Energy Target Designs and Driver Development
    - "The University of Rochester Laboratory for Laser Energetics ($1.75M) and the Naval Research Laboratory (NRL) ($1.75M) will advance inertial fusion energy (IFE) by developing (1) innovative direct-drive, high-bandwidth, high-gain target designs using high-bandwidth laser technologies with < 1 MJ of laser input energy, and (2) high-efficiency, high-bandwidth IFE drivers to eventually enable experimental demonstration of the advanced target designs. The new laser-driver technologies, including both diode-pumped solid-state and excimer lasers, are expected to mitigate laser-plasma instabilities, potentially allowing for greater and more-symmetric energy coupling to the target. This work leverages the multiple decades of investment into inertial confinement fusion (ICF), which has achieved high values of fusion triple product, and will help place ICF on a path toward lower-cost IFE. The DOE Office of Science, Fusion Energy Sciences, is jointly supporting this work, contributing an additional $1.25M each to the University of Rochester and NRL."(BETHE, n.d.)

- University of Rochester - A Simulation Resource Team for Innovative Fusion Concepts
    - "Numerical simulations are critically important for the design and development of fusion concepts. However, establishing an adequate simulation capability for a fusion concept can easily be more expensive and time-consuming than building the first experiment. This Capability Team will provide simulation support for fusion-concept teams and independent analysis of fusion concepts. The FLASH, TriForce, and OSIRIS codes were chosen for this project because they are flexible, high-performance, multi-dimensional codes, all with the potential to be used by concept teams to carry out their own simulations in the future. FLASH is a magnetohydrodynamics code, widely used by the plasma physics and astrophysics communities. TriForce is a particle-based hybrid fluid-kinetic code currently under development. OSIRIS is an electromagnetic particle-in-cell code, with multiple physics packages."(BETHE, n.d.)

- University of Washington (UW) - Demonstration of Low-Density, High-Performance Operation of Sustained Spheromaks and Favorable Scalability toward Compact, Low-Cost Fusion Power Plants
    - “The University of Washington will advance the technical viability of a novel method, Imposed-Dynamo Current Drive (IDCD), for sustaining and heating spheromak plasmas as the basis of compact, low-cost fusion power plants. A traditional tokamak fusion reactor has a toroidal confinement area, similar shape to a donut, with a hole in the middle. The spheromak reduces the size of the hole as much as possible, resulting in a spherical plasma shape similar to a cored apple. IDCD can efficiently couple large amounts of power to the plasma at much lower costs relative to other methods of higher-frequency plasma heating. The proposed R&D aims to achieve spheromak ion and electron temperatures > 100 eV during sustainment on an existing experimental prototype. Other R&D activities include computational tasks to support both the scientific and engineering design of next-step prototypes with higher fusion performance. This project will increase the technological readiness level of this lower-cost fusion concept to encourage further development toward commercial fusion energy with both public and private support.” (BETHE, n.d.)

- University of Wisconsin-Madison (UW-Madison) - An HTS Axisymmetric Magnetic Mirror on a Faster Path to Lower Cost Fusion Energy
    - “The Wisconsin High-field Axisymmetric Mirror (WHAM) project at the University of Wisconsin-Madison will leverage advances in the stability and confinement of the mirror fusion concept, innovative plasma heating, and high-field superconducting magnets to demonstrate a potentially transformative development path toward a low-cost linear fusion device. Two mirror coils will be constructed using high temperature superconducting material. Hot and high-density target plasmas will be created using high-frequency electron-cyclotron heating from modern gyrotrons. Fast, sloshing ions will be created and energized by a novel radio-frequency heating scenario in which neutral beam injection is used to fuel ions, which are then accelerated in situ to high energy by high harmonic fast waves. The project aims to demonstrate a novel “end cell” that confines stable, heated plasmas at the end of 24 months. If successful, the plan is to demonstrate electron temperatures exceeding 1 keV and a fusion triple product in the end cell exceeding 1018 keV s/m3 at the end of 42 months. Success in this project could justify pursuit of the low-cost Break-Even Axisymmetric Tandem (BEAT) device, which would use two of the end cells at the two ends of a longer central mirror cell to pursue breakeven conditions.” (BETHE, n.d.)

- Virginia Polytechnic Institute and State University (Virginia Tech) - Capability in Theory, Modeling, and Validation for a Range of Innovative Fusion Concepts Using High-Fidelity Moment-Kinetic Models
    - “As fusion machines move toward a burning-plasma regime, liquid first walls and blankets may be needed to handle first-wall heat-flux, reduce erosion, and eventually to convert energy and generate tritium fuel. Repetitively pulsed fusion designs may require extreme electrode survivability, where the electrode may be solid, liquid, or a combination of both. It is critical to address how plasma dynamics in the fusion plasma will couple with both liquid-metal and electrode-material dynamics for fusion energy to become realizable. This Capability Team will use fluid and reduced kinetics, including building on its existing open-source simulation technology, Gkeyll, and a multi-phase, incompressible magnetohydrodynamic model, to study liquid- and solid-wall dynamics in the presence of fusion plasma and to experimentally validate aspects of the modeling tools. The team will perform high-fidelity kinetic plasma simulations that can account for complex plasma-wall interactions to support the development of multiple lower-cost fusion concepts.” (BETHE, n.d.)

- Zap Energy - Sheared Flow Stabilized Z-Pinch Performance Improvement
    - “A Z-pinch fusion device has an electrical current driven through the fusion fuel, creating self-generated magnetic fields that compress and heat the fuel toward fusion conditions. While a Z-pinch with no equilibrium flows has rapidly growing instabilities that disrupt the plasma within nanoseconds, the Z-pinch can be stabilized if an axial plasma flow varying strongly enough with radius is introduced. This sheared-flow stabilized (SFS) Z-pinch may be the simplest and most compact of all known controlled-fusion approaches, as it does not require magnetic coils nor any external heating systems other than the source to drive the electrical current. Under the ALPHA and OPEN 2018 programs, the SFS Z-pinch provided evidence of a fusion triple product exceeding 1017 keV s/m3, a factor of 50 increase in 3–4 years. This project will enable Zap Energy to build a more versatile SFS Z-pinch device to eventually allow for independent control of the plasma formation and acceleration stages. They will use the new device to advance their triple product toward breakeven conditions.” (BETHE, n.d.)