Prologue

The goal of this report is to inform the reader about the challenges facing magnetic confinement nuclear fusion technology, which could someday provide the planet with a new and unique source of energy. Like the other Andlinger Center Energy Technology "Distillates," this Distillate aims to provide succinct yet substantive information to policymakers, educators, students, and other citizens – to fill a gap between presentations in textbooks and in the popular literature.

This Distillate was researched, synthesized, and written by 10 Ph.D. students in the Princeton Energy and Climate Scholars (PECS) program at Princeton University, along with our faculty mentor, Robert Socolow. PECS is a platform that enables a group of Ph.D. students working on disparate aspects of energy and climate to have an interdisciplinary exchange of ideas. The students involved in this Distillate have a range of expertise: biogeochemistry, climate modeling, ecology, electrical engineering, psychology, and public policy. Notably, none of us is engaged in a dissertation related to nuclear fusion.

The lack of fusion scientists among the authors has required significant effort on our part to learn and understand the intricacies of the fusion field. We were aided by extensive consultations with experts. We hope that the reader will benefit from our collective learning process and our fresh perspective on the fusion enterprise. An exposition emphasizing objectivity may be particularly helpful for fusion because the field is currently conducting expensive experiments that compete for very limited government funding in many nations, resulting in discourse that may at times be hindered by the high stakes between competing approaches and projects.

A special challenge to our objectivity arises from the fact that the Princeton Plasma Physics Laboratory (PPPL) is located at the University. Although we consulted with several fusion experts at PPPL, this report was written independently of PPPL and does not represent its views. Nonetheless, the reader may well anticipate that any document from Princeton will present fusion's potential to become a future energy generation option in an excessively favorable light. We have sought to write an impartial and rigorous assessment, the kind that we would most want to read ourselves. In the process, we hope we have written a document that will be useful for every reader with an appetite for introductory technological analysis and a desire to understand nuclear fusion as an energy source.

Article 1: Overview

In the current century the world faces a dual challenge: providing the energy that enables continued growth in desired human activity, while limiting the severity of climate change by constraining the emissions of carbon dioxide from fossil fuels. Although this dual challenge is expected to be met in part by efficient use of energy and extensive deployment of already well-envisioned low-carbon energy sources, additional low-carbon options could help secure a robust path to sustainable global development. Nuclear fusion energy may be such an option, provided that significant progress in several areas of science and technology is made in the next few decades.

Fusion-generated energy would be uniquely valuable because of a combination of characteristics not shared by any existing technology:

1) Fusion could dependably provide energy at a sufficient scale to meet a significant fraction of global demand.
2) Locations for fusion plants include sites where renewable energy sources are unsuitable.
3) Fusion power is expected to have low impact on public health and local environments.
4) Fusion power has no direct carbon dioxide emissions. The indirect emissions that are associated with plant construction and fuel production are modest.
5) The global supply of fusion fuels is essentially inexhaustible. Lithium and deuterium extracted from seawater could provide enough fusion fuel to meet foreseeable energy demand for millions of years.

Several significant challenges help explain why the multiple benefits of fusion energy have not yet led to its presence in the global energy system, even though the theory of fusion reactions was developed in the 1920s and 1930s. The most direct challenges are in science and technology. Nuclear fusion is the method by which the Sun creates its energy, and replicating such a process on Earth requires recreating conditions comparable with those found in the Sun's core. The temperature of the fusion fuel must be raised to approximately 200 million degrees Celsius, *versus* 15 million degrees Celsius in the core of the Sun. At such temperatures, the fuel is fully ionized, that is, the fuel's atoms have been stripped of all their electrons. This distinctive state of matter is called "plasma." Magnetic confinement uses magnetic fields to retain plasma heat and to control plasma movement while energy is produced within the plasma by nuclear reactions.

Creating, maintaining, and manipulating a high-temperature plasma are unique scientific challenges. Basic questions in the science of plasma physics and applied questions related to engineering and materials have been addressed in both small and large facilities, but many questions can be tested only in the largest facilities, which have become steadily more expensive.

Early research focused on plasma control and limited the number of nuclear fusion events in order to reduce complications. Now the frontier includes "burning plasmas," where enough fusion reactions occur to maintain the high temperature of the plasma with little or no external heating. The behavior of a burning plasma is new territory for science.

The scientific, technological, and economic challenges of fusion energy research go hand in hand with the policy challenges of fusion energy. Because fusion research requires large and long-term financing, funding has come primarily from governments rather than private investors. However, in national politics, it is difficult to sustain many decades of investments on the scale of hundreds of millions of dollars annually when the outcomes are uncertain and the end goal – a commercial reactor – will at best be economically competitive decades in the future. The fusion endeavor struggles to fund expensive research facilities and long-term horizons with bounded and fluctuating budgets.

One way that the fusion community is dealing with financial challenges is by forming international collaborations to pool funds for its larger experiments. The most ambitious collaboration in fusion is the International Thermonuclear Experimental Reactor (ITER), which is currently under construction in France. It will be discussed at some length in this Distillate. ITER is expected to allow for extensive experimentation under burning plasma conditions.

Magnetic confinement fusion is one of the two principal approaches to achieving nuclear fusion energy currently being explored. The other is inertial confinement fusion, which uses pulses from multiple lasers or particle beams to squeeze tiny pellets of fuel and trigger a rapid succession of fusion reactions. Both magnetic and inertial confinement fusion are based on the same nuclear fusion reactions, but due to their vastly different configurations, the obstacles in these two paths to commercial fusion energy are entirely different. Here, we focus nearly exclusively on magnetic confinement fusion, presenting the major technological and economic issues associated with its potential for commercial success. To further bound our Distillate, we do not discuss the relatively few, small-scale, private-sector-funded fusion ventures that are seeking alternatives to the mainstream government-funded approaches.

A commercially competitive fusion power plant would be a remarkable human achievement. As the science unfolds, however, it is possible that the emergent technological, economic, and political requirements will not reveal a path forward. For now, achieving competitive nuclear fusion energy is an open-ended endeavor.

The remainder of this Distillate consists of five articles. Article 2, “Key Concepts and Vocabulary,” provides background for the later articles. Article 3, “Technology,” presents some of the basic science relevant to fusion energy and a few of the central technical challenges being addressed in current fusion research. Article 4, “Economics” discusses issues likely to determine the prospects for commercial fusion: the costs of reactor construction and ongoing maintenance, the strength of climate policy, and the success of fusion’s competitors. Article 5, “Fusion and Fission,” discusses how well nuclear fusion power will address several of the vexing problems that currently challenge nuclear fission power. Article 6, “Politics and Progress,” reviews the current global effort to develop nuclear fusion.