The Fusion Enterprise Paradox:

The Enduring Vision and Elusive Goal of Unlimited Clean Energy

Melvin L. Eulau

Dissertation submitted to the Faculty of Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

In

Science and Technology Studies

Sonja Schmid
Barbara Allen
Matthew Wisnioski
David Tomblin

10 December 2019
Falls Church, Virginia

Keywords:

Fusion Energy, Sociotechnical Imaginaries, Co-production, Large Technological Systems

The Fusion Enterprise Paradox:
The Enduring Vision and Elusive Goal of Unlimited Clean Energy

Melvin L. Eulau

ABSTRACT

In an age of shrinking research and development (R&D) budgets, sustaining big science and technology (S&T) projects is inevitably questioned by publics and policy makers. The fusion enterprise is an exemplar. The effort to develop a viable system to produce unlimited and environmentally benign electricity from fusion of hydrogen isotopes has been a goal for six decades and consumed vast financial and intellectual resources in North America, Europe, and Asia. In terms of prolonged duration and sustained resource investment, the endeavor has developed into a huge fusion enterprise. Yet, no practical system for the generation of electricity has yet been demonstrated. This is the paradox at the heart of the fusion enterprise.

Why, despite unfulfilled visions and broken promises, has the grand fusion enterprise endured? How can such a long-term enterprise persist in a funding culture that largely works in short-term cycles?

Adapting Sheila Jasanoff's thesis of "sociotechnical imaginaries", I examine the relationship of shared and contrasting visions, co-produced expressions of nature and society, and distinct

political cultures in the quest for viable fusion. A systematic cultural and technological comparison of three fusion ventures, the National Spherical Torus Experiment Upgrade, the International Thermonuclear Experimental Reactor (ITER), and Wendelstein-7X, exposes how these projects and the institutions they inhabit frame the goals, risks, and benefits of the fusion enterprise and sustain a common set of fusion imaginaries. Positioned within the Princeton Plasma Physics Laboratory in the United States, the international ITER Organization sited in France, and the Max Planck Institute for Plasma Physics in Germany, the three projects are prime examples of big science and technology. Rigorous research and analysis of these cases advance the thesis of the unfulfilled utopian vision of fusion energy that has endured for more than sixty years.

The Fusion Enterprise Paradox:
The Enduring Vision and Elusive Goal of Unlimited Clean Energy

Melvin L. Eulau

GENERAL AUDIENCE ABSTRACT

In an age of shrinking research and development budgets, sustaining big science and technology projects is inevitably questioned by publics and policy makers. The fusion enterprise is an exemplar. The effort to develop a viable system to produce unlimited and environmentally benign electricity from fusion of hydrogen isotopes has been a goal for six decades and consumed vast financial and intellectual resources in North America, Europe, and Asia. In terms of prolonged duration and sustained resource investment, the endeavor has developed into a huge fusion enterprise. Yet, no practical system for the generation of electricity has yet been demonstrated. This is the paradox at the heart of the fusion enterprise.

Beyond articulating a possible path forward for the fusion enterprise, the intent of this study is to inform decision makers who will shape energy strategy for the second half of the twenty-first century.

Acknowledgments

I would like foremost to thank my wife, Linda, for supporting my passion for discovery and for tolerating the many hours embedded in this dissertation, a milestone in a passionate life-long mission to expand my universe. The interest that my adult children, David, Kevin, and Jenn, expressed also deeply moved me to explore my personal imaginary. My grandchildren, Owen, Sarah, Kendall, Amanda, Connor, and Nathan have been loving inspirations as they reveal their life experiences; they open widows of perception in my mind as they live and share their voyages of discovery. My immigrant parents, Herman and Selma, instilled both the value of acquired knowledge to contribute to their new homeland and that joy could be found in formal education.

Finally, I am so grateful for the guidance and persistent encouragement of my doctoral committee: Sonja Schmid, Barbara Allen, Matt Wisnioski, and David Tomblin. Their thoughtful recommendations guided me though the open seas of dissertation work when landfall was nowhere to be seen. In particular, Sonja, my doctoral committee chair, has provided the academic harbor to which I frequently returned to be further energized. Without the personal and academic love with which these people blessed me, this dissertation would have been an impossible journey.

These motivations to operationalize alternative futures has enriched my worldview and in recent years opened up an unforeseen opportunity to become a science and technology consultant to a federal government agency, a role that dramatically expanded the domains of skill and experience I accumulated as a systems engineering technical advisor over a period of decades.

Table of Contents

CHAPTER ONE – Introduction: Always Fifty Years Away 1
Genesis in Imagination 3
Origin of the Tokamak 5
Quest for a World Set Free 6
Sociotechnical Climate Change 10
Analytical Tools 15
Expressions of a Terrestrial Star 18
Instrumental Action in the Fusion Enterprise 21
Sociotechnical Momentum 24
Global Knowledge Infrastructures and Context 26
Political Cultures and Energy Policy Trends 27
Organization of the Dissertation 29

CHAPTER TWO – Comparative Fusion Futures 32
A Comparative Project 32
Shared Collection of Fusion Imaginaries 34
Multidimensional Paradox 36
Foundations of the Comparitive Study 38
Large Technological Systems 41
Co-Production of Knowledge and Social Order 43
Alternative Futures: Social Order and Science 47
Alternative Futures: Imaginaries of Individual Scientists 50
Sociotechnical imaginaries 51
Synthesis of Analytical Toolset 53

CHAPTER THREE – Rise, Fall, and Revival of American Fusion: National Spherical Torus Experiment Upgrade (NSTX-U) 55
Encounter at Princeton 55
An American Technological Imaginary 58
The Plasma Physics Laboratory Emerges from Princeton University 62
Lyman Spitzer, Jr., Fusion Energy Pioneer 66
PPPL in the Age of the Tokamak 68
A Personal Temporal Narrative 70
Controversy at PPPL 71
Scientific Research in an Era of Short-Term Cost-Benefit Reckoning 73
Instruments of PPPL's ITER Association and Complementary American Alternative 76
An Opportunity for an American Alternative Future 77
PPPL Scientists Join Stellerator Research at IPP 80
Interdependence of PPPL and ITER 82
A Spherical Sociotechnical Expression of the Fusion Enterprise 84

CHAPTER FOUR – Global Fusion Supremacy and Controversy: International Thermonuclear Experimental Reactor (ITER) 86
Technology and French National Identity 86
Dawn of the Soviet Fusion Enterprise: Tokamak 90
November 21, 1985 94
Q=1: Plasma Energy Breakeven Point 98
The High Cost of the Enterprise 103
Debates Fuse 106
A Candid View from the Office of the ITER Communications Lead 111
Twenty-First Century Moonshot 117
Size Matters 119
The Way? 122

CHAPTER FIVE – Anti-Nuclear Germany Weaves Thermonuclear Alternative: Wendelstein-7X (W7-X) 124
German Technological Imaginary 124
Tokamak's Rebellious Cousin 129
Climate Change and the Climate of the German Energy Debate 132
A Sociological Planck's Constant 135
Max Planck Society 138
Diversity, Institutional Landscapes, and Advances in the German Fusion Enterprise 140
Exploration of Alternative German Energy Futures 144

CHAPTER SIX – Conclusion: Alternative Futures 151
November 21, 2085 151
A Planetary Energy Revolution 153
End of the Anthropocene 155
'One Small Step' Shaped by Imaginaries 157
Astronomical Energy Embedded Everywhere 158
Operationalizing Sociotechnical Imaginaries through Innovation Policy 161
No Zero Risk Technology 166
Toward a Fusion-Centered Energy Ecosystem 168
Convergence of Technology and Politics 172
Politics of Persuassion 174
Convergence of Sociotechnical Imaginaries, S&T, and Social Order 175
Momentum, Not Technological Determinism 177

APPENDIX A – Generic Interview Questions 181

References 182

Table of Figures

Figure 1. Deuterium-Tritium Reaction. Courtesy Princeton Plasma Physics Laboratory. 2
Figure 2. Tokamak Concept. Courtesy University of South Florida. 5
Figure 3. Change in Global Surface Temperature, 1880-2017. Courtesy National Aeronautics and Space Administration, NASA Goddard Institute for Space Studies. 10
Figure 4. Atmospheric CO_2 at Mauna Loa Observatory. Courtesy NOAA................................ 11
Figure 5. ITER's Evolving Budget. Courtesy ITER Organization. 36
Figure 6. NSTX-U. Courtesy Princeton Plasma Physics Laboratory. 69
Figure 7. Photo of NSTX-U Control Room Screen. April 14, 2016 by the author. 71
Figure 8. Photo of National Compact Stellarator Experiment. April 14, 2016 by the author. 72
Figure 9. First W7-X Plasma. Courtesy Max Planck Institute for Plasma Physics. 82
Figure 10. Fusion – Tokamak. Courtesy IAEA. 91
Figure 11. ITER. Courtesy The ITER Organization. 93
Figure 12. Funding for ITER Construction. Courtesy The ITER Organization. 103
Figure 13. Funding for ITER Operations. Courtesy The ITER Organization. 104
Figure 14. ITER Panorama. Courtesy The ITER Organization. 111
Figure 15. Schematic of Staged Structure for First 10 Years of ITER Operations. Courtesy The ITER Organization. 114
Figure 16. Scale of Toroidal Field (TF) Coil Structures of the ITER Magnet System. Courtesy The ITER Organization. 120
Figure 17. Wendelstein 7-X (W7-X). Courtesy Max Planck Institute for Plasma Physics. 129
Figure 18. Scientific Visualization of 3-D Optimized W7-X. Courtesy UCLA Physics. 130
Figure 19. Nuclear Phase-out. Courtesy Energy Agency of German State of Nordrhein-Wesfalen. 132

CHAPTER ONE – Introduction: Always Fifty Years Away

In an age of shrinking research and development (R&D) budgets, publics and policy makers inevitably question sustaining big science and technology (S&T) projects. The fusion enterprise is an exemplar. The effort to develop a viable system to produce unlimited and environmentally benign electricity from fusion of hydrogen isotopes has been a goal for six decades and consumed vast financial and intellectual resources in North America, Europe, and Asia. In terms of prolonged duration and sustained resource investment the endeavor has developed into a huge fusion enterprise. Yet, no practical system for the generation of electricity has yet been demonstrated. This is the paradox at the heart of the fusion enterprise.

Why, despite unfulfilled visions and broken promises, has the grand fusion enterprise endured? How can such a long-term enterprise persist in a funding culture that largely works in short-term cycles? Analysis that emerges from these questions is central to understanding the paradox of the fusion enterprise.

The historical foundation of the fusion enterprise "had its beginning in the hammered flint and the fire-stick of the savage".[1] In humanity's effort to liberate unprecedented amounts of energy in the twentieth century, the predecessor to fusion was fission. The first nuclear chain reaction was achieved on 2 December 1942 by the team led by Enrico Fermi at the University of Chicago.[2] The fuel for fission is typically mined uranium that must be rigorously processed or plutonium produced as a product of fission in a nuclear reactor.[3] Rather than the fission of heavy elements into lighter elements to release energy, fusion is the result of combining the isotopes of

[1] H.G. Wells, *The World Set Free*, (1914), http://www.online-literature.com/wellshg/worldsetfree/.

[2] Richard L. Garwin and Georges Charpak, *Megawatts and Megatons: The Future of Nuclear Power and Nuclear Weapons*, (Chicago: University of Chicago Press, 2002), 31-32.

[3] While uranium and plutonium are typical fuel sources, there are alternative fuels, e.g., thorium.

the lightest element, i.e., isotopes of hydrogen (e.g., deuterium and tritium) under conditions typical in the core of stars. The principal fuel for fusion, the hydrogen isotope, deuterium, can be derived from seawater, and the companion isotope, tritium, is a byproduct of the fusion reaction itself (Figure 1).

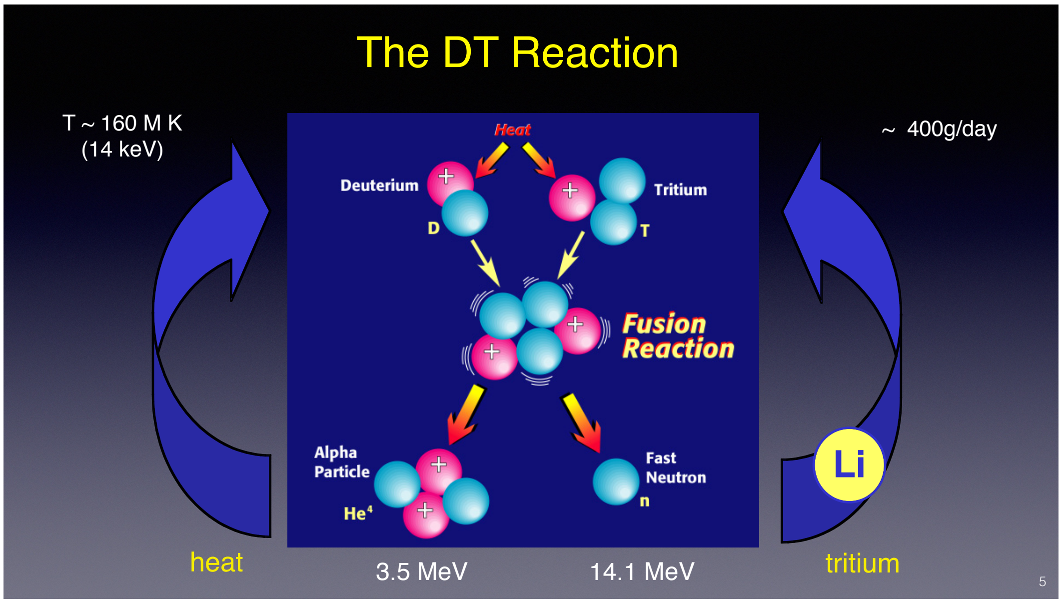

Figure 1. Deuterium-Tritium Reaction. Courtesy Princeton Plasma Physics Laboratory.

MIT professor Richard K. Lester tags fusion as 'Nuclear 3.0',[4] i.e., the expression of nuclear power after 2050.   Parkins provides another perspective on fusion as an advanced version of nuclear. "But although practical, controlled energy release from fission followed the discovery of that process by only 3 years, fusion power is still a dream-in-waiting".[5] The observations of Lester and Parkins reflect the Janus-headed nature of the fusion enterprise.

[4] Richard K. Lester, "A Roadmap for U.S. Nuclear Energy Innovation", *Issues in Science and Technology*, (2016, Winter) No. 32(2), 54.

[5] William E. Parkins, "Fusion power: Will it ever come?", *Science*, (2006), No. 311, 1380.

A persistent joke among expert communities and publics is that fusion is and always will be fifty years away.[6] The prolonged quest for fusion energy and its sustained resource investment has fueled its collective imaginary and has grown into a grand fusion enterprise. The founder of a Canadian fusion start-up company, General Fusion, acknowledges an inherent key element of the enigma during a 2014 TEDxKC talk, as he asserted "it's not that it [fusion] cannot be done, but it's how to make it cost-effectively".[7]

"Persistent myths"[8] are central to the fusion energy discourse. Smil refers to advocates of fusion energy who evangelize that technological innovation will bring salvation for the hydrocarbon sins of the past and present. He reiterates the irony of a half-century of fusion dreams not realized in observing that "promoters of nuclear fusion have never relinquished their hopes that another investment of $20 billion or $30 billion… will make it the dominant method of energy conversion in a matter of several decades".[9]

Genesis in Imagination

The genesis of the fusion enterprise surfaced in literature, such as the prescient 1914 H.G. Wells novel, *The World Set Free*[10], but the premiere physical manifestation was the first hydrogen bomb detonation in 1952 by the United States. A professor in Wells' narrative inspires a young student, one of the main characters in humanity's drive to unlock the key to immense energy.

---

[6] F. Sievert and D. Johnson, "Creating Suns on Earth", *The Nonproliferation Review*, No. 17(2), (2010), 323.

[7] Michel Laberge, TEDxKC Talk, August 28, 2015, https://www.youtube.com/watch?v=b-LCfx9v4YQ.

[8] Vaclav Smil, *Energy Myths and Realities: Bringing Science to the Energy Policy Debate*, (Washington DC: AEI Press, 2010), 6.

[9] Smil, *Energy Myths and Realities*, 9.

[10] Wells, *The World Set Free*, Chapter The Second.

> This--this is the dawn of a new day in human living. At the climax of that civilisation which had its beginning in the hammered flint and the fire-stick of the savage, just when it is becoming apparent that our ever-increasing needs cannot be borne indefinitely by our present sources of energy, we discover suddenly the possibility of an entirely new civilisation. The energy we need for our very existence, and with which Nature supplies us still so grudgingly, is in reality locked up in inconceivable quantities all about us. We cannot pick that lock at present, but----' He paused. His voice sank so that everybody strained a little to hear him. '----we will.'[11]

More than a century has elapsed since the transformational vision in the pages of Wells' novel. In the decades prior to the first ominous thermonuclear explosion in the mid twentieth century, humanity experienced the trauma of two world wars and fission-based nuclear power. Utopian and dystopian visions coexisted and persist today in a world at risk.[12]

The arc of this study is influenced by *co-production* analysis of fusion visions and three tangible expressions of the fusion enterprise. The three instances are literally illuminated in the dancing images of terrestrial stars on control room screens in North America, Europe, and Asia. The images represent a powerful tool "by the association of the sense of sight with science, technology, and the modern experience of the real".[13] At this stage of the study, a concise introductory definition of co-production is necessary. "[The concept is] an idiom – a way of interpreting and accounting for complex phenomena so as to avoid the strategic deletions of most other approaches in the social sciences".[14] The prime objective of this dissertation is to suggest a framework to make sense of the socio-technical factors that might explain why multiple nations continue to invest in an envisioned fusion-centered energy ecosystem. While the research is

---

[11] Wells, *The World Set Free*, Prelude, Section 8.

[12] Ulrich Beck, *World at Risk*, (Cambridge: Polity Press, 2009).

[13] Yaron Ezrahi, *The Descent of Icarus,* (Cambridge, MA: Harvard University Press, 1990), 269.

[14] Sheila Jasanoff, *States of Knowledge: The Co-production of Science and Social Order,* (New York: Routledge, 2004), 3.

bounded by case studies sited in three countries, one of the cases is a massive international project, the International Thermonuclear Experimental Reactor (ITER), and reveals more than the national political culture in which the project is under construction. At the center of that project a device is being constructed on an enormous scale, the largest Tokamak[15] on Earth.

Origin of the Tokamak

The first tangible manifestation to transform the dream of unlimited clean energy into a functioning source of electricity and a device design that has persisted for over a half-century is the donut-shaped magnetic confinement vessel called Tokamak (Figure 2).

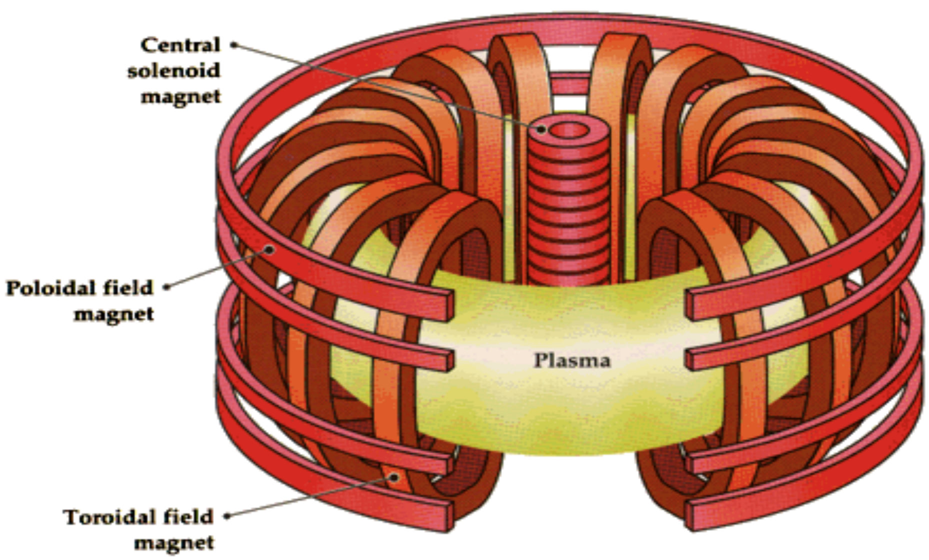

Figure 2. Tokamak Concept. Courtesy University of South Florida.

In the early twenty-first century, Tokamaks are operating on three continents. Isotopes of hydrogen are heated to 100-150 million degrees Celsius and powerful electromagnets suspend

[15] The term, Tokamak, was "formed from the Russian words toroidalnaya kamera and magnitnaya katushka meaning 'toroidal chamber' and 'magnetic coil'" (John Wesson, *Tokamaks*, (Oxford: Oxford University Press, 2011), 13.).

the superheated plasma in magnetic fields.[16] To date, the core problem is that more energy enters the system than is output by any operational Tokamak.[17] The current state of the technology still falls short of the 'holy grail' of practical viability. The conventional Tokamak approach is one of three magnetic confinement methods used as case studies in this dissertation.

While there have been several methodologies proposed and/or used for experimentation, the other two approaches that characterize the cases studied in this dissertation are the spherical Tokamak and the stellerator.[18] As the name implies, the spherical Tokamak resembles a sphere, rather than a donut. The stellerator – in contrast to the axial symmetry common to other magnetic confinement devices – has an asymmetrically sculptured, highly optimized design shaped by decades of images of twisting super-heated hydrogen plasma in Tokamaks. The theoretical basis for the three cases studies and for every other alternative approach to controlled fusion can be traced back to a minimal equation that surfaced in the mind of Albert Einstein in the early twentieth century.[19]

Quest for a World Set Free

The simple elegance of $E=mc^2$ expresses the potential to liberate massive energy[20] from the fusion of hydrogen isotopes. Subsequent to Einstein's revelation, it became theoretically

[16] John Wesson, *Tokamaks,* (Oxford: Oxford University Press, 2011), 14-17.

[17] No other fusion energy device has achieved net energy production either.

[18] National Academies of Sciences, Engineering, and Medicine. 2018. "Progress in Burning Plasma Science and Technology" in *Final report of the committee on a strategic plan for U.S. burning plasma research*, (Washington, DC: The National Academies Press, 2018), 2.

[19] Albert Einstein, "On the Electrodynamics of Moving bodies", *Annalen der Physik*, No. 17 (1905), 891–921.

[20] Albert Einstein, "On the Electrodynamics of Moving bodies", *Annalen der Physik*, No. 17 (1905), 891–921.

possible to convert one kilogram of mass into 25 billion kilowatts of electricity.[21] While the media exploited this vision of releasing vast energy from relatively small mass, the mainstream scientific and engineering communities of the early twentieth century dismissed the notion as fantasy or, at best, projected any such capability into the distant future. It was evidently more appropriate for these visions to reside in the works of H.G. Wells than in the pages of *Nature* or *Science*. Their skepticism turned out to be shortsighted.

In 1914, H.G. Wells published *The World Set Free.*[22] After physicist Leó Szilárd read the book in 1932, in which nuclear energy is woven into the novel, he filed a British patent, *Improvements in or Relating to the Transmutation of Chemical Elements* and proposed that "a neutron chain reaction generates power and produces radio-active isotopes".[23] Whether he was primarily motivated by H.G. Wells' fictional account of an imagined future world or if the work just exerted a subtle influence, by 1933 Szilárd was formulating a theory of the nuclear chain reaction, and in 1934 filed the historic patent.

In the mid twentieth century, a utopian vision of unlimited fusion energy emerged from the globally menacing landscape of hydrogen bomb detonations. Transformation of the destructive power unleashed in ominous explosions into a *world set free*, that is a fusion-powered electrical system that will change the world, is a tangible manifestation of the global effort to operationalize a persistent vision of a planetary energy revolution.

Transition to practical fusion energy from the pages of science fiction to a trusted reality requires a concrete milestone at which point humankind can declare in bold media headlines that

---

[21] Garwin and Charpak, *Megawatts and Megatons*, 17.

[22] Wells, *The World Set Free*, Chapter The Second.

[23] Leo Szilard, *Improvements in or Relating to the Transmutation of Chemical Elements*, UK Patent 19157/34, Filed June 28, 1934, and issued Mar. 30, 1936.

the dawn of the 'age of abundant fusion energy' has arrived. Is there a collectively held and institutionally stabilized[24] definition of "viable fusion"? Hirsch cites a finding by a 1994 panel as a hint upon which to construct a definition, i.e., a "marketable product".[25]

> In 1994, sensing progress toward a potentially viable fusion power system, the Electric Power Research Institute (EPRI), the research arm of the U.S. utility industry, convened a panel of utility technologists to develop "Criteria for Practical Fusion Power Systems." Noting that "Fusion power's potential benefits to humanity and the environment are immense," the report observed that "as the technology is developed and refined, a vision of fusion plant buyer requirements is essential to providing a marketable product."[26]

That vision of a marketable product implies the social construction of knowledge as well as the study of the sociotechnical factors that drive the consumers of power;[27] that perception echoes elements of Mackenzie's study of "Nuclear Missile Testing and the Social Construction of Accuracy".[28] Mackenzie exposes the socio-technical network comprised of sociological and political actors that frame accuracy and his study describes the political fallout that emerges from interpretations of the key word, accuracy. Mackenzie describes a technological system and its environment with a porous boundary. The functionality of the guidance system of the nuclear missile interacts with the values of different actors with various agenda advance,[29] i.e., social groups "influence the meaning given to an artifact".[30]

---

[24] Jasanoff, *States of Knowledge*, 4.

[25] Robert L. Hirsch, "Fusion research: Time to set a new path", *Issues in Science and Technology*, No. 31(4), (2015, Summer), 36.

[26] Hirsch, "Fusion research: Time to set a new path", 36.

[27] David E. Nye, *Consuming power: A Social History of American Energies,* (Cambridge, MA: MIT Press, 1998).

[28] Donald MacKenzie, "Nuclear missile testing and the social construction of accuracy", in *Science Studies Reader*, ed. Mario Biagioli, (New York: Routledge, 1999), 342-357.

[29] MacKenzie, "Nuclear missile testing and the social construction of accuracy", 348-350.

[30] Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other, in *The Social Construction of Technological*

Just as the challenging problems of controlled fission appeared as facets of the Manhattan Project, advocates of controlled fusion anticipated a similar scenario with comparable outcomes. Masco's thesis is that the Manhattan Project started as a monumental defense project during World War II but its socio-technical legacy is essentially eternal.[31] There is an unmet milestone, to overcome the challenge to demonstrate a controlled and economically practical fusion system to produce electricity.[32] In spite of the failure to demonstrate a sustainable system to provide fusion energy to the global power domain, the half-century fusion enterprise persists.

An alternative future is emerging in the imagination and laboratories of humankind. The clumsy solution of fusion might co-exist with with improved photovoltaic systems and wind power, and advanced energy storage capacity. Decomposing the sociotechnical factors that infuse momentum to the fusion enterprise provides a foundation to understand why the fusion enterprise has survived since the mid twentieth century and has appeared in several variations.

The demand for energy continues to increase, in particular in large developing countries, e.g., China and India. Electricity demand requires significant investment in power plants and transmission lines by 2025[33] and energy needs are projected to double by 2100.[34] However, the pressure to mitigate human impact on climate presents nations with the conundrum of vastly

---

Systems: New Direction in the Sociology and History of Technology, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, (Cambridge, MA: The MIT Press, 1987), 46.

[31] J. Masco, *The Nuclear Borderlands: The Manhattan Project in Post-Cold War New Mexico,* (Princeton: Princeton University Press, 2006).

[32] D. Campbell, Challenges in Burning Plasma Physics: The ITER Research Plan. 24th IAEA Fusion Energy Conference, 8-13 October 2012.

[33] United States Government Accountability Office, *Meeting Energy Demand in the 21[stC] century*. Testimony Before the Subcommittee on Energy and Resources, Committee on Government Reform, House of Representatives, 2005), 22.

[34] Robert J. Goldston, Overview of Fusion Energy Research. 4[th] Annual Intelligence Community Academic Research Symposium, 25-27 September 2018, (Washington, DC: National Academy of Sciences).

expanding electrical generating capacity without amplifying greenhouse gases in the atmosphere. The lens of climate change offers the prospect for innovative views of technology options.[35]

Sociotechnical Climate Change

The meaning of the term, climate change, is politically charged and obscured as uniform global transition. Yet, there is a broadly socialized objective that spans institutions and diverse identities in the debate: containing a global average temperature increase to 2° C (Figure 3).

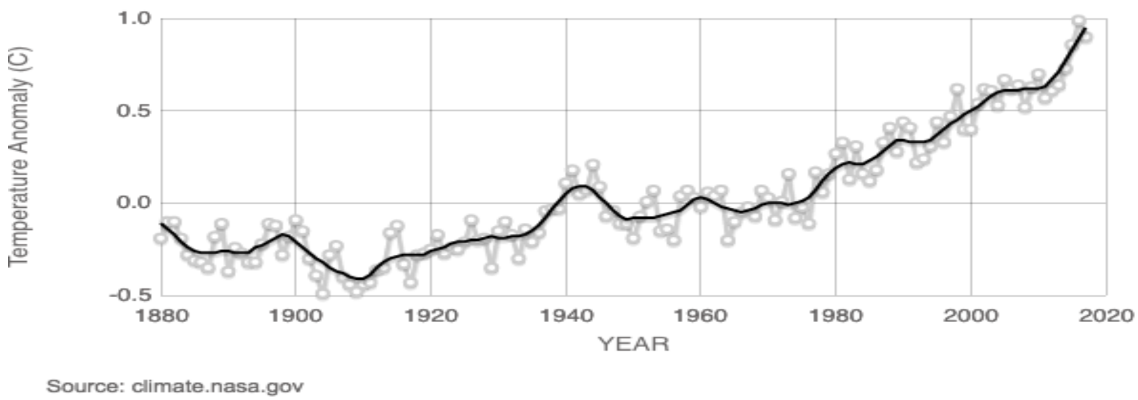

Figure 3. Change in Global Surface Temperature, 1880-2017. Courtesy National Aeronautics and Space Administration, NASA Goddard Institute for Space Studies.

Temperature increase as a measure of climate change does not show the whole picture. Rather, there is a measurable phenomenon that corresponds to and triggers the temperature increase: change in greenhouse gases, e.g., the concentration of carbon dioxide (CO_2). A National Oceanic and Atmospheric Agency (NOAA) provided graph (Figure 4) is a dramatic visualization of the data that substantiates the increase of of CO_2 in our planet's atmosphere.

[35] Mike Hulme, *Why We Disagree About Climate Change: Understanding Controversy, Inaction and Opportunity,* (New York: Cambridge University Press, 2009), 362-363.

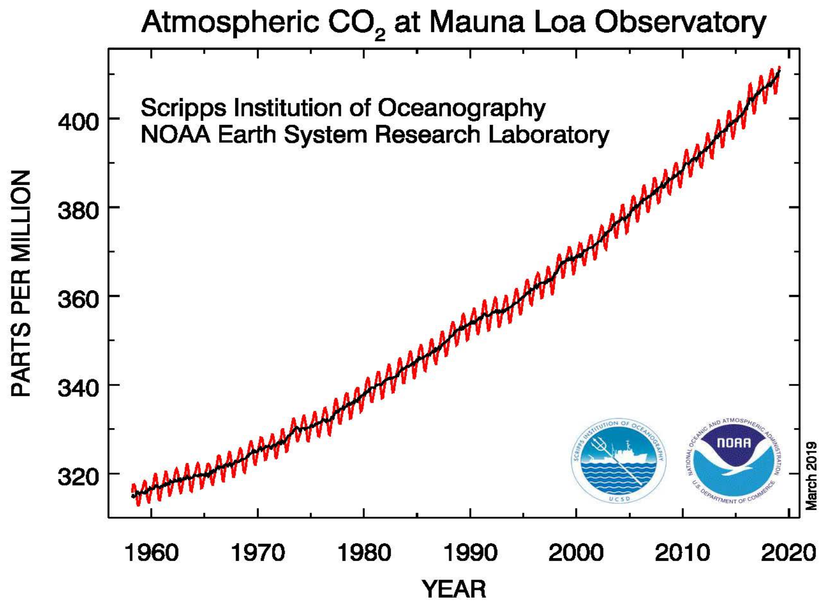

Figure 4. Atmospheric CO_2 at Mauna Loa Observatory. Courtesy NOAA.

Recent Intergovernmental Panel on Climate Change (IPCC) press releases[36] stress a threshold of a 1.5° C temperature increase rather than 2° C that has been at the center of the climate change narrative for years. The newly proposed target will be an even more challenging goal for the world community of nations to achieve.

The narrative of climate change predicts that the impact of exceeding the temperature threshold will trigger an unstoppable slide toward sociotechnical Armageddon. Hulme concisely observes that using global average temperatures as indicators of climate change "both hides and reveals".[37] "It hides all of the heterogeneity of weather experienced in local places by local people and yet by collapsing this diversity into a single numerical index, it reveals the behavior

[36] IPCC. 2018, 8 October. 2018/24/PR. IPCC press release: Summary for policymakers of IPCC special report on global warming of 1.5° C approved by governments. Incheon, Republic of Korea.

[37] Hulme, *Why We Disagree About Climate Change*, 8.

of a large and complex global system".[38] This dichotomy in perceiving what climate change means in diverse locations and in different cultural environments captures the challenge inherent in putting a stable label on what is essentially an unstable idea. Hulme recognizes the local and regional assortments of climate change as well as its diverse impact on weather conditions and within societies. He asserts risks associated with climate change are known in terms of cultural and sociological factors, rather than through a universal perception of IPCC assessments.[39]

Anthony Giddens, certainly not an advocate of technological determinism, cites fusion energy in a context of selective trust in expertise. In *The Politics of Climate Change*,[40] Giddens affirms fusion as a potential low-carbon energy source. "If nuclear fusion suddenly becomes a reality, it could provide endless cheap, renewable energy".[41]

Giddens lists nine "tasks in which the state has to be the prime actor"[42] in his consideration of whether a systematic approach, "a return to planning",[43] is a useful or for that matter an essential element of designing and implementing a plausible program of success in dealing with climate change. "Two countries, the United States and China, have the ability to make or break our chances of success."[44] He acknowledges the dynamic character of climate change and the impossible task of precisely predicting how and over what time frame the earth's climate is transforming.

---

[38] Hulme, *Why We Disagree About Climate Change*, 8-9.

[39] Hulme, *Why We Disagree About Climate Change*, 208-209.

[40] Anthony Giddens, *The Politics of Climate Change* (2nd edition), (Cambridge, UK: Polity Press, 2011).

[41] Giddens, *The Politics of Climate Change*, 10.

[42] Giddens, *The Politics of Climate Change*, 94.

[43] Giddens, *The Politics of Climate Change*, 94-128.

[44] Giddens, *The Politics of Climate Change*, 230.

1. The state must help us to think ahead.
2. Climate change and energy risks must be managed in the context of other risks faced by contemporary societies.
3. The state must promote political and economic convergence, as the main driving forces of climate change and energy policy.
4. The state must make interventions into markets to institutionalize 'the polluter pays' principle.
5. The state must act to counter business interests which seek to block climate change initiatives.
6. The state must keep climate change at the top of the political agenda.
7. An appropriate economic and fiscal framework must be developed for moving towards a low-carbon economy.
8. The state must prepare to adapt to the consequences of climate change, which will now be felt in any case.
9. Local, regional, national and international aspects of climate change must be integrated.[45]

I posit a tenth high priority task: Recalibrate initial quantitative targets based on indicators and trends over short timeframes – as short as 18 months. Uncertainty is high regarding both the rate and impact of change. "We are talking therefore of alternative and plural futures, where adjustments, even radical revisions, are made as time unfolds and then built into other scenarios".[46] A long-term plan with qualitative objectives of initially slowing the growth of greenhouse gasses, and subsequently, stabilizing the atmospheric proportions of these gasses needs to be measured in short, finite periods to determine the validity of predictive models. One such plan is the *European Research Roadmap to the Realisation of Fusion Energy.*[47] As a symbol of its priority, the first section of the roadmap is titled "Combating Climate Change".

---

[45] Giddens, *The Politics of Climate Change*, 94-97.

[46] Giddens, *The Politics of Climate Change*, 100.

[47] EuroFusion, European research roadmap to the realisation of fusion energy.

Rather than an "inconvenient truth",[48] Hulme presents the "uncomfortable reality" of lack of progress toward "the prize being sought".[49] Prins and Rayner introduce a "silver buckshot"[50] approach that I find a compelling and a pragmatic governance proposal. The characterization of climate change as a 'wicked problem'[51] with potential 'clumsy solutions'[52] is a vital confession of humility. However, Hulme claims that the clumsy solutions are no better than the effort to solve the 'climate change problem' with reduced, elegant solutions. I'm not convinced by his argument in which he dismisses the silver buckshot approach due to the inability to accurately predict outcomes due to multiples variables. The earth and its ecosystems cannot be reduced to the controlled experiments of the laboratory.

Hulme reveals opportunities in the identities, institutions, discourses, and representations[53] that comprise climate change. In place of blind faith in the narrative of objective science, he recognizes value in the creation of new myths that emerge from the range of interpretations of climate change. I contend that the clumsy solutions might co-exist with the new "stories in support of our projects",[54] ambitious projects such as the fusion enterprise.

The fusion enterprise is such an ambitious project, in which potent alliances among government, industry, and academia endorsed and energized fusion energy R&D for more than

---

[48] Al Gore, "An Inconvenient Truth", Paramount Pictures, Release Date: May 24, 2006.

[49] Hulme, *Why We Disagree About Climate Change*, 332.

[50] Gwyn Prins and Steve Rayner, "The Wrong Trousers: Radically Rethinking Climate Policy", (Oxford: Joint Discussion Paper of the James Martin Institute for Science and Civilization, University of Oxford and the MacKinder Centre for the Study of Long-Wave Events, London School of Economics, 2007).

[51] Hulme, *Why We Disagree About Climate Change*, 334.

[52] Hulme, *Why We Disagree About Climate Change*, 337.

[53] Jasanoff, *States of Knowledge*.

[54] Hulme, *Why We Disagree About Climate Change*, 364.

six decades and still appear to endure, but the fusion enterprise is vulnerable. On the other hand, persistent barriers to practical fusion power generation include the following:

- Containment of viciously complex plasma fluctuations and continuously sustained ignition at temperatures greater than the core of the Sun;
- A system that produces net energy output and efficiently produce electricity; and
- A robust social order and energy policies to support a resource intensive long-term fusion enterprise in light of more than a sixty-year effort so far.

A synthesis comprised of an analysis of key institutions and the perspectives that surface from leading actors that comprise the quest to overcome the barriers maps a landscape that guides this study.

Analytical Tools

Science and Technology Studies (STS) tools upon which I draw include sociotechnical imaginaries, co-production, and the evolution of large technological systems. Sociotechnical imaginaries "are collectively held, institutionally stabilized, and publically performed visions of desirable futures (or of resistance against the undesirable), animated by shared understandings of forms of social life and social order attainable through, and supportive of, advances in science and technology".[55] The multi-dimensional lens of co-production[56] of knowledge and social order, and complementary sociotechnical imaginaries illuminate a complex landscape in which science and technology are paired elements of a human enterprise, magnified through shared utopian and dystopian visions of modernity. Thomas Hughes posits a life cycle of large

[55] Sheila Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", in *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*, eds. Sheila Jasanoff and Sang-Hyun Kim, (Chicago: The University of Chicago Press, 2015), 19.

[56] Jasanoff, *States of Knowledge*.

technological systems and associates biological evolution with an interdependent sociotechnical network.[57]

> The possibility of critical engagement is perhaps most apparent when a co-productionist eye is brought to the analysis of emerging orders. It is at the point of emergence, before things are completely stabilized or black-boxed, that one most clearly observes the mutual uptake of the social and natural. It is also at this moment of flux that processes of co-production are most influential for setting the stage for future human development.[58]

Rather than a closed, autonomous, or self-regulating system, a large technological system interacts with its environment.

Sheila Jasanoff introduces a landscape of multilateral relationships in emerging orders comprised of ordering instruments – identities, institutions, discourses, and representations.[59] The making of these ordering instruments is a central action as these orders surface. "The identity of the expert, in particular, that quintessential bridging figure of modernity"[60] is vital in each case studied in this dissertation. Institutions serve as "vehicles through which the validity of new knowledge can be accredited, the safety of new technological systems acknowledged, and accepted rules of behavior written into the as yet unordered domains that have become accessible through knowledge-making".[61] In the process of making discourses "scientific language often takes on board the tacit models of nature, society, culture or humanity that are current at any time within a given social order".[62] The means by which representations are made is aligned to how

---

[57] Thomas P. Hughes, "The Evolution of Large Technological Systems," in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, eds. Wiebe Bijker, Thomas P. Hughes, and Trevor Pinch, (Cambridge, MA: MIT Press, 1987).

[58] Jasanoff, *States of Knowledge*, 278.

[59] Jasanoff, *States of Knowledge*, 39-41.

[60] Jasanoff, *States of Knowledge*, 39.

[61] Jasanoff, *States of Knowledge*, 40.

[62] Jasanoff, *States of Knowledge*, 41.

"scientific representations are produced and made intelligible in diverse communities of practice".[63] The ordering instruments comprise a network of actors and actions in a multilateral relationship from which scientific knowledge and social order emerge together.

Data sources that advanced my research include interviews and electronic communication with fusion thought leaders, contents of unclassified government archives, open source data from IAEA and technology corporations, academic studies, and articles in peer-reviewed journals. For example, the accessible government archives of DOE and US national laboratories proved to be rich data sources. The repository of studies by the National Academies of Sciences, Engineering, and Medicine (NASEM) provided analytical perspectives that enhanced my research, as a result of the world-class minds NASEM typically attracts.

Prior to drafting the dissertation and during its subsequent development into a coherent research paper, I interviewed fusion thought leaders. Before I conducted the first interview, I submitted a comprehensive application to interview to the Virginia Tech Institutional Review Board (IRB) and submitted a modification for the second and third interview respectively. IRB approval was a prerequisite before I could request a date and time for each interview. As part of the approval process, I drafted a set of generic interview questions (Appendix A) that I used as a point of departure for each interview. The questions were tailored to account for references to specific projects, institutions, and political cultures. Upon IRB approval, I reached out to each potential person I had planned to interview to obtain their approval of the interview format and guidelines, and to arrange a date and time that each person preferred. I selected the Zoom™ application as the most effective video teleconference tool due to its ease-of-use, capability for clear voice and video, recording function, and compatibility for transcription to text.

[63] Jasanoff, *States of Knowledge*.

A year before any of the formal interviews, I had an introductory meeting with the former director of the Princeton Plasma Physics Laboratory (PPPL), Dr. Robert J. Goldston, during an April 2016 visit to PPPL. In 2017, I remotely interviewed, via Zoom, the research director of the National Spherical Torus Experiment Upgrade (NSTX-U) at PPPL, Dr. Jonathan Menard. In 2018, I held an enlightening and candid interview with Laban Coblentz, Communication Lead for the ITER Organization, again via Zoom. Within a few months of the Coblentz interview, I arranged a remote Zoom interview with Dr. Sibylle Günter, scientific director of the Max Planck Institute for Plasma Physics (IPP), from her office at the site of the Wendelstein 7X (W7-X) stellerator.[64]

Dr. Rob Goldston was also a keynote speaker at the 2018 Intelligence Community Academic Research Symposium (ICARS 2018),[65] for which I was the primary organizer. During his attendance at ICARS in September 2018 I had the opportunity to discuss my research with him in an unstructured context. Dr. Goldston was also an invited subject matter expert to an unclassified Intelligence Community (IC) workshop in December 2018 addressing converging sciences and technologies and instruments of social order that could potentially lead to surprising breakthroughs. Similar to the experience at ICARS 2018, I again was fortunate to gain his perspective on nascent conclusions emerging from my research.

Expressions of a Terrestrial Star

The three cases are linked by the high-energy physics inherent in fusion S&T and by an enduring multi-national collaboration. While there are common sociotechnical threads among

---

[64] Sibylle Günter (Scientific Director, Max Planck Institute for Plasma Physics), in interview with the author, August 17, 2018.

[65] Robert J. Goldston, Overview of fusion energy research, 4th Annual Intelligence Community Academic Research Symposium, 25-27 September 2018, (Washington, DC: National Academy of Sciences).

the cases analyzed, it is useful to consider that each case has a virtual boundary, defined by different approaches within a worldwide fusion technology domain and national energy policies reflective of strong political cultures. The case studies illustrate endeavors in pursuit of fusion's promise of abundant and eco-friendly power; these are missions in aggressive pursuit of solving the wicked problems associated with safely sustaining a plasma in excess of temperatures at the core of the Sun. A key criterion in the selection of the cases to study is to explicitly limit the landscape of technological approaches to magnetic confinement, i.e., to constrain the number of technological variables. A second standard is the identification of conspicuous ordering instruments that appear to exert the most influence on the co-production of each project. A third principle is the selection of major projects sited in nations with distinct national energy policies, reflective of their political cultures. In addition to the cited approach constraints, criteria for case study selection include the likelihood of continuing resource support and political sponsorship. The research focuses on sociotechnical imaginaries and the co-production of technology and social order in each case.

I use the term, "expression" of a terrestrial star, in context of the three cases because each is a representative *model* of fusion energy.

> Models can perform two fundamentally different representational functions. On the one hand, a model can be a representation of a selected part of the world (the 'target system'). Depending on the nature of the target, such models are either models of phenomena or models of data. On the other hand, a model can represent a theory in the sense that it interprets the laws and axioms of that theory. These two notions are not mutually exclusive as scientific models can be representations in both senses at the same time.[66]

Rather than the literal creation of the sun, the star at the center of our solar system, within the ecosphere of Earth, these expressions are models of the fusion reactions that power the sun at a benign distance of 93 million miles from our home world.

[66]Models in Science, *Stanford Encyclopedia of Philosophy*, https://plato.stanford.edu/entries/models-science/.

It is important to note that there are several other promising approaches.[67] On a very large scale, Laser Inertial Fusion Energy (LIFE)[68] has been an operational experiment at the National Ignition Facility (NIF) of Lawrence Livermore National Laboratory (LLNL) since 2009. On a compact scale, magnetized target fusion[69] and Polywell fusion[70] are characterized as promising approaches in two peer reviewed journals.[71] While the alternatives are technically promising at the current maturity level of the fusion enterprise, a tempting broader scope of study in one dissertation is prohibitively complex and rather should be the focus of other research projects.

A deep examination of ITER, NSTX-U, and W7-X uncovers both common and distinct sociotechnical imaginaries. The estimated construction cost of multi-national ITER, the largest Tokamak on Earth, is estimated by the ITER Organization at €17B[72] and possibly exceeds €20B.[73] The NSTX-U is a $94M upgrade to the formerly preeminent spherical fusion device.[74] The €1B asymmetrically sculptured W7-X[75] is the world's largest stellarator. The study of the

[67] Daniel Clery, "Fusion's Restless Pioneers: Startups with Novel Technologies are Taking on Fusion's Goliaths", *Science*, No. 345 (6195), (2014, 25 July), 370-375.

[68] At the NIF, 192 lasers trigger a hydrogen isotope pellet to implode and the inertia confines the plasma.

[69] In magnetize target fusion, magnetically confined plasma is fired into a crushing device.

[70] The Polywell approach uses electric fields to accelerate fuel nuclei so that they collide and fuse.

[71] Clery, "Fusion's Restless Pioneers: Startups with Novel Technologies are Taking on Fusion's Goliaths.

[72] ITER Cost, www.iter.org.

[73] Daniel Clery and Adrian Cho, "More Delays for ITER, As Partners Balk at Costs", *Science*, No. 352 (6286), (2016, 6 May), 636-637.

[74] National Spherical Torus Experiment Upgrade (NSTX-U), https://www.pppl.gov/nstx-u.

[75] Daniel Clery, "Twisted logic", *Science*, No. 350 (6259), (2015, 23 October), 369-371.

technological systems that enable an expression of fusion at the heart of each institution provide tangible views into the forces that power sociotechnical momentum of the fusion enterprise.

Instrumental Action in the Fusion Enterprise

Sheila Jasanoff asserts "co-production insists on contextualization" and that this approach transports us from the study of "fact-making" to "sense-making".[76] There are distinct ordering instruments – identities, institutions, discourses, and representations – that support a fusion energy knowledge infrastructure and animate sociotechnical momentum. "Each of these instruments of co-production can serve varied functions in maintaining order".[77] The instruments operate simultaneously and facilitate the emergence of knowledge and social order. The technological system that is thereby co-produced is sustained and reinforced, and momentum energized even as pressures to terminate the decades-long fusion enterprise intensify.

Fusion energy visions are promulgated by expert-leaders who attain credibility through their professional *identities*. Dr. Bernard Bigot, Dr. Jon Menard, Professor Rob Goldston, and Dr. Sibylle Günter are fusion thought leaders. Their influence did not spontaneously arise but rather was inspired by past physicists such as Albert Einstein and Lyman Spitzer. The collectively held visions[78] that are inherent in the professional identities correspond to Jasanoff's concept of sociotechnical imaginaries.

Each identity helps elevate the institutions examined in this dissertation to fusion enterprise prominence. The multilateral relationship of the expert-leaders, ITER and the ITER Organization, NSTX-U and PPPL, and W7-X and IPP comprise a central set of stable actors

---

[76] Jasanoff, *States of Knowledge*, 276.

[77] Jasanoff, *States of Knowledge*, 73.

[78] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity".

from which trusted knowledge and power emanate.[79] Beyond the sites of the three case studies, another powerful actor in the fusion sociotechnical system deserves detailed study: The International Atomic Energy Agency (IAEA).

In addition to the robust stability that the ITER Organization, PPPL, and IPP represent, IAEA is a crucial *institution* that helps sustain momentum of the fusion enterprise. IAEA is recognized as the principal international oversight organization in the field of nuclear energy. It is revealing to observe the transformative role of IAEA as the organizing institution for the biennial international Fusion Energy Conference (FEC). The twenty-seventh conference was held on 22–27 October 2018 in Gandhinagar, India. Dr. Rob Goldston attended in-person and contributed to the conference discourse.

> The 27th IAEA Fusion Energy Conference (FEC 2018) aims to provide a forum for the discussion of key physics and technology issues as well as innovative concepts of direct relevance to the use of nuclear fusion as a source of energy.[80]

The FECs bring scientists together to present recent results and provides a predictable window of opportunity to discuss various options for streamlined approaches with the goal of building the first demonstration power plant by the middle of the 21st century and the next FEC explicitly refers to *next step fusion devices* such as ITER and the W7-X.[81] The conference objective is endorsed and elevated by the international reputation for trust and objectivity that the conference organizer, IAEA, commands.

The *representations* especially as mediated through modern culture and politics create constructed realities of fusion energy science and social order. Rhetorical devices represent

[79] Jasanoff, *States of Knowledge*.

[80] Fusion Energy Conference (FEC 2018), https://www.iaea.org/events/fec-2018.

[81] Fusion Energy Conference (FEC 2018), https://www.iaea.org/events/fec-2018.

efforts to transmit optimistic images of each restatement of the quest to obtain the 'holy grail' of fusion energy. In each of the three cases in this study, positive outcomes are self-described as 'firsts' – that is, first to demonstrate a milestone on the roadmap to commercially viable fusion energy. Each program can thereby claim a game changing breakthrough, sought since the mid twentieth century, has been met. The representations that emerge from the three political cultures in which each of the case studies are sited embodies a national distinctiveness to each expression of the fusion enterprise.

Finally, the *discourses* reflected in the papers presented during the FECs develop scientific and social arguments, as well as establish boundaries, such as the distinctions between safe and unsafe technology, carbon free and hydrocarbon dependent energy, and reliability and conditional predictability. The FECs concentrate attention on the 'wicked problems'[82] of fusion energy and amplify discussions of potential clumsy solutions.[83] The dramatic characterization of the complex challenges of the fusion enterprise does not however deter rigorous discourse.

The presentations and discussions through the FECs are dominated by mainstream approaches, i.e., primarily Tokamak magnetic confinement (e.g., ITER) and, to a lesser extent, laser inertial confinement (e.g., National Ignition Facility of the Lawrence Livermore National Laboratory). On the other hand, the growing controversy associated with ITER has introduced alternate discourses. The discourses that emerge from the other two case studies, NSTX-U and W7-X, enrich both the body of knowledge addressing the wicked problems of ITER and illuminate the potential of spherical magnetic confinement and the remarkably shaped stellarator.

[82] Hulme, *Why We Disagree About Climate Change*, 334.

[83] Hulme, *Why We Disagree About Climate Change*, 337.

These cases are, thereby, able to derive momentum from the ITER program and simultaneously offer alternatives to the endeavor that dominates the contemporary fusion enterprise.

Sociotechnical Momentum

Technological momentum[84] typically refers to a large operational technological system that has matured and achieves a persistent stable state through closure.[85] Rival approaches to technological systems are usually proposed before the design of the artifact is stabilized.

> Important normative choices get made during the phase of emergence: in the resolution of conflicts; the classification of scientific and social objects; the standardization of technological practices; and the uptake of knowledge in different cultural contexts. Once the resulting settlements are normalized (social order) or naturalized (natural order), it becomes difficult to rediscover the contested assumptions that were freely in play before stability was effected.[86]

One of the attributes of the fusion enterprise is that it has not achieved closure. The half-century fusion initiative is a technological system that has to date *not* fulfilled its potential. The distinct ordering instruments analyzed in this dissertation support a fusion energy knowledge infrastructure and provide power to what I call *sociotechnical momentum*, a term meant to capture the co-production of science, technology, and social order within an embryonic fusion energy ecosystem. The attributes of this phenomenon are revealed in an analysis of ordering instruments, as a network that emerges from a primordial array of fusion sociotechnical imaginaries and is the foundation of an operationalized form of sociotechnical momentum.

---

[84] Hughes, "The Evolution of Large Technological Systems", 76-80.

[85] Trevor J. Pinch and Wiebe E. Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other", in *The Social Construction of Technological Systems: New Direction in the Sociology and History of Technology*, eds. Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, (Cambridge, MA: The MIT Press, 1987), 44.

[86] Jasanoff, *States of Knowledge*, 278-279.

What are the implications that emerge from the study of sociotechnical momentum? The forces that enabled the fusion enterprise still energize the promise of this exotic energy source. However, the current trend of funding and a narrowing band of fusion energy options is expected to continue. "Momentum does not contradict the doctrine of the social construction of technology, and it does not support the erroneous belief in technological determinism".[87] The 1945 report of Vannevar Bush, *Science, the Endless Frontier*[88], promoted an approach that explicitly declares unpredictable benefits emerge from a reservoir of knowledge, a direct result of 'basic research'. Bush's thesis is that a reservoir of basic research is worthy of policy decisions that support and fund such 'pure science'. On the contrary, there needs to be recognition of multi-lateral, non-linear relationships among science, politics, and policy.

In recent years, The US Congress has wavered in its support of fusion energy[89] but in each fiscal cycle finally restored funding roughly to the previous fiscal year levels. In the first budget proposed by the Trump administration, funding for FY 2018 Fusion Energy Sciences (compared to FY 2016, enacted) had been cut by 29.2%, $128M[90] but the US Congress again restored funds.

> The $1.3 trillion omnibus spending bill that President Donald Trump signed into law on March 23 [2018] ended up preserving many of the scientific initiatives the White House wanted to kill, including funding for the ITER nuclear fusion project.[91]

---

[87] Hughes, "The Evolution of Large Technological Systems", 80.

[88] Vannevar Bush, *Science, The Endless Frontier*, (Washington, DC: US Government Printing Office, 1945).

[89] Richard K. Lester, "A Roadmap for U.S. Nuclear Energy Innovation", *Issues in Science and Technology*, (2016, Winter) No. 32(2), 54.

[90] FY 2018 Congressional Budget Justification, U.S. Department of Energy, Office of the Chief Financial Officer.

[91] Karen Graham, "U.S. budget bill doubles funding for ITER nuclear fusion project", in *Science*, 2018, 27 March

There is growing socio-political ballast on the fusion energy ship. Just as Hughes highlights reverse salients[92] in the concept of technological momentum, there are potent counter-forces that could obstruct the fusion enterprise.

The ITER Organization was formed as an outcome of experimental results over decades of work with the Tokamak design and as a tangible product of a 1985 agreement between the USSR and the US. ITER is a transparent effort to establish a matter-of-fact: *the way* to viable fusion energy. In contrast to that self-evident view, Jasanoff insists that there are socio-political factors that shape matters-of-fact and that knowledge and social order are co-produced.[93] The conclusions that surface in the social order that frames the fusion enterprise (inclusive of, but beyond ITER), shape the narrative of the greater fusion community that the global knowledge infrastructure of the fusion enterprise is *the wa*y to a planetary energy revolution, a vision that to provide high-capacity energy and reduce damaging human impact on climate change.

Global Knowledge Infrastructures and Context

"Knowledge infrastructures comprise robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds".[94] Each knowledge infrastructure is comprised of distinct elements but also shares attributes and constituent elements. While we can look at the Earth as a single system as represented for example in iconic Apollo 8 photographs, we should remember the context of distance as a factor in the image. Representations are important when we consider the co-

---

[92] Hughes, "The Evolution of Large Technological Systems".

[93] Jasanoff, *States of Knowledge*, 278-279.

[94] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming,* (Cambridge, MA: MIT Press, 2010), 17.

production of knowledge and social order.[95] Consequently, the 1968 Earth image has become part of our global knowledge infrastructure[96] and the image drives a persistent theme that is central to global climate change and other global ideas: one interconnected world, a world without borders. Spaceship Earth is also emblematic of the systems that comprise our home world. As we decompose each system of system, we observe distinctions and commonality.

We might construct a definition that incorporates Jasanoff's construct of ordering instruments[97] and thereby establish more comprehensive language as a central focus from which to launch studies of knowledge infrastructures (e.g., to include those of climate change, energy, etc.). I suggest the following: Knowledge infrastructures comprise robust networks of people, identities, artifacts, institutions, discourses, and representations that generate, share, and maintain specific knowledge about the world. The NSTX-U, ITER, and W7-X are knowledge infrastructures that can be decomposed through ordering instruments and political cultures.

Political Cultures and Energy Policy Trends

The three projects selected as case studies do not solely represent three distinct national political cultures but also a heterogeneous international network of cultures. The radiance of France[98] clarifies the potent politics affecting the direction of French nuclear energy policy, in context of both fission and fusion. "France derives about 75% of its electricity from nuclear

---

[95] Jasanoff, *States of Knowledge.*

[96] Paul N. Edwards, *A Vast Machine: Computer Models, Climate Data, and the Politics of Global Warming,* (Cambridge, MA: MIT Press, 2010), 1.

[97] Jasanoff, *States of Knowledge*.

[98] Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity After World War II,* (Cambridge, MA: MIT Press, 1998).

energy, due to a long-standing policy based on energy security".[99] Consequently, the high percentage of electricity currently produced from fission of heavy elements and reprocessed nuclear fuel and the siting of the ITER project shape the roadmap of nuclear technology in the nation's energy landscape in the second half of the twenty-first century.

The drivers for Germany's energy roadmap are dramatically different than its European neighbor. A key factor in German energy policy is to address climate change in the largest economy in Europe. The economic system and standard of living in that nation is dependent on sources of energy to meet its high demand and yet by 2022 it will be reducing by 125 the amount of electricity it obtains from a non-polluting source, nuclear energy.

> Germany until March 2011 obtained one-quarter of its electricity from nuclear energy, using 17 reactors. The figure is now about 12% from seven reactors, while 42% of electricity comes from coal, the majority of that from lignite. A coalition government formed after the 1998 federal elections had the phasing out of nuclear energy as a feature of its policy. With a new government in 2009, the phase-out was cancelled, but then reintroduced in 2011, with eight reactors shut down immediately. Public opinion in Germany remains broadly opposed to nuclear power with virtually no support for building new nuclear plants. Over 40% of Germany's electricity is generated from coal, and there are no plans to phase this out.[100]

On the other hand, there is political commitment and public support for advancing the fusion enterprise in context of both the ITER project and the indigenous W7-X stellerator.

Fusion energy is envisioned as an enabling technology to lift global society,[101] a quality that in the US glows as an "electrical sublime".[102]

---

[99] World Nuclear Association, Nuclear Power in France, www.world-nuclear.org/information-library/country-profiles/countries-a-f/france. Note: The share of electricity provided by nuclear energy in France might be reduced to 50% by 2035 as a result of increased capacity from advanced renewables.

[100] World Nuclear Association, Nuclear Power in Germany (updated March 2019), www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.

[101] Jonathan D. Menard (Research Director, National Spherical Taurus Experiment, Princeton Plasma Physics Laboratory), in interview with the author, August 17, 2017.

> Electricity was invoked as the panacea for every social ill and the key to a whole range of social and personal transformations that promised to lighten the toil of workers and housewives, to provide faster and cleaner forms of transport, and to revolutionize the farm.[103]

The lighting of the American cityscape became a visible manifestation of invisible electricity.[104] The synthetic experience of electric lighting literally displayed control of a force of nature that humans had witnessed for millennia solely as violent, thunderous, and uncontrollable lightning. Electricity from fission, transforming the ominous destructive power of atomic weapons into a peaceful controlled power source became a form of the atomic sublime. The vision of benign high-capacity electrical generation from fusion is a future manifestation of the *American Technological Sublime*.[105]

Organization of the Dissertation

Chapter One, Introduction: Always Fifty Years Away, explores how and why fusion energy is the epitome of a large technological system with dramatic contradictory qualities. The chapter is the launch point of a dissertation sparked by the persistent dark joke that "fusion is and always will be fifty years away"[106] and the phrase embodies the paradoxical outcome of a continuing enterprise more than six decades in the making and counting. An analytic toolset is introduced that is comprised of sociotechnical imaginaries, co-production, and large technological systems, forming the foundation and structural elements of a penetrating study.

---

[102] David E. Nye, *American Technological Sublime,* (Cambridge, MA: MIT Press, 1994), 143-172.

[103] Nye, *American Technological Sublime*, 143.

[104] Nye, *American Technological Sublime*, 144.

[105] Nye, *American Technological Sublime*.

[106] Sievert and Johnson, "Creating Suns on Earth", 323.

Chapter Two, Comparative Fusion Futures, presents a multi-dimensional landscape in which the fusion energy community operates. There are themes and challenges that characterize the contemporary fusion ecosystem and three expressions of the fusion enterprise provide cases to illuminate the comparative study. The fusion futures explored in each case reveal distinct elements comprising the co-production of S&T of this exotic form of energy and its corresponding social order, as well as the embodiment of shared visions. The arc of the comparative study spans sociotechnical imaginaries, and the evolution and alternative futures of the fusion enterprise.

Chapter Three, Rise, Fall, and Revival of American Fusion: National Spherical Torus Experiment Upgrade (NSTX-U), studies a twenty-first century expression of the American technological sublime.[107] The project is a case in which I apply the making of institution and identity as instruments of co-production analysis, complemented by sociotechnical fusion energy imaginaries to shape an instance of the analytical framework tailored to NSTX-U. The primary drivers of the project and its institutional support landscape are the imaginary of the US as a high energy society with limitless potential[108] and PPPL as a pioneering fusion S&T center.

Chapter Four, Global Fusion Supremacy and Controversy: International Thermonuclear Experimental Reactor (ITER), explores the largest expression of the fusion enterprise to date. Rather than a purely technological challenge, the largest Tokamak ever built is a truly global undertaking with qualities of geopolitics at its core. In this chapter, I decompose the global dimensions of the components that comprise ITER. I reveal that ITER's size and complexity relative to other fusion projects require an international social order to facilitate a corresponding

[107] Nye, *American Technological Sublime*.

[108] Nye, *Consuming Power*.

support infrastructure. The study of the dimensions of ITER's enabling network and the scope and depth of its inevitable controversies amplify a view to inform the co-production analysis of this largest of case studies in the fusion enterprise, the ITER Tokamak.

Chapter Five, Anti-Nuclear Germany Weaves Thermonuclear Alternative: Wendelstein-7X (W7-X) Stellerator, examines the most recent entry in the fusion enterprise, a remarkable device that resides at the Max Planck Institute for Plasma Physics (IPP) in Germany. W7-X is based on a concept originally pioneered at Princeton University in the 1950s. In this chapter, I acknowledge fusion imaginaries[109] shared by each project but I introduce an imaginary that rules the discourse in the German expression of the fusion enterprise: an ecological vision of a high-energy landscape that not only eliminates fossil fuel sources. This German energy vision also discards a carbon neutral energy source, nuclear fission, and yet supports thermonuclear fusion.

Chapter Six, the Conclusion: Alternative Futures, encapsulates a synthesis of the three case studies. In this chapter, I arrive at a closing argument that the analytic concept of sociotechnical imaginaries is the product of, and yet also molds instruments of co-production analysis.[110] These dual qualities enable science and technology, and fosters alternative futures. Thereby, we are equipped to envision two scenarios that illustrate elements of a conceivable ecosphere of our planet one-hundred years after the historic agreement between the US and the USSR at the 1985 Geneva Summit.[111] We can also imagine alternative futures enabled by sociotechnical imaginaries, S&T, and a matrix of socio-political mechanisms.

---

[109] Larry Bernard, "10 facts you should know about fusion energy", (Princeton Plasma Physics Laboratory), www.pppl.gov.

[110] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 19.

[111] By mutual agreement, President of the United States Ronald Reagan and General Secretary of the Central Committee of the Communist Party of the Soviet Union Mikhail Gorbachev met in Geneva 19-21 November 1985.

CHAPTER TWO – Comparative Fusion Futures

A Comparative Project

The objective of my research is to add to a body of knowledge to inform an assessment of the fusion enterprise. Central to this dissertation is the study of the relationship of shared and contrasting visions, co-produced expressions of nature and society, and the impact of distinct political cultures. A systematic cultural and technological comparison of three fusion ventures exposes how these projects and the institutions they inhabit frame goals, risks, and benefits of the half-century fusion enterprise. Positioned within the Princeton Plasma Physics Laboratory (PPPL) in the United States, the international ITER Organization sited in France, and the Max Planck Institute for Plasma Physics (IPP) in Germany, the three projects are exemplars of big S&T in an age of dwindling investment in scientific research. PPPL's NSTX-U, ITER, and the W7-X of IPP are the case studies selected to advance the thesis. The institutions that these preeminent fusion initiatives inhabit are iconic centers of fusion S&T.

ITER is by far the most ambitious effort to date to demonstrate net energy output through a large scale Tokamak device. The scale at which the project is forming is not only large in terms of material technology but it is also a global undertaking. Yet, the study of this massive project is the second in the sequence of cases. Rather, NSTX-U is the first case studied. PPPL is the US national laboratory that hosts NSTX-U and conducted cutting-edge fusion S&T work decades before the ITER Organization began construction of ITER and without whose identities and key research, the objectives of ITER would be even more challenging than they are.

ITER appears to be successfully leveraging a potent array of institutions and inter-government agreements that reinforce its organization with far greater impact on the fusion enterprise than the any other institution, e.g., relative to PPPL or IPP. The ITER network of institutions and agreements is a key point of study to understand the centrality of ITER in the fusion enterprise. The Communications Lead of the ITER Organization, Laban Coblenz, offers an unexpectedly candid view into the ITER project. While the momentum imparted to ITER by PPPL and IPP helps advance the project, that quality does not preclude the emergence of counterforces.

One alternative to ITER's specific approach to produce viable fusion energy is the focus of the first case study, PPPL's spherical fusion device, NSTX-U, sited near the Princeton University campus. Thirty years ago, theories were promoted there, that a spherical magnetic confinement device would produce a more stable plasma than the donut-shape of the conventional Tokamak.[112] NSTX-U is the largest of its kind on Earth and fifty-eight fusion research centers across the globe have been collaborating on a five to ten-year research program. In spite of the contrast to the massive size and funding streams of the ITER Organization, the institutional identity of PPPL, nurtured over decades, is still recognized and the DOE laboratory continues as an influential actor on the international stage of the fusion enterprise.

The geopolitical dimensions of the ITER Organization eclipses PPPL and yet the institutional impact of two key voices at PPPL, Dr. Jon Menard and Dr. Rob Goldston, at PPPL rivals that of the Director-General of ITER, Dr. Bernard Bigot, and that influence becomes evident in this study. The identities of Menard, the current PPPL Deputy Director for Research and former Research Director of the NSTX program at PPPL, and Goldston, former director of PPPL (1997-2009) and current Princeton University Professor of Astrophysical Sciences, are huge in the relatively smaller NSTX-U program.

---

[112] Daniel Clery, "Private fusion machines aim to beat massive global effort", *Science*, (2017, 28 April), No. 356 (6336), 360-361.

The third case is the stellerator at IPP. The W7-X is now the world's largest and most advanced stellarator. This latest iteration of the fusion device is sculptured, revealing uniquely shaped electromagnets beneath the external surface. Rather than symmetry typical of big techno-science and the axial symmetry of ITER and NSTX-U, its three-dimensional form emerged as a function of the chaotic dances of plasma imaged in Tokamaks over several decades. The goal of the W7-X program is to probe viability of a power plant based on the stellarator.

IPP is also a partner of the ITER Organization[113] through research conducted on its Axially Symmetric Divertor Experiment (ASDEX) Upgrade. The project is preparing a physics baseline for ITER and simulating conditions for a fusion power plant based on the planned ITER design. IPP is simultaneously exploring two approaches to sustainable fusion power. Dr. Sibylle Günter, the IPP Scientific Director, articulates the multi-dimensional facets of IPP's relationship to ITER, to the global fusion enterprise, and to the indigenous German energy policy.[114]

The goal of this STS based comparative project is to develop a theoretical framework for understanding national and international energy policies and grasp the resource intensive fusion energy initiatives. Conclusions derived from this research might contribute to policy analysis for a fusion-centered sustainable energy ecosystem in the second half of the twenty-first century.

Shared Collection of Fusion Imaginaries

Utopian visions reside at the core of all three case studies. PPPL, a leader in magnetic confinement for more than three decades, expresses the way to the energy future in finite terms, as the laboratory announces ten fusion energy *facts*[115] on their public facing website.

---

[113] ITER Cooperation, Max Planck Institute for Plasma Physics, http://www.ipp.mpg.de/16617/iter.

[114] Günter, in interview with the author, August 17, 2018.

[115] Bernard, "10 facts you should know about fusion energy".

1. It's natural. In fact, it's abundant throughout the universe. Stars – and there are billions and billions of them – produce energy by fusion of light atoms.
2. It's safe. There are no dangerous byproducts. It produces some radioactive waste, but that requires only decades to decay, not thousands of years. Further, any byproducts are not suitable for production of nuclear weapons.
3. It's environmentally friendly. Fusion can help slow climate change. There are no carbon emissions so fusion will not contribute to a concentration of greenhouse gases that heat the Earth. And it helps keep the air clean.
4. It's conservation-friendly. Fusion helps conserve natural resources because it does not rely on traditional means of generating electricity, such as burning coal.
5. It's international. Fusion can help reduce conflicts among countries vying for natural resources due to fuel supply imbalances.
6. It's unlimited. Fusion fuel – deuterium and tritium – is available around the world. Deuterium can be readily extracted from ordinary water. Tritium can be produced from lithium, which is available from land deposits or from seawater.
7. It's industrial scale. Fusion can power cities 24 hours a day regardless of weather.
8. It's exciting. Fusion produces important scientific and engineering breakthroughs and spinoffs in its own and other fields.
9. It's achievable. Fusion is produced in laboratories around the world and research is devoted to making it practicable.
10. It's the Future. Fusion can transform the way the world produces energy.[116]

PPPL's promotion of what are labeled as facts is a method to communicate the low probability of major risks typically associated with new energy sources in our contemporary world, through apparently inherent qualities of operational safety, positive environmental impact, proliferation resistance, and unlimited availability. A synthesis of the collection of fusion facts serves as a common set of imaginaries and a foundational belief system in the fusion enterprise. The challenge I pose is to decompose a sociotechnical system of an unrealized energy source that is literally confinement and exploitation of a terrestrial star. The paradox of an enduring vision of unlimited clean energy and the elusive goal of a practical system of electrical generation spawns the research questions of this dissertation. The study is an effort to understand the fusion energy enigma and to ultimately reveal distinct factors in each case that are likely to shape alternative futures.

[116] Bernard, "10 facts you should know about fusion energy".

Multidimensional Paradox

Multiple paradoxes coexist in the fusion enterprise. Each of the three projects illuminate distinct views of the common contradictions. ITER, as the world's most prominent project and the one with the most sweeping international participation, demonstrates that scale and geopolitics matter in context of the competing forces. The continuing huge investment in ITER focuses energy policy debates. Diverging priorities have emerged among the main partner nations that have committed vast financial and intellectual resources. The prime example is the astronomical investment in ITER by multiple nations with one grand goal, viable fusion, but with contrasting sociotechnical criteria shaping roadmaps to the 'holy grail'.

Controversy characterized by slipping schedules and rising costs (Figure 5) for the ITER device and its supporting infrastructure has become a feature of the fusion enterprise and is emerging as a counter-force to the momentum of this large nascent technological system. The planned initial operating capability date for first plasma has slipped from 2020 to 2025 and the estimated cost has ballooned from €5B[117] to €20B.[118]

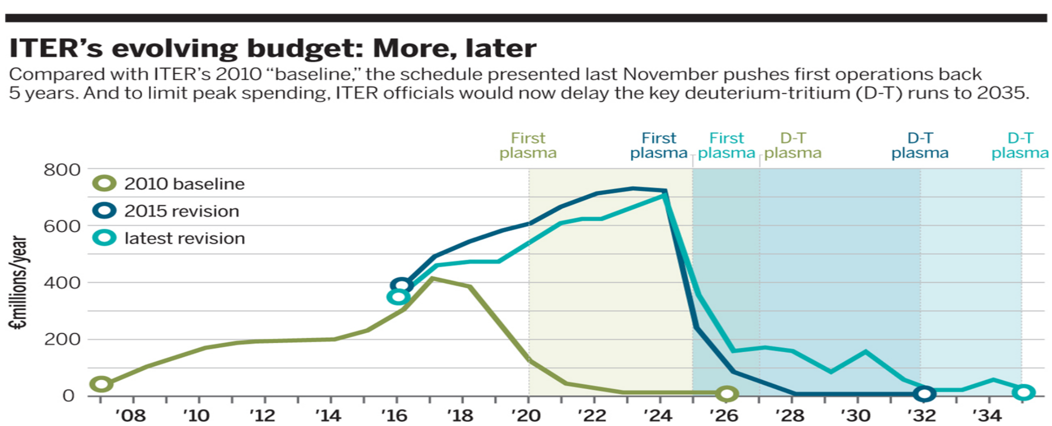

Figure 5. ITER's Evolving Budget. Courtesy ITER Organization.

---

[117] Estimated cost at the time of the 2001 design review was €5B.

[118] Daniel Clery and Adrian Cho, "More Delays for ITER, As Partners Balk at Costs", *Science*, No. 352 (6286), (2016, 6 May), 636-637.

The commercialization of fusion at the end of the first decade of the twenty-first century "remains as elusive as ever".[119]

PPPL contains artifacts that display both the impact of the wicked problems of fusion S&T killing off a *revolutionary* fusion device and evidence of advancing the fusion enterprise with *evolutionary* technology. The design for the National Compact Stellarator Experiment (NCSX) was inching forward in the course of labor-intensive evaluation of data gathered from decades of fusion plasma experiments but in 2008 the DOE funding decision-makers did not *perceive* that the problem had been solved. PPPL, the national laboratory that pioneered the stellarator, could not escape the growing skepticism related to cost-benefit calculus of effective viability. Starting with nascent efforts under the auspices of Princeton University shortly after the Second World War and the enduring sequence of endeavors through the current NSTX-U project, these projects have been instances of converging sciences, technologies, and corresponding instruments of social order, a narrative through which one expression of the fusion energy paradox is explored.

The migration of the center of stellerator R&D from PPPL to IPP sited in a country that promises to phase out nuclear fission as power source expresses a paradox based on Germany's political culture. The irony that Germany will need to progressively rely more on fossil fuels to make up for the planned dramatic decrease on fission-based nuclear energy introduces a counter-intuitive variable into the energy debate. That sociotechnical variable distorts the logic of imaginaries at the heart of Green Party signature issues that have become part of the mainstream political discourse in Germany. As an element of its Ecological Modernization Vision, Germany has committed to phase out all of its nuclear power plants by 2022 and simultaneously phase out

[119] Smil, *Energy Myths and Realities*, 31.

fossil fuel power plants. As a consequence of the dual drivers of mitigating climate change and supplying adequate energy for a highly industrial country, the Germany polity currently supports pursuit of fusion energy as an element of its vision. That sociotechnical energy vision and W7-X, in addition to IPP fusion projects in direct support of ITER are testimonies to the country's commitment.

Another dimension of the paradox is revealed through the American and German cases in the dual tracks to advance the fusion enterprise, i.e., through alternative approaches to ITER and simultaneous financial, intellectual, and material commitments to ITER. For each of the three cases studied, a key individual has been interviewed to provide a first-hand perspective to the overarching paradox: The fusion energy enterprise has endured for decades while the endeavor is yet to achieve its objective as a practical source of energy for electricity generation.

Foundations of the Comparitive Study

Central elements include big science, international collaborative S&T projects, energy policy, and the wicked technical challenges that comprise fusion energy systems. A rephrasing of my primary research questions is useful to guide this study. In an age of shrinking funding for 'big science', how do we make sense of the endurance of the half-century fusion enterprise and its corresponding visions?

The body of work of Sheila Jasanoff is an initial means to explore the paradox of an enterprise that continues to consume vast resources while it is yet to achieve its sustainable goal. In multiple works in which she is an author as well as an editor, assorted interpretations support Jasanoff's thesis of co-production of knowledge and social order. The prime value of the study of S&T through co-production analysis is that there is a transformation of analytical outcomes from the construction of facts into making sense.[120] Jasanoff condenses co-production into "shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it".[121] Jasanoff's thesis adds sociotechnical imaginaries to the analyst's co-production toolbox, as "these imaginaries are at once products of *and* instruments of the coproduction of science, technology, and society in modernity".[122] What explanatory work can sociotechnical imaginaries enable? Jasanoff asserts sociotechnical imaginaries can overcome descriptive limitations associated with past STS and political theory.[123] How might sociotechnical imaginaries explain the fusion enterprise?

> Imaginaries help explain why, out of the universe of possibilities, some envisionings of scientific and social order tend to win support over others—in other words, why some orderings are co-produced at the expense of others.[124]

A central theme explored in this study is the shared utopian vision of a planetary energy revolution coupled to the ultimate emergence of viable fusion.

I draw from the works of STS scholars. In particular, I construct a theoretical foundation based on technological momentum, co-production, and sociotechnical imaginaries. The themes primarily appear in "The Evolution of Large Technological Systems", [125] *States of Knowledge:*

---

[120] Jasanoff, *States of Knowledge*, 276.

[121] Jasanoff, *States of Knowledge*, 2.

[122] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 19.

[123] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 21.

[124] The Sociotechnical Imaginaries Project, Program on Science, Technology & Society, Harvard University, http://sts.hks.harvard.edu/research/platforms/imaginaries/.

[125] Hughes, "The Evolution of Large Technological Systems".

The Co-production of Science and Social Order,[126] "Sociotechnical Imaginaries and National Energy Policies", [127] and *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*.[128] Sociotechnical imaginaries correspond to large technological systems but are primarily comprised of "visions, dreams, and ambitions".[129] The linkage between these two concepts augments the explanatory power of the analysis of the large technological system that the fusion enterprise represents.

The purpose of the methodology is to understand an operationalized form of momentum, as represented in three cases of an emerging fusion energy technological system. "Technoscientific imagination and instrumental action"[130] of the embryonic fusion technological system outline the shape of the theoretical framework. Shared visions provide a foundation. The proposed methodological model has tangible structure and support through the lens of an array of ordering instruments – identities, institutions, discourses, and representations – tailored to diverse political cultures. This set of ordering instruments is the analytical structure through which the co-production of the immensely large fusion energy technological system and the corresponding social order can be decomposed and understood in a richly layered context.

---

[126] Jasanoff, *States of Knowledge*.

[127] Sheila Jasanoff and Sang-Hyun Kim, "Sociotechnical imaginaries and National Energy Policies", in *Science as Culture*, (2013, 30 May), No. 22:2, 189-196.

[128] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity".

[129] Sheila Jasanoff, "Imagined and Invented Worlds", in *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*, eds. Sheila Jasanoff and Sang-Hyun Kim, (Chicago: The University of Chicago Press, 2015), 326.

[130] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 10.

Large Technological Systems

The large technological fusion energy system is a sociotechnical construct, i.e., it is system comprised of both technical and sociological elements. While co-production is the primary analytical lens I use to study the fusion enterprise, the social construction of technology, i.e., SCOT,[131] and actor-network theory, i.e., ANT,[132] are precursors to co-production analysis. SCOT and ANT explore technology from different, somewhat conflicting perspectives. The sociological characteristic of SCOT is distinct from the way ANT objectifies both human and non-human actors. SCOT provides a methodology to understand S&T through the study of human activity on an individual and group level.[133] The interactive thread of co-production derives this capacity from SCOT. The analytical power of ANT is that it contextualizes the asymmetrical actors, human and non-human, and the social domains in which they operate. Exploring the interaction among institutions, processes, groups, individuals, and artifacts using visual analogies helps decompose the complex web around technology and assists in understanding its formation. This constitutive tradition is inherent in another strand of co-production analysis. Where STS frameworks, such as SCOT and ANT, deconstruct S&T black boxes, a co-production view is constructive and helps us see how STS scholarship relates to issues of public energy policy.

---

[131] Pinch and Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other".

[132] Bruno Latour, *Reassembling the Social: An Introduction to Actor-Network Theory,* (New York: Oxford University Press, 2005).

[133] David Bloor, *Knowledge and Social Imagery*. London: Routledge and Kegan Paul, 1976) and Bruno Latour and Steve Woolgar, in *Laboratory Life: The Social Construction of Scientific Facts,* (Beverly Hills: Sage Publications, 1979).

Thomas P. Hughes contributes to a collection of SCOT essays with "The Evolution of Large Technological Systems".[134] Hughes posits a model of an entire life cycle of large technological systems and applies an analogy to biological evolution to an interdependent socio-technical network. In contrast to the closed, autonomous self-regulating system, the large technological system interacts with its environment. Inventors, engineers, and financiers are key actors in the invention phase of large technological systems.[135] Entrepreneurs are central in the development phase. Other human actors such as industrial scientists perform vital roles during the innovation phase and "inventor-entrepreneurs fade from the focal point of activity".[136] Also, institutions become key actors at various stages of evolution. Each actor exerts influence in the social order that coalesces in the environment of the large technological system. The evolution is not necessarily linear as Hughes explores cases of "reverse salient",[137] related to system components that either devolve or the rate of progress does not coincide with the momentum of other elements of the system. Hughes introduces technological momentum. "Technological systems even after prolonged growth and consolidation, do not become autonomous; they acquire momentum".[138] Hughes, however, highlights that large systems such as electric utilities appear to display autonomy but "appearances of autonomy have proved deceptive".[139]

The electric utility technological system is a case that Hughes cites in several of the evolutionary phases. As the generation of electricity is a primary measure of fusion viability, the

[134] Hughes, "The Evolution of Large Technological Systems".

[135] Hughes, "The Evolution of Large Technological Systems", 57.

[136] Hughes, "The Evolution of Large Technological Systems", 66.

[137] Hughes, "The Evolution of Large Technological Systems", 73.

[138] Hughes, "The Evolution of Large Technological Systems", 76.

[139] Hughes, "The Evolution of Large Technological Systems", 79.

case that Hughes studies is relevant to examination of the fusion enterprise through the SCOT model. In particular, in the Technological Style segment, he decomposes common components and qualities and notably explores a comparative study of systems of electricity generation and distribution in London and Berlin.

> The historian can search for an explanation for different characteristics of a particular technology, such as electric power, in different regions… [and in the twentieth century] international pools of technology are available to the designers of regional technology because of the international circulation of patents, internationally circulated technical and scientific literature, international trade in technical goods and services, the migration of experts, technology transfer agreements, and other modes of exchange of knowledge and artifacts.[140]

In the UK and Germany, political values mold the regulatory legislation from which the contrasting designs are shaped. The small scale facilities in London were a reflection of the conservation of local governmental power.[141] In Berlin, the represented large scale power plants enhanced the concentration of power in a centralized metropolitan authority.[142] The revelation of contrasting designs and implementing strategies based on a common set of enabling technology highlights the impact of socio-political factors in the life cycle of this large technological system. The three projects selected for this dissertation are cases that demonstrate this point and a co-production examination builds upon the analytical method that Hughes employs and advances the analysis of the fusion enterprise.

Co-Production of Knowledge and Social Order

Co-production analysis illuminates the relationship between fusion knowledge and the social order that enables the enterprise. Sheila Jasanoff states "co-production insists on

[140] Hughes, "The Evolution of Large Technological Systems", 69.

[141] Hughes, "The Evolution of Large Technological Systems".

[142] Hughes, "The Evolution of Large Technological Systems", 70.

contextualization" and this approach transports us from the study of "fact-making" to "sense-making".[143] Beyond the lenses of the SCOT and ANT, but incorporating some of the same elements of these perspectives and compatible, a co-production analysis should reveal more of the complex relationships that construct fusion technology and its attribute of risk mitigation. Lessons learned from this compelling socio-technical quality can be, at least, conceptually applied to fusion reactors and other large-scale nuclear technologies yet to be developed. Co-production is "an idiom – a way of interpreting and accounting for complex phenomena so as to avoid the strategic deletions of most other approaches in the social sciences".[144]

Among the cases upon which Jasanoff comments, *Leviathan and the Air-Pump*[145] is an example of the co-production of science and social order in the seventeenth century.[146] In reference to the 1985 study by Shapin and Schaffer, Jasanoff summarizes "in this view of co-production, human beings seeking to ascertain facts about the natural world are confronted, necessarily and perpetually, by problems of social authority and credibility".[147] Co-production as an analytical lens is equally appropriate to apply to more contemporary ways of knowing such as fusion knowledge. The three fusion cases studied are thus expressions rather than precise replicas of the natural world.

Boyle and his peers created new technologies of persuasion, i.e., virtual witnessing, "in effect, redrafting the rules of social order pertaining to the trustworthiness and authority of

---

[143] Jasanoff, *States of Knowledge*, 276.

[144] Jasanoff, *States of Knowledge*, 3.

[145] Steven Shapin and Simon Schaffer, *Leviathan and the Air-Pump: Hobbes, Boyle, and the Experimental Life,* (Princeton, NJ: Princeton University Press, 1985).

[146] Jasanoff, *States of Knowledge*.

[147] Jasanoff, *States of Knowledge*, 29.

individuals and institutions… to convince skeptics and absent colleagues".[148] Today, virtual witnessing is a central element in contemporary S&T knowledge sharing, e.g., peer-reviewed journals. *Science* and *Nature* are primary publications in the scientific community and as such become media for the witnessing of fusion experiments. *Scientific American* is a publication with multiple language translations intended to broaden virtual witnessing publics beyond those people principally identified in the domain of S&T. Just as the air-pump was an imperfect mechanism, the current state of fusion energy has not matured adequately to produce fusion to enable practical generation of electricity.

The colorful dynamic images projected on an immense screen in the control room of NSTX-U during an April 2016 visit to PPPL were human-constructed expressions of the current state of fusion energy, magnetically confined in an advanced-yet-imperfect spherical machine. The unique expertise required to produce the imperfect fusion reaction at PPPL and the presence of a cloud of witnesses, my colleagues and I among them, is a twenty-first century expression of the experimental program that Robert Boyle and his contemporary colleagues pioneered. The expertise evident in the NSTX-U control room is a contemporary version of Boyle's operation of the air-pump to assist in establishing the public image of the device as an instrument of natural philosophy and, thereby, attracting private funding.[149]

Fusion science as much as air-pump science is a product of co-production, that is "the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it".[150] Shapin and Schaffer conclude that the heirs of the

[148] Jasanoff, *States of Knowledge*.

[149] Lisa Jardine, *Ingenious Pursuits: Building the Scientific Revolution,* (New York: Anchor Books, 2000), 56.

[150] Jasanoff, *States of Knowledge*, 2.

seventeenth century experimental program artificially create knowledge and that the scientific method does not purely reveal reality. In the sociological environment that the experimental program was operating, there was a major population group absent: women.

The emerging science enterprise of the seventeenth century was a male endeavor.   In *Reflections on Gender and Science*, Evelyn Fox Keller explores an alternative to the gender ideology that developed during the scientific revolution of the 17th century and had persisted into the 20th century.[151] Barbara McClintock, a respected and far-sighted geneticist of the 20th century, is a case in Keller's study that exemplifies the value of inclusion in the science enterprise. McClintock's use of language in the acquisition of knowledge about nature distinguished her from typical male peers. "Her vocabulary is consistently a vocabulary of affection, of kinship, of empathy".[152] The result was an attention to detail that yielded valuable insights into the study of chromosomes. It was a type of emersion into the entities she studied, quite unlike observing an alien object.

Even with the sociological barriers faced by women in science, the imagination and S&T insight of women such as Marie Curie and Rosalind Franklin in areas as diverse as physics and biology produced landmark advances. The inclusion of fully half of the human race that had formerly been largely excluded is an entirely different model for the contemporary understanding of the relationship between the human mind and nature and provides of a glimpse of the benefit of diversity to address the wicked problems at the heart of the fusion enterprise. The gender dimension of identity as an instrument of co-production analysis is increasingly recognized in the composition of teams facing the challenges of making fusion energy a practical reality.

[151] Evelyn Fox Keller, *Reflections on Gender and Science,* (New Haven: Yale University Press, 1985).

[152] Keller, *Reflections on Gender and Science*, 164.

The technical, sociological, and political dimensions of large technological systems provide a vast landscape worthy to explore through co-production analysis. Especially when humankind pursues new S&T endeavors, imagination is an essential ingredient.[153] Imagination in combination with the creative potential of science and technology enables the study of alternative futures.[154]

Alternative Futures: Social Order and Science

Imaginaries are not confined to the genre of science fiction. The nonfiction study, *The Social Function of Science*,[155] also provides a window into sociotechnical imaginaries immediately preceding the trauma of world war as much as a view of a world that Wells created in his prescient science fiction. How can two books written in two different genres and published 25 years apart in the early twentieth century inform the study of sociotechnical imaginaries in the context of an energy ecosystem with the potential to change the world? The first half of the twentieth century was a time of dramatic social and technological change. The two world wars, during the periods 1914-1918 and 1939-1945, represent an extreme of self-imposed impact to humanity as all elements of human life and ingenuity were applied to destruction on an immense industrial scale.

It is revealing that both works, in spite of the quarter century between publication dates, each expose the paradox of a dark contemporary evaluation of social order and knowledge, and simultaneously offers the seeds of a utopian vision. On one hand, Bernal asserts rejection of the

---

[153] Howard E. McCurdy, *Space and the American Imagination,* (Washington, DC: Smithsonian Institution Press, 1997), 29.

[154] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity".

[155] J.D. Bernal, *The Social Function of Science,* (G. Routledge & Sons, 1939).

utopias of writers such as Wells as “hardly worth while sacrificing much of the present if this is all the future has to offer.”[156] On the other hand, he contradicts his non-utopian view as he promotes a utopian vision emerging from the Soviet Union of 1939.

In 1967, the MIT Press characterized *The Social Function of Science* as “this blueprint for the function of science in a vigorous society.”[157] While this work is a scholarly thesis in contrast to Wells’ fiction, Bernal credits *and* critiques Wells’ visions in context of his study of the social factors that comprise scientific disciplines. Bernal applauds the concept of a World Encyclopedia, “a coherent expression of the living and changing body of thought; it should sum up what is for the moment the spirit of the age”[158] as a facilitator of “popular science”.[159] On the other hand, Bernal dismisses the utopian vision as “all utopias present two repulsive features: a lack of freedom consequent on perfect organization, and a corresponding lack of effort”.[160] While Bernal praises the Soviet Union as the antithesis of the Nazi regime in context of the social application of science, he fails to recognize the malevolence of the Stalinist Soviet Union that his utopian critique ironically characterizes.

In a 1967 prologue, “After Twenty-Five Years”, Bernal emphasizes that from the view of 1964, his 1939 thesis has been justified: to make people aware of the new function that science was acquiring then and would increasingly acquire in the future, in determining the conditions of human life and – as it is now tragically revealed – of the very existence of humanity. The events

[156] Bernal, *The Social Function of Science*, 381.

[157] Bernal, *The Social Function of Science*, back cover, 1967 edition.

[158] Bernal, *The Social Function of Science*, 306.

[159] Bernal, *The Social Function of Science*, 304.

[160] Bernal, *The Social Function of Science*, 381.

of World War II that followed, very soon after its 1939 publication, were to bring this home to everyone.[161]

His reference to an existential threat to human life is clearly associated with the Cold War stockpiles of atomic and thermonuclear weapons. Bernal contradicts his utopia critique as he fails to acknowledge the utopian attributes of his future vision. “If we find a practical way of producing directed molecular beams, or even better, beams of neutrons, the problem [of spaceflight] would be completely solved and we should have gained at the same time a generalized source of concentrated energy”.[162] He argues that prediction of discoveries, such as radioactivity, is not only possible but that “the larger and more important discoveries are not made *in vacua*”.[163] To reiterate McCurdy’s observation, “imagination matters when societies contemplate new ventures”.[164]

There are imaginaries, “collectively imagined forms of social life and social order reflected in the design and fulfillment of nation-specific scientific and/or technological projects”,[165] that both Bernal and Wells identify. In spite of Bernal’s assertion to the contrary, he believes the Soviet Union in the era of Stalin is a nascent utopia without labeling it as such. Instead, he considers the label itself a stigma to be contrasted with the ‘reality’ of the Soviet state. Whereas Bernal sees the Soviet Union as a model of future altruistic nation state, Wells envisions the only solution to deter the destruction of the human race is World Government; that

---

[161] Bernal, *The Social Function of Science*, 1964, xvii.

[162] Bernal, *The Social Function of Science*, 366.

[163] Bernal, *The Social Function of Science*, 343.

[164] McCurdy, *Space and the American Imagination*, 29.

[165] Sheila Jasanoff and Sang-Hyun Kim, “Containing the Atom: Sociotechnical Imaginaries and Nuclear power in the United States and South Korea”, *Minerva*, No. 47(2), (2009, June), 120.

global government is counterintuitively triggered by the use of atomic bombs in global war among nations. In recent decades, there has been ongoing debate among strategic policy analysts whether the possession of nuclear stockpiles has (a) deterred world war in the nuclear age or (b) if we have been lucky. Overall, Bernal's thesis does correspond to Wells' historical and imaginary view of the Janus-headed nature of science, with the potential to destroy as well as create new worlds – of plenty and poverty, of stability and conflict, and of unlimited energy and total destruction. "We have the potentiality of the age of abundance and leisure, but the actuality of a divided world with greater poverty, stupidity, and cruelty than it has ever known".[166]

Alternative Futures: Imaginaries of Individual Scientists

Jasanoff launches her thesis in the first chapter of *Dreamscapes of Modernity*[167] by acknowledging an elementary relationship to *technoscientific imaginaries*[168] but rather she defines a distinct boundary between sociotechnical imaginaries and the domain of Marcus' edition of ethnographic conversations that exposes the imaginaries of scientists.[169] "In inventing special relativity, Einstein imagined surfing a light wave; for general relativity, he envisioned walking off a roof".[170] Marcus' volume of highly individualized imaginaries is "tied more closely to their positionings, practices, and ambiguous locations in which the varied kinds of

[166] Bernal, *The Social Function of Science*, 1967 edition prologue, xix.

[167] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity".

[168] George E. Marcus, ed., *Technoscientific Imaginaries: Conversations, Profiles, and Memoirs,* (Chicago: University of Chicago Press, 1995).

[169] Marcus, ed., *Technoscientific Imaginaries*.

[170] Margaret Moerchen and Robert Coontz, "Einstein's Vision: General Relativity Turns 100", *Science*, (2015, 6 March), 347 (6226), 1083.

science they do are possible at all".[171] The social actors in the 2015 work to which Jasanoff and Kim contribute, both as authors and editors, are wide-ranging with multi-disciplinary qualities and "spatially and temporally larger and more symmetrical",[172] rather than Marcus' narrower focus on ethnographic studies of individuals in the scientific community.

A promising starting point is the notion of "technoscientific imaginaries" developed by Marcus and his colleagues in the anthropology of S&T. The term appears to perform similar bridging that *Dreamscapes of Modernity* seeks to accomplish.[173] On the other hand, a goal of *Dreamscapes* is to "investigate how… science and technology become enmeshed in performing and producing diverse visions of the collective good" and thereby justifies selection of the term 'sociotechnical' for Jasanoff's thesis on imaginaries.[174] The sociotechnical qualities are reflected in the identities in the fusion enterprise landscape and in particular are revealed in the interviews that inform this study.

Sociotechnical imaginaries

The 2015 collection of essays, *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*[175], edited by Jasanoff and Kim and to which they each contribute, is positioned as the central literary launch point from which threads of this dissertation emerge. The pivotal work is a survey of diverse scholars who express visions of a contemporary sociotechnical environment in which imagination and the creative potential of science and

[171] Marcus, ed., *Technoscientific Imaginaries*, 4.

[172] Marcus, ed., *Technoscientific Imaginaries*, 11.

[173] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity, 10.

[174] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity, 11.

[175] *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power*, eds. Sheila Jasanoff and Sang-Hyun Kim, (Chicago: The University of Chicago Press, 2015.

technology enables the study of alternative futures.[176] Compelling imaginaries surface from and enrich the analysis of the fusion enterprise. The three expressions of the fusion enterprise exhibit both a common set of imaginaries encapsulated in PPPL's fusion energy facts[177] and articulated through distinct political cultures. Controversy spawned by risks closely associated with energy produced by fission of heavy elements has diluted the corresponding utopian nuclear sociotechnical imaginaries envisioned in the twentieth century.

In the analysis of controversies in the domain of S&T, *framing* in a loosely defined sense implies an approach that might provide context and hints at an analytical quality that corresponds to illuminating outcomes that emerge from the concept of sociotechnical imaginaries.[178] The specific frame reflective discourse of Schön and Rein is centered on "intractable policy controversies".[179] Their thesis and sociotechnical imaginaries share a common point of departure at the most general level: an *as-is* state and *to-be* goal. *Frame Reflection*[180], however, is a discourse that follows a path with explicit reference to policy statements on controversial issues for which political entities are accountable. "We see policy positions as resting on underlying structures of belief, perception and appreciation, which we call 'frames'. We see policy controversies as disputes in which the contending parties hold conflicting frames."[181]

---

[176] Jasanoff, "Imagined and Invented Worlds", 339.

[177] Bernard, "10 facts you should know about fusion energy".

[178] Jasanoff and Kim, "Containing the Atom: Sociotechnical Imaginaries and Nuclear power in the United States and South Korea".

[179] D.A. Schön and M. Rein, *Frame Reflection: Toward the Resolution of Intractable Policy Controversies,* (Basic Books, 1995), ix.

[180] Schön and Rein, *Frame Reflection: Toward the Resolution of Intractable Policy Controversies*.

[181] Schön and Rein, *Frame Reflection: Toward the Resolution of Intractable Policy Controversies*, 23.

Synthesis of Analytical Toolset

The merging of themes that surface through primary and secondary sources provides a complex landscape through which to decompose the paradox of the fusion enterprise. Interviews of fusion thought leaders represent one set of primary sources of perspective, discussions framed by questions (Appendix A) drafted to correspond to key elements of the dissertation. STS literature is guidance to an analytical toolset and a survey of fusion-specific research comprises a multifaceted panorama of the large fusion technological system to navigate via that toolset.

The enigma of a large technological system that has not produced its objective appears to violate logic. More than the current state of the global endeavor, predictions of when advocates of this exotic form energy anticipate its viable form has been repeatedly delayed. Yet, contradicting qualities are not uncommon in S&T, e.g., the utopian and dystopian of imagined technological innovation.[182] The extraordinary contrast of decades-long sustainment of the fusion enterprise without even the perception of closure can be understood through the analytical instruments of co-production[183] and sociotechnical imaginaries.[184]

The formation of each instrument and sustained growth and persistent reinforcement over decades generated unique momentum, unlike the quality of mature large technological systems, i.e., technological momentum.[185] Sociotechnical imaginaries infuse institutions, identities, discourses, and representations and energizes the momentum of the fusion enterprise. The

[182] Wells, *The World Set Free*, Prelude, Section 8.

[183] Jasanoff, *States of Knowledge*.

[184] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity".

[185] Hughes, "The Evolution of Large Technological Systems", 76-80.

synthesis of these themes comprises an analytical toolset with which to not merely collect facts but make sense of the overarching paradox of the fusion enterprise.

CHAPTER THREE – Rise, Fall, and Revival of American Fusion: National Spherical Torus Experiment Upgrade (NSTX-U)

This chapter focuses on the National Spherical Torus Experiment (NSTX-U). The $94M upgrade to NSTX is a contemporary product of decades of S&T emergence in a pioneering world-class fusion landscape, a disruptive 2008 federal agency cancellation of a groundbreaking project, and subsequently, a measured resurgence of fusion R&D at the Princeton Plasma Physics Laboratory (PPPL). The NSTX-U project, sited at the national laboratory in proximity to Princeton University, is a case in which I apply the making of institution and identity as instruments of co-production analysis, complemented by sociotechnical fusion energy imaginaries to shape an instance of the analytical framework tailored to NSTX-U. The current project is a twenty-first century manifestation of the American technological sublime.[186] The primary drivers of the project and its institutional support landscape are the imaginary of the US as a high energy society with limitless potential[187] and PPPL as a pioneering fusion S&T center. A recent episode at PPPL, one of the three key sites of this study, exposes the enigmatic qualities of the fusion enterprise in a singular location.

Encounter at Princeton

In April 2016, my doctoral committee chair, Dr. Sonja Schmid, was invited to brief the staff of the Princeton Plasma Physics Laboratory (PPPL) on her book published by MIT Press, *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry*.[188] Dr. Schmid

---

[186] Nye, *American Technological Sublime*.

[187] Nye, *Consuming Power*.

[188] Sonja D. Schmid, *Producing Power: The Pre-Chernobyl History of the Soviet Nuclear Industry,* (Cambridge, MA: MIT Press, 2015).

also offered three graduate students, including myself, to accompany her on the two-day visit to the US Department of Energy (DOE) national laboratory. While we were waiting for our hosts, we would already be exposed to the utopian vision that inhabits PPPL in *A Star for Us*,[189] a booklet offered upon entry to the main PPPL administration building, the Lyman Spitzer Building.

> Imagine a new world where our urban ambitions yield new natural ecosystems. Humanity's accelerating hunger for lighting, transportation, and communication, integrated into a renewable reality. A world free from the fears of an atmospheric carbon budget. Where our children take up an intimate bond with land and sea... profiting from a bounty of electricity as limitless as the oceans.[190]

The majestic prose is representative of the entire text.

As we were taken on a tour of PPPL, one of the first stops was a counterpoint to this soaring vision. A partially constructed *National Compact Stellarator* is on display. This ruin of what was intended to be the most advanced device of its kind is a huge memorial to abrupt withdrawal of funding.[191] It is the victim of the complex, unpredictable design as its form was being dynamically shaped by seemingly endless hours of computer analysis of complex plasma instabilities that emerged from images derived over decades in Tokamaks. It is ironic that funding was withdrawn from PPPL, in proximity to the Princeton University campus, where in 1951 physicist Lyman Spitzer first conceived the stellerator in research papers to which contemporary theoretical and experimental physicists still cite.

In contrast, we were then guided to the control room of the central PPPL experiment: a spherical magnetic confinement fusion device, the National Spherical Torus Experiment

---

[189] Sajan Saini, *A Star for Us,* (Princeton Plasma Physics Laboratory, 2015).

[190] Saini, *A Star for Us*, 1: The Fusion Barrier.

[191] Adrian Cho, "Energy Department Pulls Plug on Overbudget Fusion Experiment", *Science*, No. 320 (5880), (2008, 30 May), 1142-1143.

Upgrade or NSTX-U. It is the most powerful of its kind on Earth. The first generation NSTX was used to conduct experiments from 1999 to 2011. A three-year $94 million upgrade was completed in 2015, an example of leading edge twenty-first century technology. Several times, we had the opportunity to observe real-time imaging of the formation and containment of a terrestrial star, and the undulating magnetic field outlined by the 15-million-degree Celsius plasma. In just two days at PPPL, we experienced paradoxical elements central to this study.

David Nye characterizes the American social construction of technology as the American technological sublime.[192] The history of the US and technological progress has been linked since the pre-Revolutionary period. Technology as a realm to solve problems and as the method to create a new world in the New World is an element of American culture that persists today. By the nineteenth century, the celebration of the Fourth of July "began to emphasize the [positive] social effects of technology and [was an opportunity] to compare America to other civilizations".[193] For the past six decades, the fusion enterprise has been an expression of the American technological sublime and it is linked to the electrical sublime.[194]

The framework of co-production, amplified by sociotechnical imaginaries facilitates an understanding of the fusion energy paradox as it is revealed in a landscape of shared visions, unique institutional qualities, and professional identities embodied in the principal fusion experimental device at PPPL. The concept of sociotechnical imaginaries in American culture, i.e., a distinctly American technological imaginary, establishes a solid foundation from which to launch a study of the first of three expressions of the fusion enterprise.

---

[192] Nye, *American Technological Sublime*.

[193] Nye, *American Technological Sublime*, 42.

[194] Nye, *American Technological Sublime*, 143-172.

An American Technological Imaginary

With a clear view from the far side of the Hudson River, the nighttime Manhattan skyline in the early twentieth century became an icon for the electrical cityscape.[195] The light from that iconic image of New York City symbolically illuminated the entire US, which became "the high-energy economy" with "an injection of power that had no historical precedent".[196] The demand for energy expanded exponentially during the first half of the twentieth century and the cost of energy from fossil fuels became progressively less expensive. Consequently, the timing to develop a new source of energy could not have been worse. That new source of energy was the result of the fission of heavy elements, e.g., uranium and plutonium. A milestone moment at the dawn of the Atomic Age came in the form of a letter penned by Albert Einstein.

A group of scientific colleagues convinced Albert Einstein, a lifelong pacifist, to pen a letter to US President Franklin D. Roosevelt "informing the President about the dangers of a nuclear chain reaction bomb" possibly in the hands of Nazi Germany.[197] The Manhattan Project emerged, the 2.2-billion-dollar effort to create a functional atomic bomb, was the most massive S&T undertaking in American history. Fortunately, by the time Germany was defeated in World War II the Nazi regime had not succeeded in developing such a weapon. By August 1945, one operational nuclear weapon was tested and two bombs were unleashed by the US against imperial Japan[198] rather than Nazi Germany.

---

[195] Nye, *American Technological Sublime*.

[196] Nye, *Consuming Power*, 187.

[197] Einstein Letter, Franklin D. Roosevelt Presidential Library and Museum, August 2, 1939.

[198] Hiroshima was the first target on August 6, 1945. The second target was Nagasaki on August 9, 1945.

The venture was a war-time union of sciences and technologies, and social order at the pinnacle of the American high-energy society[199] and hinted at the possibility of an unlimited reservoir of power with a transformative quality for the planet.[200] "Increases in all forms of energy use made the United States the most highly powered society in world history".[201] An analysis of the Manhattan Project through a union of ordering instruments reveals a convergence of S&T disciplines and military-industrial social order that unleashed a post-war sociotechnical imaginary to leverage a new powerful energy source, nuclear energy.

> Congress established the United States Atomic Energy Commission [AEC] to foster and control the peacetime development of atomic science and technology. Reflecting America's postwar optimism, Congress declared that atomic energy should be employed not only in the Nation's defense, but also to promote world peace, improve the public welfare, and strengthen free competition in private enterprise.[202]

Only six years after the first use of a fission weapon, the AEC approved funding for a project to study a broad range of *fusion* applications, ranging from a thermonuclear bomb to controlled release of net energy from a fusion reactor.

The American technological sublime acquired an ominous quality with the dawn of the Atomic Age and the maturing of rocket technology, a source of "sublime terror".[203] Even before the Space Age, long-range bomber aircraft capable of carrying nuclear weapons that could devastate a city and continue to harm its inhabitants (e.g., with radiation), created a new vision of war terror. In several hours of flight time, an American city might become the next Hiroshima. The intercontinental ballistic missile (ICBM) and the submarine launched ballistic missile

[199] Nye, *Consuming Power*.

[200] Nye, *Consuming Power*, 201.

[201] Nye, *Consuming Power*, 202.

[202] Alice L. Buck, *The Atomic Energy Commission,* U.S. Department of Energy, 1983.

[203] Nye, *American Technological Sublime*, 234.

(SLBM) amplified that frightening vision. The nexus of nuclear weapons and intercontinental rockets was "more frightening than either by itself. The guided missile made the bomb an immediate threat".[204] Instead of several hours, a nuclear war could start in 30 minutes or less, from launch to initial detonation. "Reliable information about the doings of secretive Soviet Union"[205] was a factor crucial to a realistic American nuclear policy in a world with the potential for an abundant order of Hiroshima terror, multiplied by tens of thousands.

On the other hand, the visceral power of the atomic bomb refers back to the vision of atomic energy that surfaces in the H.G. Wells novel, *The World Set Free*[206] and in the writing of science fiction authors during the period between the first and second world wars. Wells paints a future landscape in which an inexhaustible radioactive source would power a future of prosperity but also reveals the dystopian side of such humbling power. Indeed, the AEC was a post-war manifestation of this sociotechnical imaginary and "underscores the shift away from terror and toward control that is a central characteristic of the technological sublime".[207]

> But the awesome destructive power of the energy unleashed at Hiroshima suggested the possibility of an infinite power supply. Atomic energy emerged as a major government program in the 1950s, promoted as the ultimate breakthrough to a perpetual high-energy economy. Atomic power gave the United States international prestige and confirmed its technological leadership. The public media depicted atomic power as inexpensive – perhaps too cheap to meter. Prewar enthusiasts and the science fiction of the 1930s had proclaimed that it would give Americans the power to control the climate, increase productivity, travel cheaply, and create a social utopia.[208]

---

[204] Nye, *American Technological Sublime*, 225.

[205] Walter A. McDougall, *The Heavens and the Earth: A Political History of the Space Age,* (Baltimore: Johns Hopkins University Press, 1985), 234.

[206] Wells, *The World Set Free*.

[207] Nye, *American Technological Sublime*, 234-235.

[208] Nye, *Consuming Power*, 201.

The promotion of a new power source came when the US was the embodiment of the high energy society.

The energy capacity from commercial fission nuclear plants added to the glut of fossil fuels in the mid twentieth century and "made the United States the most highly powered society in world history".[209] The technological optimism that emerged as a consequence of thermonuclear test detonations produced a vision similar to what followed the first use of fission weapons. At the 1964 New York World's Fair, "the visitor was assured that fusion would prove to be 'a source of electricity great enough to last for billions of years, with the oceans of the world serving as an inexhaustible reservoir of fuel for the new industrial civilization'".[210]

As there is no fusion technological system that has achieved closure, the promise of these qualities is yet to be demonstrated. There are perhaps indications on a small scale that imply these qualities but evidence on a practical scale is speculative. An implementation approach to a fusion centered energy ecosystem, tempered by technological humility, might indeed minimize threatening scenarios that have tragically appeared in the *fission* energy domain – primarily in three high-profile accidents: Three Mile Island, Chernobyl, and Fukushima. This trio of focusing events,[211] acts to amplify indicators of risk, offer diverse "avenues for political intervention"[212] in national energy policy options and one of the persistent responses is commitment to the fusion enterprise. A persistent comparison between the risk landscape of fission and that of fusion,

---

[209] Nye, *Consuming Power*, 202.

[210] Nye, *Consuming Power*, 213-214.

[211] John W. Kingdon, *Agendas, Alternatives, and Public Policies*, (New York: Longman, 2003), 94.

[212] Giddens, *The Politics of Climate Change*, 114.

highlights the envisioned reduction in risk and the ease of managing worst-case elements of the fusion enterprise.

While Jasanoff and Kim observe "a well-known feature of the American sociotechnical imagination is that technology's benefits are seen as unbounded while risks are framed as limited and manageable",[213] the historic letter from Einstein to President Roosevelt identified a potentially existential risk of nuclear technology. The letter was written from the physicist's desk at Princeton University. The setting could not have have been a more appropriate location based on the university's history and as a key American site of pioneering S&T.

The Plasma Physics Laboratory Emerges from Princeton University

It is not a coincidence that one of the global centers of the fusion enterprise is not only in proximity of Princeton University but the university itself. The institutional power of Princeton University is manifested through global recognition of physics distinction associated with this academic repository of knowledge and influence since the nineteenth century.

> The long and distinguished history of physics at Princeton began with a watchmaker's apprentice who became a legendary teacher and one of the most acclaimed research pioneers of the 19th century. Joseph Henry arrived on campus in 1832, conducted courses in natural philosophy and engineering, and performed a series of experiments in electromagnetic induction that put him at the forefront of the first golden age of science in America.[214]

The corresponding world-class minds linked to the university for more than a century represent "quintessential bridging figures of modernity".[215] "In the 20th century, Princeton's prominence in relativity theory influenced Albert Einstein's choice of refuge and residence and led to his long

---

[213] Nye, *American Technological Sublime*, 190.

[214] History of Physics at Princeton, Department of Physics, Princeton University, https://phy.princeton.edu/department/history.

[215] Jasanoff, *States of Knowledge*, 39.

friendship with the University".[216] Einstein was no doubt identified by the American public and the scientific community as the preeminent physicist of the early twentieth century but the reason for Einstein's decision to emigrate to America also drove many of the leading scientists to migrate from Europe. Princeton University, in particular the Institute for Advanced Study,[217] became the home of a significant émigré community. This influx of great minds added further to the prestige of Princeton and to the influence of American science and technology, as European dominance diminished in the shadow of the Third Reich. Consequently, the landscape of the Princeton scientific sublime was enriched.

Princeton University was the incubator of the Princeton Plasma Physics Laboratory (PPPL). This American national laboratory represents a contemporary exemplar of the American technological sublime and it is where and when the first case of the fusion enterprise is positioned. Since the early 1950s, PPPL has been the site of expressions of the fusion chronicle and each project has been an element in the American fusion narrative. The staff of PPPL has leveraged core competencies that include plasma physics, physical chemistry, and engineering disciplines to include nuclear engineering and materials. The structure of each program still retains the need for R&D leadership that weaves a tapestry of skills and experience into a systematic endeavor, with an eye on maintaining a balance of a long-term investment strategy and understanding the need for earned-value calculations in each phase of R&D. Spanning seven decades, each project, from Project Matterhorn to NSTX-U, has been a chapter in the continuing story of the co-production of fusion R&D and institutional norms at PPPL.

[216] History of Physics at Princeton, Department of Physics, Princeton University, https://phy.princeton.edu/department/history.

[217] The Institute for Advanced Study was founded in 1930.

Dr. Jon Menard, PPPL Deputy Director for Research has shared insights into links between the university and endeavors within the walls of the fusion research laboratory.

> I actually think a lot of it is intellectual vitality and breadth. PPPL is a single-purpose laboratory focused exclusively on plasma physics and that is not simply fusion plasma physics. We also worked on plasma astrophysics, low-temperature plasma physics, we're branching out into nanomaterial synthesis using plasmas and plasma chemistry. So it brings together a wide range of people in plasma science and also different applications. I think that allows the lab and its people to see some opportunities or ways to advance fusion perhaps that other groups may not have access to it.
>
> The linkage to Princeton University is also very strong and academically, it's one of the best if not "the best" in some areas especially in physics and that carries over to the quality of the graduate program here at the lab. It's number one in the US and has been for decades so the quality of students and collaborative researchers and people who want to visit is simply excellent. So I think that underlying intellectual power really helps the lab a lot and it keeps on going.[218]

The genesis of PPPL is linked to the origin of the endeavor to produce viable fusion energy. As the newly established AEC endorsed advancing fusion energy, the Princeton project became PPPL. The National Spherical Torus Experiment – Upgrade (NSTX-U) is certainly the most recent chapter in that long historical narrative and PPPL still occupies a key position in the network of institutions that comprise the fusion enterprise and, in particular, the DOE Princeton-based laboratory's support of ITER. For more than a half-century, PPPL has demonstrated its continuous role as a stable center of fusion science, engineering, and global influence.

> The U.S. Department of Energy's Princeton Plasma Physics Laboratory is dedicated to developing fusion as a clean and abundant source of energy and to advancing the frontiers of plasma science. The Laboratory pursues these goals through experiments and computer simulations of the behavior of plasma, the hot electrically charged gas that fuels fusion reactions and has a wide range of practical applications.[219]

The body of fusion knowledge is articulated through progressively more refined models of the wickedly complex plasma at the core of fusion experiments.

---

[218] Menard, in interview with the author, August 17, 2017.

[219] Research, Princeton Plasma Physics Laboratory, https://www.pppl.gov/research.

In plasma physics, PPPL staff is comprised of notable contributors to advance the ITER project. The institution also contributes hardware components that are essential to the completion of the massive Tokamak device in Cadarache, France. Before the start of ITER construction in 2010 and indeed decades before the 1985 agreement between Gorbachev and Reagan[220] that laid the foundational agreement from which the "International Thermonuclear Energy Reactor" project (i.e., the meaning of the acronym "ITER", as it was first known) would emerge, PPPL was already established as one of the primary centers of the fusion enterprise.

The timeline of the Princeton Plasma Physics Laboratory (PPPL) and the project that spawned PPPL imparts context to fusion milestones and provides temporal boundaries to the S&T elements of my research into the enigma of the enduring fusion enterprise.

> Magnetic fusion research at Princeton began in 1951 under the code name Project Matterhorn. Lyman Spitzer, Jr., Professor of Astronomy at Princeton University, had for many years been involved in the study of very hot rarefied gases in interstellar space. Inspired by the fascinating but highly exaggerated claims of fusion researchers in Argentina, Professor Spitzer conceived of a plasma being confined in a figure-eight-shaped tube by an externally generated magnetic field.
>
> He called this concept the "stellarator," and took this design before the Atomic Energy Commission in Washington. As a result of this meeting and a review of the invention by designated scientists throughout the nation, the stellarator proposal was funded and Princeton University's controlled fusion effort was born. In 1958, magnetic fusion research was declassified allowing all nations to share their results openly.[221]

The classified Princeton University project was called Project Matterhorn. By 1953, the Model A stellerator was operational at Princeton, as the university's first experimental fusion device. In 1961, Project Matterhorn officially became the Princeton Plasma Physics Laboratory (PPPL).

[220] Joint Soviet-United States statement on the summit meeting in Geneva, Reagan Library Archives, November 21, 1985.

[221] History, Princeton Plasma Physics Laboratory, http://www.pppl.gov/about/history.

Lyman Spitzer, Jr., Fusion Energy Pioneer

The simple, innovative qualities that distinguish the work of Lyman Spitzer, Jr. are reflected in the ground-breaking research papers and explain the longevity of Spitzer's impact.

> Lyman Spitzer was born in Toledo, Ohio, in 1914. Educated at Yale University, and Cambridge, he received his Ph.D. from Princeton University in 1938. During World War II he participated in underwater warfare research. In 1947 he was appointed chairman of the Astrophysics Department at Princeton University, beginning a long and fruitful tenure. In 1951, Spitzer outlined the basic concept for creating the stellarator, a device for confining and heating ionized hydrogen gas to release fusion energy for the production of power. He was able to receive support from the US Atomic Energy Commission as well as Princeton University which lay the foundation for starting Project Matterhorn. Project Matterhorn became later the Princeton Plasma Physics Laboratory (1961). In 1952 Spitzer was elected to the National Academy of Sciences.[222]

The theoretical and experimental elements which comprise Spitzer's identity as a fusion energy pioneer still apply today in pursuit of the holy grail of net power from fusion. Two decades after his death his identity is a factor in the enduring institutional power which spans fusion plasma research at Princeton University and, further, to encompass PPPL's mission to advance humanity toward viable fusion energy. Spitzer's identity has been associated across multiple domains in which his passions and mind were applied. The main administration building at PPPL,[223] the entry point for visitors to the national laboratory bears his name. The NASA Spitzer Space Telescope provides "a unique, infrared view of the universe and allow us to peer into regions of space that are hidden from optical telescopes".[224] In each representation, his pioneering identity instills objects with qualities associated with Spitzer.

---

[222] Lyman Spitzer papers (C0682): A finding aid prepared by Matthew Robb, class of 1994 and Gena Bursan. 1991, 2000. Manuscripts Division Department of Rare Books and Special Collections, Princeton University Library.

[223] Princeton Plasma Physics Laboratory, https://www.pppl.gov/.

[224] Spitzer Space Telescope, NASA, https://www.nasa.gov/mission_pages/spitzer/main/index.html.

Following Spitzer's death in 1997, Thomas H. Stix of the Department of Astrophysical Sciences dedicated a paper, "Highlights in Early Stellerator Research at Princeton"[225], to the late fusion pioneer. Stix's overview of the first fifteen years of stellerator work at Princeton is centered on Spitzer's leadership and ground-breaking scientific research.

The first research into the stellerator concept by Lyman Spitzer, Jr. was a revelation of remarkably simple analysis of the wicked challenges essential to overcome in order to create a controlled fusion plasma as a stable source of power. In a scant page and a half of the first paper Spitzer calculated the energy in a deuterium-tritium plasma and concludes with tiny energy loss as well as the potential to amplify the energy released by a blanket of fissile material. The prescient insights that surfaced in Spitzer's research in the early 1950s are as relevant six decades later and still form a R&D base as fusion inches toward viability.[226]

As a result of Spitzer's early research in the nascent fusion enterprise, several progressively more sophisticated stellerators were designed, constructed, and operated on the Princeton University campus. The aptly named Model A first surfaced in the mind of James A. Van Allen,[227] a University of Iowa physicist who in 1953 to 1954 conducted a program of experiments at Princeton University using a simple yet elegant figure-8 design.

> The vacuum chamber of the Model A Stellarator was made from sections of 5 cm diameter Pyrex glass tube comprising a figure-8 shape about 350 cm in length. Magnet coils to produce a 1000-gauss steady-state field were wound directly onto the Pyrex tubing and were energized by a dc motor-generator set.

---

[225] Thomas H. Stix, 1997, Highlights in early stellarator research at Princeton. Department of Astrophysical Sciences, Princeton University, Princeton, NJ. *Journal of Plasma Fusion Research* SERIES, Vol.1 (1998), 3-8. Japan Society of Plasma Science and Nuclear Fusion Research.

[226] Stix, Highlights in early stellarator research at Princeton, 3-4.

[227] In 1958, Van Allen discovered radiation belts as an outcome of the launch of America's first artificial satellite, Explorer 1. This near-Earth zone of high energy particles would later be named the Van Allen radiation belts.

> Model A came into operation early in 1953. The plasma was produced with a radio-frequency electric field linked inductively to the stellarator loop. Some years ago, the Model A Stellarator was taken out of storage and given to the Smithsonian Museum in Washington, D.C.[228]

The Model A led to several iterations of the Model B, with the first three variations utilizing the basic figure-8 design and subsequent designs with squared corners.[229]

The Model C was the first relatively large stellerator built by the nascent Princeton Plasma Physics Laboratory but the scaled-up device fell far short of anticipated performance, especially in contrast to confirmed progress on the T-3 Tokamak of the Soviet Union's fusion program. By 1969, the Model C was recreated as a symmetrical Tokamak.[230] While the stellerator as an experimental fusion device that emerged from Spitzer's theoretical research was never again operational at PPPL, his theoretical treatises exposed issues of "equilibrium plasma profiles, mechanical stresses, heat generation and dissipation, refueling, neutron moderation, tritium inventory, and lithium-blanket design"[231] that persist today. Stellarator R&D at PPPL would not again emerge until the ill-fated[232] National Compact Stellarator Experiment (NCSX).

PPPL in the Age of the Tokamak

In subsequent decades, PPPL was both a national center of magnetic confinement research and a global leader of experiments using the Tokamak design introduced in Soviet research laboratories. In operation from 1982 to 1997, the Tokamak Fusion Test Reactor (TFTR) was a leading edge device that would break the record for performance. "Beginning in

[228] Stix, Highlights in early stellarator research at Princeton, 5.

[229] Stix, Highlights in early stellarator research at Princeton. 6-7.

[230] Stix, Highlights in early stellarator research at Princeton, 7.

[231] Stix, Highlights in early stellarator research at Princeton, 5.

[232] DOE cancelled the program in 2008.

1993, TFTR was the first in the world to use 50/50 mixtures of deuterium-tritium, yielding an unprecedented 10.7 million watts of fusion power".[233] In 1999, the spherical National *Spherical* Torus Experiment (NSTX) became the central PPPL fusion device and operated until 2011.

In theory, a spherical torus is more compact and cost-effective than a Tokamak, and enables the confinement of plasma with lower power magnetic fields.[234] A three-year $94 million upgrade to the first generation NSTX, NSTX-U (Figure 6), was completed in 2015 and is now operational.[235] PPPL is a partner laboratory to *US ITER*, a DOE Office of Science endeavor managed by Oak Ridge National Laboratory. NSTX-U research includes "studies of the cause of plasma disruptions that can thwart fusion reactions by allowing the plasma to flash apart… [and] could help developers of ITER create tools to mitigate the disruptions".[236]

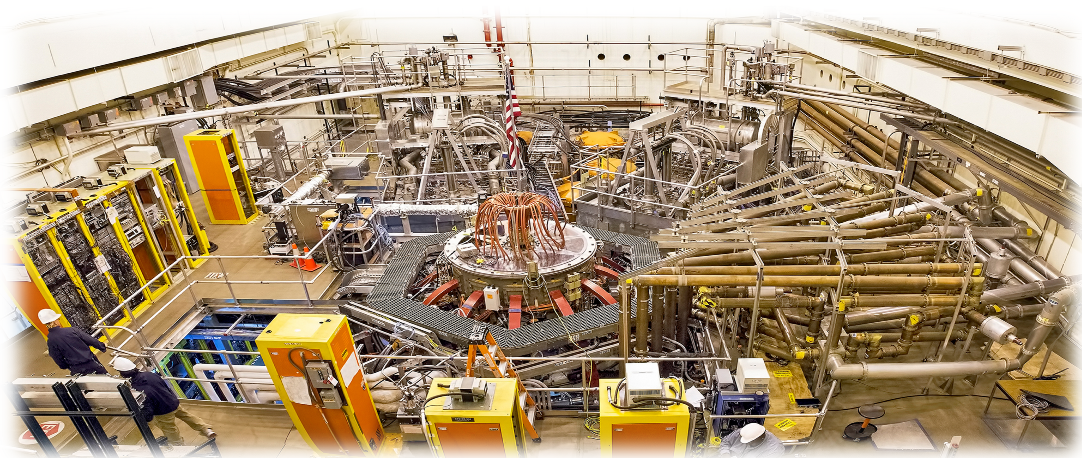

Figure 6. NSTX-U. Courtesy Princeton Plasma Physics Laboratory.

[233] History, Princeton Plasma Physics Laboratory, http://www.pppl.gov/about/history.

[234] National Spherical Torus Experiment Upgrade (NSTX-U), History, https://www.pppl.gov/nstx.

[235] In August 2016, a magnetic coil failed, rendering NSTX-U inoperable (*Science*, 2016). NSTX-U is expected to resume operations during CY2020 (National Academies of Sciences, Engineering, and Medicine 2018, G-6).

[236] Princeton Plasma Physics Laboratory, www.pppl.gov.

A Personal Temporal Narrative

There is more to my interaction with PPPL than the introductory narrative of my 2016 visit conveys. My two close encounters with the national laboratory are separated by nearly forty years. Each occurrence captures the essence of the paradox that this dissertation examines.

Immediately after I successfully completed a New York University 'boot camp' in systems design and analysis in 1977, I applied for an IT position at PPPL. My action was prompted as a consequence of reading an article about the groundbreaking ceremonies for the Tokamak Fusion Test Reactor (TFTR) at PPPL. There is an enduring PPPL declaration that fusion "is the future" and the TFTR was the embodiment of that vision, a design to advance the mainstream approach to fusion energy.

While I considered my application a 'long shot', I longed to be part of that envisioned future. Alas, it was not to be as I soon read a compassionate rejection letter that wished me the best in my future endeavors. The attraction by an idealistic twenty-something to an energy technology viewed as a manifestation of America's technically deterministic future simmered for decades until the robust study of the fusion enterprise emerged as a compelling challenge during my doctoral studies at Virginia Tech.

In 2016, three academic colleagues and I had an informal conversation with Dr. Rob Goldston, former director of PPPL (1997-2009). That conversation and the opportunity to observe multi-million-degree fusion reactions on the large screen in the NXTX-U control room (Figure 7) provided fulfillment of a personal imaginary that simmered for four decades.

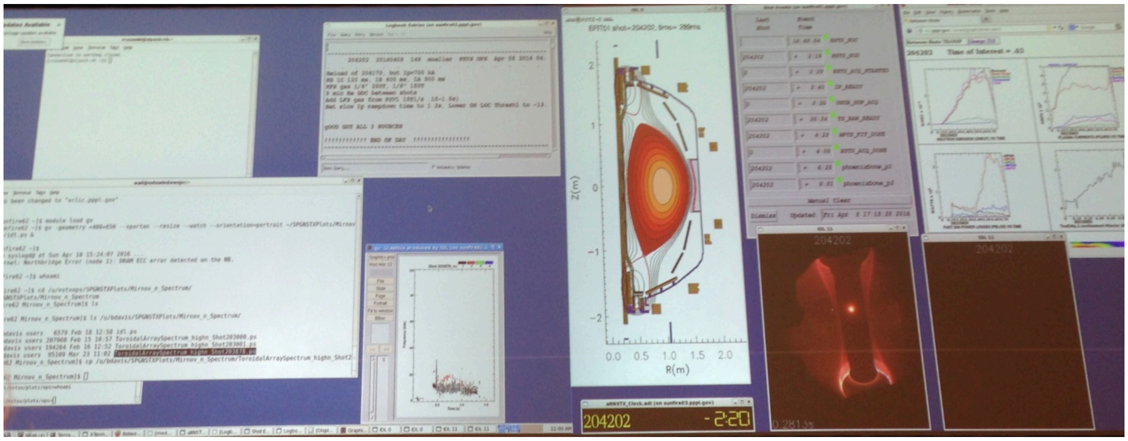

Figure 7. Photo of NSTX-U Control Room Screen. April 14, 2016 by the author.

Beyond the long duration that bookends my interaction with PPPL, i.e., for more than a half-century, PPPL has been an essential partner in numerous domestic and international fusion projects.

Controversy at PPPL

As the personal narrative reveals, PPPL is not immune to negative outcomes resulting from the dual, often inverse, relationship between development duration and cost. In the 2017 *Science* essay, "Data-Driven Predictions in the Science of Science", the authors affirm "predictions are important to the public, who fund the majority of all scientific research through tax dollars".[237] By 2008, 80% of the National Compact Stellarator Experiment (NCSX) had been built or procured but DOE cancelled the program due to cost overruns and schedule slips.[238] The incomplete device now stands inert (Figure 8), a memorial to abrupt withdrawal of funding.

[237] Aaron Clauset, Daniel B. Larremore, and Roberta Sinatra, "Data-driven predictions in the science of science", *Science* (2017, 3 February), No. 355, 6324, 477.

[238] Adrian Cho, "Energy Department Pulls Plug on Overbudget Fusion Experiment", *Science*, No. 320 (5880), (2008, 30 May), 1142-1143.

Figure 8. Photo of National Compact Stellarator Experiment. April 14, 2016 by the author.

The twenty-first century ruin was the victim of a complex design of the most advanced fusion device of its kind, a design that resisted closure.

> To close a technological controversy, one need not *solve* the problems in the common sense of that word. The key point is whether the relevant social groups *see* the problem as being solved.[239]

A social group can range from an informal assembly of human beings to a structured corporate or government institution, e.g., the US Department of Energy (DOE).

> It's not sufficient for the DOE that we have a good idea or even a great idea. It also has to be buildable and you have to have a reasonable handle on the project management aspects of anything you're going to fabricate; and so there's an art and a science to figuring out how much things will cost and how long it will take in addition to the underlying business and technology of the object that you're trying to build.[240]

Menard's comments typify the view that support of government and private funding sources, decision makers, and publics are a 'social contract', i.e., "the government really tolerates a

[239] Pinch and Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other", 44.

[240] Menard, in interview with the author, August 17, 2017.

certain level of risk or deviation in terms of cost and schedule for a given project and part of that is responsiveness to taxpayers and other stakeholders".[241]

Scientific Research in an Era of Short-Term Cost-Benefit Reckoning

Research, Development and Innovation (RDI) in an era of short-term evaluation of return on investment (ROI) is a challenge for promoters, administrators, and practitioners in an enterprise that has been underway for more than a half-century. Dr. Jon Menard, a key actor in the fusion enterprise, shares his candid perceptions.

> It is very true that patience is required but, we have made steady progress over multiple years in improving fusion performance… this is representative, an analogue Moore's Law plot of fusion power, of fusion energy produced per year and at least through the 1990s…, that derives power is increasing. So fusion is making substantial gains through the year and decade by decade. [and it is] still a research enterprise.[242]

More than seventy years after the 1945 report of Vannevar Bush, *Science, The Endless Frontier,* a belief in the scientific community endures: basic research inevitably leads to tangible benefits that just cannot be prophesied. Upon being asked what motivates scientists in 2017 to persist in yet-unfulfilled quest for viable fusion energy, the PPPL Deputy Director for Research echoes Bush's thesis. On the other hand, Menard's confidence that expanding the body of knowledge advances humanity's ability to know ourselves and our place in the universe is both reinforced and tempered by political and sociological realities.

Menard's primary role at the time of the interview was to define the NSTX-U research programs, science goals, objectives, priorities and work with the research team at PPPL and across the US.[243] That impressive portfolio reflects the influence of Jon Menard on the central

[241] Menard, in interview with the author, August 17, 2017.

[242] Menard, in interview with the author, August 17, 2017.

[243] Menard, in interview with the author, August 17, 2017.

position PPPL occupies as an institution with global reach. Menard's passion for the enterprise is tempered with technological humility and his view as pragmatic advocate emerges.

> So it's often difficult to predict when you're doing this kind of research and development – what you're going to come across or what the barriers will be. So it is difficult to make time projections as to when you'll have a working fusion object; but the progress and an understanding of performance has been significant enough that I think it's still motivational for many people and of course the end product of large electricity production without the production of CO_2 and, arguably, limitless fuel and all the advantages of fusion certainly keep us motivated… [but] unfulfilled promises… give us pause in terms of making promises based on prediction and as good as the computational physics models are the real experiments still have a tendency to surprise this.
> And in part it's intrinsic to the problem of trying to create something hotter than the core of the sun and a couple meters away having something that's room temperature or close enough and the fundamental thermodynamic drives trying to make that hot temperature cold and mix it with the cold temperature to make it hot, are just very strong.
>
> I mean you mentioned technological challenge or complexity of promise but, I think it's also the physics to a large degree that has proved very challenging. You'll get certain results and in that certain regime, the things look favorable for extrapolating and then you go to this new regime and you find out that new physics comes in that you hadn't or couldn't anticipated given the models and understanding that you have available.[244]

Menard's insights also echo that "some discoveries seem impossible to predict because they represent puzzle pieces that change how we think the puzzle is organized".[245] A common practice in high technology organizations especially those that push the boundaries of what is possible in R&D is to heavily rely on models. But models do not account for low probability, high impact events, e.g., a sustained high-energy plasma from which practical electricity is derived. Models work much like laboratory experiments. If the variables are known and stable, the outcomes tend to be predictable. Humility is central for real world conditions, where empirical data for events is minimal or nonexistent for negative outcomes. "Thinking about models as needing a penumbra of responses for model failure shifts the focus away from

[244] Menard, in interview with the author, August 17, 2017.

[245] Aaron Clauset, Daniel B. Larremore, and Roberta Sinatra, "Data-driven predictions in the science of science", *Science* (2017, 3 February), No. 355, 6324, 476.

technological optimism toward practices of humility, recognizing that models provide useful, but incomplete, guidance".[246] Dr. Menard describes the effort to bridge the gap between models and a technological system to operate in the real world.

> So, there is a certain aspect over a field where we do have to go out and build these machines. Sometimes they're… new parameter regimes and [we] see what happens… ITER [is] meant to produce industrial levels of fusion power. *But it really still is a physics experiment.* [my italics] We've never accessed this controlled fusion burn before. And that's what makes it so compelling and to keep us going and doing it, to try to access that burning plasma state. But it does require significant resources and time.[247]

There is a continuing need for investment in resources and time for an endeavor that Menard characterizes as an enduring physics experiment to operationalize the sociotechnical imaginary.

> So there are I think overall national energy need differences that change the landscape for a perspective on things as long-term as fusion. I think in terms of funding models or the way their governments work, the time scales over which things are planned and funded seem to be longer in Europe. More of a three to five-year timescale. That's good for stability for long-term projects. I think that there is an advantage to the US…
>
> You can be… more frequently updating your plans and funding profiles to carry things out. There is a certain sense I would say for running projects that not in the US but in some other countries, time is treated as a contingency. So if you need more money because of a cost overrun you wait longer and I think there is less tolerance for that in the project management schemes that DOE has.
>
> And it's not without reasons… [but for] other projects that have gone on in DOE and other branches of the government, [it's] the taxpayer and overall fiscal accountability issue [and] they want a certain level of predictability and delivery on the project that they fund.[248]

Dr. Menard indirectly points forward to a relevant 2018 National Academies report.[249]

[246] Christopher F. Jones, Krishanu Saha, Sebastian M. Pfotenhauer, and Sheila Jasanoff, "Learning from Fukushima", *Issues in Science and Technology* (2012, Spring), 28(3): 79-84.

[247] Menard, in interview with the author, August 17, 2017.

[248] Menard, in interview with the author, August 17, 2017.

[249] National Academies of Sciences, Engineering, and Medicine, "Progress in Burning Plasma Science and Technology".

Instruments of PPPL's ITER Association and Complementary American Alternative

The 2018 consensus NASEM study, *Final Report of the Committee on a Strategic Plan for US Burning Plasma Research,* cautions that events such as the cancellation of NCSX jeopardize the US position in the quest for viable fusion.

> The U.S. research program motivated world-leading contributions to science and technology in support of the International Thermonuclear Experimental Reactor (ITER) and other major international fusion experiments.
> However, the closure of domestic fusion research facilities and the failure either to upgrade or to start new medium-scale experiments, together with substantially decreased funding to fusion nuclear science and technology research, creates concern as to whether the United States will continue to be a scientific leader in the field.[250]

The experimental physics and skills relevant to that technology fostered over decades at PPPL and the corresponding knowledge that emerged has not, however, been lost. Rather, there is strong collaboration between PPPL and IPP in Germany, the principal focal point of contemporary advanced stellarator research. While these programs support ITER, the theoretical and experimental infrastructures simultaneously dedicate resources to alternative configurations in the quest to control and sustain the super-hot plasma. "Development of simpler models that are less expensive computationally enable efficient prediction and model validation".[251]

The Executive Summary of the NASEM report captures the essence of the report in two recommendations, points of reference for a strategic plan for US burning plasma research.

- First, the United States should remain an ITER partner as the most cost-effective way to gain experience with a burning plasma at the scale of a power plant.

[250] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 4(I-29).

[251] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 3(14).

- Second, the United States should start a national program of accompanying research and technology leading to the construction of a compact pilot plant that produces electricity from fusion at the lowest possible capital cost.[252]

In that pair of recommendations, the committee identifies the asymmetrical maximum benefit for the US, i.e., most essential fusion knowledge from ITER for a small fraction of investment in the project. According to any standard calculation of return on investment, that is a clearly advantageous business deal. On the other hand, the committee also recognizes a dangerous void: the absence of an alternate plan by the US to ensure that the American technological sublime is not jeopardized by its sole dependence on ITER as a primary source of fusion knowledge.

> Although the United States provides only part of the cost of ITER, if the United States is to profit from its share of the ITER investment, the nation's strategic plan for fusion should combine its ITER experience with the additional science and engineering research needed to realize reliable and economical fusion electricity. Without this additional research, the United States risks being overtaken as other nations advance the science and technology required to deliver a new and important source of energy.[253]

The pair of recommendations is not intended to be a choice between two paths, i.e., either one or the other. Rather, the combination of the two recommendations comprises the best path forward for the US in order to maintain its technological and strategic energy and its key position among international leaders in the fusion enterprise.

An Opportunity for an American Alternative Future

Converging factors have recently emerged and comprise a realistic American path to a fusion energy infrastructure. This collection of elements includes advances in plasma physics theory and experimental fusion in a new generation of fusion devices. "Major advances in both

---

[252] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", ES-1.

[253] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", ES-1.

experimental and theoretical fusion science provide a strong foundation for rapid progress toward fusion development".[254] Advances in computing power continue to break records largely spurred on by an emerging competition among the US, China, Europe, and Japan. The next milestone is a supercomputer at the exascale level, i.e., a billion billion calculations per second.[255]

> But one of the other things that keeps me motivated is improved understanding to improve diagnostics of what happens in the plasmas. Computational models have increased with the computing power and the understanding and a much better idea of what's really going on in these plasmas.[256]

The convergence of emerging fusion science theory, imposing experimental machines that leverage super-conductivity and advanced materials, and computers that were unimaginable at the turn of the twenty-first century operationalize the American technological sublime.

There is also a network of institutions and institutional identities that is coalescing around the converging core of S&T and the sociotechnical imaginary at the center of the distinctly American fusion enterprise. The 2018 study, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*,[257] is a bridging instrument that joins the Princeton Plasma Physics Laboratory (PPPL), the National Academies of Sciences, Engineering, and Medicine (NASEM), the Royal Society, the ITER Organization, and the Max Planck Institute for Plasma Physics (IPP). "The [NASEM] committee envisions a US pilot plant producing power similar to that expected in ITER but in a device much smaller in size and cost and employing design

---

[254] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", Summary.

[255] Sebastian Moss, "The race to exascale: A story of superpowers and supercomputers", *Data Center Dynamics*, (2019, 15 March).

[256] Menard, in interview with the author, August 17, 2017.

[257] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology".

improvements that would allow net electricity production".[258] Overall, the findings and recommendations of the report represent a body of knowledge assembled from a collaboration of subject matter experts with a common passion motivated by a vision of a fusion-centered energy ecosystem.

Two of the reviewers of the 2018 NASEM report are key actors, at PPPL and IPP. Dr. Jon Menard was the research director for the premier spherical torus device at the iconic national laboratory in Princeton, New Jersey, and Dr. Sibylle Günter is the scientific director of the plasma physics laboratory in Greifswald, Germany and directs experiments using the record-breaking W-7X stellerator.

Dr. Jon Menard was a presenter at the 27 March 2018 "Royal Society workshop in London that explored accelerating the development of tokamak-produced fusion power with compact tokamaks"[259] and in February 2019 published the fully developed corresponding paper in the journal, *Philosophical Transactions of the Royal Society A*. Menard's paper is an in-depth discourse that harmonizes on a technical level with the goal associated with the second of two major findings by the committee that produced the final NASEM report, i.e., R&D for a compact pilot plant that produces electricity from fusion.[260] Based on the uneven direction of funding decisions by Congress over the past decade, the final 2018 NASEM report recommends prudent planning. "If the United States decides to withdraw from the ITER project, the US DOE OFES [Office of Fusion Energy Sciences] should initiate a plan to continue research that will lead

---

[258] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", ES-1.

[259] John Greenwald, "Speeding the development of fusion power to create unlimited energy on Earth", *PPPL News,* March 19, 2019.

[260] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", ES-1.

toward the construction of a compact fusion pilot plant".[261] Menard's paper explores that option in context of use of high temperature superconducting magnets to produce far higher magnetic fields to control the super-hot plasma in a compact fusion energy facility.

> The findings are "very significant," said Steve Cowley, director of PPPL. Cowley noted that "Jon's arguments in this and the previous paper have been very influential in the recent National Academies of Sciences report," which calls for a U.S. program to develop a compact fusion pilot plant to generate electricity at the lowest possible cost. "Jon has really outlined the technical aspects for much smaller tokamaks using high-temperature magnets," Cowley said.[262]

The spherical design of NSTX-U, for which Menard was the research director, is highlighted as a candidate design for a compact plant as recommended in the NASEM report but Menard admits confirmation of theoretical confinement strength will only be validated through experiments conducted with the NSTX-U and other similar spherical torus devices, e.g., the Mega Amp Spherical Tokamak (MAST) facility at Culham Centre for Fusion Energy in the U.K.[263]

PPPL Scientists Join Stellerator Research at IPP

As stellerator development ended at PPPL in 2008 upon the withdrawal of DOE funding for the partially constructed advanced stellerator, research nevertheless continued. The *development* part of R&D did not wither away entirely but rather shifted to more modest[264] theoretical science in support of, and construction of components for, the W7-X stellerator at IPP. While completion of the cancelled device at PPPL would have added to the body of

---

[261] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology".

[262] Greenwald, "Speeding the development of fusion power to create unlimited energy on Earth".

[263] Greenwald, "Speeding the development of fusion power to create unlimited energy on Earth".

[264] Investment averages approximately 1% of the annual US fusion budget (Feder 2011).

knowledge in the fusion enterprise, the international collaborative quality of the effort to create a fusion-centered energy ecosystem salvaged value from the programs and expertise at PPPL.

> Fusion is very collaborative… We're all over the world already… So there's many conversations and collaborative research activities, data sharing… So, let me put it this way, there usually aren't too many surprises we don't already know about when we get to IAEA…
> IAEA is really excellent for seeing an international perspective on fusion all of them in place especially is focused on fusion energy. But we know what all the other groups are doing already.[265]

As a result of the continuing international collaboration, there was a seamless transition for PPPL scientists to shift their stellerator research focal point from their parent institution to IPP and to the W7-X construction and operational phase.

> PPPL leads the U.S. collaboration with W7-X, which is funded by $4 million from the Department of Energy's Office of Fusion Energy Sciences. The Laboratory built some key components of the machine, which was planned for nearly ten years before construction began and 1 billion Euros to build. Collaborators include researchers from LANL and Oak Ridge National Laboratory, as well as researchers and students from MIT, the University of Wisconsin, and the University of Auburn.[266]

When Chancellor Merkel engaged the ceremonial W7-X start switch on 10 December 2015, PPPL scientists were among the honored guests at the German R&D laboratory, a flourishing center of advanced stellerator R&D.

[265] Menard, in interview with the author, August 17, 2017.

[266] Jeanne Jackson DeVoe, "A collaboration bears fruit as W7-X celebrates first research plasma", *PPPL News, December 14, 2015*.

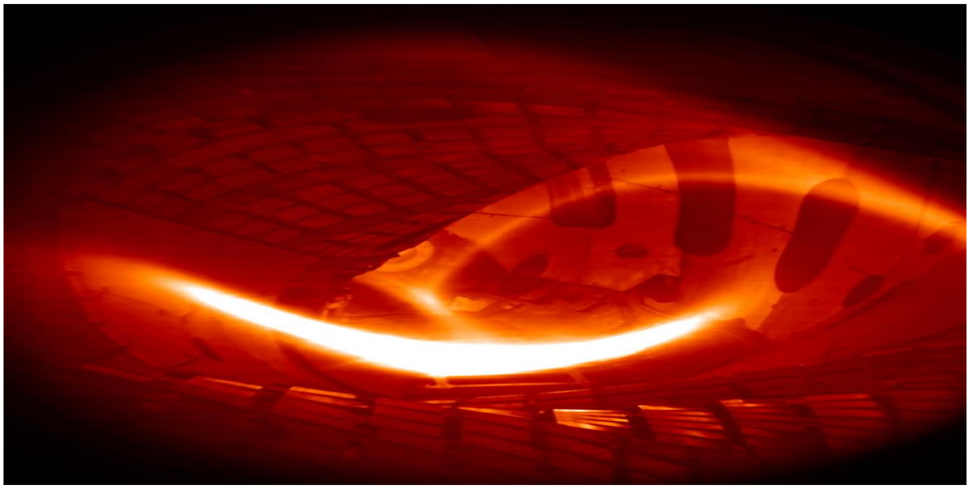

Figure 9. First W7-X Plasma. Courtesy Max Planck Institute for Plasma Physics.

The plasma that was imaged (Figure 9) on the first day of W7-X operation was a bittersweet reminder to the PPPL guests of the validation of Lyman Spitzer's vision and that PPPL was not the site of that fulfillment.

Interdependence of PPPL and ITER

There are intermediate scale experimental programs at institutions that support ITER in critical research, such as NSTX-U and W7-X, even as alternative theoretical and experimental physics is conducted at their respective laboratories in the US and Germany. PPPL scientists and engineers are deeply engaged with the fusion research needed to advance ITER to operational status. Plasma power calculations only validated through experiment on the current PPPL spherical Tokamak, NSTX-U, and to be conducted on the future ITER system are equally critical to obtain the in-depth understanding of the physics that is essential for viability at the reactor scale.[267]

[267] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 3-13.

The key word in the International Atomic Energy Agency (IAEA) is "international" and the biennial Fusion Energy Conference (FEC) is a venue in which as recently as during the 2018 iteration, Dr. Rob Goldston, former PPPL Director (1997-2009) and currently Princeton University Professor of Astrophysical Sciences, presented a contributing paper.

Dr. Goldston has voiced his views of ITER in opportunities over the past several years. While he has an institutionally vested interest in the NSTX-U device at PPPL, he has shared a forthcoming perspective on ITER. On 11 July 2017, BBC News cited his perspective as a counterpoint to the central theme of an online article, "Fusion energy pushed back beyond 2050".

> Robert Goldston… is "very confident" that ITER can produce "industrial amounts of heat" and believes that once it has done so generating electricity from fusion will be "a question of commitment of manpower". But he says that commercial power plants won't necessarily use tokamaks. An alternative, he says, is the stellarator - a reactor exploiting strangely-shaped magnets that is hard to build but potentially easier to operate.[268]

As a keynote speaker at the 2018 Intelligence Community Academic Research Symposium (ICARS 2018), Dr. Goldston characterized ITER as a major milestone on the path to viable fusion energy.[269] During his presentation at the symposium, he stated ITER should reach thermal power output equal to 10 times the thermal power input when the system is fully operational. The "industrial amounts of heat" to which Goldston referred is the ITER program objective of 500 MW (thermal), i.e., to produce 50 MW of electricity for 1,000 seconds.

Dr. Goldston, as a globally-recognized leader in plasma physics and magnetic fusion energy, is a bridging figure[270] in the fusion enterprise and envoy of PPPL. He was awarded the American Physical Society Prize for Excellence in Plasma Physics and he is a fellow of the

---

[268] Edwin Cartlidge, "Fusion energy pushed back beyond 2050", *BBC News, (*2017, 11 July*)*.

[269] Robert J. Goldston, Overview of fusion energy research, 4th Annual Intelligence Community Academic Research Symposium, 25-27 September 2018, (Washington, DC: National Academy of Sciences).

[270] Jasanoff, *States of Knowledge*, 39.

American Physical Society. He also received a 2014 Leading Global Thinker award from Foreign Policy magazine for his work on arms control. Goldston's standing in the fusion enterprise adds weight to his positive evaluation of ITER's potential without minimizing promising alternative approaches to obtaining the 'holy grail' of viable fusion energy. He clearly acknowledges the centrality of ITER in the fusion enterprise.

A Spherical Sociotechnical Expression of the Fusion Enterprise

The qualities of Princeton and the national laboratory intimately linked to the iconic university expose the instruments of the co-production of plasma physics, engineering, and social order of NSTX-U as a sociotechnical expression of fusion energy in the laboratory. The analytical view through the co-production lens is further amplified as an outcome of my interaction with two key voices, Dr. Menard and Dr. Goldston. As senior leaders and researchers in PPPL's plasma physics initiatives, their views[271] enriched my study. Within a stable repository of power and knowledge, their leadership helps animate the sociotechnical momentum that sustains this American expression of the fusion enterprise. Menard and Goldston are also key voices that nurture an impactful global presence for PPPL. Viewed as a co-produced ensemble, the instruments of institution and identity, reinforced by sociotechnical imaginaries, e.g., as concisely articulated in the ten fusion energy facts,[272] comprise a well-defined, vibrant, and shared foundational vision and a resilient structure for fusion S&T endeavors, e.g., NSTX-U, W7-X, and ITER.

[271] Jonathan D. Menard (Research Director, National Spherical Taurus Experiment, Princeton Plasma Physics Laboratory), in interview with the author, August 17, 2017; and Robert J. Goldston, Overview of fusion energy research, 4th Annual Intelligence Community Academic Research Symposium, 25-27 September 2018, (Washington, DC: National Academy of Sciences).

[272] Bernard, "10 facts you should know about fusion energy".

While Nye's thesis of the American technological sublime is linked to sociotechnical imaginaries,[273] a corresponding French imaginary also links national identity and technology. The centrality of nuclear energy in all of its fission and fusion expression occupies a central space among French technologies.

[273] Jasanoff and Kim, "Sociotechnical imaginaries and National Energy Policies", 189-196.

CHAPTER FOUR – Global Fusion Supremacy and Controversy: International Thermonuclear Experimental Reactor (ITER)

ITER, the immense international project emerging in southern France, is the focal point of this chapter. Rather than a purely technological challenge, the largest Tokamak ever built is a truly global undertaking with qualities of geopolitics at its core. In this chapter, I decompose the global dimensions of the components that comprise ITER. I reveal that ITER's size and complexity relative to other fusion projects require an international social order to facilitate a corresponding support infrastructure. The ITER Organization is the virtual body and soul of the project and an examination of its genesis during the Cold War reveals sociotechnical features of this massive expression of the fusion enterprise that persist today. The study of the dimensions of ITER's enabling network and the scope and depth of its inevitable controversies amplify a view to inform the co-production analysis of this largest of case studies in the fusion enterprise, the ITER Tokamak. The location of the massive campus in France was not an arbitrary choice but rather the nuclear radiance of France[274] appears to have been a decisive factor.

Technology and French National Identity

Gabrielle Hecht's 1998 study, *The Radiance of France*, is a model of scholarship that examines the relationship of not only nuclear technology and French national identity but the intimate connection between the state and technological development in general.[275] It is interesting to note that Hecht occasionally refers to Donald MacKenzie's historical and

[274] Gabrielle Hecht, *The Radiance of France: Nuclear Power and National Identity After World War II,* (Cambridge, MA: MIT Press, 1998).

[275] Hecht, *The Radiance of France*.

sociological analysis of nuclear missile guidance[276] to compare observations made in two technological cultures, France and the US in roughly the same time frame.

> Technologies, especially large, complex, technical systems, are not always simple tools that can be improved without wider consequences. Changes in technology go hand-in-hand with changes, small and large, in the preconditions of their use, in the ways they are used, in who uses them and in the reasons for their use. Nor is this a question of a one-way "impact of technology upon society." For the way technology changes cannot be explained in isolation from the economic, political, and other social circumstances of that change.[277]

MacKenzie scrutinizes the black box to reveal the relationship of people and their institutions to the development of technology.

Unlike the engineers in MacKenzie's work who neglected the social dimensions of technological activities, many of the technologists interviewed by Hecht revealed sociological attributes of French nuclear technology. One prominent project engineer explicitly admitted the relationship. "These were not scientific or technical decisions! They were economic decisions! They were political decisions!".[278]

Hecht explores the spectrum of historical, sociological, and political factors affecting the nuclear complex that evolved in the years following World War II. Just as the surprise attack by the Japanese on Pearl Harbor remained in the psyche of American leaders after the Second World War and constructed a foundation of US nuclear policy, the French humiliation by Nazi occupiers represented a key driver of French post-war cultural reconstruction. France, as an

[276] Donald MacKenzie, *Inventing Accuracy: A Historical Sociology of Nuclear Missile Guidance*, (Cambridge, MA: MIT Press, 1990).

[277] MacKenzie, *Inventing Accuracy*, 9.

[278] Hecht, *The Radiance of France*, 56.

“imagined community",[279] is expressed in terms of the future, an outlook that captures pre-war global influence of France and using the language and artifacts of a dynamic technological age. "National identity discourse constructs a bridge between a mythologized past and a coveted future".[280] The nation's nuclear accomplishments represent this connection of the traditional past and a truly modern France "and between national radiance and technological prowess".[281] To occupy a place of leadership in a changing world of technology, the French psyche required a transformation from the pre-war status quo to a mentality that recognized "modernity was not a physical condition, but a state of mind".[282]

When Charles de Gaulle returned to power after a 12-year hiatus, he "and his allies attached tremendous symbolic importance to French nuclear achievement"[283] as well as its development to a level so that other nations would covet the assistance of an advanced French state. This emphasis on nuclear technology, both military (i.e., atomic bomb) and civilian (i.e., large-scale electricity generation) provided both an impetus to the nuclear regimes and a "greater scrutiny".[284] Consequently, nuclear policy and the direction of development was driven from above, mainly the President of France. A similar array of techno-political events in the US occurred when Cold War geopolitical forces made the vision of space exploration real and leadership shifted from visionary rocket scientists to the American technocracy. Political

---

[279] B.R. Anderson, Imagined Communities: Reflections on the Origin and Spread of Nationalism, (London: Verso, 1991).

[280] Hecht, *The Radiance of France,* 12.

[281] Hecht, *The Radiance of France*, 42.

[282] Hecht, *The Radiance of France*, 44.

[283] Hecht, *The Radiance of France*, 91.

[284] Hecht, *The Radiance of France*.

speeches in the US included grandiose visions about space exploration and a new manifest destiny but the rhetoric of the awesome wonder through exploration faded as technocratic state emerged as the most efficient structure vehicle to facilitate exploration.[285]

As the products of the American technocracy that were constructed to win the Space Race became the defining elements of American technological prowess in a bi-polar world, the organization and artifacts of the nuclear techno-political regime of France became the pinnacle of French technological leadership. French nuclear progress was a declaration of independence in a world dominated by the Soviets and Americans through massive arsenals and international hegemony. "Technological development was central to this independence".[286] The dual-purpose nuclear program that emerged in the Fourth Republic and matured in the Fifth Republic were considered by President de Gaulle "to be the jewel in France's technological crown".[287] The Alternative Energies and Atomic Energy Commission (CEA) and Électricité de France (EDF), the French electric utility company, had competing techno-political regimes that both sought to rekindle the radiance of France. Fundamentally, the techno-political regime of the CEA was nationalistic with an initially implicit and, eventually, explicit nuclear weapon objective. The EDF represented a nationalized regime with a goal of efficient production of electricity for civilian use. The preferred designs of nuclear reactors reflected these regimes.

The struggle between the French nuclear institutions, industries, ministries, and other government entities created a series of gas-graphite reactors that produced "both [weapons-

[285] McDougall, *The Heavens and the Earth*, 324.

[286] Hecht, *The Radiance of France,* 93.

[287] Hecht, *The Radiance of France*, 94.

grade] plutonium and electricity".[288] Even after the decision was made to adopt the American system of light-water reactors, the impact of resurrecting a French approach to technological development had a lasting effect on technology and French national identity. The "high-speed train (the TGV), the Minitel communications system, the Concorde airliner, [and] the Ariane rocket... continue to cultivate the association between technology and French radiance".[289]

Support for nuclear power in France and Germany before and after the 2011 Fukushima Daiichi disaster are oriented in different policy directions as they pertain to fission power. France's major political contenders in the 2012 elections debated whether to close its oldest reactors (still leaving 60% in operation) or maintain the country's overwhelming dependency (i.e., over 75% of French electrical generating capacity). On a cultural level, there is a strong thread of national French pride in its nuclear technology as it plays out on the global stage and it is not surprising that the largest fusion demonstration project on Earth, ITER, is being constructed in southern France. Germany has already decided to decommission its reactors by 2022 but that nation is investing in the fusion enterprise in context of an imaginary surfacing from their political culture. ITER, when complete, will be, by far, the largest Tokamak on Earth, a scaling up of a design that dates back to the 1960s and that was first developed in the USSR.

Dawn of the Soviet Fusion Enterprise: Tokamak

A word that first appeared in the fusion energy discourse in the late 1960s and that still dominates experimental physics in the fusion enterprise, i.e., Tokamak (Figure 10), is comprised

[288] Hecht, *The Radiance of France*, 334.

[289] Hecht, *The Radiance of France*, 329.

of the Russian phrase "*toroidalnaya kamera and magnitnaya katushka*" and roughly translates to the English terms, toroidal chamber with magnetic coils.[290]

> The heart of a Tokamak is its doughnut-shaped vacuum chamber. Inside, under the influence of extreme heat and pressure, gaseous hydrogen fuel becomes a plasma—the very environment in which hydrogen atoms can be brought to fuse and yield energy. The charged particles of the plasma can be shaped and controlled by the massive magnetic coils placed around the vessel; physicists use this important property to confine the hot plasma away from the vessel walls.[291]

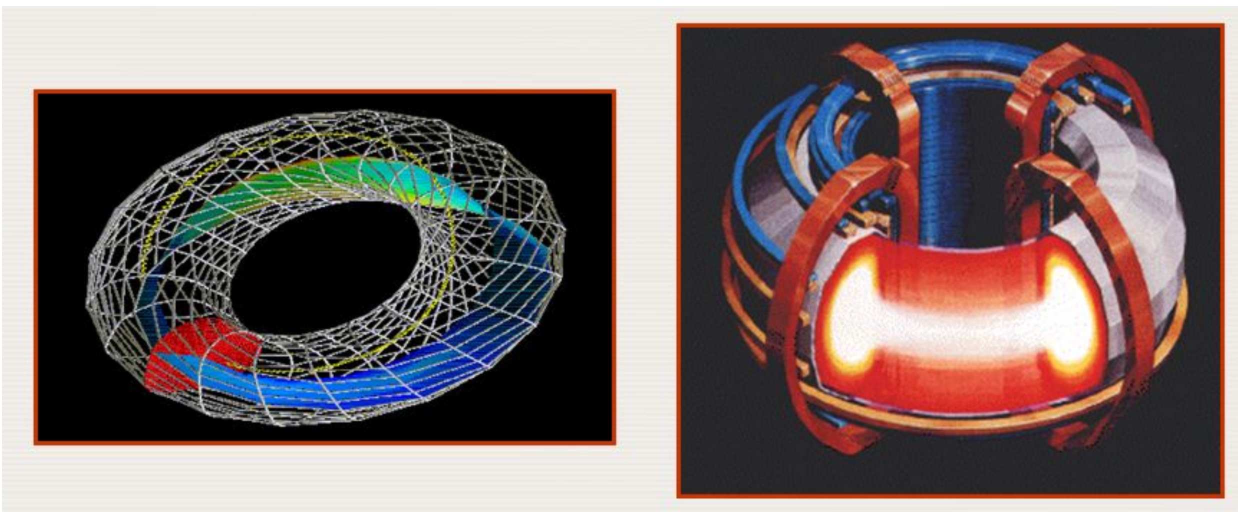

Figure 10. Fusion – Tokamak. Courtesy IAEA.

The torus shape that characterizes the Tokamak fusion device since its first years in 1960s era Soviet laboratories have been symbolic of the fusion enterprise. While the US was exploring nuclear energy as a source of infinite military, commercial, and geopolitical power, the USSR was simultaneously conducting an ambitious program with the same global goal and to further establish the technological radiance of communism.

[290] John Wesson, *Tokamaks*, (Oxford: Oxford University Press, 2011), 13.

[291] What is ITER? https://www.iter.org/proj/inafewlines#4.

> In the USSR, nuclear fusion research began in 1950 with the work of I.E. Tamm, A.D. Sakharov and colleagues. Experimental research on plasma initiation and heating in toroidal systems began in 1951 at the Kurchatov Institute. From the very first devices with vessels made of glass, porcelain or metal with insulating inserts, work progressed to the operation of the first Tokamak, T-1, in 1958. More machines followed and the first international collaboration in nuclear fusion, on the T-3 Tokamak, established the tokamak as a promising option for magnetic confinement. Experiments continued and specialized machines were developed to test separately improvements to the Tokamak concept needed for the production of energy. At the same time, research into plasma physics and Tokamak theory was being undertaken which provides the basis for modern theoretical work.[292]

The successes that the Soviet Union was to realize with the T-3 Tokamak was to have direct impact on the design approach that PPPL was pursuing. Consequently, PPPL was to dramatically shift from a focus on maturing stellerator designs to follow the apparently more promising Tokamak approach.

As proof of the preeminence of Soviet science, advocates of nuclear power in the USSR had successfully promoted a vision of a nuclear-powered state so that "their vision was included in the country's ambitious sixth five-year plan (1956-1960) which foresaw 2-2.5 million kilowatts of power generated in nuclear reactors by the end of 1960".[293] The Soviet Union was already demonstrating its leadership in space exploration but the fusion enterprise exhibited a dramatic contrast to the extraterrestrial contest. Unlike the Space Race which was a geopolitical contest between the two Cold War superpowers and a surrogate for nuclear war, the pursuit of fusion energy became a cooperative international effort during a time of deep distrust between the Eastern and Western bloc. Following the Soviet revelation in 1968 that their scientists had achieved a temperature of 10 million degrees Celsius in a Tokamak device, the USSR moved

[292] V.P. Smirnov, Tokamak foundation in USSR/Russia 1950–1990, IAEA: Vienna. *Nuclear Fusion*, 50(1), (2010, January), Abstract.

[293] Schmid, *Producing Power*, 20-21.

forward on activity that was unprecedented in the advance of S&T. First, scientists from the U.K. were invited to collaborate and thereafter American scientists.

> They invited the British to come to the Kurchatov Institute in residence for a year to work together with them on how to perfect this, optimize this technology for mutual societal benefit. They recognized the unlimited qualities and quantities of deuterium and lithium as the primary fuel sources. They saw a geopolitical future that was different and they worked collaboratively, and really from that date fusion has been a collaborative enterprise so there is a certain degree to which both of the technology and different method of working has driven not only the Russians but others who derived their inspiration from that.[294]

The cooperation was reinforced through bilateral and multi-lateral exchanges and biennial IAEA Fusion Energy Conferences – from 1961 to 2018 – and the robust collaboration was codified in the climactic 1985 agreement signed in Geneva Switzerland by the American President and the General Secretary of the Central Committee of the Communist Party of the Soviet Union.

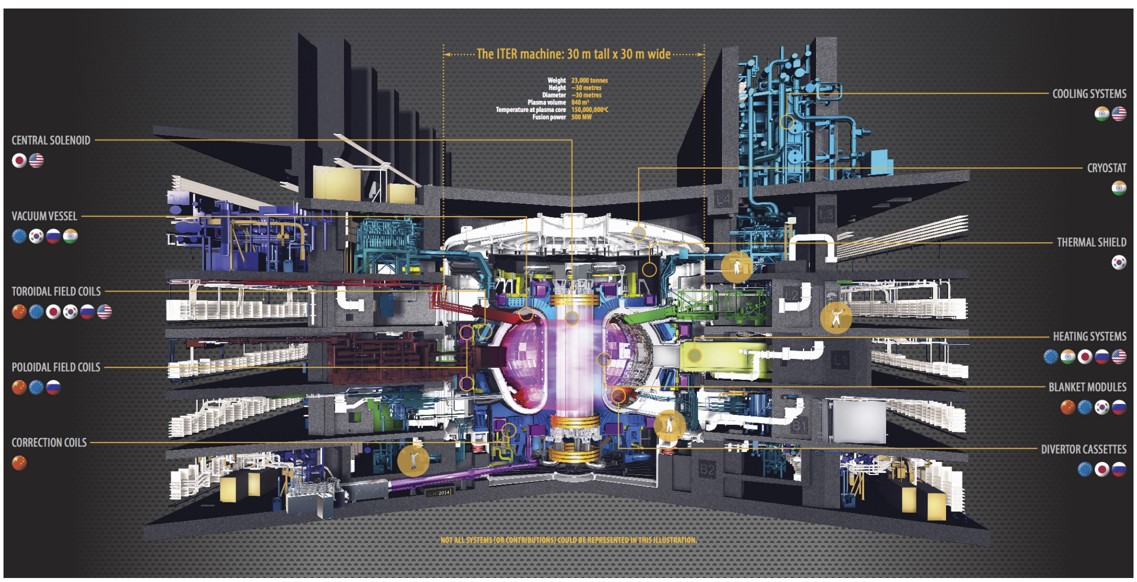

Figure 11. ITER. Courtesy The ITER Organization.

---

[294] Laban L. Coblentz (Head of Communication, ITER Organization), in interview with the author, July 28, 2018.

ITER (Figure 11) will use a Tokamak design of unprecedented scale to demonstrate *the way* to commercial fusion energy. The ITER Tokamak, when completed, is a machine towering more than 30 meters, weighing 23,000 tons, and containing over 1 million component parts.[295]

November 21, 1985

ITER conceptually surfaced in 1985 as the concept crossed a threshold from imagination into a tangible international goal. After a quarter-century of fusion experiments in the USSR and the US and as relations warmed between the Cold War adversaries, President Ronald Reagan and General Secretary Mikhail Gorbachev shared a utopian vision.

> The two leaders emphasized the potential importance of the work aimed at utilizing controlled thermonuclear fusion for peaceful purposes and, in this connection, advocated the widest practicable development of international cooperation in obtaining this source of energy, which is essentially inexhaustible, for the benefit for all mankind.[296]

The agreement that emerged would now shift the focus of the two superpowers away from mutual assured destruction, toward a mutual effort to create a planetary energy revolution.

In 1986, the E.U. Japan, USSR, and US concurred on an interim joint agreement on the concept to jointly design a massive international fusion facility. A series of progressively more evolved designs commenced that concluded with an approved final design in 2001. Three nations, China, Republic of Korea, and India, subsequently became core members. Thereafter, member nations conducted negotiations from which details of construction, organization structure and resource staffing, and investment coordination for the ITER Organization emerged.[297] Agreement on the Establishment of the ITER International Fusion Energy

[295] ITER – the way to new energy, http://www.iter.org.

[296] By mutual agreement, President of the United States Ronald Reagan and General Secretary of the Central Committee of the Communist Party of the Soviet Union Mikhail Gorbachev met in Geneva 19-21 November 1985.

[297] ITER Project History, https://www.iter.org/proj/ITERHistory.

Organization for the Joint Implementation of the ITER Project[298] and the subsequent Cooperation Agreements with Intergovernmental Organizations[299] represent the foundation of the ITER Organization, an institutional ordering instrument that governs the ITER project from construction to sustained operations.

In southern France, a tangible expression of the fusion vision is rising. "ITER", Latin for "the way", replaced the former project label, the International Thermonuclear Experimental Reactor. ITER embodies a central idea and has become the official name of the endeavor. "The ITER project is an experiment aimed at reaching the next stage in the evolution of nuclear energy as a means of generating emissions-free electricity".[300] ITER is an international coalition to construct and operate the world's largest Tokamak.

The device and its large support campus, under construction, represents the crown jewel of the donut-shaped magnetic confinement approach to fusion energy. The declared objective of ITER is to demonstrate sustainable fusion ignition with net output at ten times the energy level[301] flowing into the front-end of the fusion energy life cycle. This undertaking draws massive financial intellectual resources across the continents of North America, Europe, and Asia. ITER is a collective focal point in the fusion enterprise and dwarfs other international and domestic efforts and is the dominant case study in this dissertation.

---

[298] International Atomic Energy Agency. 2007, 25 April. Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project.

[299] International Atomic Energy Agency. 2008, 18 July. Cooperation agreements with intergovernmental organizations.

[300] Nathanial Gronewold, "World's largest nuclear fusion experiment clears milestone", *Scientific American, E&E News,* (2019).

[301] The goal as ambiguously stated for several years as "ten times" implied electrical power output but it actually represents thermal power, that is, heat to be used to run turbines that will ultimately produce electrical current.

The persistent counterpoint, however, is that nuclear fusion is endlessly fifty years away.[302] If the goal of this immensely scaled-up approach to fusion is successfully demonstrated in 2035 (i.e., the most recent completion date communicated to the ITER international consortium of nations) with the paired hydrogen isotopes of deuterium-tritium as the fuel source, it will arrive 50 years after the historic 1985 mutual agreement between the US and USSR. That agreement, in Geneva, Switzerland, highlighted the goal of a "source of energy, which is essentially inexhaustible, for the benefit for all mankind".[303] ITER was to demonstrate *the way* to commercial fusion energy.[304]

The geopolitics that is embodied in the international relationships that comprise the fusion enterprise is central to ITER. In addition to the core members of the ITER Organization, more than thirty-five countries participate in the massive project. "Doing science merges, in other words, into doing politics".[305]

The link between the ITER Organization and the International Atomic Energy Agency (IAEA) reinforces the international bonds that unite the coalition of diverse nations in this endeavor. IAEA as *the* principal international nuclear energy institution, "works for the safe, secure and peaceful uses of nuclear science and technology".[306]

> The IAEA helps countries to meet the growing energy demand for development, while improving energy security, reducing environmental and health impacts and mitigating climate change.

---

[302] Sievert and Johnson, "Creating Suns on Earth", 323.

[303] Joint Soviet-United States statement on the summit meeting in Geneva, Reagan Library Archives, November 21, 1985.

[304] ITER – the way to new energy, http://www.iter.org.

[305] Jasanoff, *States of Knowledge*, 29.

[306] IAEA – Overview, https://www.iaea.org/about/overview.

> When charting out their energy strategies, experts can use the IAEA's energy planning and modelling tools and assistance to help them plan their country's energy future — which may or may not include nuclear power.
> These tools help countries consider all aspects of energy supply and demand while adhering to sustainable development goals. The tools are already used by over 135 countries and 20 international organizations.
>
> For countries considering or setting up a nuclear power programme, the IAEA, upon request, provides guidance and support on establishing and maintaining a nuclear power programme in line with internationally recognized safety standards and security guidelines. The IAEA also assists countries new to nuclear technology in developing the proper infrastructure to help them build their way to sustainable energy. The IAEA provides technical support in all aspects of the nuclear fuel cycle and the life cycle of nuclear facilities, as well as support related to emerging innovative technologies.
>
> The Agency also promotes international collaboration and facilitates the exchange of scientific and technical information toward advancing energy research and technology, including in nuclear fusion.[307]

The iconic international agency provides core competencies in converging sciences and technologies that advance magnetic and inertial fusion[308] and IAEA acts as a stable repository of power and nuclear knowledge infrastructure, one that energizes the ITER Organization.

The professional identities, especially those that emerged after an initial period of growing disorder stabilized a project that might have otherwise disintegrated. "When the world one knows is in disarray, redefining identities is a way of putting things back into familiar places".[309] The ITER Organization and its central fusion energy project essentially reside at the nexus of geopolitics, physics, engineering, and resource coordination.

On the ITER website, the program concisely explains the basic technology, approach and envisions the successor, based on an expectation of ITER's demonstrated viability.

---

[307] IAEA – Overview, https://www.iaea.org/about/overview/sustainable-development-goals/goal-7-affordable-and-clean-energy.

[308] IAEA – Fusion, https://www.iaea.org/topics/fusion.

[309] Jasanoff, *States of Knowledge*, 39.

> ITER… uses magnetic fields to contain and control the hot plasma. The fusion between deuterium and tritium (D-T) will produce one helium [nucleus], one neutron, and energy. The helium nucleus carries an electric charge which will respond to the magnetic fields of the Tokamak and remain confined within the plasma. However, some 80 percent of the energy produced is carried away from the plasma by the neutron which has no electrical charge and is therefore unaffected by magnetic fields. The neutrons will be absorbed by the surrounding walls of the Tokamak, transferring their energy to the walls as heat…
> In ITER, this heat will be dispersed through cooling towers. In the subsequent fusion plant prototype DEMO and in future industrial fusion installations, the heat will be used to produce steam and—by way of turbines and alternators—electricity.[310]

When ITER is operational, it will exist at the outer limit of demonstration – on the boundary of experiment and utility. ITER will be the pinnacle of this Tokamak technological path to magnetic confinement of hydrogen plasma and promises to provide a demonstration of net power production by a factor of 10, i.e., 500 MW output from 50MW input,[311] i.e., $Q_p = 10$ plasma gain for 16 minutes.

Q=1: Plasma Energy Breakeven Point

Quite early in the history of the fusion enterprise, PPPL as well as Soviet plasma laboratories had already established, in practice, that fusion of light elements in the laboratory could be achieved. Experiments conducted since those early accomplishments have been a steady progression of scaling up, only to discover the elusiveness of a viable technological system even as plasma energy levels continued to break records.

---

[310] ITER – How does fusion produce energy, http://www.iter.org/sci/whatisfusion.

[311] Electricity requirements for the ITER plant and facilities will range from 110 MW to up to 620 MW for peak periods of 30 seconds during plasma operation. Power will be provided through the 400 kV circuit that already supplies the nearby CEA Cadarache site—a one-kilometre extension now links the ITER plant into the network. Emergency backup power for the ITER plant and facilities will be covered by two diesel generators. (https://www.iter.org/mach/PowerSupply)

> Steady progress has been made since in fusion devices around the world. The Tore Supra tokamak in France holds the record for the longest plasma duration time of any tokamak: 6 minutes and 30 seconds. The Japanese JT-60 achieved the highest value of fusion triple product—density, temperature, confinement time—of any device to date. US fusion installations have reached temperatures of several hundred million degrees Celsius.
>
> Achievements like these have led fusion science to an exciting threshold: the long sought-after plasma energy breakeven point (Q=1). Breakeven describes the moment when plasmas in a fusion device release at least as much energy as is required to heat them.
> Plasma energy breakeven has never been achieved: the current record for energy release is held by JET [Joint European Taurus], which succeeded in generating 16 MW of fusion power, for 24 MW of power used to heat the plasma (a Q ratio of 0.67).[312]

The viability of fusion is not just about a finite breakeven formula. The unambiguous values that numbers communicate are meaningless in the absence of context and interpretation. Porter's thesis shatters the myth of the human ability to determine quantitative objectivity.[313]

Quantitative data does not ensure a body of evidence to establish the foundation for rational policy decision making. However, the problematic construction and use of statistics also does not universally invalidate its potentially positive contribution to analysis and maturing a pragmatic policy. A synthesis comprised of quantitative and qualitative analysis is the key.

Numbers are imbued with a quality of precision but that attribute should not be mistaken as representing reality. As Porter cites Nancy Cartwright, "it is impossible to set up a statistical analysis without assuming some explanatory structure".[314] Quantitative measures reflect qualities of what is being measured as well as defining what is being measured.

Among the shortcomings of statistics are the tools and formulae that are used to reduce information - e.g., averaging. The role of the bureaucrat is facilitated with statistics, but

---

312 ITER – 60 Years of Progress, https://www.iter.org/sci/BeyondITER.

313 Theodore M. Porter, *Trust in numbers: The Pursuit of Objectivity in Science and Public Life*, (Princeton, NJ: Princeton University Press, 1995).

314 Porter, *Trust in numbers*, 19.

"inevitably meanings are lost",[315] averaging "away everything contingent, accidental, inexplicable, or personal, and left only with large scale regularities".[316]

MacKenzie's 1999[317] study focused on nuclear missile testing in *The Science Studies Reader* is an analog that corresponds to the social construction of accuracy in evolving experiments that comprise a roadmap to the demonstration of *Q=1*, characterized as the plasma energy breakeven point. Rather, the net production of energy that exceeds the *scientific* breakeven point is the goal of ITER. The *scientific* breakeven point is "when the power being released by the fusion reactions is equal to the required heating power",[318] rather than the *commercial* breakeven point.

> Commercial breakeven relies on factors outside the technology of the reactor itself, and it is possible that even a reactor with a fully ignited plasma will not generate enough energy to pay for itself. Whether any of the mainline concepts like ITER can reach this goal is being debated in the field.[319]

MacKenzie's thesis, i.e., accuracy is socially constructed, applies to the numerical framing of the net energy to emerge from the world's largest Tokamak device.

> This does not mean that accuracy is a mere fiction, an "invention" in the pejorative sense, for this absence of "atomic" fact is characteristic of all scientific knowledge. It does mean, however, that the more deeply one looks inside the black box of technologies, the more one realizes that "the technical" is no clear-cut and simple and simple world of facts insulated from politics.[320]

---

[315] Porter, *Trust in numbers*, 85**.**

[316] Porter, *Trust in numbers*, 86**.**

[317] MacKenzie, "Nuclear missile testing and the social construction of accuracy", 342-357.

[318] Dipak K. Basu, (ed.), *Dictionary of Material Science and High Energy Physics*, (New York: CRC Press, 2001).

[319] Hirsch, Fusion research: "Time to set a new path".

[320] MacKenzie, "Nuclear missile testing and the social construction of accuracy", 356.

As we analyze the numbers that embody the projected output of ITER, we do not discover matters of fact, “matters that cannot be rationally disputed”.[321]

The reductionist quality of precise numbers applied to messy nature, and political structures and organizations is reminiscent of the constraints of the laboratory.[322] Thereby, nature, scientific observation, and policy are linked in a social construction that narrowly simplifies relationships and bypasses deep qualitative issues.

Hirsch’s controversial observation about the goal of demonstrating net energy output from an “operational” ITER fusion device, however it is measured, is an echo of the uncertainty that MacKenzie asserts and contradicts a deterministic assumption that “testing is sufficiently like use to allow inferences to flow”.[323] The scientific breakeven point is based on a *thermal* energy value equal to thermal energy input, i.e., plasma gain.

This value of net thermal energy is essential but represents only *one* milestone. In addition to plasma gain, fusion power density and reliable component longevity are equally vital to assemble a viable fusion energy system, to produce net electricity at useful levels.[324]

The blurring of the distinction between the terms, *scientific* breakeven and *commercial* breakeven, in context of the marketing of ITER since its inception creates inevitable controversy. An online article in *New Energy Times* illuminates intriguing discrepancies in quantitative data provided by the ITER Organization on its public-facing website for years.[325] The article

[321] MacKenzie, “Nuclear missile testing and the social construction of accuracy”, 342.

[322] Bruno Latour, “Give me a laboratory and I will raise the world”, in *Science Observed: Perspectives on the Social Study of Science,* eds. K. Knorr-Cetina and M.J. Mulkay. (London: Sage, 1983).

[323] MacKenzie, “Nuclear missile testing and the social construction of accuracy”, 345.

[324] Goldston, Overview of fusion energy research.

suggests a reverse salient[326] that could overwhelm the project's sociotechnical factors that energize its momentum. Eventual expressions of candor and technological humility, however, by the current ITER head of communications and in statements by the former head might reinforce the immense project's sociotechnical momentum.

> ITER, may have been sold to the public and elected officials using misleading information… The actual input power of "50 megawatts," as claimed on the ITER Web site is not 50 MW electric: It is 50 MW thermal.[327]

Coblentz's 2017 email was a preview his comments during my interview in 2018. The author of the *New Energy Times* article further gives an indication of an increasing level of candor from ITER's new Communications Head that would become more evident in the 2018 interview.

> This revelation about the real value for ITER's input power explains why Coblentz told New Energy Times recently that the total amount of power produced by the reactor — accounting for all power input — was no longer important.
> He wrote that it was "completely irrelevant to the success of ITER." Rather than concede that ITER likely will not achieve the publicly implied performance goal…
> Coblentz, on behalf of ITER management, has changed the character of the stated goal to be a large-scale, publicly funded scientific experiment.[328]

The narrative also highlights the hypocrisy of "truth in numbers… without assuming some explanatory structure",[329] i.e., the need to provide a sense-making context and to establish a distinction between thermal energy and electrical energy.

There are competing forces at work in ITER: on one hand, powering momentum and inducing inertia to impede the enterprise. The 2008 IAEA Cooperation Agreements with

---

[325] Steven B. Krivit, "Former ITER spokesman confirms accuracy of New Energy Times story", *New Energy Times ,* (2017, 19 January), http://news.newenergytimes.net/2017/01/19/former-iter-spokesman-confirms-accuracy-of-new-energy-times-story/).

[326] Hughes, "The Evolution of Large Technological Systems".

[327] Krivit, "Former ITER spokesman confirms accuracy of New Energy Times story".

[328] Krivit, "Former ITER spokesman confirms accuracy of New Energy Times story".

[329] Porter, *Trust in numbers*, 19**.**

Intergovernmental Organizations is a potent international commitment to the ITER Organization to provide substantial financial and intellectual resources. The signatories envision sharing the benefits of an energy revolution centered on fusion energy. However, the diverging priorities of European and Asian participants might derail the ITER enterprise and could also postpone the prospect of the vision of planetary revolution that advocates of fusion energy promulgate. The financial and material investment has increased and the scheduled completion of construction of the mammoth device and support campus, and initial operation has been delayed.

The High Cost of the Enterprise

The ITER Organization estimates the total cost of construction at €17B until ITER has sustained a deuterium-tritium plasma in 2035. During the construction phase, Europe will be shouldering the largest proportion of the cost (Figure 12).[330]

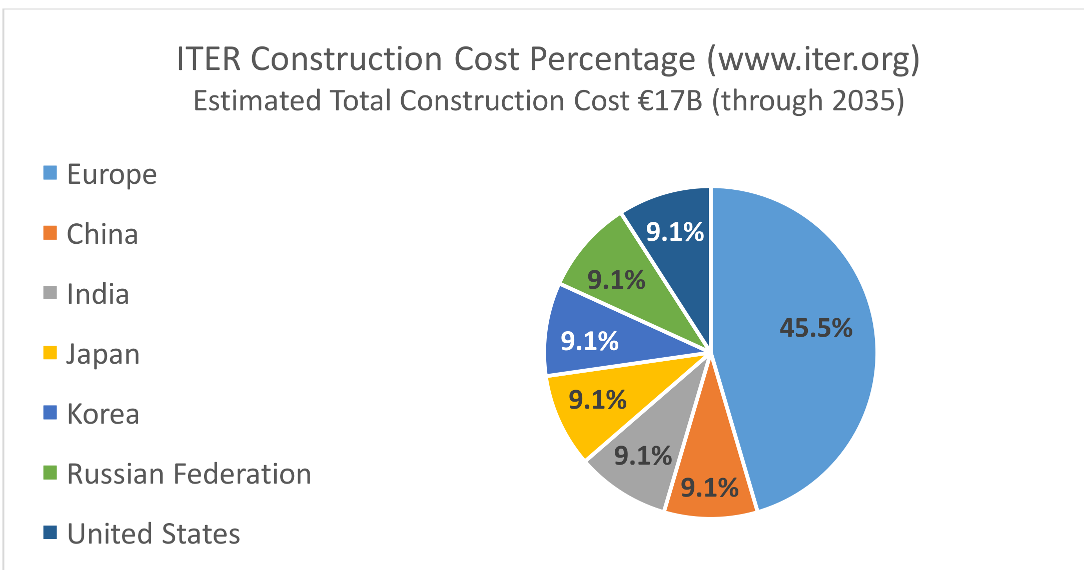

Figure 12. Funding for ITER Construction. Courtesy The ITER Organization.

[330] ITER – the way to new energy, https://www.iter.org/.

The massive investment by the multiple countries participating in ITER is justified by the anticipated return on investment (ROI); ROI is calculated for the impact on growing energy needs of developed and developing nations and to mitigate the cost of human-induced climate change on the biosphere. In the planned operational phase, expected to endure for twenty years, Europe will continue to shoulder the largest proportion of cost (Figure 13).

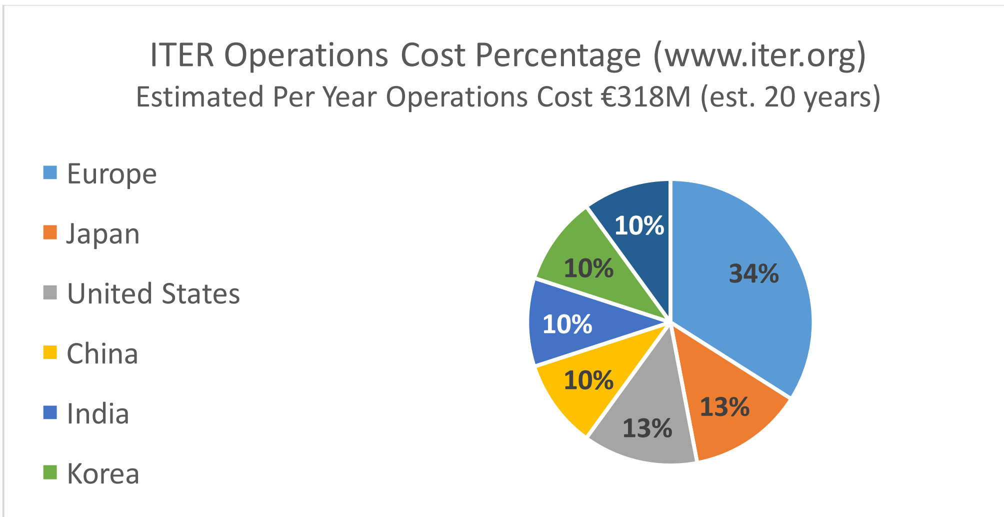

Figure 13. Funding for ITER Operations. Courtesy The ITER Organization.

Yet, more than a half-century into the fusion enterprise, no viable power fusion is available. Other large non-military S&T efforts, at best, expand for a period (e.g., the programs and achievements of the technocracies of the Cold War Space Race), only to shrink or nearly disappear all together when short-term goals are met or fail to achieve objectives. The fusion enterprise persists.

The ITER Organization is an exemplar "for the testing and reaffirmation of political culture".[331] The collection of institutions comprised of enduring centers of influence are well

[331] Jasanoff, *States of Knowledge*, 40.

positioned to restore order when disorder arises.[332] The institutions are an energy source that provides thrust and thereby imparts momentum to the ITER behemoth.

For example, there is an explicit link between IAEA and ITER. Analysis of the 2008 IAEA-ITER agreement among many international partners demonstrates unambiguously that the first priority in the agreement is to build an international partnership and create momentum for the world's largest magnetic confinement program.

> A consortium of nations—China, the 28 states of the European Union plus Switzerland, India, Japan, Korea, Russia and the United States—is building ITER collaboratively, in an ambitious wager to advance fusion science and technology to the point where demonstration fusion power plants can be designed.[333]

The relationship of IAEA and the ITER Organization mutually reinforces the impact of each repository of trusted knowledge. The magnetic force pulling financial and intellectual resources to ITER is the sociological equivalent of the powerful electromagnets at the core of ITER's technology.

The sheer scale of ITER gauged through several valued dimensions is stunning. The span of years of the project, the size of the device and the support campus, the scope of international engagement, the proportion of financial and intellectual investment, and the astronomical units of measure for energy input and output dwarf other fusion endeavors.

The massive ITER construction program has been plagued by cost overruns and administrative controversies.[334] Skepticism grows from escalating costs, schedule slips, and questions of the feasibility of net energy production. While the multi-national effort survives,

---

[332] Jasanoff, *States of Knowledge*, 39-40.

[333] ITER – Milestones, https://www.iter.org/proj/itermilestones.

[334] Daniel Clery, "More delays for ITER project", *Science*, (2015, 27 November), No. 350(6264), 1011.

the decibel level rises between advocates and skeptics, and even among the international coalition at the core of the ITER administration.[335]

Diverging priorities, e.g., cost and schedule have emerged among partner nations that have committed vast financial and intellectual resources to ITER. The schedule for sustained burning plasma continues to slip, apparently now to a date nineteen years beyond that forecast in 2006. Japan and South Korea "are not going to be happy to hear that the date for D-T [Deuterium-Tritium] burning is as far away as 2035".[336] While the Asian partners are motivated by schedule, the European countries are focused on cost.

Debates Fuse

The former director of the US federal fusion program from 1972-1976, Robert L. Hirsch, provides a compelling argument that challenges the premise that ITER will be the proof-of-concept for a viable model of fusion. Hirsch anticipates a public backlash which might imperil ITER and possibly dilute the six-decade support of the fusion enterprise.[337] Rather than dismissing fusion as a dead-end, Hirsch suggests five lessons learned from the history of fission.

1. Managerially, that requires a viable, continuing engineering design function that analyzes evolving physics concepts and challenges those whose reactor embodiments show potentially significant weaknesses.
2. Concepts that are inherently small can progress more rapidly and at lower cost.
3. Plasma configurations that easily or inherently disrupt are not desirable.
4. If superconducting magnets are to be used, configurations that are inherently more stable should be favored.

[335] Daniel Clery and Adrian Cho, "More Delays for ITER, As Partners Balk at Costs", *Science*, No. 352 (6286), (2016, 6 May), 636-637.

[336] Clery and Cho, "More Delays for ITER, As Partners Balk at Costs", 637.

[337] Hirsch, "Fusion Research: Time to Set a New Path", 35-42.

5. The fewer new technologies associated with the introduction of a basically new technology, the better.[338]

Hirsch emphasizes that a positive outcome could surface if wishful outcomes are discarded and practical concerns are faced head on by potential stakeholders, especially electrical utilities.

There is a distinct opinion that emerged from another center of the fusion enterprise, PPPL, through a former PPPL principal physicist who has introduced controversy in the fusion enterprise discourse and specifically through the ITER case. Daniel Jassby was a PPPL physicist, with a Princeton PhD in astrophysical sciences, researching plasma physics and neutron production from 1974 through 1999. He is an unexpected source of controversy based on the sociotechnical imaginaries that dominate the culture of PPPL.

> If successful, ITER may allow physicists to study long-lived, high-temperature fusioning plasmas.
>
> But viewed as a prototypical energy producer, ITER will be, manifestly, a havoc-wreaking neutron source fueled by tritium produced in fission reactors, powered by hundreds of megawatts of electricity from the regional electric grid, and demanding unprecedented cooling water resources. Neutron damage will be intensified while the other characteristics will endure in any subsequent fusion reactor that attempts to generate enough electricity to exceed all the energy sinks identified herein…
>
> When confronted by this reality, even the most starry-eyed energy planners may abandon fusion. Rather than heralding the dawn of a new energy era, it's likely instead that ITER will perform a role analogous to that of the fission fast breeder reactor, whose blatant drawbacks mortally wounded another professed source of "limitless energy" and enabled the continued dominance of light-water reactors in the nuclear arena.[339]

[338] Hirsch, "Fusion Research: Time to Set a New Path", 35-42.

[339] Daniel Jasby, "ITER is a showcase … for the drawbacks of fusion energy", *Bulletin of the Atomic Scientists,* (14 February 2018).

As the title of his article in *Bulletin of the Atomic Scientists* declares "the drawbacks of fusion energy",[340] Jasby's argument is intended to convince the reader that fusion energy is a pipedream not worthy of investing resources because after sixty years, viable energy has not been achieved.

Fusion's Missing Pieces[341] focuses on the promise and challenges of making ITER the basis of viable fusion energy via the magnetic confinement path. Brumfiel, in addition to authoring the *Scientific American* article, is also a writer for *Nature*. He characterizes ITER as "the world's most complex science experiment".[342] As many observers of the quest for fusion energy express, Brumfiel exhibits both skepticism and hope – not to expect delivery of net fusion energy according to some predetermined time table but anticipating eventually that all the wicked problems will be solved. There is an alternative approach to fusion from which a cautionary tale of technological optimism materialized, i.e., laser inertial fusion at the National Ignition Facility (NIF) at Lawrence Livermore National Laboratory (LLNL).

An exemplar of technological optimism in fusion was diminished by failed promises, i.e., the fiscal year 2012 goal of *ignition* by NIF, formally known as the National Ignition Campaign (NIC). A *New York Times* article[343] encapsulates arguments to terminate American public support as manifested in US funding for the NIC and the project to obtain a self-sustaining fusion reaction from a laser inertial fusion energy system. The essence of the article is to challenge the viability and wisdom of the entire fusion energy quest. The premise is that decades of effort has not yielded success and a revolutionary approach to fusion energy, inertial confinement at NIF,

---

[340] Jasby, "ITER is a showcase … for the drawbacks of fusion energy".

[341] Geoff Brumfiel, "Fusion's missing pieces", *Scientific American*, (2012, June), 56-61.

[342] Brumfiel, "Fusion's missing pieces", 56.

[343] W.J. Broad, "So far unfruitful, fusion project faces a frugal Congress", *New York Times*, September 29, 2012.

cost US taxpayers $4B to build. Since the NIF administrators established a tangible objective of ignition and failed to achieve the milestone by 30 September 2012, Broad argues continued funding should end especially in the current financial crisis atmosphere.

A compelling counter-narrative emerges from an interim study by the Committee on the Prospects for Inertial Confinement Fusion Energy Systems of the National Academies of Sciences, Engineering, and Medicine (NASEM). The work is a sober evaluation of the potential for inertial fusion energy. Several different channels within the inertial confinement path are examined. The report recognizes impressive progress and endorses the range of approaches being applied at the various national laboratories engaged in inertial confinement fusion. The executive summary cites LIFE at NIF, in particular, with its concluding recommendation: "Planning should begin for making effective use of the National Ignition Facility as one of the major program elements in an assessment of the feasibility of inertial fusion energy".[344]

Andrew Holland, a Senior Fellow for Energy and Climate at the American Security Project, a bi-partisan think-tank examining the big strategic choices facing the US asserts another counter-argument to the *New York Times* article[345] and subsequent articles and editorials critical of NIF. Holland addresses major points of the series.[346] He asserts "it's like having a cure for cancer by a certain date".[347] His statement highlights the wicked nature of the fusion energy quest. The second argument he refutes is that scientists do not fully understand fusion. Holland cites the 2012 NASEM report contradicting the *New York Times* contention. Beyond the 2012

---

[344] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 2.

[345] Broad, "So far unfruitful, fusion project faces a frugal Congress".

[346] A. Holland, "Why the New York Times is wrong on the National Ignition Facility", *AOL Energy* (2012).

[347] Holland, "Why the New York Times is wrong on the National Ignition Facility", 2.

NASEM report, research shared at recent IAEA Fusion Energy Conferences provides explicit amplification of Holland's point supporting evidence of comprehension of the wicked problems inherent in fusion. The *New York Times* argument is reminiscent of similar arguments during the 1960s, i.e., money spent on the space program should be used on Earth to cure poverty and hunger, and other energy sources. Holland finally frames a key point. "The most important question is whether or not the facility's research is worth the investment".[348]

Technological optimism is likely to lead to socially and politically counterproductive results. The missed milestone of 'ignition' in 2012 by the NIF and the rhetorical reinforcement of "soon enough to make a difference" intensified skepticism by journalists and experts, many of whom would otherwise celebrate the breakthrough if realized. "Technological hypes"[349] of controlled fusion have created peaks of inflated expectations, subsequent to the first H-bomb detonations and most recently through NIF and ITER.

NIF, however, is a *dual-use* facility administered by the National Nuclear Security Administration (NNSA). "NNSA is responsible for the management and security of the nation's nuclear weapons, nuclear nonproliferation and naval reactor programs".[350] The mission statement of NNSA reflects half of the dual-use character of NIF and its sister fusion projects. In addition to a large scale inertial fusion energy experiment, NIF functions as a non-destructive simulator of thermonuclear detonations.[351] NIF is the US flagship for thermonuclear weapon simulation. In addition, there are promising nuclear (i.e., fission) waste disposal capabilities that

---

[348] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 2.

[349] S. Bakker, "The car industry and the blow-out of the hydrogen hype", *Energy Policy*, No. 38(2010), 6540.

[350] NNSA – Missions, http://nnsa.energy.gov/ourmission.

[351] Sievert and Johnson, "Creating Suns on Earth", 330.

can still be explored such as “a way to ‘burn to a nuclear crisp’ all the [spent nuclear fuel] SNF now destined for transportation and storage”.[352] The facility generates energy at the astronomical extremes sufficient to instill high confidence in NNSA experts and administrators in its potential to validate computer simulations.

There is a path to mitigate the tenacious perception that fusion is and always will be many years away. Persistent pursuit of the ‘holy grail’ tempered with technological humility would provide more political traction than making predictions that depend on solving wicked problems on a fixed timetable. A view that acknowledges the wisdom of modest milestones in complex S&T endeavors surfaced from the 2018 interview of the ITER Communications Lead.

A Candid View from the Office of the ITER Communications Lead

A 2018 conversation with Laban Coblentz provides candid insights that illuminate the fusion enterprise as it is expressed in the ITER project. Before the formal interview began, Mr. Coblentz swiveled his laptop computer in the direction of his office window.

Figure 14. ITER Panorama. Courtesy The ITER Organization.

[352] J.C. Farmer, T. Diaz de la Rubia, and E. Moses, *The Complete Burning of Weapons Grade Plutonium and Highly Enriched Uranium with [Laser Inertial Fusion-Fission Energy] LIFE Engine,* (Lawrence Livermore National Laboratory, 2009).

Coblentz shared a view[353] of a bustling construction site (Figure 14), comprised of structures taking shape that will house the massive ITER Tokamak as well as buildings to provide assembly and operational support.

The action by Coblentz is intended to communicate renewed vitality visible on a project that was apparently faltering prior to a new set identities arriving in 2015.

> When I arrived at the project in September 2015 we were heading full tilt into organizational reform… So the current director general Bernard Bigot had taken over the reins as of March 2015 and there was a good deal of concern at that time about whether the organization if it stayed on that trajectory was going to be able to survive and succeed…I was part of a new management team that came in and because of that context the communication role was defined perhaps a bit more broadly than it is customary…
>
> The customary role is press, external relations, that kind of thing which is certainly a huge part of my role because we faced the central paradox externally and with the media frequently that we have arguably the world's most complex science project and nobody knows about us. So, that's sort of an irony that we were trying to... overcome and we're doing somewhat better on recognition at least…
>
> The second role however was also internal communication because as the result of cost, overruns and delays, and arguably some management shortcomings we had a fairly dispirited staff and there is in addition the 35 countries involved the seven members, Europe plus China, India, Russia, Japan, Korea, and the United States, and as a result we had a high priority on ensuring the accuracy of the communication between cultures, between the possibilities of a cultural misunderstanding, the needing to work as an integrated team. There were silos that had grown up both here and France and quite naturally among the different organizations, the different domestic agencies that represent each one of the ITER members, so internal communication in those two senses was really important; and finally stakeholder communication.
>
> Also a consequence of the project, less than optimal performance. We had political discouragement so we had to ask how are we going to regain the confidence of the parliaments and the executive offices and congresses and so forth and the scientific communities that were deeply involved and invested both financially and in what they have been promised, how could we restore the confidence that we were going to deliver on those promises? So my scope and role encompassed each of those three areas: external, internal and stakeholder.[354]

---

[353] Figure 14 is similar to the view from Laban Coblentz's office window.

[354] Laban L. Coblentz (Head of Communication, ITER Organization), in interview with the author, July 28, 2018.

The Director-General of ITER, Dr. Bernard Bigot, as an expert with decades of experience in the field of energy research and research management, contributes to a cohesive vision for the ITER program and equally evokes trust in the knowledge that informs policy making.

The tangible progress to which Coblentz affirmed provides reasonable evidence of the positive impact of the identities of two key actors in administration of the ITER project.

> A staple category of post-structuralist social analysis, identity is particularly germane to co-productionalist accounts because, whether human or non-human, individual or collective, it is one of the most potent resources with which people restore sense out of disorder.[355]

As Jasanoff asserts, the making and reinforcement of identities plays an essential role in the co-production of S&T and social order.

Mr. Coblentz's description of his role as Communications Lead for the largest expression of the fusion enterprise on Earth transcends what is typical of that role in large technological projects. His responses during the 2018 interview were uniquely informative and unexpected. The reviving impact of the Director-General of ITER, Dr. Bernard Bigot, and the unique triple role of Laban Coblentz represent professional identities as a central ordering instrument that advance an alternative future with fusion energy.

Bigot had been Chairman and CEO of the French Alternative Energies and Atomic Energy Commission, a government-funded technological research organization active in low-carbon energies, defense and security, information technologies and health technologies.[356]

> On his long experience in the field of energy, he says: "I've always been concerned with energy issues. Energy is the key to mankind's social and economic development.

[355] Jasanoff, *States of Knowledge*, 39.

[356] ITER – Director Corner, https://www.iter.org/proj/director-corner.

> Today, 80 percent of the energy consumed in the world comes from fossil fuels and we all know that this resource will not last forever. With fusion energy we have a potential resource for millions of years. Harnessing it is an opportunity we cannot miss".[357]

He became Director-General in 2015, when ITER was plagued by controversy comprised of dramatically slipping schedules and escalating costs, in conjunction with deceptive communication practices. Dr. Bigot's leadership introduced a level of candor that mitigated the negative direction in which the international project appeared to be heading.

> More than half of the work required to achieve First Plasma in ITER has been completed, as measured by an activity-based metric agreed when the 2016 Project Baseline was adopted… [and this] prepares the facility and staff to achieve First Plasma in 2025.[358]

Progress tends to spawn confidence by stakeholders and reinforces investment stability. The phased project (Figure 15)[359] now appears to be on schedule to reach first plasma in 2025.[360] The staged approach had been unanimously approved by the ITER Council, comprised of all members of the ITER project, in 2016.[361]

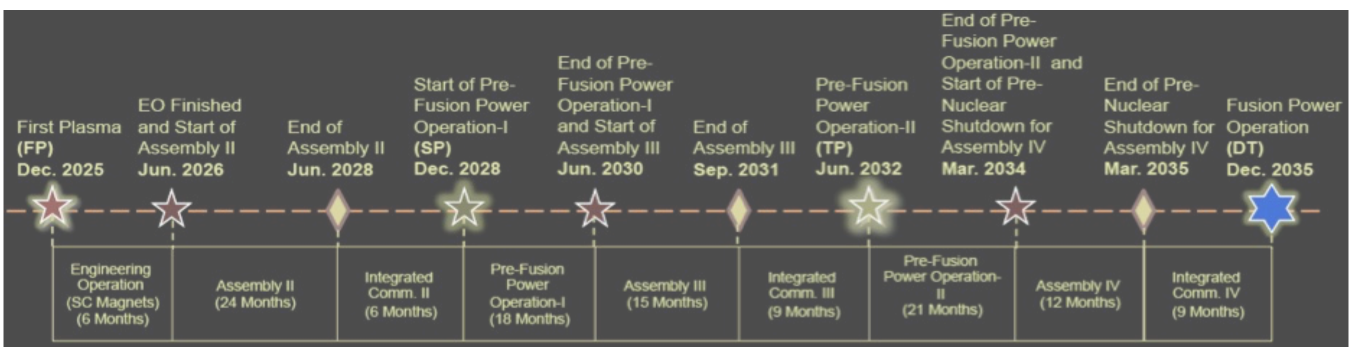

Figure 15. Schematic of Staged Structure for First 10 Years of ITER Operations. Courtesy The ITER Organization.

---

[357] ITER – Director Corner.

[358] Bernard Bigot, "Progress toward ITER's first plasma", *Nuclear Fusion*, (59) (2019), Published 5 June 2019.

[359] Bigot, "Progress toward ITER's first plasma".

[360] Nathanial Gronewold, "World's largest nuclear fusion experiment clears milestone", *Scientific American, E&E News,* (2019).

[361] *World Nuclear News,* (21 November 2016), "New schedule agreed for ITER fusion project".

The risk mitigation built into the milestone structure enables evolutionary experimentation during each phase. In July 2019, ITER cleared a milestone to first plasma in 2025.[362]

As the interview progressed and in a seamless narrative, Coblentz provided his perspective on the research questions at the center of this study. *Why, despite unfulfilled visions and broken promises, has the grand fusion enterprise endured? How can such a long-term enterprise persist in a funding culture that largely works in short-term cycles?*

> So, I think the motivation varies across the project because you know people of different nationalities and age brackets or generations, the young set coming in tends to be very inspired. The older set many of whom expected to see fusion operational by this point in their careers have a more cautious sort of prediction line in terms of timeline of when they think things are going to mature… There is always, you can always find discouragement on any given particular piece of the project or what they think of this or that political or other situation. I have yet to find a single fusion engineer or scientist who has any belief that we should be relinquishing our hope or slowing down or anything like that. They're relentless. I think the answer to that question varies some from one to the other, from one person to the other but ultimately it's driven by the dream of changing the legacy we leave to our future generations.[363]

Coblentz thereby expresses a generation gap among individuals invested in the fusion enterprise. In spite of the muted inspiration by those who have spent decades in pursuit of the 'holy grail' of fusion energy, the motivation is "relentless". The interview response also exposes momentum energized by the sociotechnical imaginary of a utopian gift to humanity in the years to come.

An enlightening and nuanced answer emerges in the interview, related to the logical conflict between short-term funding cycles and the fusion enterprise that spans generations. Coblentz prefaces his comprehensive narrative in the following apparently contradictory thought. "The short and best answer is no, but I want to explain what I need and then I tell you why the

[362] Gronewold, "World's largest nuclear fusion experiment clears milestone".

[363] Coblentz, in interview with the author, July 28, 2018.

answer is yes".[364] It is evident that the US, especially since the current administration acquired power in the Executive Branch, presents the most immediate challenge to sustained funding and reliable delivery of components to which previous commitments were made.

> The no comes from the fact that if you look at the choice that the ITER members made of how this project would be constructed it's utterly strange and it ranges from the incredibly beneficial to the nightmarish and hellish; and that is the strategy that said we all want to contribute our funding to the ITER project in 80 to 90 percent in kind contributions, meaning in the form of components mostly. The desire to do that was because different countries have different expertise and so there was a desire to learn from each other.
>
> So, each country would develop as much they wanted to of independent knowledge of superconductor magnetism of all the different disciplines associated (so that was part of the motivation); but the other motivation was that each of these countries had already developed certain skills and we felt that you needed a combination of all those skills, not just the science… to be able to build this machine.[365]

Coblentz indicates that dependence on each contributor for delivery of the components to be integrated describes a critical path to complete assembly of the ITER Tokamak and its support infrastructure. Due to the leading-edge technology and advanced knowledge that comprises each component contribution, obtaining alternative sources would definitely delay the project – perhaps to damage the project beyond restoration.

> The yes answer, [to] what is our strategy, is number one we try to figure out who the power players are in the US and we talked to Senator Feinstein's people and Senator Feinstein and we talked to her counterpart of the Republican side Lamar Alexander and his staff [and]… looking at all of the congressional bits and we find where we have real champions. For example, the House authorization committee [and] science base technology committee headed by right now by Lamar Alexander. He has become a massive advocate and… an op-ed that he published a couple of months ago where in a committee that had debated the merits of climate change the chairman only a few years ago that chairman is coming out in saying directly that fusion is an essential enterprise and we've got to stay onboard and fund this.[366]

[364] Coblentz, in interview with the author, July 28, 2018.

[365] Coblentz, in interview with the author, July 28, 2018.

[366] Coblentz, in interview with the author, July 28, 2018.

Bigot and Coblentz are instrumental figures that bridge the gaps between a shared utopian vision in the fusion S&T community as well as diverse advocate communities, and the power brokers in the complex network of the socio-political stakeholder community.

Twenty-First Century Moonshot

ITER has been characterized as a twenty-first century "moonshot"[367] and by association this brand also conveys to the greater fusion enterprise. In addition to the stunning dimensions of the ITER program, and its supporting infrastructure and socio-political order that echoes the technocracies of the Space Age, the moonshot analogy prompts the pondering of similarities and contrasting features of the fusion enterprise to qualities that characterize the Space Race. How relevant is the moonshot analogy to ITER, the overwhelmingly dominant fusion enterprise project? One common theme is the need for a huge investment in financial and intellectual resources. "No bucks, no Buck Rogers".[368]

In the Space Race of the 1960s, the USSR and the USA were striving for 'firsts' that were intended to decisively demonstrate the superiority of their contrasting worldviews. The spark that launched the early Space Age was the Soviet launch of Sputnik I in 1957, shortly after NASA's inception. The competition between the two great post World War II powers was framed by the goal declared by President John F. Kennedy in 1961, to send a man to the moon and return him safely to Earth. To successfully launch an object into Earth orbit was an obstacle that required the best resources to overcome. Kennedy stated that the civilian space goals were

[367] Fareed Zacharia, Fareed Zacharia GPS: Moonshots for the 21st century. Segment 3 of CNN series: Creating a star on Earth, (2015, 15 March).

[368] Tom Wolfe, *The Right Stuff,* (New York: Farrar, Straus, and Giroux, 1979).

undertaken "not because they are easy but because they are hard".[369] The race to the moon developed into a surrogate for warfare between the two nuclear-armed states. The contest shifted back and forth until the first humans, Neil Armstrong and Buzz Aldrin, stood on the surface of the moon. The furious pace to develop the Saturn V, Apollo spacecraft, and Lunar Excursion Module (LEM), and the corresponding Soviet efforts rapidly decelerated on that day in July 1969. The huge funding for the Apollo program had its critics but the potent geopolitical factor sustained funding levels until the US appeared to be on the cusp of success.

In addition to the challenge of reliable funding for big science in a age of shrinking R&D budgets, similarities between the race to the moon and the quest for the 'holy grail' of viable fusion energy include the following trio of features: (1) the extreme level of difficulty in achieving the corresponding goals; (2) the technocracies that coalesced around the unprecedented goals; and (3) publicly performed imaginaries enabled through science and technology, i.e., soaring shared visions that had emerged from images of potential Armageddon.

After World War II, the US had assumed the role of leader of the free world based on the perception it was superior to and stronger than its rival, the USSR. Sputnik not only propelled the USSR into strategic parity with the US, it "suggested to a half-informed world that American reliance on the marketplace and the discoordinated efforts of the private sector, corrupted by consumerism, was anachronistic in an age of explosive technical advance".[370] The Eisenhower administration understood the economic and moral consequences of an unrestrained race with the USSR but the reality of Soviet moons overhead unleashed the technocratic model and the American military-industrial complex and the scientific-technological elite were mobilized.

[369] John Cloud, "Imaging the world in a barrel: CORONA and the clandestine convergence of the Earth sciences", *Social Studies of Science*, 31(2), (2001), 231.

[370] McDougall, *The Heavens and the Earth*, 7.

The fusion paradox is that while an identical gap between promises and results remains unresolved, momentum has persisted over several decades. As the lunar landings did not result in human colonization of the moon, the first demonstration of significant net electricity energy production does not herald a fusion energy revolution. "Although fusion technologies become available in the system from 2050, real penetration does not start until 2070".[371] The most striking contrast between "moonshots" is that the race to the moon during the first Space Age was a geopolitical contest whereas the pursuit of the holy grail of fusion energy is a collaborative effort with both traditional allies (e.g., the US and the UK) and geopolitical competitors (e.g., the US and Russia). In a period of time equivalent to the duration of the fusion enterprise, powered human flight leaped from a brief airborne experiment in 1903 at Kitty Hawk to first human on the moon in 1969. The ITER project is the contemporary exemplar of the fusion moonshot.

Size Matters

ITER's infrastructure is built upon a strong political foundation, as potent as its advocates' technological optimism. There are features of international collaboration and complexity of the ITER project, similar to the International Space Station (ISS).[372] The ISS is a construct of a US led program to test the robustness of mature space technologies, to explore the viability of long-duration human spaceflight, and the Earth orbiting facility provides a modest platform for innovative terrestrial technologies. The scale, however, of the ITER project far surpasses the ISS, in sheer size (Figure 16) as well as the number and diversity of nations.

---

[371] Helena Cabal, et al, Exploration of fusion power penetration under different global energy scenarios using the EFDA Times energy optimization model, (2016), 5. Received funding from the EURATOM research and training programme 2014-2018 under grant agreement No. 633053.

[372] NASA – International Space Station, International Cooperation, http://www.nasa.gov/mission_pages/station/cooperation.

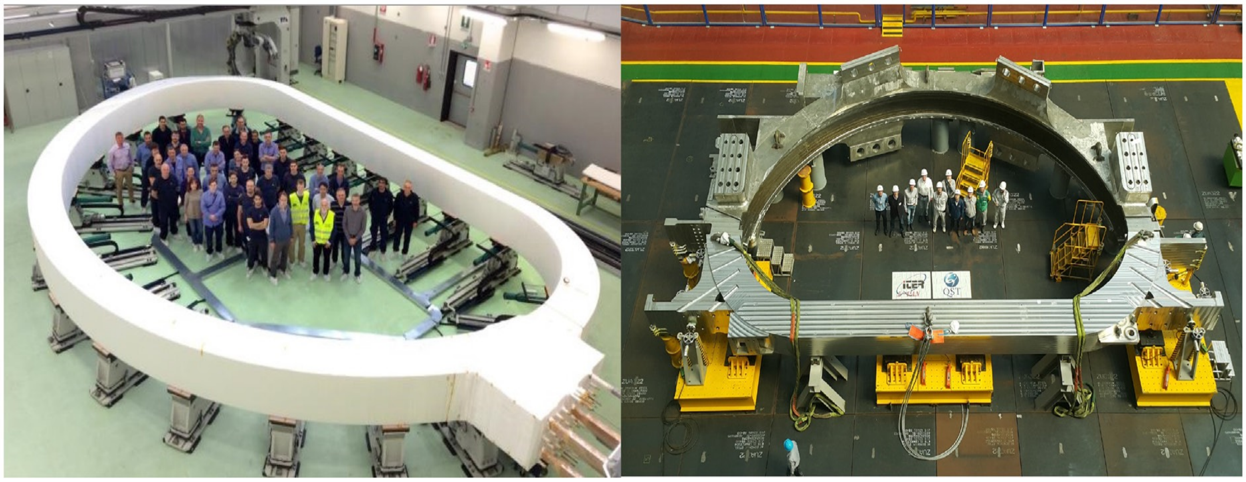

Figure 16. Scale of Toroidal Field (TF) Coil Structures of the ITER Magnet System. Courtesy The ITER Organization.

ITER leadership and nation state participation and financing are a broad international coalition and the program is a large scale proof-of-concept, intended to have global impact on the Earth's energy future.[373] Both international projects are adapting existing technology on a grand scale and require complex, formal international agreements among sovereign nations.

Whereas the ISS is an effort to adapt humans to extraterrestrial environments, ITER is an initiative to bring star power to Earth. The corresponding sites of big S&T share common sociotechnical elements related to solving wicked problems in each context. On the ISS, the most challenging objective is to resolve the inherent contradiction of humans enduring in hostile environments, e.g., microgravity aboard spacecraft and on worlds without Earth's benign atmosphere, and protective gravitational and magnetic fields.

The unwavering goal of ITER is to demonstrate viable fusion energy. ITER is not the first fusion project to promise to demonstrate net power generation but the project is the first to be solely focused on proof-of-concept, rather than fusion endeavors with other primary goals. Notably, the National Ignition Facility (NIF) of the Lawrence Livermore National Laboratory

[373] Osamu Motojima, et al, The status of the ITER project, 24th IAEA Fusion Energy Conference, 8-13 October 2012.

(LLNL)[374] employs 192 lasers to induce inertial confinement fusion and it serves as a high-visibility example.

By the end of fiscal year 2012, NIF promised results "soon enough to make a difference".[375] However, the milestone to which NIF committed, 'ignition', was missed.[376] NIF Senior Scientist, John Lindl unambiguously stated "Nature does not give up her secrets easily".[377] The proportion of experiment time invested at NIF was then replaced with the facility's primary function,[378] nondestructive thermonuclear weapon simulations.

> For now, thanks in large part to the NIF's role in nuclear-weapons science, politicians will allow the research programme to trundle on at a cost of US$280 million per year. But the great unfulfilled promise of the NIF should serve as a cautionary lesson for scientists who promote Hollywood solutions from their research.[379]

The pressure to produce tangible results also applies to ITER, the imposing Tokamak device designed to be among the last of *experimental* torus-shaped magnetic confinement machines. Unlike NIF, ITER is a single-purpose facility. On the other hand, ITER is like a massive socio-technical planet, pulling the world's finite resources into its gravitational sphere of influence.

For decades, Tokamaks have dominated the effort to create a sustained ignition of hydrogen plasma and a model of a fusion energy plant. ITER is an expression of the Tokamak on an enormous scale.

---

[374] NIF: The "crown joule" of laser science, https://lasers.llnl.gov/about/nif/about.php.

[375] The phrase, "soon enough to make a difference", has been *removed* from the LLNL.gov web site.

[376] Daniel Clery, "Ignition facility misses goal, ponders new course", *Science*, No. 337, 6101, (2012, 21 September), 1444.

[377] LLNL – The Pursuit of Ignition, https://lasers.llnl.gov/10-years-of-dedication/pursuit-of-ignition.

[378] Clery, "Ignition facility misses goal, ponders new course", 1445.

[379] "Ignition Switch", *Nature*, No. 491, (2012, 8 November), 159.

The Way?

As in the case of NSTX-U, sociotechnical imaginaries play a vital role. Before the first construction component appeared, the name of the project was, and still is, consistently represented through the Latin word for "the way", i.e., the way to a future planetary revolution. The project name encapsulates the utopian vision PPPL advances as ten fusion energy facts,[380] blurs the boundary between fact and imaginary, and PPPL's list represents a collection of imaginaries shared by the global fusion enterprise. However, in this case the geopolitical genesis of the utopian imaginary was a shared vision by the leaders of the two rival Cold War superpowers a half-century ago and established the foundation for the current ITER project. In context of the fusion enterprise, the superpower impact of the leaders of the US and USSR in 1985 might endure for a century or longer. In particular, the interview I conducted with the ITER Communications Lead, Laban Coblentz, infused my study with clarity regarding the impact of identity of the director of the ITER Organization as well as Coblentz himself. Since 2015, the perspective of Director General Bigot and as echoed in Coblentz's actions formed a collaboration that mitigated waning confidence in the project by the many nation-state stakeholders. ITER's central position in the fusion enterprise and controversy are coexisting qualities embedded in the current state of the project. That Janus-headed attribute is also reflected in the approach to fusion research and experimentation at PPPL and IPP, where those plasma physics laboratories support ITER and simultaneously advance the active exploration of alternative paths to fusion.

The analytical framework I applied considers the scale of the project, its ambitious goals, and as the dominant fusion project, its high visibility. In a large technological system, its sheer

[380] Bernard, "10 facts you should know about fusion energy".

size can power sociotechnical momentum but controversy in a high visibility system with great expectations can also induce inertia. In the ITER case study, I explored the fusion energy paradox as it appears on a massive scale, where global institutions and professional identities play key roles in understanding the building and future operation of the largest Tokamak on Earth from a sociotechnical perspective.

In Garching, Germany, IPP is also running experiments on a Tokamak, the Axially Symmetric Divertor Experiment (ASDEX) Upgrade, just as PPPL continues research on its spherical device in the US; both programs support ITER. IPP scientists continue to conduct research using the ASDEX Upgrade on plasma properties, density, and pressure[381] but at the IPP site in Greifswald, Germany, "tokamaks' rebellious cousin is stepping out of the shadows".[382]

---

[381] IPP – ASDEX Upgrade, https://www.ipp.mpg.de/16195/asdex.

[382] D. Clery, "Twisted logic", *Science*, No. 350 (6259), (2015, 23 October), 369.

CHAPTER FIVE – Anti-Nuclear Germany Weaves Thermonuclear Alternative: Wendelstein-7X (W7-X)

The uniquely sculptured Wendelstein 7X (W7-X) device is the focal point of the final case study. In this chapter, I acknowledge a collection of fusion imaginaries[383] shared by all three projects and I introduce an imaginary that dominates the discourse in the German instance: an ecological vision of a high-energy landscape that not only eliminates fossil fuel sources but discards nuclear fission as a carbon neutral source and yet supports fusion. That vision introduces a multi-dimensional paradox worthy of exploring through the lens of co-production of S&T and social order, and in context of a distinctly German technological imaginary.

German Technological Imaginary

While fission power has been firmly rejected by the German polity, fusion as a future source of exotic high-capacity power generation is embraced by a significant proportion of the German public, academia, industry, and political leadership. "The 2011 Fukushima accident was an external, destabilizing shock that triggered the decision to phase out nuclear power and to embrace energy transition as a political goal".[384] While Geels, et al. assert the nuclear accident prompted the political decision to decommission Germany's remaining 17 reactors, the event rather resurrected policy of a coalition government in 1998 to phase out nuclear energy.[385]

---

[383] Bernard, "10 facts you should know about fusion energy".

[384] Frank W. Geels, et al, "Sociotechnical Transitions for Deep Decarbonization", *Science*, (2017, 22 September), No. 357, 6357, 1242.

[385] World Nuclear Association, Nuclear power in Germany (updated March 2019), http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx.

As nuclear energy is phased out, a simultaneous withdrawal of coal "would leave the country without the necessary resources to ensure it has the energy it needs".[386] As of August 2017, the World Nuclear Association reports the following on sources of electricity in Germany.

> Germany until March 2011 obtained one-quarter of its electricity from nuclear energy, using 17 reactors. The figure is now about 14% from eight reactors, while 43% of electricity comes from coal, the majority of that from lignite.[387]

The conversion of energy sources in Germany is still evolving but the commitment to 'renewable' technologies has solid constituencies. Those renewable technologies include wind and photovoltaic, and corresponding enabling capabilities such as the improvement of energy storage and smart grid management. The high-profile unveiling of W7-X in December 2015 is an explicit declaration that fusion energy is envisioned as an element of an ecological energy ecosystem. The nineteen year financial and intellectual investment in W7-X testifies to the contrast between support for viable fusion and the rejection of 'conventional' fission energy.

There is a German ecological modernization vision that accounts for support of thermonuclear (i.e., fusion) energy and repudiation of nuclear (i.e., fission) energy. That vision coincides with the ten fusion energy facts promoted by PPPL and a common theme of the fusion enterprise. That statement does not imply that Germany is relying on fusion to be the sole power source but that the German leaders and publics understand that dependence on the contemporary set of renewable technologies will not provide the total energy needs of Germany in the future. The cost, e.g., energy surcharges, to facilitate an aggressive policy solely based on renewables

---

[386] Griff Witte and Luisa Beck, "Germany's coal reality smudges green rhetoric", *The Washington Post*, 2017, 12 November.

[387] World Nuclear Association, Nuclear power in Germany (updated March 2019), http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx.

has become a political debate in the last few years but an emphasis on phasing out fossil fuels and fission energy still enjoys substantial political support.

A set of low-risk fusion imaginaries is reprised in PPPL's promotional fact statements and these imaginaries are accepted as elements of an ecological modernization vision in the German polity: "It's natural. It's safe. It's environmentally friendly. It's conservation-friendly. It's international. It's unlimited. It's industrial scale. It's exciting. It's achievable. It's the Future".[388] Ulrich Beck posits a *risk society* in which we are reflecting on a modernity that emerged from the industrial age, not solely on the benefits of wealth production but the risks that technology inevitably brings and now dominates the social consciousness.[389]

Beck argues that we normalize acceptable levels of danger but nuclear radiation occupies a special position. With the dawn of the nuclear age and the maturing of rocket technology in the mid twentieth century, the technological sublime acquired an ominous quality[390] – of imminent Armageddon.

> By risks I mean above all radioactivity, which completely evades human perceptive abilities... together with the accompanying short- and long-term effects on plants, animals and people.
>
> They induce systematic and often irreversible harm, generally remain invisible, are based on causal interpretations, and thus initially only exist in terms of the (scientific or anti-scientific) knowledge about them. They can thus be changed, magnified, dramatized or minimized within knowledge, and to that extent they are partially open to social definition and construction.[391]

388 Bernard, 10 facts you should know about fusion energy.

389 Ulrich Beck, *Risk Society: Towards a New Modernity,* (London: Sage Publications, 1992).

390 Nye, *American Technological Sublime*.

391 Beck, *Risk Society*, 22-23.

In response to that technological omen, there is a counter-narrative: an energy ecosystem centered on the fusion of hydrogen isotopes can dramatically mitigate that high-priority risk. The sociotechnical power borne of those imaginaries is instead transferred to the fusion enterprise as a future vison of a fusion-centered energy ecosystem that addresses each of the dystopian fears of the contemporary *fission* project.

Tightly coupled complex systems are vulnerable to risk.[392] Each of the two paths to fusion energy, magnetic and inertial confinement, is a tightly coupled system and susceptible to cascading failures if unpredictable thresholds are breached.

> So, it doesn't take much to mess up fusion [and] that's the blessing and the curse. Fusion is more like keeping a very flaky gasoline engine on just giving at the right amount of fuel and the right temperature and it's easier for it to go out which makes it safer but also harder to achieve…[393]

One the one hand, a failure of a fusion energy power plant would not result in catastrophic meltdown or explosion. On the other hand, failure of fusion energy as a reliable source of electricity could still be catastrophic to fusion as a high-capacity energy option.

Based on the temporal landscape in which Beck wrote - in unified Germany – he was likely affected by economic optimism. Beck assumes industrial society is inevitably disappearing, to be replaced by the risk society. I contend that industrial society is still primary in the developing world, persists in the first-world, and manifests itself in Germany as an S&T centered ecological modernization vision. But "Germany's ambitious vision for 'Energiewende', or energy transformation, has proved far more difficult to execute than it was to plan".[394] In

---

[392] Charles Perrow, *Complexity, Coupling, and Catastrophe, in Normal Accidents: Living with High-Risk Technologies*, (New York: Basic Books, 1984), 62-100.

[393] Menard, in interview with the author, August 17, 2017.

[394] Griff Witte and Luisa Beck, "Germany's coal reality smudges green rhetoric", *The Washington Post*, 2017, 12 November.

particular, the absence of indigenous sources of energy (e.g., natural gas) as a bridge technology and the decision to quickly phase out indigenous fission reactors is a challenge to the formation of a pragmatic energy policy.

The importance of viable fusion as a high-capacity complement to renewables (e.g., wind and solar) has emerged as critical to realistically achieve the green energy transformation that the German polity has embraced for the mid twenty-first century.

> Germany is pioneering an epochal transformation it calls the *Energiewende*—an energy revolution that scientists say all nations must one day complete if a climate disaster is to be averted. Among large industrial nations, Germany is a leader. [In 2014] about 27 percent of its electricity came from renewable sources such as wind and solar power, three times what it got a decade ago and more than twice what the United States gets today. The change accelerated after the 2011 meltdown at Japan's Fukushima nuclear power plant, which led Chancellor Angela Merkel to declare that Germany would shut all 17 of its own reactors by 2022.[395]

The German ecological modernization vision is driven by the need to power a high energy economy and to measurably mitigate the dire trend in climate change. The position that IPP occupies in that vision has been amplified by the imminent loss of base-load capacity following total shutdown of Germany's nuclear (fission) plants. W7-X is the device at the center of IPP's contribution to a decarbonized energy ecosystem.

The sociotechnical path to W7-X can be traced back more than a century to the predecessor of IPP, the Kaiser Wilhelm Society for the Advancement of Science, and to the ancestor of PPPL, the Institute for Advanced Study at Princeton University. Albert Einstein, the twentieth century personification of physics and originator of $E=mc^2$ bridged the Kaiser Wilhelm Institute and the Institute for Advanced Study. Einstein was the director of the Kaiser Wilhelm Institute before he emigrated to the US and became the human centerpiece of the Princeton

[395] Robert Kunzig, "Germany could be a model for how we'll get power in the future", *National Geographic,* (2015, November).

institute. The current collaborative relationship between PPPL and IPP thus has its roots in the early twentieth century. The bond after World War II was to arise even stronger as a result of the physics icon and an entire generation of German scientists in a compelled emigration to the US.

Stellerator technology is an alternative to produce fusion reactions to the Tokamak, the design that ITER is advancing. The current instance of the stellerator at the Max Planck Institute for Plasma Physics (IPP) represents a direct link back to pioneering S&T at PPPL but diverges from the negative outcome of recent stellerator history at the US national laboratory.

Tokamak's Rebellious Cousin

In Greifswald, Germany, there is a machine at the Max Planck Institute for Plasma Physics (IPP) that externally reflects the tortured shape of both the energy debate in Germany and the powerful electro magnets surrounding the core of the W7-X (Figure 17).

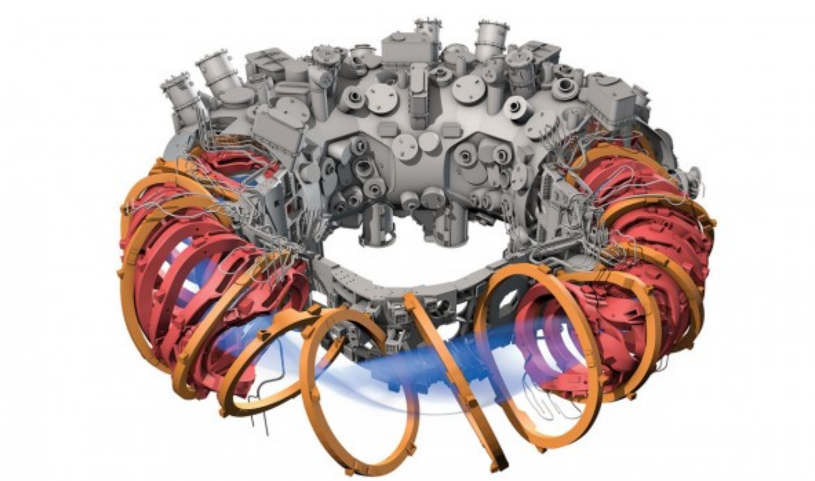

Figure 17. Wendelstein 7-X (W7-X). Courtesy Max Planck Institute for Plasma Physics.

The long path to operational status was punctuated by milestones that included a ten-year period of assembly, followed by presentation of a detailed design to companies contracted to build components.[396] Fifty superconducting magnets that emerged from years of sophisticated optimization calculations form a magnetic cage (Figure 18) for the super-heated plasma.[397]

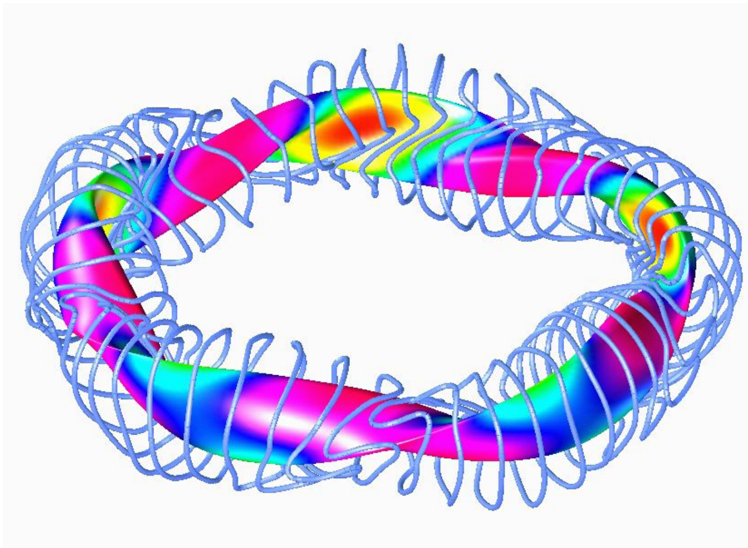

Figure 18. Scientific Visualization of 3-D Optimized W7-X. Courtesy UCLA Physics.

The W7-X has the potential to showcase a stellerator design to compete with the most advanced Tokamak designs. Planned evolutions of W7-X will enable continuous operation for 30 minutes.

> The tokamak achieves better plasma performance in terms of temperature, density and confinement, but disruptions—now a major research topic in tokamak physics—can be a challenge. Stellarators on the other hand are disruption-free machines, however you pay the price by having to build a device with a challenging geometry. In the past, the performance of the stellarator could never match that of the tokamak, but it is now catching up and with upcoming optimizations some of the performance-related disadvantages can be overcome.[398]

[396] Günter, in interview with the author, August 17, 2018.

[397] Isabella Milch, Wendelstein 7-X: Second round of experimentation started, (Max Planck Society, 2017, 11 September).

[398] ITER Newsline, "What's next for the stellerator?", *Fusion World* (2018, 12 November), https://www.iter.org/newsline/-/3169.

The dual track that IPP and PPPL elected to pursue is echoed in a 2013 Master Plasma Class, presented by Dr. Günter.[399] Just as the experiments at both institutions are intended to advance ITER, Dr. Günter similarly devotes a large proportion of her class to ITER as the prime case study. While she compares the benefits and disadvantages of the Tokamak, ITER's approach, and the stellerator, she continues to voice her confidence that eventually the enormous scale-up of the Tokamak design will yield viable fusion. On the other hand, she also points out that the broad international effort has its drawbacks, mainly the triple challenge of coordination, efficiency and speed due to the shared design, manufacturing, and assembly of components.

Dr. Günter suggests fully developing two promising approaches, e.g., "we have two types of [fossil fuel] engines today, gasoline and diesel".[400] Finally, she admits that the stellerator might be a technological backup plan for viable fusion – "just in case… you never know… how the Tokamak reactor behaves…" ITER will *probably* reach its goal of 'factor-of-10' net energy output[401] but by then the currently less mature technology of the stellerator might be ready to be adopted as a viable and more economically attractive source of reliable and eco-friendly electrical generating capacity for 'the grid' in the second half of the twenty-first century.

While the first phase of W7-X operations that commenced in December 2015 produced successes, e.g., operation of an optimized stellerator that generated "much hotter, denser, and longer plasmas than expected",[402] this phase also highlighted the wicked problems that lay

---

[399] Physics@FOM Veldhoven 2013, Sibylle Günter, Masterclass. Physics basis of magnetic fusion reactors. OpenWebcastCh2 (Published on Jan 30, 2013).

[400] Physics@FOM Veldhoven 2013, Sibylle Günter, Masterclass. Physics basis of magnetic fusion reactors. OpenWebcastCh2 (Published on Jan 30, 2013).

[401] The electrical power coming out of ITER will not be significantly greater than the level of electricity used to initiate the fusion reaction, (Krivit, S.B. 2017).

[402] Daniel Clery, "The new shape of fusion", *Science*, No. 348, 6237, (2015, 22 May), 854-856.

ahead, e.g., events revealed through diagnostic tools “that are not yet explained or explored”.[403] Germany has committed to phase out fission nuclear power by 2022 (Figure 19) and fossil fuels, e.g., coal, the German polity also supports pursuit of fusion energy as an element of its Ecological Modernization Vision.

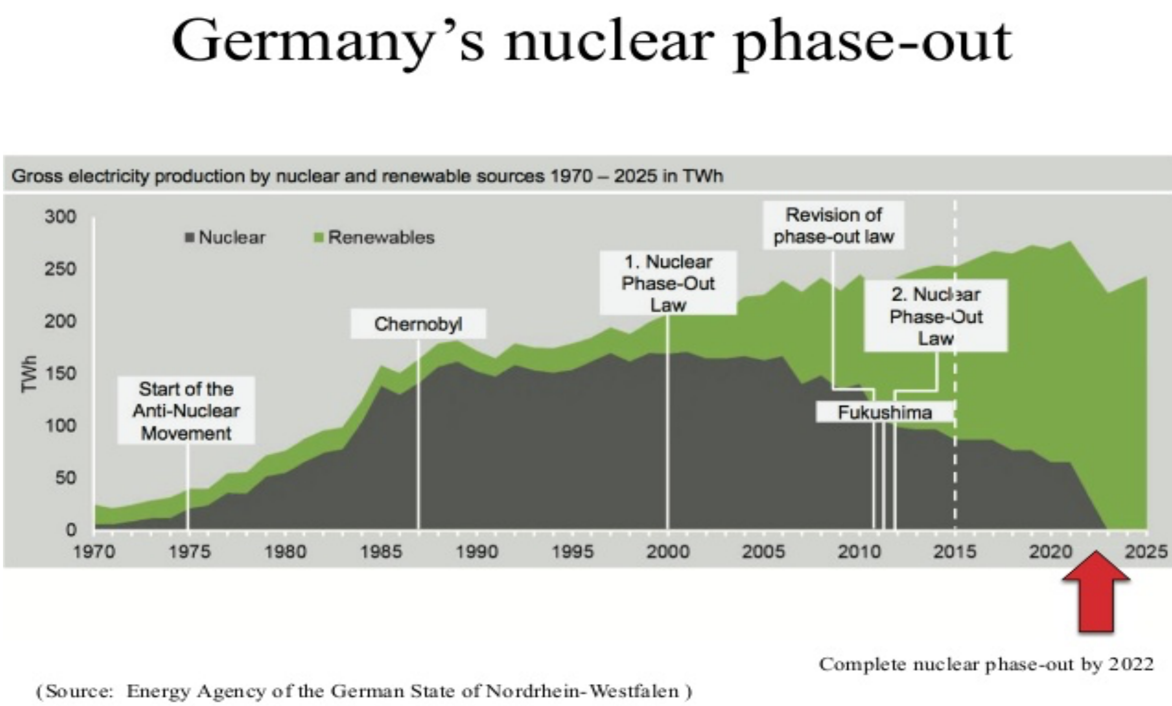

Figure 19. Nuclear Phase-out. Courtesy Energy Agency of German State of Nordrhein-Wesfalen.

That sociotechnical vision is shaped by the dual drivers of mitigating climate change and supplying adequate energy for a highly industrial country.

Climate Change and the Climate of the German Energy Debate

The Green Party in Germany has been so successful in recent decades that mainstream parties running for seats in the Bundestag and ruling coalitions have adopted Green Party

---

[403] Oliver P. Ford, Colloquium: Wendelstein 7-X: Highlights from the first operational phase of the new optimized stellarator, Presented by Dr. Oliver P. Ford, Max-Planck Institut für Plasmaphysik, Greifswald/Garching, Germany, At Princeton, NJ: Princeton Plasma Physics Laboratory, on June 15, 2016.

signature issues, such as the move away from fission power that amplified following the Fukushima-Daiichi nuclear accident. There is an imaginary held by a significant proportion of the German polity that renewable energy sources will provide all the energy that Germany will require to make up for any shortfall resulting from the decommissioning of nuclear plants and reduction of dependence on fossil fuels below 20%. However, the removal of fission from the German energy ecosystem by 2022 has potential negative implications. Increasing the use of coal as a power source to compensate for decommissioning fission power plants is a prime ironic consequence. Dr. Günter observes this paradox as well as a utopian vision of renewable energy sources providing all the power that a high energy society requires.

> I think that 2% of the CO_2 is from oil on earth and then there's a prediction that the population will grow in particular in the bigger cities. So, I think that the 50% of the population on Earth will be living in cities bigger than 10 million inhabitants. For such cities, it's hard to imagine that you can do this all by solar or wind. You might think of continuing with oil, gas and coal but on the other hand the CO_2 problem and global warming at this stage is serious. And then you better look out for alternatives. If society at the end buys into fusion nobody knows but I see my role – our role – in providing that option. If you don't provide that option today you don't have that option in those times and there's not… If you do not want to continue with fossils there's not much alternative.[404]

Dr. Menard is also well aware of the German conundrum and shared relevant thoughts from his PPPL perspective, a view that is not solely centered in Princeton, New Jersey. That view not only encompasses a US expression of the fusion enterprise but spans the globe.

> I mean Germany has, as you know, probably large natural gas pipelines from Russia. They may be reverting back to burning more coal. We'll see how long that lasts. You may have visited [W]7-X but on the way up to Griefswald [Germany] you know very well the highway is lined with giant wind turbines. So they're trying to make up for those losses but time will tell how viable that really is.[405]

[404] Günter (Scientific Director, in interview with the author, August 17, 2018.

[405] Menard, in interview with the author, August 17, 2017.

While climate change is no longer the supreme issue for the Greens or the ruling coalition of Germany, it still occupies a priority position in the political landscape of Germany.

Grandiose rhetoric by politicians and technocrats that declares potential solutions to recurring energy crises since the 1970s is common. The big plans that emerge from ambiguous rhetoric is frequently doomed due the absence of coherent policy, but there is no ideal policy – a one-size-fits-all solution for our interconnected global society or a universally acceptable local, e.g., German, American, or French, solution. The dominant "parable... in the high energy society: an admission of weakness and vulnerability is followed by a proclamation that a new technological breakthrough will alleviate the problem".[406] In recent years, a variation of the narrative is emerging: the world has reached a threshold in which our escalating use of fossil fuels to meet the insatiable appetite for energy consumption represents an existential threat to the climate. Unfortunately, the rhetoric of the climate policy debate is laced with domestic and geo-political issues that deter the universal adoption of coherent policy.

The radiance of France resides deeply in French culture and thereby establishes a nuclear foundation of new energy technologies and a launch pad for a new utopian vision in which fusion is central. In contrast, Germany's shared energy vision has no such dependency on a nuclear energy legacy central to its national identity. It might appear peculiar that these two nations coming from dramatically different points on the nuclear compass share a common utopian vision of viable fusion and its imagined impact on global humanity.

After nineteen years of development, IPP unveiled the W7-X. In December 2015, German Chancellor Angela Merkel threw the switch that triggered the first plasma. Merkel has a Ph.D. in Physics and an appreciation for fusion that transcends the political and sociological

[406] Nye, *Consuming Power*, 232.

domain. In recognition of a shared historical connection, key PPPL staff were honored guests. Over fifty years earlier, “the stellarator” was born as Princeton University's first effort to demonstrate controlled fusion. In contrast to PPPL’s dormant stellerator project, IPP also faced a long, nineteen-year road to build W7-X but its funding support continued.

Consequently, the focal point of stellarator technology has now shifted to that German R&D facility. The W7-X is far more complex than than the figure-8 shape that characterized the first generation of stellerators developed at PPPL decades earlier and the design could not have emerged without supercomputing capacity that has been developed in recent years. The collaborative feature across S&T disciplines that characterizes the quest for viable fusion energy and the quantum leaps in computer power memorialized in Moore’s Law[407] unite to advance the IPP program to ambitious milestones.

While the W7-X represents the tangible realization of a revolutionary design conceived in the mind of Lyman Spitzer decades earlier, there is a sociological transformation advancing simultaneously with technical innovations in the German expression of the fusion enterprise, energizing advancement. The success evident in IPP is an outcome of the qualities of the institution and those institutional qualities emerged due to people and organizations that heralded IPP many years earlier.

A Sociological Planck’s Constant

The name and the qualitative identity of Max Planck is explicitly linked to 84 research institutes in Germany and collectively they comprise the basic research arm of the Max Planck Society. The instantly recognizable name of the physicist is followed by an unambiguous short

[407] A computing term which originated around 1970 that states processing power for computers will double every two years, (www.mooreslaw.org)

description of each center of this German knowledge enterprise, e.g., the Max Planck Institute for Plasma Physics (IPP). In that massive and diverse institutional system, IPP is the site of the third case of the fusion enterprise explored in this dissertation.

What accounts for this individual's identity being so closely linked to leading-edge research following the dark years of the Third Reich (1933-1945)? That ominous period reveals a vision of an imperial Germany under Adolph Hitler that unleashed global war, i.e., World War II, and murder of civilians on an industrial scale based on an ideology of racial purity, a period in which the *principle of certainty* created a horror-filled dystopian reality with no parallel in modern history. In light of Germany emerging from the literal and sociological ashes of World War II, it is perhaps fitting that Planck's identity is prominent in the German research enterprise and that the 'father' of the *Uncertainty Principle,*[408] Werner Heisenberg, became professor of physics and director of the Max Planck Institute for Physics.[409] In quantum physics, the essence of the uncertainty principle is that causality breaks down at the boundary of what is universally termed *Planck's Constant.*[410] That brings the analysis back to who was Max Planck?

Max Karl Ernst Ludwig Planck (1858-1947) was born in Kiel, Germany. At the age of twenty-one, Planck was awarded a doctorate of Philosophy by the University of Munich and immediately thereafter served in teaching roles for ten years in Munich and Kiel. Subsequently, he attained a full professorship at Berlin University and remained in that role from 1879 to 1926. In 1894, he also became a member and by 1912 Permanent Secretary of the Prussian Academy

---

[408] The uncertainty principle states that one cannot assign exact simultaneous values to the position and momentum of a physical system. (https://plato.stanford.edu/entries/qt-uncertainty/)

[409] Upon his return to Germany following his arrest by the US for his role in the German weapons program.

[410] Planck's Constant is a fundamental constant, equal to the energy of a quantum of electromagnetic radiation divided by its frequency, with a value of 6.626×10^{-34} joule-seconds (Oxford Dictionaires). C. Bek, "The uncertainty principle", *Philosophymagazine: Philosophy and science for the third millennium,* (2018, 1 September).

of Sciences. Planck retired from teaching but from 1926 to 1937, he served as President of the Kaiser Wilhelm Society, an ancestor institution of the Max Planck Society. Max Planck was also recognized by the Royal Society, as he was elected as a foreign member in 1926 and in 1928 received the Copley Medal, the Society's oldest[411] and most prestigious award.

Planck explored the research questions that emerged from the phenomenon of radiation and, from his observations, identified a relationship between energy and frequency in context of radiation.

> In a paper published in 1900, he announced his derivation of the relationship: this was based on the revolutionary idea that the energy emitted by a resonator could only take on discrete values or quanta. The energy for a resonator of frequency v is hv where h is a universal constant, now called Planck's constant.[412]

For generations, the Nobel Prize has been considered the pinnacle of recognition of scientific achievement. In 1918, Max Planck was the recipient of the Nobel Prize for Physics. He was awarded the iconic prize "in recognition of the services he rendered to the advancement of Physics by his discovery of energy quanta".[413]

While Planck was enormously respected to the point of reverence by his German and international colleagues, his presence in Germany during the Nazi regime radiated a dark cloud over a lifetime of achievement. Yet he openly opposed government policies, in particular the persecution of Jews and experienced a personal heartbreak associated with the Nazi regime in

---

[411] The Copley Medal was awarded 170 years before the first Nobel Prize. (https://royalsociety.org/grants-schemes-awards/awards/copley-medal/)

[412] The Nobel Prize in Physics (1918), Max Planck Biographical, https://www.nobelprize.org/prizes/physics/1918/planck/biographical/.

[413] The Nobel Prize in Physics (1918), Max Planck Biographical, https://www.nobelprize.org/prizes/physics/1918/planck/biographical/.

1944 when one of his sons was executed for his part in an unsuccessful attempt to assassinate Hitler. Planck never relinquished his passion for pursuit of basic research.

It was not long before the impact of his immense body of innovative contributions was resurrected in a recreated German democracy in West Germany and associated with the new institution built on the pre-war legacy of the Kaiser Wilhelm Society.

Max Planck Society

One year after the death of Max Planck and just three years after the end of the defeat of Nazi Germany, the Max Planck Gesellschaft, the Max Planck Society, was established. The identity of the late Max Planck as Nobel Prize laureate was reproduced eighteen times through scientists, who as members of the Max Planck Society, were also awarded the most prestigious scientific honor. Through the world-class quality of the researchers among the diverse landscape of institutes, their frequently cited work, and the honors collected by thousands of associates, the Max Planck Society is an organization on par with the leading research institutions across the globe.

Beyond gathering an impressive collection of seasoned scientists in the natural and social sciences, technologists and researchers with long histories of accomplishments, in 1998 the Max Planck Society under the auspices of the International Max Planck Research Schools (IMPRS) established a fellowship program for young male *and female* Ph.D. students from diverse countries. The fellowship program has proved to be a motivational instrument over the past twenty years and has been emulated by many other academic institutions both domestically and internationally.

Schiebinger opens her volume, *The Mind Has No Sex*,[414] with the resistance to the admission of Marie Curie to the French Academie des Sciences.[415] Curie was rejected despite her landmark accomplishments, for which she earned two Nobel prizes – in 1903 and 1911 – and notwithstanding her international prestige in the scientific community. This event can be traced back centuries to the prejudice women experienced in post-Renaissance European institutions, such as the universities, and the scientific societies of France and England. The exception was the Italian academy, in which "a small number of women did study and teach".[416] The Max Planck Society. in contrast to that European chronicle, has been a force for positive change by not only recognizing the value of women in scientific research but the institution has tangibly nurtured that view, through the Minerva Program.

> In the last ten years, this program has succeeded in doubling the percentage of women among Max Planck scientists. In 2008, the figure stood at 26 percent and rising, positioning the Max Planck Society as one of the top-ranking research institutions in Germany in this respect. Women also receive additional support through mentoring programs, advanced training seminars and childcare options.
> The Max Planck Society was the first scientific organization to undergo the family-friendliness audit "berufundfamilie" (job and family), and successfully obtained certification.[417]

The significant impact of Dr. Sibylle Günter, the IPP scientific director, on the German S&T enterprise punctuates the importance of the society's promotion of gender diversity. IPP is the site of the third case studied in this dissertation. The Wendelstein-7X (W7-X) stellerator not

---

414 Londa Schiebinger, *The mind has no sex? Women in the origins of modern science,* (Cambridge, MA: Harvard University Press, 1989).

415 Schiebinger, *The mind has no sex?*

416 Schiebinger, *The mind has no sex?*, 14.

417 IPP – History of IPP, https://www.ipp.mpg.de/17194/geschichte.

only literally reshapes fusion S&T but the German expression of the fusion enterprise is also the site of enhancing fusion science through the power of diverse teams.

Diversity, Institutional Landscapes, and Advances in the German Fusion Enterprise

The social enhancement to S&T that I infer is the engagement of the female half of humanity in that human activity tagged as science, i.e., embracing people historically isolated from recognition as contributors to the scientific revolution solely based on gender, the female gender.[418] Dr. Günter's narrative is an exemplar for the co-production of S&T and a key element of progressive social order. In 2015, during the same year the long-serving first female Chancellor of Germany, Angela Merkel, presided over initial operation of W7-X, Dr. Sibylle Günter was awarded the Emmy Noether Distinction for Women in Physics by the European Physical Society (EPS). Dr. Günter received the prize in recognition of her world-leading "role in the study of the effects of microphysics on the large-scale behaviour and stability of hot magnetized plasmas in fusion devices".[419]

The institutionalization of gender diversity is critical to maintaining momentum in its progressive contribution to the S&T landscape. Dr. Günter notably affirms the centrality of formal organizations, echoing Jasanoff's emphasis among instruments of co-production characterizing institutions as stable repositories of power, e.g., PPPL, IPP, research institutions, and companies associated with fusion components – organizations that comprise an ecosystem assembled in pursuit of viable fusion energy. For example, a network of German firms has been

[418] Evelyn Fox Keller, *Reflections on Gender and Science,* (New Haven: Yale University Press, 1985); Londa Schiebinger, *The Mind Has No Sex? Women in the Origins of Modern Science,* (Cambridge, MA: Harvard University Press, 1989); Cynthia Fuchs Epstein, "Great Divides: The Cultural, Cognitive, and Social Bases of Global Subordination of Women, *American Sociological Review*, (2007), 72(1).

[419] IPP – Scientific Director of IPP awarded Emmy Noether Prize, http://www.ipp.mpg.de/4005098/01_16.

manufacturing components for W7-X and multiple research institutes were central to construction of the most advanced stellerator on Earth.

> Karlsruhe Institute of Technology [was] developing the microwave plasma heating and are responsible for providing the entire microwave system. Jülich Research Centre manufactured the connecting components for the superconducting magnet coils and took on diagnostic development work. Over 160 person-years of work was invested by specialists in superconductivity technology from the Polish Academy of Sciences at Cracow to install the connections of the stellarator coils.
>
> The fusion institutes at Princeton, Oak Ridge and Los Alamos contributed auxiliary magnetic coils, measuring instruments and planning of sections of the wall cladding to a value of 7.5 million dollars for equipping Wendelstein 7-X.[420]

Within that German fusion energy ecosystem, there is also a sociological thread that promises to advance the enterprise, i.e., diversity.

While Dr. Günter has the eminent role of IPP Scientific Director and is a member of several prestigious scientific societies, I inquired what challenges she had encountered as a woman in science during her journey to lead scientific programs at the pinnacle of German plasma physics.

> Well I think, ultimately not all challenges I have had are… nowadays already still there. I mean, when I started as a young scientist, there was several men who thought women should stay home [as] they're not good enough for science anyway. I don't feel this any longer is the case.[421]

The internationally-recognized scientific director shared that as a young scientist she had experienced gender bias but fortunately the prejudice has been mitigated if not overcome in the contemporary German science community.

---

[420] Günter, in interview with the author, August 17, 2018.

[421] Günter, in interview with the author, August 17, 2018.

Dr. Günter asserts that diversity enhances the productive outcome of activity at IPP, i.e., multiple dimensions – gender, ethnic identity, and diverse S&T disciplines. She describes her view of diverse teams in scientific research.

> Mixed teams usually perform better than just male or female dominated. It's not about male versus female, it is—actually it's a mixture of it, a good mixture of female and male teams… They seem just the mixture is really good… So, I think that it's always much better when you have mixed teams, so I wouldn't just refer to science teams and then how it could be as many as possible females, it's just the mixture of the two species enriches the scientific life as well. I think this is very positive.
>
> [We] have a collaboration with two other Max Planck Institutes one on, for example, astrophysics and one for solar system research… We also reached out to mathematical faculties, for example, the joint with university and mathematics department and informatics department, so we try to reach out much further than just human science.[422]

Evidently, Dr. Günter recognizes the potential benefits and implements those observations to advance the enterprise, at IPP and in her role as an influential leader in the global enterprise.

There is a convergence of scientific disciplines (e.g., physics and chemistry), engineering disciplines (e.g., materials and computer engineering), sociological factors (e.g., gender and cultural diversity), and self-actualizing practitioner teams. That union of sciences, technologies, and social instruments has driven socio-technical momentum for decades and ensures that the distinctively sculptured W7-X that has slowly emerged will continue to advance the fusion enterprise. W7-X appeared in a landscape almost exclusively occupied by the Tokamak.

As Scientific Director of IPP and internationally recognized thought leader of the fusion enterprise, Dr. Günter was selected as a reviewer reviewer of the *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*[423] alongside her PPPL colleague, Dr. Jon

[422] Günter, in interview with the author, August 17, 2018.

[423] National Academies of Sciences, Engineering, and Medicine, "Progress in Burning Plasma Science and Technology" in *Final report of the committee on a strategic plan for U.S. burning plasma research*, (Washington, DC: The National Academies Press, 2018).

Menard. On the surface, the selection of Dr. Günter as a reviewer of a US focused study by the National Academies might appear counterintuitive. On the other hand, the choice by the committee reflects the collaborative nature of the enterprise and of the significance of the IPP scientific director in the international discourse. From her leadership position at IPP, she represents a key pragmatic advocate of a fusion centered energy ecosystem.

> *Why is fusion research such a protracted project?* The required parameters are unlike anything on earth. Temperatures ten times that of the sun's core, 200 million degrees… Then you have to ensure that the walls and the material can withstand it all… The parameters for measuring research success have nearly doubled each year. Just like the famous Moore's Law in the computing industry. Of course the computing industry has seen major successes. But in nuclear fusion research, it is not as apparent to the public. That is because we still cannot produce energy and need even more to heat plasma.[424]

There is an emerging threat to the fusion enterprise in the form of a recent reactionary tide in many nations, a distrust in science. That trend in Germany is an echo of the reflexive response to the risk society.[425]

According to Beck, our society is transitioning into one comprised of a set of social systems that respond to our perception of risk. "Risk may be defined as a systematic way of dealing with hazards and insecurities induced and introduced by modernization itself".[426] Beck also explores the undermining of national boundaries through risks that endanger on a global level, but he underestimates the counter-effect of local national politics on the utopia of a world society. Beck projects a new type of international solidarity in a post-traditional risk society and a role for the UN in some form of new world order.[427] On the other hand, there is an emerging

---

[424] Interview, 2012, for "Sonnenwende" Exhibition, Berlin Max Planck Science Gallery.

[425] Beck, *Risk Society*.

[426] Beck, *Risk Society*, 21.

[427] Beck, *Risk Society*.

threat to liberal democracy that has characterized post World War II Europe. The political risk is a populism that is authoritarian, xenophobic and rejects globalization. While the Green Party and mainstream parties in Germany continue to sustain the ecological and global agenda, the nationalist reflexivity is a tangible challenge, as evidenced in recent parliamentary elections in both Germany and the E.U.

The attributes of her status in the fusion enterprise are revealed via the lens of identity, a relevant ordering instrument in the co-production of fusion energy and the socio-political order in the German polity. Dr. Günter's views position her as a pragmatic advocate who candidly recognizes the wicked problems that characterize the fusion enterprise. The recurring query, "Why is fusion research such a protracted project", reveals half of the paradox central to this dissertation and by its frequency implies a constant demand for a reliable forecast.

Diversity thereby has tangible, measurable qualities to effectively address wicked problems, i.e., complex problems affected by multiple variables with multilateral relationships. The challenges that comprise the fusion enterprise can be described, as the narrative of the enduring six-decade quest for the holy grail of energy testifies. While the attributes evident in powerfully diverse teams at IPP imply positive outcomes, successful milestones are not achieved in the absence of debate in the German community.

Exploration of Alternative German Energy Futures

While the outcome at IPP on the journey to an operational advanced stellerator sharply contrasts with the DOE killing off stellerator development at PPPL in 2008, the W7-X project has not been immune from controversy. The special position that "nuclear" occupies in the risk society[428] and the historical reality in that transitions in complex energy systems take decades

[428] Beck, *Risk Society*.

rather than years,[429] comingle to affect the fusion enterprise. The nineteen-year duration from design to operation of W7-X is a microcosm of the co-production of technological and sociological controversy in the quest for viable fusion energy.

By contrast to frame reflection, sociotechnical imaginaries are evocative of attainable futures[430] and embody debate framing mechanisms[431] through imaginaries and instruments. Are both concepts equally effective tools to explore the fusion energy project? Each approach frames an environment in which S&T issues are understood but the paths and mechanisms to develop an evolved policy diverge. Based on the immaturity of contemporary fusion energy policy, I contend that sociotechnical imaginaries "give shape to national policy-making initiatives"[432] in this case and inform co-production analysis rather than potential policy formation/reconciliation through the frame reflexive discourse as defined by Schön and Rein. Jasanoff and Kim[433] construct a framework that provides an understanding of the value-laden origins of ordering instruments from which distinct choices emerge among many candidate orderings (and establish why other orderings are not selected).

In the first 30 years of the Atomic Age, the dangers of nuclear power were evident to, though perhaps not fully understood by many in Germany and other industrially developed nations. The icon of the mushroom cloud dominated the public imagination. Among those in

[429] Smil, *Energy Myths and Realities*, 149.

[430] Eva Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", *Debating Innovation*, No. 2(3), (2012), 86.

[431] Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", 85.

[432] Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", 87.

[433] Jasanoff and Kim, "Containing the Atom: Sociotechnical Imaginaries and Nuclear power in the United States and South Korea".

the insular community of scientists and engineers in the post World War II military-industrial-academic nuclear complex embedded in nations that were regarded as "being nuclear",[434] the dominant comprehension of risk was acquired from study in their respective disciplines and from acquired knowledge. Before the TMI accident in 1979, this group of world-class technologists proposed systems of hardware to mitigate the potential dangers lurking in the effort to control the atom's potential power. The Institute of Nuclear Power Operations (INPO) managed to gradually develop credibility for safety practices based on US nuclear navy experience and established legitimacy among stakeholders at all levels in the American commercial nuclear energy sector.

However, broad public acceptance of nuclear reactors as a power source to generate electricity suffered a nearly fatal heart attack from which nuclear power generation is only partially starting to recover but the outcome is firmly the reverse in Germany. The negative legacy of TMI, Chernobyl, and other accidents has been attached to everything nuclear in many of the nations that embraced nuclear power in the late twentieth century. In 2011, the catastrophic damage to the Japanese Fukushima Daiichi nuclear plants triggered by the twin natural disasters of an historic earthquake and huge tsunami created a contemporary focusing event.[435] It is not a coincidence that Germany firmly committed to decommission its entire system of nuclear plants following the Fukushima Daiichi catastrophe, a perfect storm of techno-natural disasters. Is the apparent German commitment to *thermo*-nuclear energy (i.e., fusion energy) therefore a paradox?

---

[434] Gabrielle Hecht, *Being Nuclear: Africans and the Global Uranium trade,* (Cambridge, MA: MIT Press, 2012).

[435] John W. Kingdon, *Agendas, Alternatives, and Public Policies*, (New York: Longman, 2003), 94.

Rather, there was an uneven path during which the W7-X program evolved in design and development from the 1990s until first plasma in 2015. The unpredictable design and funding issues were no less challenging that those that doomed PPPL's advanced stellerator program. In contrast to PPPL's experience, the eventual completion of W7-X construction and its current operational status has created a leading international center of stellerator research.

> Political support depends very much on the person… [and] parties, [as] not everybody in Germany supports fusion research… [or] fusion energy. There [are] not too many similarities between fusion power plants and fission power plants and this is what we also educate our politicians about… [and] I think we have convinced many of the politicians that this is the case… We did have a problem of funding… as hard as that in the U.S. We did have a seeding of fuel research so we didn't get any compensation for inflation and for sudden increases since 2003 and this was a political decision.
> For example, the previous coalition, stated in their contract even that fusion research would be funded at the level it had been funded so that not a single Euro more [was allocated]. And just the recent coalition has now agreed on that we would get an inflation reimbursed again. So, we are politically in a quite positive situation at the moment. So there is at the moment… secure funding both for management of W7-X and for the Tokamak experiment at Garching so it looks quite positive at the moment.[436]

Advocates of the German fusion enterprise to include IPP scientists and engineers are practitioners of politics as well as technology, that is, *technopolitics*, the convergence of technological design and application that embodies political objectives.[437] In the German case, the political goal is the Ecological Modernization Vision and the current political coalition has acknowledged that the fusion enterprise enterprise coincides with that projected future. The trials in Dr. Günter's candid reflections of this German expression of the fusion enterprise reveals an outcome of a risk society[438] landscape that dominated the German psyche during the since the period of preliminary design of the W7-X in the 1990s. The acceptance of the nascent

[436] Günter, in interview with the author, August 17, 2018.

[437] Hecht, *The Radiance of France*, 15.

[438] Beck, *Risk Society*).

fusion enterprise by the German polity in contrast to rejection of an operational *fission* energy infrastructure does not characterize an intractable controversy resolved via framing but rather expresses a political resolution through effectively communicated sociotechnical imaginaries.

On the other hand, when a viable fusion energy ecosystem attains initial closure state and technological momentum, frame reflection could possibly have traction in forming a method of resolving intractable policy controversies. In that envisioned future state, a set of sociotechnical imaginaries would still provide insight into the values that comprise a policy controversy and its resolution options, e.g., "like the actors in the Cuban Missile Crisis who might have more reliably reduced the risk of catastrophe by putting themselves in one another's shoes… and creating a frame-reflexive policy conversation".[439] Rather than simply dismiss a frame reflexive discourse for the enduring fusion enterprise, I propose its potential relevance in a future state and yet to be encountered intractable controversies. While fusion energy might be positioned as the high-capacity power generation component of the German Ecological Modernization Vision, renewable energy sources still occupy a dominant position in the contemporary German psyche.

Dr. Günter expresses that the energy mix in the energy ecosystem in the future will likely depend on the geographical location in Germany and across the European Union (E.U.). There are discussions underway between IPP and organizations conducting research in advanced solar applications and storage capacity. Dr. Günter also emphasizes leveraging the rich human resources of the Max Planck Society that has recently begun an initiative to research options for a future energy ecosystem and the role of large scale eco-friendly power plants. Both the broader German and European academic systems are conducting multiple studies.

[439] Schön and Rein, *Frame Reflection*, 184.

These research efforts produce a bilateral effect on German energy policy. I asked Dr. Günter if there is anything tangible or written in German energy policy from a governmental perspective that reflects that a vision of that type of energy ecosystem.

> The German political system is a little more forward leaning. They do have a plan for increasing the renewables. The German government will submit the whole [plan] this year then again the energy research program and what they usually say is that, last time also, how the German government wants the research be performed and then they obviously say for a long term vision they also wish to continue to do research.
> And this is usually about this point but they do not mind anything about how this would look like because they focus on the time to 2030 or a maximum to 2050 that fusion research will not be part of the energy mix and therefore, this is not part of any German government paper except for any new research when they mention nuclear fusion.[440]

That policy omission leaves a gap in any realistic energy plan for the mid twenty-first century. For the past few years the Ecological Modernization Vision in Germany has encountered an uncomfortable truth, i.e., that Germany has run up against the limits of renewables.

> Germany is giving the rest of the world a lesson in just how much can go wrong when you try to reduce carbon emissions solely by installing lots of wind and solar… the variability of those sources forces Germany to keep other power plants running. And in Germany, which is phasing out its nuclear plants, those other plants primarily burn dirty coal.[441]

The discussion returns to the energy policy debate, to the conundrum that fuels the argument, and gives weight to candid observations that Dr. Günter and Dr. Menard articulate.

When the remaining operational nuclear plants in Germany are shut down (as planned) in 2022, the impact of the shortfall in assured 24x365 energy production would be massive, to the economy and political stability of Germany and thereby to the E.U. "In May 2007 the International Energy Agency warned that Germany's decision to phase out nuclear power would

---

[440] Günter, in interview with the author, August 17, 2018.

[441] Richard Martin, "Germany runs up against the limits of renewables", *MIT Technology Review*, (2016, 24 May).

limit its potential to reduce carbon emissions 'without a doubt'".[442] Indeed, as the time of total nuclear plant shutdown approaches, the leadership of Germany and the Bundestag will likely endorse a continued relatively large dependency on the burning of dirty coal to generate electricity as a necessity and actually increase the amount of CO_2 Germany puts into the atmosphere. That result would invalidate the "ecological" in the German modernization vision. Even if support for the fusion enterprise remains stable and milestones are met, actual electricity production is likely to enter the grid only around 2050 and significant impact would only occur around 2070. That scenario will heighten the intensity of the energy policy debate in Germany. If publically transparent deliberation does not occur and either lights dim or atmospheric pollution rises to unacceptable levels, the politicians will be held accountable.

The political ambiguity in Germany and other nations heavily invested in the fusion enterprise opens up the discourse to speculate on alternative futures that range from utopian to dystopian visions.

[442] World Nuclear Association, Nuclear Power in Germany (updated March 2019), http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx.

CHAPTER SIX – Conclusion: Alternative Futures

In this dissertation, I have explored fusion energy history and surveyed the contemporary landscape of the fusion enterprise in the context of three cases: NSTX-U, ITER, and W7-X. The approach to this study parallels H.G. Wells' narrative method applied to a fictional history in his prophetic work, *The World Set Free*,[443] that unfolds using a chronological blueprint. Wells' chronicle is woven via the assembly of institutions, identities, discourses, and representations – i.e., ordering instruments.[444] Both fiction and case studies expose international cooperation and conflict, and controversy. In other words, *The World Set Free*[445] is a fictional, yet co-produced, world of technology and social order (and disorder). Wells' invented world is an exemplar of science fiction and, more noteworthy, it is a foundational element that reflects attributes of fusion sociotechnical imaginaries. The narrative is also an imaginative model for co-production analysis of the fusion enterprise. The analytic concept of sociotechnical imaginaries is simultaneously the product of and shapes instruments of co-production analysis.[446] The ingenious potential of science and technology is enabled by these dual qualities and as a result advances our ability to envision alternative futures.

November 21, 2085

Imagine. It is the one-hundredth anniversary of the 1985 Geneva agreement between US President Ronald Reagan and USSR General Secretary Mikhail Gorbachev, in which the Cold

[443] Wells, *The World Set Free*.

[444] Jasanoff, *States of Knowledge*, 39-41.

[445] Wells, *The World Set Free*.

[446] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity, 19.

War rivals share a vision of controlled thermonuclear fusion for "the benefit of all mankind".[447] What does the picture of the planet's ecosphere and energy ecosystem look like and how did we get to this portrait of Earth?

The measure of accuracy of a prediction, in particular one that requires multiple converging variables, is typically inversely proportional to the length of time between the date of the prediction and the target date. Just think about hurricane prediction. "Uncertainty about where certain events might occur, such as the trajectory of a hurricane, can be represented on a map as a 'cone of uncertainty'".[448] Nevertheless, "predictions are important to the public, who fund the majority of all scientific research through tax dollars".[449] Is this a conundrum that defies resolution?

On the contrary, alternative futures emerge from a synthesis of imagination and the creative potential of S&T.[450] Ted Nordhaus articulates a fictional 2020 narrative[451] in which the just elected President Jay Inslee declares a national climate emergency as his first act.[452] A key element of the President's legislative agenda is an energy ecosystem comprised of solar panels, wind turbines, and the building of two-hundred light water reactors of a single advanced

---

[447] Joint Soviet-United States statement on the summit meeting in Geneva, Reagan Library Archives, November 21, 1985.

[448] David Spiegelhalter, et al, "Visualizing uncertainty about the future", *Science*, (2011, September 9), No. 333, 1393-1400.

[449] Aaron Clauset, Daniel B. Larremore, and Roberta Sinatra, "Data-driven predictions in the science of science", *Science* (2017, 3 February), No. 355, 6324, 477.

[450] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity.

[451] Ted Nordhaus, "The empty radicalism of the climate apocalypse", *Issues in Science and Technology*, (2019, Summer), No. 35(4), 69-78.

[452] Nordhaus, "The empty radicalism of the climate apocalypse, 69.

design.[453] In the account, the President's actions are intended to answer the question that is reflected in the article's subtitle: "What would it mean to get serious about climate change?"[454]

The Nordhaus scenario that introduces the cover story in *Issues in Science and Technology* triggers a discourse that is distinctly sober and relatively dark. He ultimately characterizes his imaginative chronicle as "fanciful [and expresses that] technological change will likely continue to prove more easily seeded and sustained than political change".[455] However, the fictional tale based on a series of assumptions serves as a utopian point of reference and as a model to adapt for this dissertation. Rather than gazing into the abyss of an unknown future, we can picture two opposing scenarios that illustrate elements of a conceivable ecosphere of our planet and the corresponding energy ecosystem one-hundred years after the historic Reagan-Gorbachev Geneva agreement.[456] We can also envision policies that might pave the roadmap to these alternative futures, one utopian and the other dystopian.

A Planetary Energy Revolution

During the period between the Paris climate agreement of 2015 and 2075, the average global temperature increased by 1.8 degrees Celsius but, in the following ten years, by 2085 the average temperature had *fallen* by 0.2 degrees Celsius. The cumulative climate change during the intervening seventy years following 2015, while indeed inducing more frequent extreme weather and shifting crop growing regions, has not produced severe cascading impact on human

[453] Nordhaus, "The empty radicalism of the climate apocalypse", 70.

[454] Nordhaus, "The empty radicalism of the climate apocalypse", 69.

[455] Nordhaus, "The empty radicalism of the climate apocalypse", 78.

[456] By mutual agreement, President of the United States Ronald Reagan and General Secretary of the Central Committee of the Communist Party of the Soviet Union Mikhail Gorbachev met in Geneva 19-21 November 1985.

populations. By mitigating human exacerbated climate change, a catastrophic tipping point has been avoided. What accounts for this scenario?

First, the political landscape during the 2020s was shaped by populations in both developed and developing countries insisting on a renewed focus on a sustainable energy ecosystem. The effect of that political vigor was to alter the trajectory away from support for continued reliance on fossil fuels. As renewable energy technologies, such as solar and wind power and new energy storage capabilities continued to develop at an accelerated rate, fossil fueled energy plants were decommissioned as rapidly as the new sources came online. In nations that used first and second generation nuclear plants, i.e., those that used fission of heavy elements as a low-carbon thermal power source, a roadmap to phase out fission by the end of 2100 was established. All forms of transportation are now powered solely by electricity, produced from non-polluting energy sources.

Further, a convergence of S&T and socio-political factors followed the successful proof-of-concept demonstration of reliable net electrical energy from ITER in 2035. That alignment coproduced the technology and social order for a follow-on international project to produce a utility-scale fusion power plant in 2045 on the site of an expanded ITER campus in Cadarache France. By 2050, one fusion power plant based on the "Cadarache model" had been built on the territory of each party of the original ITER agreement: People's Republic of China; European Atomic Energy Community (Euratom); Republic of India; Japan; Republic of Korea; Russian Federation; and United States of America. Over the next 30 years, the number of fusion energy plants has grown from seven to over one-hundred, not all based on the Cadarache model. The advanced stellerator design predominates in Germany while a variety of compact designs predominate in Japan, the US, and Canada. The fusion centered energy ecosystem envisioned nearly one-hundred years earlier has created a planetary energy revolution of the first order. Yet, this fulfillment of a long-held sociotechnical imaginary was not an inevitable outcome.

End of the Anthropocene

> Doomsday is no longer a religious concept, a day of spiritual reckoning, but a possibility imminent in our society and economy. If unchecked, climate change alone could produce enormous suffering. So also could the drying up the energy resources upon which so many of our capabilities are built. There remains the possibility of large-scale conflicts, perhaps involving the use of weapons of mass destruction.[457]

The 2020s was a time in which spikes in average global temperature occurred, not at a constant linear rate but a decade-long trend that culminated in an average increase that far exceeded predictions made in the first decade of the twenty-first century. While some nation states and scattered regions across other countries made regional efforts to mitigate climate change, the political climate in key developed and developing countries was characterized by a blind eye to the threat emerging from overwhelming scientific data. The rush to consume relatively cheap fossil fuels and the exponential increase in net energy demand in the United States, China, and India – in particular – crushed the impact of efforts in the rest of the world. The fusion enterprise withered away as an energy source as power producers sought quick returns on their investments and governments were unwilling to mitigate the lack of interest by utilities. The fusion enterprise became a dream that only lived in the imagination of a dying generation.

By 2030, the US Army Corps of Engineers constructed progressively more ambitious flood control structures around coastal population centers along the east and west coasts of the US. Manhattan island, largely residing at the *old* sea level, endured frequent flooding as severe storms became more commonplace. The population of New York City significantly declined for

---

[457] Giddens, *The Politics of Climate Change*, 230.

the first time in four centuries. Coastal land mass across the globe contracted as a consequence of the relentless rise of sea level.

After a two-decade rush to consume fossil fuels and with the dramatic evidence of impact on people's lives, the 2038 US presidential election witnessed the election of a president from the Radical Green Party (RGP) and the formation of a dominant coalition of RGP and Sierra Party members in both houses of Congress. The common theme in both parties' platforms was to mitigate the impact of human activity that had been amplifying the destructive climactic change that took center stage in most areas.

With climate change having already reached a tipping point, the new American ruling coalition ushered in a period of draconian energy austerity and, as a result, persistent economic decline. An aggressive effort to derive more energy from wind and solar was inadequate to sustain economic growth. The research funds needed to convert to a sustainable energy ecosystem to support energy-hungry enterprises was no longer available. In China and India, similar political upheaval emerged as well as economic depression. Rather than saving the planet, the political turnabout prompted internal and external strife and decay, exacerbated pandemics, and spawned warfare among nations for diminishing resources.

The sociological instability in subsequent years and the climactic tipping point that occurred decades earlier in retrospect shaped a dark, violent world. In a perfect storm of despair and with a legacy of available nuclear weapons, one nation unleashed the dogs of global war that tragically produced the nuclear winter of 2085 and heralded the end of the Anthropocene.

The imagined narrative echoes Giddens' warning[458] but the dystopian future need not occur if an international perspective is galvanized among the nations. The fusion enterprise is

[458] Giddens, *The Politics of Climate Change*, 230.

not the first human effort to operationalize soaring S&T imaginaries with a global viewpoint. The iconic Apollo program photograph, Earthrise, represents an image of humanity sharing one world. The image of our planet floating in the black of space is credited with "inducing a sudden, radical, and far-ranging shift in political consciousness, as human beings redefined their understanding of what it means to live together on the earth".[459] The Space Age that climaxed with the first human voyage to the moon fifty years ago is an exemplar of a massive human endeavor, in which sociotechnical imaginaries surfaced into a reality. The primary driver for the Apollo program was geopolitical but national identities did not deter global humankind from savoring the achievement of the landing of humans on another world and returning them safely to the Earth.

'One Small Step' Shaped by Imaginaries

While the 1957 launch of Sputnik I spawned the Space Race between the world's Cold War rivals, the seeds of the Space Age were sown in the pages of the science fiction of Jules Verne and H.G. Wells. Writers such as Verne and Wells inspired the fathers of modern rocketry, Konstantin Tsiolkovskii, Robert Goddard, Hermann Oberth, as well as the second generation, Sergei Pavlovich Korolyov, and Wernher von Braun.[460] The first generation of rocket pioneers were evidently encouraged by errors in nineteenth-century imagination, such as Verne's scientifically flawed method of launching a capsule to the Moon from a massive cannon.[461] Recognizing such errors and the dream of space travel drove the early pioneers to devise a

[459] Sheila Jasanoff, "Image and imagination: The formation of global environmental consciousness" in *Changing the Atmosphere*, by Clark Miller and Paul Edwards, (Cambridge, MA: MIT Press, 2001), 318.

[460] McDougall, *The Heavens and the Earth*, 20.

[461] McCurdy, *Space and the American Imagination*, 13-14.

realistic means to travel in outer space. Based on the landmark theories and experiments by the first generation and motivated by the same fictional writers, von Braun and Korolyov, and their contemporaries built the first rockets to leave the atmosphere. The vision that emerged from the pages of popular writers of science and science fiction and from the promotion of space enthusiasts had a major impact on the American imagination.

The most dramatic exception to the gap between the vision of space advocates and reality was the Apollo program of the 1960's. The driving force, however, that made the vision real was geopolitical, national pride and prestige, tied to national security. The Apollo "megamachine" powered by political resolve transformed von Braun's visions into reality. During the same period as the crash program to go to the Moon was the top priority American space policy, the dreams of the engineers who devoted their lives to the long-term vision of space exploration faded into the distance.

In a genuine sense, the fusion enterprise is the exploration of a star, revealing its secrets reluctantly over a human lifetime. The title of the booklet offered upon entry to the PPPL administration building is *A Star for Us*.[462] In few words, the title encapsulates the exploratory theme. Instead of traveling *to* the Sun, humanity is bringing the Sun to the Earth. The goal of the fusion enterprise is the creation of a terrestrial star. The corresponding sociological transformation is a vision of a planetary revolution based on a limitless energy source upon which alternative futures are formed.

Astronomical Energy Embedded Everywhere

As predictions of the future from the perspective of a current reality have been notoriously inaccurate, the two extreme scenarios just articulated are unlikely, as detailed in the

---

[462] Saini, *A Star for Us*.

fictional accounts. However, features of both fictional scenarios might well emerge depending on the co-produced knowledge infrastructure and corresponding social order and at the very least shaped by policy decisions as much as fifty years earlier. Howard E. McCurdy declares "Imagination matters when societies contemplate new ventures".[463] Energy policy can emerge as an outcome of the union of imagined futures and a solid foundation of S&T concepts and practices. However, just because we have the ability to construct an endeavor from imagination, that capacity does not mean we should or will do it. The constraints of ethical norms and politically driven action are major factors. Foremost, science fiction articulates the potency of imagination in context of the co-production of fusion S&T and the socio-political order that sustains the quest for the elusive goal.

Writers have repeatedly inspired generations of engineers and physicists. "Technological innovation often follows on the heels of science fiction, lagging authorial imagination by decades or longer",[464] e.g., the works of Jules Verne and the motivation, theories, and actions of the 'fathers of rocketry", Korolyov, and von Braun.[465] High energy physics was likewise inspired. The prescient science fiction of H.G. Wells, provides a window into sociotechnical imaginaries immediately preceding the trauma of world war and exposes a paradox of a dark social order and simultaneously offers the seeds of a utopian vision. The literary works designated as science fiction are creations of utopian and dystopian worlds.[466]

---

[463] McCurdy, *Space and the American Imagination*, 29.

[464] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 1.

[465] McDougall, *The Heavens and the Earth*, 20.

[466] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 1.

The genre provides Wells with latitude to construct a chronicle of a future described at the level of granularity of an historical retrospective. Wells paints a speculative picture based on a pre-World War I survey of human endeavor and builds a plausible imaginary. He creates a thick narrative in which through the lens of ordering instruments the reader can observe the co-production of a fictional global social order and an energy technology to transform the world: atomic energy. In Wells' plot, technology, people, and events, converge to produce unintended consequences.[467] The new energy source is a sociotechnical force that produces both wealth and poverty as a consequence of opportunity and economic dislocation. There are references to the Sun as an awesome unattainable power in the eyes of primitive humans and as, eventually, an achievable symbol of globally-united humanity to control unlimited energy. Ultimately, the "Last War" is fought using atomic bombs and the massive devastation coupled with the actions of key personalities eventually leads to the end of war and the establishment of World government.[468] Wells' imagined future represents a literary legacy from which the utopian and dystopian alternative futures of 2085 expressed in this chapter surface.

A century after publication of *The World Set Free*,[469] Jonathan Menard, the Research Director of the primary fusion energy project at the Princeton Plasma Physics Laboratory (PPPL), expressed his vision of how viable fusion might transform society.

> I think the big one is electricity production would arguably be more egalitarian and widespread. I think the correlation between productivity and overall standard of living is very strong with energy-electricity usage so I think lifting people or countries out of poverty provided they had the wherewithal to purchase or use the technology I think could create, be pretty transformative.

---

[467] Wells, *The World Set Free*.

[468] Wells, *The World Set Free*.

[469] Wells, *The World Set Free*.

> Yeah, there are other—based on power production, fusion, you know, looks attractive if we can make it work. There are other applications as well for space travel, more rapid missions to Mars if fusion could work. Just the power density and other applications that it would open up I think could also be transformative. There is a range of applications for fusion beyond just electricity production on Earth.[470]

While Menard's words are not equal to the dramatic prose of the professor who represents a spark in the life of the central character in in Wells' 1914 narrative, the 2017 interview response in a US national laboratory vital to the fusion enterprise is representative of frontiers shaped by imaginaries. Menard's sociotechnical vision has its genesis in socialized imaginaries.

Operationalizing Sociotechnical Imaginaries through Innovation Policy

Common themes emerge from the three interviews referenced in this dissertation, e.g., common sociotechnical imaginaries, and the dual features of wicked problems in the long journey to viable fusion energy and the sociotechnical revolution that a fusion-centered energy ecosystem will spawn. Yet, the three key voices do not merely parrot one another but rather offer insightful differences as a product of their identities, which are comprised by far more more than their defined roles in their respective projects and institutions.

As a collectively imagined human activity, sociotechnical imaginaries are related to instruments of political action,[471] e.g., innovation policy. The fusion energy project is dependent on innovation, i.e., imaginaries as "conceptual tools for problematizing responsible innovation"[472] that might shape national innovation policy.

[470] World Nuclear Association, Nuclear Power in Germany (updated March 2019), http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx.

[471] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 20.

[472] Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", 85.

- An imaginary of progress and competiveness;
- An imaginary of technology fix;
- An imaginary of consumer choices and decentralization; [and]
- An imaginary of local sustainable development.[473]

The potential to innovate and foster 'niche technologies' have been energized, by multiple sociotechnical factors.[474] "But accelerated transitions also depend upon widespread social acceptance (to create legitimacy and support for strong transition policies)".[475] Fusion imaginaries anchor and blend with events, sociotechnical imaginaries and leading-edge projects, especially during windows of opportunity, to pressure the existing energy ecosystem to realign around maturing innovations.[476]

In each of the interviews, common emphasis is articulated on how the politics of each national identity (i.e., European Union, France, United States, and Germany) coincides with the international quality of the fusion enterprise. This socio-political feature is quite different than the geopolitical contest that the Space Race represented and at the same time time each outcome echoes what is inscribed on the plaque left on the lunar surface that declares the purpose of the enterprise "for all mankind." Coblentz's revelation that the most massive fusion program ever undertaken, ITER, was in serious political trouble for its first few years of construction. Its subsequent resurrection was an apparent result of the political socialization by the new director-general and himself[477] is clear evidence of the political impact on the global ITER stakeholders.

[473] Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", 87.

[474] Geels, et al, "Sociotechnical Transitions for Deep Decarbonization", 1242-1244.

[475] Geels, et al, "Sociotechnical Transitions for Deep Decarbonization", 1243.

[476] Geels, et al, "Sociotechnical Transitions for Deep Decarbonization", 1244.

[477] Coblentz, in interview with the author, July 28, 2018.

Dr. Menard identifies the reality of a 'social contract' between PPPL and the government in context of risk tolerance and schedule and cost deviation, i.e., that the taxpayer expects fiscal accountability and milestone predictability in exchange for each project that the US DOE funds.[478] The US government acts as a mediator between the national lab and the taxpayer-citizens as stakeholders in the enterprise.

In spite of the positive outcome of nineteen years of design and development resulting in the world's most advanced stellerator, Dr. Günter admits that the political road to an operational W7-X was not a simple path to passively follow. There are "moments of resistance, when new conceptions of how to change the world bump up against the old, or when powerful competing imaginations struggle to establish themselves on the same social terrain".[479] Political support depends very much on individuals and political parties. Fusion research and fusion energy does not enjoy universal support in Germany, even as the German Chancellor, Angela Merkel, threw the switch that initiated operation of the W7-X in 2015.[480] Forecasting the future of fusion energy in Germany is problematic.

Prediction of a viable fusion energy ecosystem appears to share similar constraints as projecting the precise path of an approaching hurricane, i.e., a cone representing the possible area of destructive impact expands based on the current measures of intensity, speed, and direction. That does not deter the National Hurricane Center from forecasting. The convergence of S&T and socio-political factors, if explored systematically, i.e., through the lens of ordering instruments, and if the study is tackled with an adequately-sized balance of human and

[478] Menard, in interview with the author, August 17, 2017.

[479] Jasanoff, "Imagined and Invented Worlds", 323.

[480] Günter (Scientific Director, in interview with the author, August 17, 2018.

computational resources that nexus has potential to provide a capability to forecast results, even to a level of "superforecasting" in the sense that Tetlock and Gardner explore in their collaboration of the same name and with the subtitle of *The Art and Science of Prediction*.[481]

Tetlock and Gardner arrive at an illuminating conclusion based on many years of in-depth research and on the results of a forecasting tournament funded by the Intelligence Advanced Research Projects Activity (IARPA), an element of the Office of the Director of National Intelligence (ODNI). Tetlock and Gardner score the forecasting performance of *superteams*,[482] each team comprised of a dozen diverse individuals with primarily diverse ways of thinking rather than solely possessing diverse knowledge. These superteams outperformed narrowly-defined sets of experts. The authors observed that the teams' superlative performance was achieved "by avoiding the extremes of groupthink… [and] fostering minicultures that encouraged people to challenge each other respectfully, admit ignorance, and request help".[483]

Dr. Günter's broad de facto definition of diversity in the IPP workplace appears to coincide with the fostering of minicultures, i.e., comprised of dimensions that counter the exclusionary restrictions cited above, i.e., gender, ethnicity, and multi-disciplinary expertise[484]. The institutionalization of that inclusive diversity in the dozens of institutes that comprise the Max Planck Society, to include the IPP, bears witness to the enhancement of German S&T research and the academic landscape in Germany. The institutionalization of diverse teams

---

[481] Philip E. Tetlock and Dan Gardner, *Superforecasting: The Art and Science of Prediction,* (New York: Crown Publishers, 2015).

[482] Tetlock and Gardner, *Superforecasting*, 193-211.

[483] Tetlock and Gardner, *Superforecasting*, 207.

[484] Günter (Scientific Director, in interview with the author, August 17, 2018.

could also lead to anticipatory qualities that exceed the predictive performance of teams that have been historically far less diverse.

Among insights derived from the interview process, diversity in particular occupies a special position in co-production analysis. That significant argument is broadly exposed via instruments of social order and through the lens of sociotechnical imaginaries. Any human activity that excludes half of humanity based on female gender identity, or ignores a significant proportion of the male population based on ethnic bias, and constrains critical thinking to narrow S&T discipline lanes inevitably limits advancing the S&T enterprise. In particular, the dual challenges of the exceedingly wicked technological problems in the co-production of the fusion enterprise and the corresponding international socio-political order must incorporate diversity as a critical success factor. It is not just about social justice but rather a tangible enhancement to the S&T enterprise.

Jasanoff cites the British television series, *Doctor Who*, as an example of science fiction in which sociotechnical change is a built-in element of the the half-century duration show's plot and yet the appearance of an actual senior female S&T leader, such as Dr. Günter preceded the appearance of the first female lead actor, the thirteenth Doctor, Jodie Whittaker. Science fiction opens our our minds to alternative futures but politics is a space in which dreamscapes of modernity emerge into reality and thrive.[485] *Doctor Who* is a suspense filled adventure in space-time, eerily coinciding with the duration of the fusion enterprise. The pursuit of viable fusion has been equally suspenseful.

[485] Jasanoff, "Imagined and Invented Worlds", 338.

No Zero Risk Technology

Scenarios can be imagined in context of the creative potential of S&T and thereby wicked problems that appear to defy solution can be embedded in constructed narratives.[486] From those imagined scenarios, risks might be identified and evaluated as to impact and probability, and consequences might well be reduced or avoided through mitigation strategies advanced through prescient policy decisions made years earlier.

The multi-dimensional risks that climate change threaten become more evident each day as measurable impact is studied across the globe. One of the imaginaries that Boxenbaum, et al, cite is an imaginary of a technological fix.[487] Repeatedly, viable fusion is endorsed as the high-energy, low-carbon-footprint technological solution.

A clear-eyed assessment of risk, i.e., a dispassionate evaluation of the fusion enterprise as it evolves in the years ahead is needed to form pragmatic energy policy. A phased approach to policy decisions will ensure that humanity does not put all of its eggs in one basket, counting on viable fusion as a panacea for the risk evident in human-enhanced climate change. Ironically, ITER as a proof-of-concept project, will provide explicit outcomes that will shape policy decisions. While sociotechnical imaginaries still remain potent drivers for the enterprise, the evidence that surfaces from the ITER project, in particular, and through other fusion projects will determine whether the potential for fusion energy is a utopian gamble or is the technological fix for climate change, nuclear nonproliferation, and social equality that advocates have promoted for decades.

---

[486] Jasanoff, "Imagined and Invented Worlds", 339.

[487] Boxenbaum, et al, "Imaginaries and instruments: Conceptual tools for problematizing responsible innovation", 876.

The ITER project dominates the fusion energy discourse. The cases of NSTX-U and W7-X substantiate that even as the technologies differ and the physics and engineering differ from the immense yet-to-be-completed ITER fusion system, the American and German fusion programs directly support ITER. Yet, there is not one path to viable fusion. For example, even as Dr. Günter recognizes the direct scientific research connection between W7-X and ITER, the scientific director of IPP has expressed the need for a backup plan "just in case".[488] The NASEM 2018 *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research* also endorsed that contingent perspective. The outcome of ITER's goal of demonstrating that a large-scale Tokamak can produce net energy will be evaluated in context of both quantitative and qualitative criteria, number of net megawatts and level of political support for the multiple objectives.

Technological alternatives will surface based on national cultures. The roadmaps might all lead to viable fusion but the path to that goal may occupy differing spaces and timeframes and the impact of the eventual energy revolution will affect regions in varying socio-political ways. The interplay of technological imaginaries and the co-production of fusion and the social order that supports its implementation will shape its impact on individuals. As we encountered in Wells' 1914 narrative, advanced technology is Janus-headed. On the other hand, the sustained support by diverse and sometimes adversarial nations in the fusion enterprise dictates that the stakeholders in this quest give deep thought to next steps in a post-ITER landscape.

[488] Physics@FOM Veldhoven 2013, Sibylle Günter, Masterclass. Physics basis of magnetic fusion reactors. OpenWebcastCh2 (Published on Jan 30, 2013).

Toward a Fusion-Centered Energy Ecosystem

> Our planet is in a perilous state. Humanity must now nudge Earth into a trajectory toward a more stable, harmonious state [but] technology alone will not rescue us. For changes to be willingly adopted by a majority of people, technology and engineering will have to be integrated with social sciences and psychology.[489]

The fusion enterprise is an example of the convergence of physics, engineering, and social order. That interconnection is trilateral rather than linear or unidirectional, and there is a temporal quality that intersects each of the three key dimensions as well as the convergent model. Key voices in the fusion enterprise envision an alternative future, in which an integrated energy policy for a matrix of clean energy sources, storage techniques, and high-capacity fusion energy will trigger a transformative planetary revolution. The central goal is a matrix of "net-zero emissions energy systems".[490] Transformation to a fusion-centered energy ecosystem is still decades away but that reality – already sixty years in the making – does not preclude continuous progress to a world set free. That is the position occupied by a pragmatic roadmap. The dimensions of physics, engineering, social order of each element along a temporal landscape help shape the policy and funding decisions until each milestone becomes reality. Momentum of the fusion enterprise is sustained by persistent utopian visions and stable repositories of knowledge and power[491] – revealed through human expressions of a terrestrial star.

What are the policy implications that emerge from the revelation that socio-technical momentum powers the fusion energy project and on what foundation is future energy policy constructed? Policy decisions that shape the fusion enterprise are politically anchored reference

[489] Jeremy Berg, "Tomorrow's Earth", *Science*, No. 360, (2018, 29 June), 6396, 1379.

[490] Steven J. Davis, et al, "Net-zero emissions energy systems", *Science*, 360, (2018, 29 June), 6396, 1419.

[491] Jasanoff, *States of Knowledge*.

points.[492] While it is improbable that one static approach or fixed long term plan will address global and local energy realities, there is a compelling methodology that is emerging that might illuminate the road ahead for energy policy. A systems approach introduced by Denholm, et al,[493] is an option to address challenges and options with an integrated energy policy that might accommodate fusion energy. The 2012 article in *Energy Policy* by Paul Denholm and his colleagues explores a proposal for decarbonizing the electric sector.[494] The magnifying glass of co-production analysis and the mirror of climate change studies offer the prospect to stimulate innovative views of technology.[495] The vision of renewables and nuclear fission that Denholm and his colleagues present is by no means an inevitable outcome but their conceptual framework of a matrix of energy sources and storage techniques, each with complementary strengths offers a useful model. That model should be considered in context of a long term infrastructure before and after fusion energy – if indeed achievable – comes on line as a viable high-capacity energy source.

For sixty years, electricity produced through the fission of heavy elements and the dream of viable fusion energy have coexisted. Even if there should be a surprising breakthrough in the fusion enterprise, the importance of "conventional" nuclear energy as a low-carbon base-load energy source would not disappear from the global stage. "National nuclear infrastructures have been and will continue to be critical national assets for the United States".[496] While

---

[492] Jasanoff, "Future Imperfect: Science, Technology, and the Imaginations of Modernity", 28.

[493] Paul Denholm, et al, "Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage", *Energy Policy*, No. 44, (2012).

[494] Denholm, et al, "Decarbonizing the electric sector, 301.

[495] Hulme, *Why We Disagree About Climate Change*, 362-363.

[496] Steven E. Aumeier and Todd Allen, "How to reinvigorate US commercial nuclear energy", *Issues in Science and Technology*, (2018, Winter), No. 34(2), 82.

acknowledging the flaw of predicting the technological landscape many decades in the future, advanced fission reactors and fusion devices are likely to co-evolve into the late twenty-first century.

The fusion energy landscape in the second decade of the twenty-first century is characterized by a handful of large scale projects. But ITER is the sole central international demonstration of viable fusion, that is of "the long sought-after plasma energy breakeven point (Q=1)",[497] with the sociotechnical momentum capable of reaching that essential milestone. Sustaining the knowledge infrastructure that comprises the contemporary fusion enterprise is a critical success factor of the imagined fusion-centered energy ecosystem of the mid twenty-first century.

ITER is undoubtedly the world's largest project in the fusion enterprise and in light of the enormous investment, the apparent result might appear to leave no margin for fusion energy innovation. Yet, the two other cases, NSTX-U and W7-X, studied through the lens of ordering instruments reveal strategies applied by PPPL and IPP contradict that assumption. Each institution co-produces a knowledge infrastructure and a globally connected socio-political order. The PPPL research director and the IPP scientific director shared confirmation of the enabling power of leveraging ITER resources and influence and the bilateral benefit to advance both ITER and their mid-size fusion projects. A sociotechnical imaginary is shared among the administrative and S&T staff of the three cases studied. Interviews of the ITER communications lead, the NSTX-U research director, and the IPP scientific director reinforce that observation.

[497] ITER – 60 Years of Progress, https://www.iter.org/sci/BeyondITER.

The fusion energy enterprise is an outcome of an "imagined and invented world".[498] Sociotechnical imaginaries virtually correspond to tangibly constructed launch pads, precisely positioned in space and time, from which S&T enterprises are launched. The narrative of imagined worlds represents the genre of science fiction, "visions that integrate futures of growing knowledge and technological mastery".[499] In all three cases explored in this study, the common imaginary theme is encapsulated in the narrative freely available at the Lyman Spitzer Administration Building of the U.S. Department of Energy (DOE) Princeton Plasma Physics Laboratory (PPPL). *A Star for Us* is described as an "illustrated science booklet".[500]

> Today, the National Spherical Torus Experiment-Upgrade (NSTX-U), the Laboratory's flagship endeavor, is set to advance the worldwide quest for fusion as a safe, clean and virtually limitless source of energy for producing electricity. The original NSTX began operating in 1999 and our 21st century upgrade is poised to bring the world closer to the dawn of a bold new Energy Age.[501]

PPPL explicitly links NSTX-U with the utopian vision in words and illustrations intended for the largest possible audience. It is "the story of the promise of fusion energy and the ambitious steps that are being taken to achieve it".[502]

Rather than characterizing the storyline as an envisioned ideal world, the author blurs the boundary between a utopia and conceivable milestones as interim objectives to that bright future. The narrative and its corresponding illustrations articulate soaring technologically deterministic rhetoric unhindered by inevitable challenges and present a literal picture of a brave new world. Simultaneously, the offering is labeled as a *science* brochure. While its content does not

---

[498] Jasanoff, "Imagined and Invented Worlds", 321.

[499] Jasanoff, "Imagined and Invented Worlds", 337.

[500] Saini, *A Star for Us*, Introduction.

[501] Saini, *A Star for Us*, Cover text.

[502] Saini, *A Star for Us*, Introduction.

coincide with the norms of a science publication, it is among the first artifacts a visitor typically encounters upon entry to the administration building of a national laboratory. This PPPL representation clearly links the essence of the fusion energy imaginary with a key institution in the fusion enterprise. When PPPL is invoked in discourses, a sociotechnical imaginary is perceived as a utopian attribute of a repository of trusted knowledge.

Convergence of Technology and Politics

A Star for Us[503] is not a unique representation of the fusion imaginary. Rather, there is a form of collective storytelling at work within the fusion enterprise and it is deeply political, i.e., a convergence of sociotechnical imaginaries, and technological design and application, which embodies political objectives.[504] Jasanoff points out that political life is an environment that is profoundly imaginative and the stories that emerge in that setting permit us to reimagine the world.[505]

On the other hand, there is a cultural shift, most notably in liberal democracies, e.g., in the U.S. and Europe, that is characterized by its advocates as populism. A disturbing feature in this contemporary political form appears to be a distrust in scientific expertise that goes beyond the reflexivity Beck describes in the *Risk Society*,[506] i.e., the emergence of dark conspiratorial imaginaries that reflect on modernity and in particular on trusted knowledge.

To counter the movement away from knowledge that evokes confidence and the breakdown of corresponding social order that enables the science enterprise, milestones to fusion

[503] Saini, *A Star for Us*.

[504] Hecht, *The Radiance of France*, 15.

[505] Jasanoff, "Imagined and Invented Worlds", 338.

[506] Beck, *Risk Society*.

viability must be skillfully socialized. That process becomes more problematic as peer reviewed knowledge is challenged in an age where "alternative facts", i.e., lies, have been normalized in political discourse. Politics authorizes and promotes dreamscapes of modernity[507] but politics can instead engender confusion in what to believe. The challenge of sustaining the six-decade effort to produce viable energy in an age of distrust in the science enterprise makes the role of communications directors in the fusion enterprise, e.g., Laban Coblentz with ITER, as critical as that of research director, e.g., Dr. Jon Menard at PPPL, and scientific director, e.g., Dr. Sibylle Günter at IPP. Indeed, listening and communications skills are critical success qualities to be exercised by S&T practitioners as well as those in roles identified explicitly in terms of communications. The interaction of Dr. Menard and Dr. Günter during their interviews bears witness to their realization of this quality and that there is direct correlation to funding sources.

The 2018 National Academies report, *Final Report of the Committee on a Strategic Plan for U.S. Burning Plasma Research*, explicitly addresses a mitigation strategy to manage the inevitable outcome of potential withdrawal of political support and zero funding of American engagement with the ITER project, i.e., the extinction of US ITER.

> Any strategy to develop magnetic fusion energy requires study of a burning plasma. The only existing project to create a burning plasma at the scale of a power plant is ITER, which is a major component of the U.S. fusion energy program. As an ITER partner, the United States benefits from the long-recognized value of international cooperation to combine the scientific and engineering expertise, industrial capacity, and financial resources necessary for such an inherently large project.
>
> *A decision by the United States to withdraw from the ITER project as the primary experimental burning plasma component within a balanced long-term strategic plan for fusion energy could isolate U.S. fusion scientists from the international effort and would require the United States to develop a new approach to study a burning plasma* [my italics].[508]

---

[507] Jasanoff, "Imagined and Invented Worlds", 338.

[508] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology", 1-8.

While the mitigation strategy as articulated in the report is primarily addressed to US fusion energy research, the theme communicated in one of seven key assessments is a model to cope with the uncertainty associated with this age of doubt and the potential political and corresponding financial fallout. The wisdom that surfaces in the 2018 National Academies report[509] can be applied to not only the three cases studied but also as a universal lesson to incorporate contingency planning in fusion projects.

Politics of Persuassion[510]

In this age of fabrications, the credibility of institutions, e.g., the National Academy of Sciences and the Max Planck Society, can be challenged as a consequence of the democratizing of S&T and the nearly instantaneous transmission of critiques – from the scholarly to the absurd. The National Academy of Sciences, founded on 3 March 1863 upon President Abraham Lincoln penning his signature to a bill passed by the U.S. House of Representatives[511], was established as a national repository of knowledge, power, and impartial credibility. The Max Planck Society and its predecessor, the Kaiser Wilhelm Society for the Advancement of Science, were German scientific institutions that maintained credibility across generations that spanned empire and republics. Both iconic institutions might well be ignored by online communities and demagogic decision makers (domestic and international) if expert-based institutional outcomes do not intelligently consider the apparent political trend and compete for trustworthiness.

[509] National Academies of Sciences, Engineering, and Medicine. "Progress in Burning Plasma Science and Technology".

[510] Jamais Cascio, The politics of persuasion, in *Scenarios from the far future,* (Institute for the Future, 2017).

[511] National Academies of Sciences, Engineering, and Medicine – History, http://www.nasonline.org/about-nas/history/.

In the contest for credibility, the politics of persuasion[512] symbolizes an enabling domain that resides at the nexus of expert knowledge, tacit knowledge, and beliefs. In an age that allows people to click their way to online affirmation, this political form might impact sociotechnical momentum and solidify support or induce rejection of the fusion enterprise. "The technologies of persuasion evolve along with the tactics, and are used to make contingent or incomplete vision of the world seem real, even overwhelming".[513] There is a responsibility among pragmatic advocates of fusion, however, to resist the temptation to persuade with a purely utopian sociotechnical imaginary to publics in the absence of its proper context but rather to expose both the risks of fusion-based electricity generation and the risks of not pursuing this form of energy.

Convergence of Sociotechnical Imaginaries, S&T, and Social Order

As explored in this dissertation, two co-produced sets of phenomena energize sociotechnical momentum of the fusion enterprise: sustained sociotechnical imaginaries and the co-production of scientific knowledge and social order. As this pair of co-equal collections of human action reveals the historical and contemporary fusion landscape, the future shape of energy policy is by no means pre-determined by past performance.

It would the height of arrogance to anticipate that a holistic approach to a fusion-centered energy ecosystem would be simple to implement or validate. Hulme criticizes 'clumsy' approaches[514] as being no better than efforts to solve difficult problem with reduced elegant solutions. On the other hand, and most notably, recent biennial IAEA sponsored Fusion Energy Conferences since the turn of the twenty-first century have provided a forum that offers

---

[512] Cascio, The politics of persuasion.

[513] Cascio, The politics of persuasion, 35.

[514] Hulme, *Why We Disagree About Climate Change*, 337-340.

tantalizing glimpses of solutions to the admittedly wicked problems at the heart of generating practical energy from a plasma hotter than the core of the sun. The conference is a key forum for discourses on building a roadmap to a viable fusion energy knowledge infrastructure. “Fusion technologies have an opportunity to participate in the future global electricity system if ambitious environmental targets are set, collaboration among nations works, and costs remain stable”.[515] In October 2018, the twenty-seventh conference in the series since inception was centered on the need to demonstrate the technological feasibility of fusion power plants as well as the economic viability of fusion energy production and the corresponding challenges.[516]

The fusion enterprise is an emerging technology that is inching toward practical viability. The co-production lens that reveals the convergence of physics, engineering and social order is not solely the essence of the fusion enterprise but characterizes other emerging S&T. There is a resulting sense-making method of decomposing the dimensions of natural sciences, engineering, and the corresponding social order. That analytical corpus magnifies the evolution of knowledge infrastructures as diverse as the S&T that comprise fusion energy, artificial intelligence (AI), machine learning (ML), and the trio of quantum computing, sensing and communications.

In spite of potent sociotechnical imaginaries that might counter public fears, arguments that challenge the assumption of the inherent benign qualities of fusion are necessary to maintain credibility. Technological humility tempers the tendency to blindly trust in positive outcomes from an emerging technology. Striking a balancing in the marketing of a fusion-centered energy ecosystem and factoring political realities, and effectively executing corresponding actions are crucial success factors on the road to viable fusion energy. There are lessons to be derived from

---

[515] Cabal, et al, Exploration of fusion power penetration under different global energy scenarios using the EFDA Times energy optimization model.

[516] Fusion Energy Conference (FEC 2018), https://www.iaea.org/events/fec-2018.

the history of nuclear energy, i.e., fission, that can be applied to the fusion enterprise so that an operational system will emerge that indeed minimizes risk to a level deemed ‘acceptable’. There are sociotechnical qualities that span the scope of those risks. Smil brands fission as a perfect example of a “successful failure of a technological innovation”.[517] He applies the lesson to the enthusiastic claims that are now made to the vision of an energy ecosystem, to include wind and solar, and it further applies equally to the fusion enterprise. Smil elaborates based on the lesson derived from the history of fission, a warning that should be absorbed by the fusion enterprise.

> In such a case, a new technique conquers a substantial share of its market and proves reliable and economical, but both because of its importance falls far short of initial and unrealistic expectations and because it has not resolved some of its long-term operational challenges, it is seen as a questionable undertaking whose further expansion is perhaps best avoided. A repetition of this experience could be the fate of one or more of the new forms of energy conversion that are now extolled as perfect long-term supply solutions.[518]

As a full century of extraordinary effort might pass before closure is attained, it would be tragic if unacceptable risks associated with fusion shatter the vision of a planetary energy revolution.

Momentum, Not Technological Determinism

ITER has enormous dimensions that overwhelm corresponding measures of other fusion projects. Even as potent instruments of co-production provide thrust to sustain momentum, the perception of an inevitable successful conclusion to the ITER project is deceptive. Calculating raw quantities, i.e., project duration, support campus infrastructure, scope of international engagement, financial and intellectual investment, and the units of measure for energy input and output yields an astronomically large sum that reflects the extent of ITER in the fusion domain.

[517] Smil, *Energy Myths and Realities*, 152.

[518] Smil, *Energy Myths and Realities*, 153.

ITER is central to the European roadmap to fusion,[519] a high level plan comprised of three stages.

Near term

- Construction of ITER
- Research & Development in support of ITER
- Deuterium-tritium operation of JET[520]
- Concept Design phase of DEMO
- Research & Development for DEMO
- Construction of a fusion materials testing facility, IFMIF-DONES[521]
- Scientific and technological exploitation of the stellarator concept

Medium term

- First scientific and technological exploitation of ITER
- First exploitation of IFMIF-DONES
- Engineering Design phase of DEMO with industrial involvement
- Development of power plant materials and technologies
- Possible further development of the stellarator concept

Long term

- High performance and advanced technology results from ITER
- Qualify long-life materials for DEMO and power plants with IFMIF-DONES
- Finalisation of the design of DEMO
- Construction of DEMO
- Demonstration of electricity generation
- Commercialisation of technologies and materials
- Deployment of fusion together with industry[522]

In "Fusion Research: Time to Set a New Path",[523] the author foresees an eventual public reaction to failure of the ITER-like Tokamak approach, but confidently states "there are other approaches to fusion power that may hold great hope for the future".[524] These projects are not

[519] EuroFusion, European research roadmap to the realisation of fusion energy.

[520] Joint European Taurus

[521] International Fusion Materials Irradiation Facility - DEMO-oriented Neutron Source

[522] EuroFusion, European research roadmap to the realisation of fusion energy.

[523] Hirsch, Fusion research: "Time to set a new path".

[524] Hirsch, Fusion research: "Time to set a new path", 42.

only technological alternatives but they also reflect contrasting perspectives on risks and benefits in each political culture, i.e., in the US and Germany, and perhaps counter-intuitively in France.

ITER, however, is the dominant contemporary expression of the fusion enterprise. The evolution of the ITER Organization and its senior staff, and the project's messaging is a prime instance in which ordering instruments have shaped the project to its current state. ITER has developed into a systematic program that is achieving tangible milestones, advanced by a potent network of instruments of institution, identity, discourse, and representation.

The Tokamak design, e.g., ITER, the spherical variation on the Tokamak, e.g., NSTX-U, and the advanced stellerator, e.g., W7-X, have a common high energy feature: magnetic confinement[525] of the plasma that exceeds the temperature of the sun's core. However, the W7-X is designed to sustain discharges for as much as thirty minutes. As of 2017, the world record for a sustained fusion reaction (using a cutting-edge Tokamak) was achieved by the WEST[526] (formerly Tore Supra): 6.5 minutes.[527] The theoretical maximum discharge duration in W7-X is an indicator of a large-scale stellerator design as a candidate for a fusion power plant.

IPP identified a list of objectives, in which the administration, scientists and engineers are committed:

- investigate the good particle confinement of the optimised magnetic field and investigate the particle transport under reactor-like conditions
- produce and heat the plasma with effective heating methods
- develop methods of impurity control and investigate impurity transport
- attain beta values (ratio of plasma pressure and magnetic field pressure) of 4 to 5 per cent and analyse the beta limit

[525] Other approaches include inertial confinement, magnetic target fusion, Polywell, and hybrid fusion (http://world-nuclear.org/information-library/current-and-future-generation/nuclear-fusion-power.aspx).

[526] WEST is derived from Tungsten (chemical symbol "**W**") **E**nvironment in **S**teady-state **T**okamak, a plasma facility near Cadarache in southern France.

[527] ITER – 60 Years of Progress, https://www.iter.org/sci/BeyondITER.

- demonstrate long-time or quasi-stationary operation
- plasma replenishment, particle control, and plasma-wall interaction under continuous operation conditions[528]

While the list emerged from the Max Planck Institute for Plasma Physics in Germany, it equally represents a way forward for each of the cases and the global enterprise.

If the collection of objectives so concisely articulated is attained, the fusion enterprise could materially advance, even in the absence of net energy production. Meeting that multi-dimensional technical goal *and* effectively executing a strategy of transparency to induce public trust is a necessity. Persistent pursuit of those equally critical aspirations might energize the global endeavor's socio-technical momentum and its core of imaginaries that has sustained the fusion enterprise for over sixty years and could ensure its continuity in the decades ahead.

Beyond articulating a possible path forward for the fusion enterprise, the intent of this study is to inform decision makers who will shape energy strategy for the second half of the twenty-first century. The historical and current state analysis of the three cases studied and corresponding envisioned futures weaves more than a rich narrative. Essentially, the dissertation uses an augmented co-production framework that might be equally effective for advisors to those empowered to ponder alternative energy futures.

[528] IPP - Introduction – the Wendelstein 7-X stellarator, https://www.ipp.mpg.de/16931/einfuehrung.

APPENDIX A – Generic Interview Questions

Domain	Question
Sociotechnical Imaginaries	1. A 2010 article in *The Nonproliferation Review*, "Creating Suns on Earth", reminds us that "an oft repeated joke in certain circles is that nuclear fusion is fifty years away – and will always be fifty years away". **What motivates you to continue to pursue the quest for the 'holy grail' of viable fusion?**
Sociotechnical Imaginaries	2. In the mid twentieth century, a utopian vision of unlimited fusion energy emerged and that dream apparently still motivates scientists. **As a respected scientist, can you explain why belief in an essentially utopian fusion vision persists in the absence of a key quality of science, i.e., supporting evidence?**
Large Technological Systems	3. As I toured PPPL in April 2016, I saw the incomplete National Compact Stellarator Experiment. The 2008 DOE funding decision to transform a device that could have been the most advanced of its type into an inert ruin must have been frustrating for the entire PPPL staff. **Are there strategies on the W7-X project to mitigate the risk of short-term political decisions that the NCSX narrative symbolizes?**
Large Technological Systems	4. A 28 April 2017 article in Science, "Private Fusion Machines Aim to Beat Massive Global Effort", reported that startups are being funded from private sources as well as receiving government funding. One small U.K. company, Tokamak Energy, is experimenting with the spherical tokamak. **If you're willing and able to share, what sources of funding are (or might become) available to the Max Planck Institute for Plasma Physics (IPP) for W7-X?**
Sociotechnical Momentum	5. PPPL has been a leader in magnetic confinement for more than three decades. **In your opinion, what institutional qualities of the MPI animate momentum of the fusion enterprise?**
Co-production of technology and social order	6. A viable fusion centered energy ecosystem does not only embody the promise of a dramatic quantitative increase in power generation but also implies a qualitative impact on societies. **What outcomes do you envision from viable fusion that might transform society, in contrast to our contemporary world?**
Co-production of technology and energy policy	7. As common as headlines in our daily newspapers, we are frequently reminded of the risks inherent in the dual uses of fission energy. **How are the proliferation risks of a fusion energy life cycle any different than what ominously emerges in the fission life cycle? What impact might that difference have in both energy policy and nonproliferation?**
Co-production of technology and political culture	8. Sited in three different nations, NXTX-U, ITER and W7-X take different technological paths to fusion. **Do you see distinctly German (or European) political advantages in the MPI's current approach to fusion energy, as well as technological value?**

References

Anderson, B.R. 1991. Imagined communities: Reflections on the origin and spread of nationalism. London: Verso.

Aumeier, S.E. and Allen, T. 2018, Winter. How to reinvigorate US commercial nuclear energy. *Issues in Science and Technology*, 34(2): 79-83.

Bakker, S. 2010. The car industry and the blow-out of the hydrogen hype. *Energy Policy*, 38(2010), 6540-6544. http://www.elsevier.com (accessed December 3, 2012).

Bacon, F. 1626. *New Atlantis*. SMK Books (published 2018).

Barnes, B. 1977. *Interests and the growth of knowledge*. London: Routledge Kegan Paul.

Barnes, B. and MacKenzie, D. 1979. On the role of interests in scientific change. In *On the margins of science*. ed. R. Wallis. University of Keele.

Basu, D.K. (ed.) 2001. *Dictionary of material science and high energy physics*. New York: CRC Press.

Beck, U. 1992. *Risk society: Towards a new modernity*. London: Sage Publications.

Beck, U. 2009. *World at risk*. Cambridge: Polity Press.

Bek, C. 2018, 1 September. The uncertainty principle. *Philosophymagazine: Philosophy and science for the third millennium*. https://riskservices.com/essay-the-uncertainty-principle-issue-17/ (accessed May 27, 2019).

Berg, J. 2018, 29 June. Tomorrow's Earth. *Science*, 360, 6396, 1379.

Bernal, J.D. 1939. *The social function of science*. G. Routledge & Sons.

Bernard, L. 2016, 25 January. 10 facts you should know about fusion energy. Princeton Plasma Physics Laboratory. www.pppl.gov (accessed May 11, 2016).

Bigot, B. 2019. Progress toward ITER's first plasma. *Nuclear Fusion*, (59) (2019). Published 5 June 2019. https://nucleus.iaea.org/sites/fusionportal/Pages/Fusion%20Portal.aspx (accessed July 26, 2019).

Bloor, D. 1976. *Knowledge and social imagery*. London: Routledge and Kegan Paul.

Boxenbaum, Eva, et al. 2012. Imaginaries and instruments: Conceptual tools for problematizing responsible innovation. *Debating Innovation*, 2(3), 84-90.

Buck A. 1983. *The Atomic Energy Commission*. U.S. Department of Energy. https://www.energy.gov/sites/prod/files/AEC History.pdf (accessed March 7, 2019).

Bush, V. 1945. *Science, the endless frontier*. Washington, DC: US Government Printing Office.

Broad, W.J. 2012. So far unfruitful, fusion project faces a frugal Congress. *New York Times*, September 29, 2012 (accessed November 19, 2012).

Brumfiel, G. 2012, June. Fusion's missing pieces. *Scientific American*, 56-61.

Cabal, H., et al. 2016. Exploration of fusion power penetration under different global energy scenarios using the EFDA Times energy optimization model. Received funding from the EURATOM research and training programme 2014-2018 under grant agreement No. 633053.

Campbell D. 2012. Challenges in burning plasma physics: The ITER research plan. 24th IAEA Fusion Energy Conference, 8-13 October 2012. http://www.fec2012.com/ (accessed November 13, 2012).

Cartlidge, E. 2017, 11 July. Fusion energy pushed back beyond 2050. *BBC News*. http://www.bbc.com/news/science-environment-40558758 (accessed July 18, 2017).

Cascio, J. 2017. The politics of persuasion. In *Scenarios from the far future*. Institute for the Future. http://www.iftf.org/en/future-now/article-detail/the-politics-of-persuasion/ (accessed July 5, 2019).

Cho, A. 2008, 30 May. Energy department pulls plug on overbudget fusion experiment. *Science*, 320 (5880), 1142-1143. http:// sciencemag.org (accessed May 16, 2016).

Clauset, A., Larremore, D.B., and Sinatra, R. 2017, 3 February. Data-driven predictions in the science of science. *Science*, 355, 6324, 477-480.

Clery, D. 2014, 25 July. Fusion's restless pioneers: Startups with novel technologies are taking on fusion's Goliaths. *Science*, 345, 6195, 370-375.

Clery, D. 2012, 21 September. Ignition facility misses goal, ponders new course. *Science*, 337, 6101, 1444-1445.

Clery, D. 2015, 27 November. More delays for ITER project. *Science*, 350, 6264, 1011.

Clery, D, and Cho, A. 2016, 6 May. More delays for ITER, as partners balk at costs. *Science*, 352, 6286, 636-637.

Clery, D. 2017, 28 April. Private fusion machines aim to beat massive global effort. *Science*, 356, 6336, 360-361.

Clery, D. 2015, 22 May. The new shape of fusion. *Science*, 348, 6237, 854-856.

Clery, D. 2015, 23 October. Twisted logic. *Science*, 350, 6259, 369-371.

Cloud, J. 2001. Imaging the world in a barrel: CORONA and the clandestine convergence of the Earth sciences. *Social Studies of Science*, 31(2), 231-251. http://www.jstor.org (accessed November 10, 2008).

Davis, S.J., et al. 2018, 29 June. Net-zero emissions energy systems. *Science*, 360, 6396, 1419.

DeVoe, J.J. 2015. A collaboration bears fruit as W7-X celebrates first research plasma. *PPPL News,* December 14, 2015. https://www.pppl.gov/news/2015/12/collaboration-bears-fruit-w7-x-celebrates-first-research-plasma (accessed April 7, 2019).

Denholm, P. et al. 2012. Decarbonizing the electric sector: Combining renewable and nuclear energy using thermal storage. *Energy Policy*, 44 (2012), 301-311. https://scholar.vt.edu/portal (accessed November 11, 2012).

Edwards, P.N. 2006. Meteorology as infrastructural globalism. *Osiris*, 21,1, 229-250.

Edwards, P.N. 2010. *A vast machine: Computer models, climate data, and the politics of global warming*. Cambridge, MA: MIT Press.

Einstein, A. 1905. On the electrodynamics of moving bodies. *Annalen der Physik*, 17, 891–921.

Einstein Letter, Franklin D. Roosevelt Presidential Library and Museum, August 2, 1939. http://www.fdrlibrary.marist.edu/archives/pdfs/docsworldwar.pdf (accessed May 22, 2019).

Epstein, C.F. 2007. Great divides: The cultural, cognitive, and social bases of global subordination of women. *American Sociological Review*. 72(1): 1-22.

EuroFusion. 2018. *European research roadmap to the realisation of fusion energy.* https://www.euro-fusion.org/eurofusion/roadmap/ (accessed November 11, 2018).

Ezrahi, Y. 1990. *The descent of Icarus*. Cambridge, MA: Harvard University Press.

Farmer, J.C., Diaz de la Rubia, T, and Moses, E. 2009. *The complete burning of weapons grade plutonium and highly enriched uranium with (laser inertial fusion-fission Energy) LIFE Engine*. Lawrence Livermore National laboratory. https://e-reports-ext.llnl.gov/pdf/368706.pdf (accessed May 4, 2013).

Feder, T. 2011, September. US narrows fusion research focus, joins German stellarator: Tight money leads to increased emphasis on tokamak plasma physics and the shuttering of some exploratory experiments. *Physics Today,* 64(9), 30. https://physicstoday.scitation.org/doi/full/10.1063/PT.3.1252 (accessed March 26, 2019).

Ford, O.P. 2016. Colloquium: Wendelstein 7-X: Highlights from the first operational phase of the new optimized stellarator. Presented by Dr. Oliver P. Ford, Max-Planck Institut für Plasmaphysik, Greifswald/Garching, Germany. At Princeton, NJ: Princeton Plasma Physics Laboratory, on June 15, 2016.

Fusion Energy Conference (FEC 2018), https://www.iaea.org/events/fec-2018 (accessed June 12, 2019).

FY 2018 Congressional budget justification, U.S. Department of Energy, Office of the Chief Financial Officer.

Garwin, R. L. and G. Charpak. 2002. *Megawatts and megatons: The future of nuclear power and nuclear weapons*. Chicago: University of Chicago Press.

Geels, F.W., Sovacool, B.K., Schwanen, T., and Sorrell, S. 2017, 22 September. Sociotechnical transitions for deep decarbonization. *Science*, 357, 6357, 1242-1244.

Gibbs, W.W. 2016, November. The fusion underground. *Scientific American*, 315, 5, 38-45.

Giddens, A. 1994. Living in a post-traditional society, In *Reflexive modernization: politics, tradition and aesthetics in the modern social order*, edited by U. Beck, A. Giddens, and S. Lash. Cambridge, UK: Polity Press.

Giddens, A. 1998. Risk society: The context of British politics, In *The politics of risk society*, edited by J. Franklin. Cambridge, UK: Polity Press, 23-34.

Giddens, A. 2011. *The politics of climate change* (2nd edition). Cambridge, UK: Polity Press.

Giordano V. and Fulli, G. 2010. A business case for smart grid technologies: A systemic perspective. *Energy Policy,* 40 (2012): 252–259.

Goldston, R. J., 2018. Overview of fusion energy research. 4th Annual Intelligence Community Academic Research Symposium, 25-27 September 2018. Washington, DC: National Academy of Sciences.

Gore, A. 2006. “An inconvenient truth”. Paramount Pictures. Release date: May 24, 2006.

Graham, K. 2018, 27 March. U.S. budget bill doubles funding for ITER nuclear fusion project. In *Science*. http://www.digitaljournal.com/tech-and-science/science/usa-budget-bill-doubles-funding-for-iter-nuclear-fusion-project/article/518441#ixzz5uSAkeuB1. (accessed July 22, 2019).

Greenwald, J. 2019. Speeding the development of fusion power to create unlimited energy on Earth. *PPPL News,* March 19, 2019. https://www.pppl.gov/news/2019/03/speeding-development-fusion-power-create-unlimited-energy-earth (accessed March 29, 2019).

Gronewold, N. 2019. World’s largest nuclear fusion experiment clears milestone. *Scientific American, E&E News*. https://www.scientificamerican.com/article/worlds-largest-nuclear-fusion-experiment-clears-milestone/ (accessed July 25, 2019).

Hagstrom, W.O. 1965. *The scientific community*. New York: Basic Books.

Hecht, G. 1998. *The radiance of France: Nuclear power and national identity after World War II*. Cambridge, MA: MIT Press.

Hecht, G. 2012. *Being nuclear: Africans and the global uranium trade*. Cambridge, MA: MIT Press.

Hirsch, R.L. 2015, Summer. Fusion research: Time to set a new path. *Issues in Science and Technology*, 31(4): 35-42.

History, Princeton Plasma Physics Laboratory. http://www.pppl.gov/about/history (accessed November 15, 2018).

Holland, A. 2012. Why the New York Times is wrong on the National Ignition Facility. *AOL Energy*. http://energy.aol.com/2012/10/17/why-the-new-york-times-is-wrong-on-the-national-ignition-facilit/ (accessed November 12, 2012).

Hughes, T. P. 1987. "The evolution of large technological systems". In *The social construction of technological systems*, edited by Wiebe E. Bijker, Thomas P. Hughes and Trevor Pinch, 51-82. Cambridge, MA and London, UK: MIT Press.

Hulme, M. 2009. *Why we disagree about climate change: Understanding controversy, inaction and opportunity*. New York: Cambridge University Press.

Ignition switch. 2012, 8 November. *Nature*, 491, 159. http://www.nature.com/news/ignition-switch-1.11748 (accessed November 22, 2012).

International Atomic Energy Agency. 2007, 25 April. Agreement on the Establishment of the ITER International Fusion Energy Organization for the Joint Implementation of the ITER Project.

International Atomic Energy Agency. 2008, 18 July. Cooperation agreements with intergovernmental organizations.

International Atomic Energy Agency. Overview. https://www.iaea.org/about/overview (accessed August 17, 2019).

International Space Station (ISS). http://www.nasa.gov/mission_pages/station/cooperation (accessed December 13, 2012).

Interview, 2012, for "Sonnenwende" Exhibition, Berlin Max Planck Science Gallery.

IPCC. 2018, 8 October. 2018/24/PR. IPCC press release: Summary for policymakers of IPCC special report on global warming of 1.5^{o}C approved by governments. Incheon, Republic of Korea.

IPP – ASDEX Upgrade. Max Planck Institute for Plasma Physics. https://www.ipp.mpg.de/16195/asdex (accessed August 8, 2019).

IPP – History of IPP. https://www.ipp.mpg.de/17194/geschichte (accessed August 8, 2019).

IPP – Introduction – the Wendelstein 7-X stellarator. https://www.ipp.mpg.de/16931/einfuehrung (accessed August 8, 2019).

ITER – Director Corner. https://www.iter.org/proj/director-corner (accessed August 17, 2019).

ITER – Fusion. https://www.iaea.org/topics/fusion (accessed September 12, 2012).

ITER – How does fusion produce energy? http://www.iter.org/sci/whatisfusion (accessed September 12, 2012).

ITER – Milestones. https://www.iter.org/proj/itermilestones (accessed September 12, 2012).

ITER – the way to new energy. http://www.iter.org/

ITER – 60 Years of Progress. https://www.iter.org/sci/BeyondITER.

ITER cooperation, Max Planck Institute for Plasma Physics. http://www.ipp.mpg.de/16617/iter (accessed September 12, 2012).

ITER cost. http://www.iter.org/ (accessed September 12, 2012).

ITER project history. https://www.iter.org/proj/ITERHistory (accessed September 12, 2012).

ITER Newsline, "What's next for the stellerator? *Fusion World* (2018, 12 November). https://www.iter.org/newsline/-/3169 (accessed August 7, 2019).

Jardine, L. 2000. *Ingenious pursuits: Building the scientific revolution*. New York: Anchor Books.

Jasanoff, S. 2001. Image and imagination: The formation of global environmental consciousness. In *Changing the Atmosphere*, by Clark Miller and Paul Edwards, Cambridge, MA: MIT Press.

Jasanoff, S. 2004. *States of knowledge: The co-production of science and social order*. New York: Routledge.

Jasanoff, S., and Kim, S.-H. Containing the atom: Sociotechnical imaginaries and nuclear power in the United States and South Korea. *Minerva*, 47(2), 119-146, 2009, June.

Jasanoff, S. and Kim, S.-H. 2015. *Dreamscapes of modernity: Sociotechnical imaginaries and the fabrication of power*. University of Chicago Press.

Jasanoff, S. and Kim, S.-H. 2013, 30 May. Sociotechnical imaginaries and national energy policies. *Science as Culture*, 22:2, 189-196. http://www.tandfonline.com/loi/csac20 (accessed April 26, 2015).

Jasby, D. 2018. ITER is a showcase … for the drawbacks of fusion energy. *Bulletin of the Atomic Scientists*. 14 February 2018. https://thebulletin.org/2018/02/iter-is-a-showcase-for-the-drawbacks-of-fusion-energy/ (accessed June 9, 2019).

Joint Soviet-United States statement on the summit meeting in Geneva, Reagan Library Archives, November 21, 1985. https://www.reaganlibrary.archives.gov/archives/speeches/1985/112185a.htm.

Jonathan D. Menard (Research Director, National Spherical Taurus Experiment, Princeton Plasma Physics Laboratory), in interview with the author, August 17, 2017.

Jones, C.F., Saha, K., Pfotenhauer, S.M., and Jasanoff, S. 2012, Spring. Learning from Fukushima. *Issues in Science and Technology*, 28(3): 79-84.

Keller, E.F. 1985. *Reflections on gender and science*. New Haven: Yale University Press.

Kingdon, J.W. 2003. *Agendas, alternatives, and public policies*. New York: Longman.

Koplow, D.A. 1991, March. Back to the future and up to the sky: Legal implications of "open skies" inspection for arms control. *California Law Review, 79(2), 421-496*. http://www.jstor.org (accessed November 12, 2008).

Krivit, S.B. 2017, 19 January. Former ITER spokesman confirms accuracy of New Energy Times story. *New Energy Times*. http://news.newenergytimes.net/2017/01/19/former-iter-spokesman-confirms-accuracy-of-new-energy-times-story/ (accessed March 2, 2018).

Krivit, S.B. 2017, 12 January. The selling of ITER. *New Energy Times*. http://news.newenergytimes.net/2017/01/12/the-selling-of-iter/ (accessed March 2, 2018).

Kunzig, R. 2015, November. Germany could be a model for how we'll get power in the future. *National Geographic*. https://www.nationalgeographic.com/magazine/2015/11/germany-renewable-energy-revolution/.

Laban L. Coblentz (Head of Communication, ITER Organization), in interview with the author, July 28, 2018.

Laberge, M. 2014, 28 August. TEDxKC Talk. https://www.youtube.com/watch?v=b-LCfx9v4YQ (accessed May 2, 2015).

Laser inertial fusion energy. https://life.llnl.gov (accessed September 12, 2012).

Latour, B. 1983. Give me a laboratory and I will raise the world. In *Science Observed: Perspectives on the Social Study of Science*. ed. K. Knorr-Cetina, M.J. Mulkay. London: Sage.

Latour, B. and Woolgar, S. 1979. *Laboratory life: The social construction of scientific facts*. Beverly Hills: Sage Publications.

Latour, B. 2005. *Reassembling the social: An introduction to actor-network theory*. New York: Oxford University Press.

Lawrence Livermore National Laboratory – The Pursuit of Ignition. https://lasers.llnl.gov/10-years-of-dedication/pursuit-of-ignition.

Lester, R.K. 2016, Winter. A roadmap for U.S. nuclear energy innovation. *Issues in Science and Technology*, 32(2): 45-54.

Logson, J.M. 1998, October. Space and the American imagination. *The American Historical Review,* 103(4), 1351-1352. http://links.jstor.org. (accessed October 31, 2006).

Lyman Spitzer papers (C0682): A finding aid prepared by Matthew Robb, class of 1994 and Gena Bursan. 1991, 2000. Manuscripts Division Department of Rare Books and Special Collections, Princeton University Library. https://web.archive.org/web/20060901164945/http://libweb.princeton.edu/libraries/firestone/rbsc/aids/spitzer.html (accessed March 11, 2019).

MacKenzie, D. 1990. *Inventing accuracy: A historical sociology of nuclear missile guidance*. Cambridge, MA: MIT Press.

MacKenzie, D. 1999. "Nuclear missile testing and the social construction of accuracy". In *Science Studies Reader*, ed. Mario Biagioli, 342-357. New York: Routledge.

Marcus, G. E., ed. 1995. *Technoscientific imaginaries: Conversations, profiles, and memoirs*. Chicago: University of Chicago Press.

Martin, R. 2016, 24 May. Germany runs up against the limits of renewables. *MIT Technology Review*. https://www.technologyreview.com/s/601514/germany-runs-up-against-the-limits-of-renewables/ (accessed May 31, 2019).

Masco, J. 2006. *The nuclear borderlands: The Manhattan project in post-cold war New Mexico*. Princeton: Princeton University Press.

McCurdy, H.E. 1997. *Space and the American imagination*. Washington, DC: Smithsonian Institution Press.

McDougall, W.A. 1985. *The heavens and the Earth: A political history of the space age*. Baltimore: Johns Hopkins University Press.

Menard, J.E. 2019. Compact steady-state tokamak performance dependence on magnet and core physics limits. 377(2141). *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. February 4, 2019. https://royalsocietypublishing.org/action/doSearch?AllField=menard (accessed April 4, 2019).

Milch, I. 2017. Wendelstein 7-X: Second round of experimentation started. September 11, 2017. Max Planck Society. https://phys.org/news/2017-09-wendelstein-x-experimentation.html (accessed July 28, 2019).

Models in science. In *Stanford encyclopedia of science*. http://plato.stanford.edu/entries/models-science/ (accessed April 28, 2013).

Moerchen and Coontz. 2015, 6 March. Einstein's vision: General relativity turns 100. *Science*, 347, 6226, 1083**.**

Moss, S. 2019, 15 March. The race to exascale: A story of superpowers and supercomputers. *Data Center Dynamics*. https://www.datacenterdynamics.com/analysis/superpowers-supercomputers-and-race-exascale/ (accessed April 2, 2019).

Motojima, O. et al. 2012. The status of the ITER project. 24th IAEA Fusion Energy Conference, 8-13 October 2012. http://www.fec2012.com/ (accessed November 13, 2012).

Mumford, L. 1963. *Technics and civilization*. New York: Harvest/HBJ.

National Academies of Sciences, Engineering, and Medicine. 2018. *Final report of the committee on a strategic plan for U.S. burning plasma research*. Washington, DC: The National Academies Press. https://www.nap.edu/download/25331 (accessed December 17, 2018).

National Academies of Sciences, Engineering, and Medicine, History. http://www.nasonline.org/about-nas/history/ (accessed December 17, 2018).

National Aeronautics and Space Administration – International Space Station, International Cooperation. http://www.nasa.gov/mission_pages/station/cooperation (accessed April 1, 2015).

National Nuclear Security Administration – Missions, http://nnsa.energy.gov/ourmission (accessed April 5, 2015).

National Research Council of the National Academies of Sciences, Engineering, and Medicine, Committee on the Prospects for Inertial Confinement Fusion Energy Systems. 2012 8 May. *Interim report—Status of the study "An assessment of the prospects for inertial fusion energy"*. Washington, DC: National Academies Press. http://www.nap.edu/catalog.php?record_id=13371 (accessed November 19, 2012).

National Spherical Torus Experiment Upgrade (NSTX-U). https://www.pppl.gov/nstx-u (accessed April 4, 2016).

NIF: The "crown joule" of laser science. Lawrence Livermore National Laboratory. https://lasers.llnl.gov/about/nif/about.php (accessed September 12, 2012).

Nordhaus, T. 2019, Summer. The empty radicalism of the climate apocalypse. *Issues in Science and Technology*, 35(4): 69-78.

Nye, D.E. 1994. *American technological sublime*. Cambridge, MA: MIT Press.

Nye, D.E. 1998. *Consuming power: A social history of American energies*. Cambridge, MA: MIT Press.

Parkins, W.E. 2006. Fusion power: Will it ever come? *Science*, 311, 1380**.**

Perrow, C. 1984. *Complexity, coupling, and catastrophe, in normal accidents: Living with high-risk technologies*. New York: Basic Books, 62-100.

Physics@FOM Veldhoven 2013, Sibylle Günter, Masterclass. Physics basis of magnetic fusion reactors. OpenWebcastCh2 (Published on Jan 30, 2013).

Pielke, R.A. 2007. *The honest broker: Making sense of science policy and politics*. Cambridge, UK: Cambridge University Press.

Pinch, T.J. and W.E. Bijker. 1987. The social construction of facts and artifacts: Or how the sociology of science and the sociology of technology might benefit each other. In *The social construction of technological systems: New direction in the sociology and history of technology*, edited by Wiebe E. Bijker, Thomas P. Hughes, and Trevor J. Pinch, 17-50. Cambridge, MA: The MIT Press.

Porter, T. M. 1995. *Trust in numbers: The pursuit of objectivity in science and public life*. Princeton, NJ: Princeton University Press**.**

Princeton Plasma Physics Laboratory, https://www.pppl.gov/ (accessed November 15, 2018).

Prins, G. and Rayner, S. 2007. The wrong trousers: Radically rethinking climate policy. Oxford: Joint Discussion Paper of the James Martin Institute for Science and Civilization, University of Oxford and the MacKinder Centre for the Study of Long-Wave Events, London School of Economics.

Programme & book of abstracts. 24th IAEA Fusion Energy Conference, 8-13 October 2012. http://www.fec2012.com/ (accessed November 13, 2012).

Research, Princeton Plasma Physics Laboratory, https://www.pppl.gov/research (accessed November 15, 2018).

Saini, S. 2015. *A star for us*. Princeton Plasma Physics Laboratory.

Schiebinger, L. 1989. *The mind has no sex? Women in the origins of modern science*. Cambridge, MA: Harvard University Press.

Schmid, S. D. 2015. *Producing power: The pre-Chernobyl history of the Soviet nuclear industry*. Cambridge, MA: MIT Press.

Schön, D. A. and Rein, M. 1995 *Frame reflection: Toward the resolution of intractable policy controversies*. Basic Books.

Shapin, S. and S. Schaffer. 1985. *Leviathan and the air-pump: Hobbes, Boyle, and the experimental life*. Princeton, NJ: Princeton University Press.

Sibylle Günter (Scientific Director, Max Planck Institute for Plasma Physics), in interview with the author, August 17, 2018.

Sievert, F. and Johnson, D. 2010. Creating suns on Earth. *The Nonproliferation Review*, 17(2), 323-346. http://dx.doi.org/10.1080/10736700.2010.485432 (accessed February 7, 2013).

Smil, V. 2010. *Energy myths and realities: Bringing science to the energy policy debate*. Washington DC: AEI Press.

Smirnov, V.P. 2010, January. Tokamak foundation in USSR/Russia 1950–1990. IAEA: Vienna. *Nuclear Fusion*, 50(1).

Spiegelhalter, D., et al. 2011, September 9. Visualizing uncertainty about the future. *Science*, 333, 1393-1400.

Spitzer, Jr., L. 1951. *A proposed stellarator*, PM-S-l, USAEC NYO- 993.

Spitzer, Jr., L. 1951. *Survey of possible oscillations in the stellarator*, PM-S-2, USAEC NYO-994.

Spitzer, Jr., L. 1952. *Magnetic fields and particle orbits in a high-density stellarator*, PM-S-4, USAEC NYO-997.

Spitzer, Jr., L., et al. 1954. *Problems of the stellarator as a useful power source*, PM-S-14, USAEC NYO-6047.

Spitzer Space Telescope. NASA. https://www.nasa.gov/mission_pages/spitzer/main/index.html (accessed November 15, 2018).

Stix, T.H. 1997. Highlights in early stellarator research at Princeton. Department of Astrophysical Sciences, Princeton University, Princeton, NJ. *Journal of Plasma Fusion Research* SERIES, Vol.1 (1998), 3-8. Japan Society of Plasma Science and Nuclear Fusion Research. http://www.jspf.or.jp/JPFRS/PDF/Vol1/jpfrs1998_01-003.pdf (accessed February 16, 2019).

Szilard, L. 1934. *Improvements in or relating to the transmutation of chemical elements*. UK Patent 19157/34, filed Jun. 28, 1934, and issued Mar. 30, 1936.

Tetlock, P.E. and Gardner, D. 2015. *Superforecasting: The art and science of prediction*. New York: Crown Publishers.

The Nobel Prize in Physics (1918). Max Planck Biographical. https://www.nobelprize.org/prizes/physics/1918/planck/biographical/ (accessed on August 8, 2019).

The Sociotechnical Imaginaries Project, Program on Science, Technology & Society, Harvard University. http://sts.hks.harvard.edu/research/platforms/imaginaries/ (accessed on June 12, 2018).

United States Government Accountability Office. 2005. *Meeting energy demand in the 21st century*. Testimony Before the Subcommittee on Energy and Resources, Committee on Government Reform, House of Representatives. https://www.gao.gov/products/GAO-05-414T (accessed October 6, 2018).

Waldrop, M.M. The fusion upstarts. 2014, 24 July. *Nature*, 511, 398-400. http://www.nature.com/news/ (accessed September 6, 2014).

Wells, H. G. 1914. *The world set free*. http://www.online-literature.com/wellshg/worldsetfree/ (accessed October 7, 2009).

Wesson, J. 2011. *Tokamaks*. Oxford: Oxford University Press.

What is ITER? https://www.iter.org/proj/inafewlines#4 (accessed September 12, 2012).

Witte, G., and Beck, L. Germany's coal reality smudges green rhetoric. *The Washington Post*, 2017, 12 November.

Wolfe, T. 1979. *The right stuff*. New York: Farrar, Straus, and Giroux.

World Nuclear Association. Nuclear power in France. http://www.world-nuclear.org/information-library/country-profiles/countries-a-f/france.aspx (accessed May 3, 2019).

World Nuclear Association. Nuclear power in Germany (updated March 2019). http://www.world-nuclear.org/information-library/country-profiles/countries-g-n/germany.aspx (accessed May 3, 2019).

World Nuclear News. 21 November 2016. New schedule agreed for ITER fusion project. http://www.world-nuclear-news.org/NN-New-schedule-agreed-for-Iter-fusion-project-2111164.html (accessed July 27, 2019).

Zacharia, F. 2015, 15 March. Fareed Zacharia GPS: Moonshots for the 21st century. Segment 3 of CNN series: Creating a star on Earth. (http://cnnpressroom.blogs.cnn.com/2015/02/11/moonshots-for-the-21st-century-a-fareed-zakaria-gps-special-now-available-exclusively-via-cnngo/).