Nuclear Fusion

Prime Movers Lab
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Prime Movers Lab

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Summary and Outlook

Key takeaways from each section.

Introduction

- Fusion can supply unlimited, reliable and clean energy.
- The physics of ignition (net energy gain) and the business case must still be proven.
- Advances in key technologies, computational power and simulation tools, available research facilities, and the increased presence of business-minded entities have made inertial confinement fusion (ICF) approaches less crazy, and maybe even feasible.

Inertial Confinement Fusion (ICF)

- Inertial Confinement Fusion (ICF) systems produce energy by repeatedly igniting small amounts of fuel with lasers.
- ICF systems have three main components: the “target” containing the fuel, the “driver” (lasers) to ignite the fuel, and the “chamber” to capture the fusion energy and begin the process of converting it to electricity.
- Both achieving ignition and demonstrating a positive energy balance require careful energy accounting.
- Improvements in the efficiency of laser technologies, in how ignition is achieved (enabled by better simulations), and in the frequency that high-power lasers can be fired have significantly improved the math for fusion concepts.

Magnetic Confinement Fusion

- Magnetic Confinement Fusion (MCF) approaches use strong magnetic fields to confine a plasma at the conditions needed for fusion.
- MCF devices are often shaped like donuts.
- The magnetic fields don’t heat the fuel directly. They merely confine the hot plasma so that the target temperature and density can be reached. Hot fuel atoms injected into the plasma provide the heat.
- Decades of experimental MCF programs around the world have culminated in ITER, a 35-nation collaboration to build the world’s largest fusion research reactor. It is expected to begin operation in 2025.
- Several startups are developing improvements to research reactor designs, or entirely new concepts utilizing magnetic confinement. Some of these companies have been active for over 20 years.

Fusion and Future Energy Markets

- Commercial fusion power is 10-15 years away. I expect my toaster to run on fusion by 2035.
- Though the cost of solar and other electricity sources will continue to fall, fusion is likely to be economical (a napkin-level analysis suggests a levelized cost of electricity of $0.06-0.11/kWh).
- The cost of fusion power is highly dependent on factors such as the size of the power plant, the cost of converting steam into electricity, and the discount rate (cost of capital).

Introduction

Why Fusion?

Nuclear Fusion could massively alter the energy landscape of the future. Fusion is incredibly attractive as an energy source because:

- It can be built almost anywhere in the world (no wind or sunshine needed).
- The fuel (deuterium) is available in ocean water. Fusion would eliminate our reliance on volatile commodity markets and enable true energy independence.
- The fuel is essentially unlimited, and can support future increases in energy demand.
- It takes up little space relative to wind and solar, and can be co-located with increasingly dense population centers. It does not require extractive mining or drilling.
- It provides dispatchable baseload power year-round.
- It is inherently safe and easy to turn off. Unlike nuclear fission with uranium and plutonium, there is no risk of runaway reactions or meltdown.
- It produces no CO_2 or other emissions, and no long-lived radioactive waste.

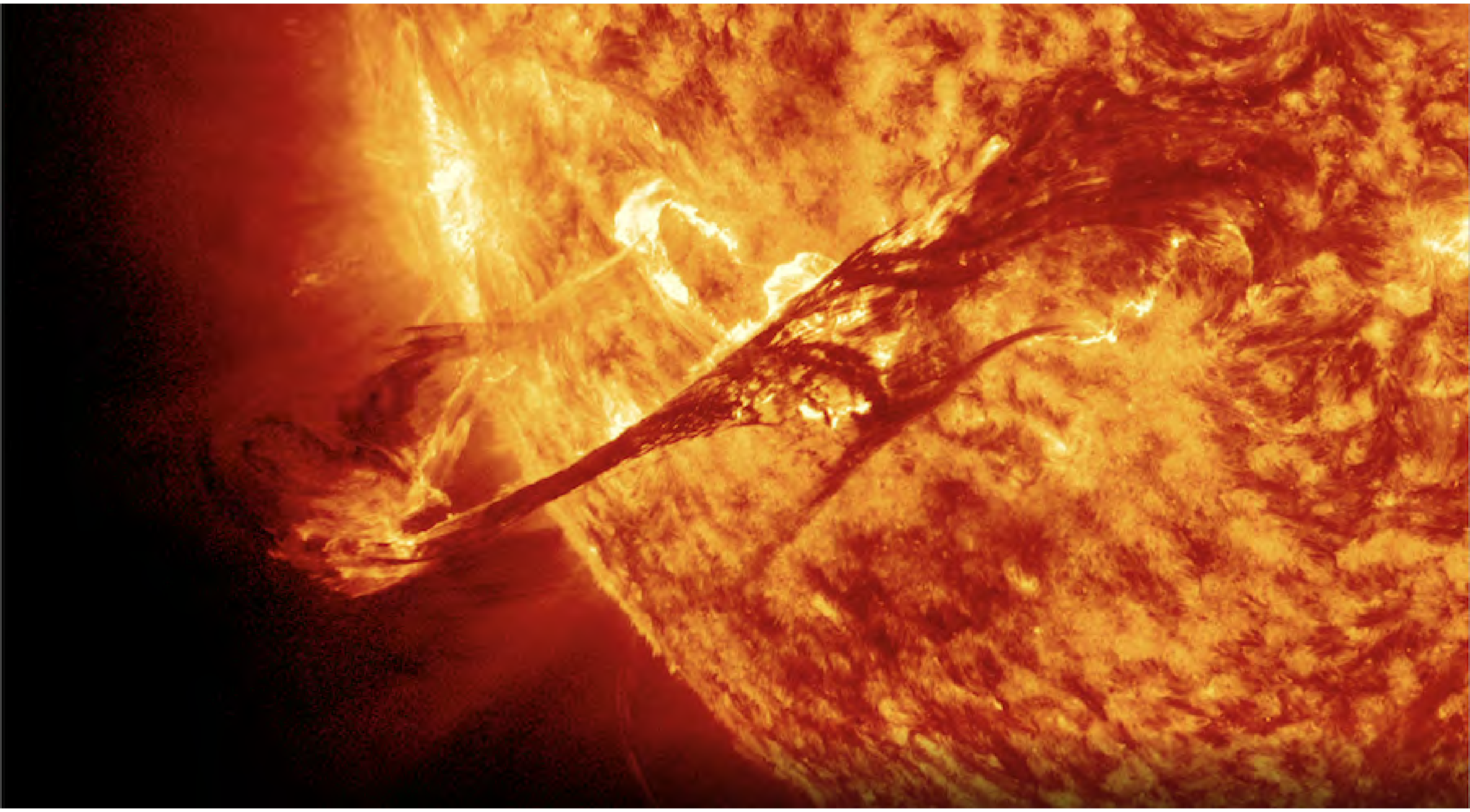
While nuclear fission (what we refer to as nuclear power today) is a carbon-free source of baseload power that is well established, there are several reasons that fusion would be even better. The fuel used by nuclear fission plants, Uranium-235, can be enriched to make bombs, leading to nuclear weapons proliferation concerns. Traditional nuclear plants also generate some radioactive waste, and there is the low probability of an accident leading to release. [1] Currently, the most significant barrier to building new conventional nuclear (fission) plants in the US is economic—the cost per kW of new capacity added simply isn't competitive with other forms of energy generation. [2]

What is Fusion?

Nuclear fusion is essentially the opposite of nuclear *fission*, which powers nuclear plants today.

*In nuclear **fission**, a single large atom, usually Uranium-235, breaks into two smaller atoms and releases energy. In nuclear **fusion**, energy is produced when two atoms are smashed together to become one larger atom.*

This process is what powers the sun, and has produced all the heavier elements in the universe. [3] On earth, the atoms used for fusion are usually isotopes of hydrogen, the lightest element on the periodic table. [4]



Our sun is a giant ball of hydrogen and helium; the pressure of gravity causes hydrogen atoms in the sun's core to fuse into helium, providing energy for the entire solar system. Source: [NASA](), under CC

The question isn't "is fusion possible". The hydrogen bombs that were tested in the 1950s (and are now in the arsenal of most of the world's nuclear powers) are called hydrogen bombs because *most of their energy comes from the fusion of hydrogen isotopes.* Their precursor, the atomic bomb deployed by the US in WWII, instead produces energy from nuclear fission of enriched uranium or plutonium. In a hydrogen bomb, fusion is triggered by a mini-atomic bomb (fission of uranium or plutonium), releasing incredible amounts of energy. While the hydrogen bomb program demonstrated that fusion can occur with sufficient energy input, it's worth noting that it relies on enriched uranium or plutonium to work—fusion on its own has not been weaponized.

Since then, we have found ways to achieve fusion other than by detonating atomic bombs. The challenge is providing enough energy to overcome the repulsive forces between atoms. Once this energy barrier is exceeded, the two atoms fuse together - the new atom weighs a tiny bit less, and that extra mass is converted into lots of energy. This is an example of Einstein's famous equation, E (energy) = m (mass) x c (speed of light)^2. Unfortunately the repulsive forces between atoms are so strong that the fuel (e.g. hydrogen) must be brought to millions of degrees C without melting the container or letting it cool off.

Inside the Joint European Torus, one of the largest magnetic confinement fusion research facilities. [Image Credit]

This is the big challenge for physicists: How can we get the atoms (1) hot enough and (2) close enough together for (3) long enough for fusion reactions to happen? These requirements have a name: the Lawson Criterion, or the "Triple Product".

Triple Product = (1) plasma temperature x (2) density x (3) confinement time

Physicists have calculated the triple product needed to make the fuel "ignite", producing enough energy from fusion to keep fusion reactions going. Over the past six decades, humans have tried many different approaches to achieve these conditions. Recent experimental fusion systems have come close. In 2018, the JT-60 in Japan reached about half of the minimum value. (Getting within an order of magnitude is a huge deal!)

One strategy to reach sustained fusion is to use powerful magnets to contain the hot fuel. At the temperatures needed for fusion (over 100 million degrees C), gases become plasmas, which conduct electricity. Because of how magnetic fields and electric fields interact, magnets can be used to keep the high temperature plasma (fuel) away from the walls while the fusion reaction takes place. This approach is called **magnetic confinement fusion (MCF)**, and the machine that results looks like a giant robot donut.

The second major non-bomb strategy to achieve fusion uses lasers and is called **inertial confinement fusion (ICF)**. A small amount of fuel is released into a chamber and then zapped with powerful lasers that quickly heat and compress the fuel before it can fly apart. We will talk more about inertial confinement fusion technology in the next section, but for now remember that there are two main routes to fusion power: magnets and lasers.

Short fusion events have been observed in research facilities all around the world. ***However, it has always required more energy to make the fusion happen than is released when the atoms come together.***

For fusion power to go from dream to reality, two things must happen. First, ignition, or net energy gain, must be achieved—this is the holy grail of all fusion programs. However, to really change the world, fusion companies must also show a credible path to power plants that are not only safe and reliable, but also make economic sense. More on both topics to come.

Why Now?

Looking back at past promises and news articles, it is easy to understand the joke—"fusion is always 20 years away". The process of getting two atoms close enough together to fuse is incredibly complex and difficult to model. Then a ton of energy and complex equipment are needed to test if the model is right. For many decades after the hydrogen bomb was developed, the money required and perceived weapons implications meant that research fusion was run by governments and was often classified.

Fusion research was slowly declassified and merged with civilian and academic plasma physics research, but fusion projects were still by necessity "Big Science". The mainstream coverage of fusion that most of us remember (circa 2000s) involves ITER, an enormous international MCF (magnet fusion) project under construction in France that began back in 2007. Undoubtedly much will and has been learned from ITER (not the least training thousands of scientists and technical tradespeople), but it was envisioned and structured as a research project, not a business.

Over the past twenty years, a growing number of private companies have formed to commercialize new fusion concepts and the advances made in research. Startups such as Commonwealth Fusion Systems (CFS) are demonstrating that fusion might be possible on a smaller scale and faster development timeframe than ITER. Importantly, CFS is leveraging development of superconducting magnet technology (which has applications beyond fusion) to make a business case.

Advances in key technologies—lasers and optics, materials, electronics, and sensors (often driven by non-fusion applications) have reduced potential costs and enabled new approaches to achieving ignition. The impact of increased speed and power of computation also cannot be understated. Without good simulations and knowledge of the underlying physics, designing a fusion experiment (let alone a power plant) is an expensive trial and error process. The ability to include more physics and materials properties in simulations has enabled better experiment and equipment designs with fewer false starts and failures.

Without good simulations and knowledge of the underlying physics, designing a fusion experiment (let alone a power plant) is an expensive trial and error process.

ELI-Beamlines (Extreme Light Infrastructure) facility in the Czech Republic opened in 2018. It enables 10 laser shots to be fired per second, vs 1–2 shots per day for facilities built 10 years ago. [Image Credit]

Complementing the great strides in simulation capabilities, several state-of-the-art facilities for laser-based plasma physics research have come online in the last 10 years, enabling more laser experiments with higher power and more precision than was ever possible. The increase in both computation and laser capabilities has vastly increased the knowledge base and confidence of the fusion community. This also means that there is now an expanded network of user facilities that early-stage fusion companies can use to prove out their technology, rather than having to spend tens if not hundreds of millions to build these facilities right out of the gate.

This combination of factors—advances in key technologies, the speed and power of computation, available research facilities, and increased presence of business-minded entities—has brought fusion energy into the realm of possibility.

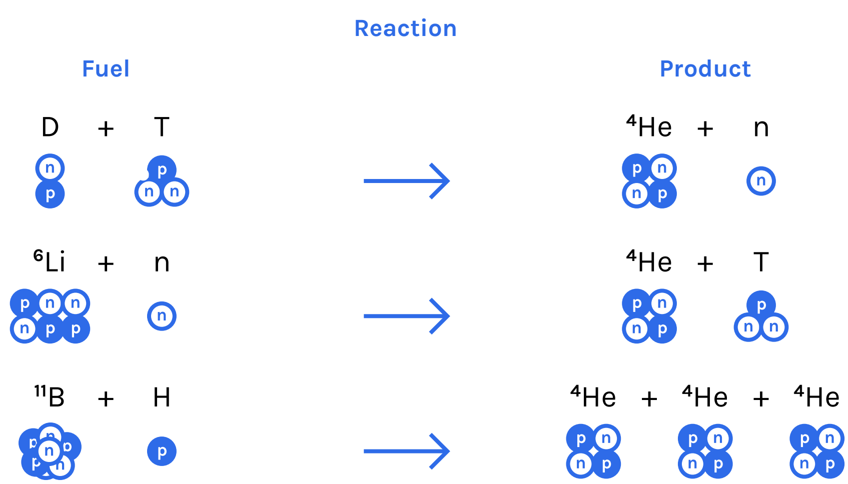
Looking halfway across the universe at light produced by fusion with the Hubble telescope [Image Credit]

Inertial Confinement Fusion Technology: "Fusion with Lasers"

One of the two main branches of fusion is Inertial Confinement Fusion (ICF) technology - fusion with lasers. The basic idea sounds like science fiction: small fuel pellets are repeatedly launched into a chamber, where they are uniformly struck by powerful laser beams until fusion occurs, releasing an even more enormous quantity of energy. In most concepts, the energy released is captured by the chamber as heat, which is converted into reliable, carbon-free electricity.

How does Inertial Confinement Fusion work?
There are three components of ICF fusion: the "target" containing the fuel, the "driver" (lasers) to ignite fusion in the target, and the chamber to contain and convert the energy released into electricity.

The Target: Fuel for Fusion
Most fusion contenders use the same mixture of hydrogen isotopes, deuterium, and tritium (DT) for fuel, because these atoms will fuse at the lowest temperatures. Deuterium is a hydrogen atom (a proton) with one extra neutron. Tritium is a hydrogen atom with two extra neutrons. When deuterium and tritium fuse, they produce a helium atom (also called an alpha particle), neutrons, and a large amount of energy. [5] Most of this energy (80%) is carried by the neutrons.



Three important fusion reactions: (Top) fusion of deuterium (D) + tritium (T) to form helium-4 and a neutron (n); (Middle) neutron capture with a lithium (Li) blanket produces helium and tritium (T); (Bottom) Hydrogen and boron-11 fusion produces 3 helium-4 atoms.

Three important fusion reactions: (Top) fusion of deuterium (D) + tritium (T) to form helium-4 and a neutron (n); (Middle) neutron capture with a lithium (Li) blanket produces helium and tritium (T); (Bottom) Hydrogen and boron-11 fusion produces 3 helium-4 atoms.

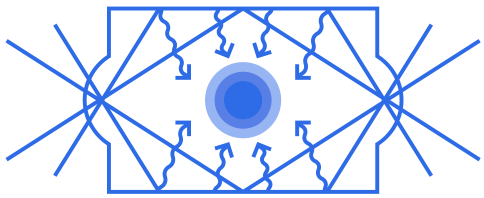
While deuterium is abundant in the ocean, tritium will be challenging to manage. Tritium is unstable, radioactive, and rare—it is currently made by bombarding lithium metal with radiation, or as a byproduct at some nuclear power plants. Luckily, the amount of tritium needed is very small—on the order of milligrams per fusion event, or perhaps 50–500 kg per year. Additionally, tritium can be produced at the fusion power plant where it is used by capturing the neutrons with lithium. So, deuterium can be harvested from the ocean, and tritium will be produced or "bred" in the fusion reactor.

An attractive alternative is to use "aneutronic" fuels rather than DT. Aneutronic fuels are combinations of atoms that produce few or no neutrons when they fuse, such as mixtures of hydrogen and boron. Aneutronic fuels have two big advantages: 1) they avoid the complexities of breeding and handling tritium, and 2) they do not produce neutrons, which induce radioactivity in materials and require a moderator. A third benefit is that the helium (He) particles released could produce electricity directly, eliminating the need for a steam turbine and other expensive equipment to convert heat into power.

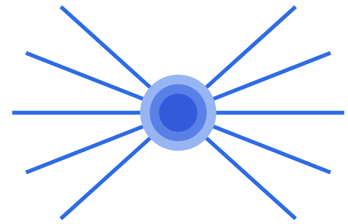
The trade-off is that the ignition temperature for aneutronic fuels is much higher, making fusion harder to achieve. For example, the temperature needed for hydrogen and boron (H-B11) fusion is ***ten times higher*** than the ignition temperature needed for DT fusion. Recent research has suggested that this barrier could be lowered significantly by exploiting new plasma physics. [6] Given that ignition of the easier DT fuel has yet to be demonstrated, and that energy losses increase dramatically with temperature, this is a big ask.

The Driver: Fire the Lasers!

A large amount of energy is needed for the atoms within the fuel to fuse—on the order of several megajoules (MJ) per target. In ICF, this energy is delivered by lasers. The lasers can either hit the fuel directly ("direct drive"), or hit a container with the fuel inside ("indirect drive"). In both approaches, fusion is initiated by focusing the laser energy on a small "hotspot", which ignites the remaining fuel so quickly that its inertia prevents it from escaping.



Indirect Drive



Direct Drive

In **indirect drive** fusion processes, the laser energy is focused on a small metal cylinder with the fuel inside. This cylinder is called the “hohlraum”. The energy from the laser is re-emitted as x-rays inside the cylinder. These x-rays heat the outer layers of the fuel pellet, causing compression and heating of the inner layers to achieve ignition.

The advantage of indirect drive is that the x-rays are more evenly distributed than the original laser beams, promoting even heating of the fuel. Instabilities that arise during heating are one of the key challenges for achieving fusion. The trade-off is that the energy transfer between the hohlraum and the fuel is poor, and a lot of energy is lost in this conversion step.

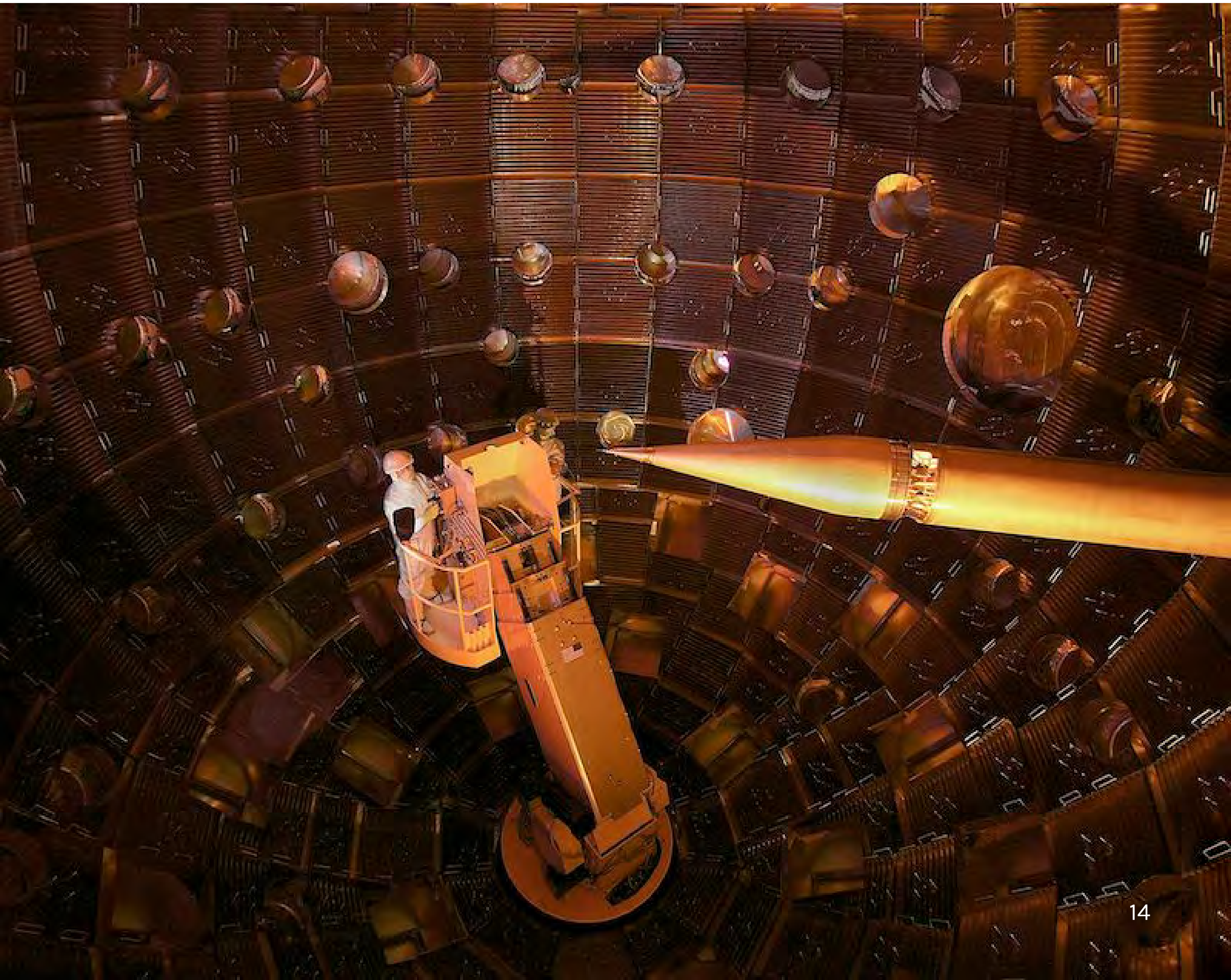
In **direct drive** fusion approaches, the lasers are focused directly on the fuel. The advantage of direct drive approaches is that they generally use laser energy more efficiently. Approaches to direct drive ICF differ by how many times they shoot the target with lasers, how long each laser shot lasts, what type of laser is used, and many other variables. A few types of direct drive fusion are described in the notes. [7]-[10]

The number of times they “fire the lasers!” in a given period is a critical performance parameter, called the **repetition rate**. The total amount of power generated by a fusion power plant is set by the net electricity produced per target, but also the number of targets burned per second or hour. Based on the amount of energy each fuel pellet is expected to release, a reasonable target for a commercial fusion facility is 1–10 Hz, or firing the lasers 1 to 10 times per second.

The Chamber: From Particles to Power

Chambers used at research centers and in concepts for future fusion plants are typically a spherical metal chamber with ports (holes) for the laser beams to hit the target. If neutrons are produced, the chamber's interior must be blanketed with something to stop the neutrons, called a moderator. Lithium is a great moderator because it reacts with neutrons to make tritium, which can then be used as fuel. [11] One design option is a liquid lithium "waterfall", where molten lithium flowing down around the chamber picks up the neutrons and heat produced by fusion.

Inside the National Ignition Facility's target chamber [Image Credit]



Most designs to date capture the fusion energy as heat, and then use this heat to generate steam as in conventional gas, coal and nuclear power plants. The steam is converted to electricity in large turbines—the efficiency depends on the temperature of the steam. Designs that produce electricity directly from fusion products—avoiding the need for steam generators and turbines—would significantly increase efficiency and cut costs.

Fusion as Energy Accounting

Achieving net power production with fusion is essentially an energy accounting problem on multiple scales. Overcoming the repulsive forces between atoms so that they can get close enough to fuse takes a lot of energy. Once a small part of the fuel has started to fuse, the fusion reactions generate a significant amount of heat energy, which can start more fusion reactions. However, anyone who has tried to heat a poorly insulated home knows that not all the energy put into the house actually raises its temperature.

The key to achieving and maintaining fusion is to design a scheme where as much fusion energy as possible contributes to more fusion, instead of being lost to the environment. If the fusion reactions keep going long enough to generate more energy than is put in, it could be the basis for a power plant.

This is measured by the **energy gain** "**Q**", or the ratio of energy produced to the driver energy used to achieve ignition. **Ignition** is the point at which the energy given off in the fusion reactions is high enough to maintain the temperature of the fuel and produce additional fusion reactions—to keep the fuel "burning".

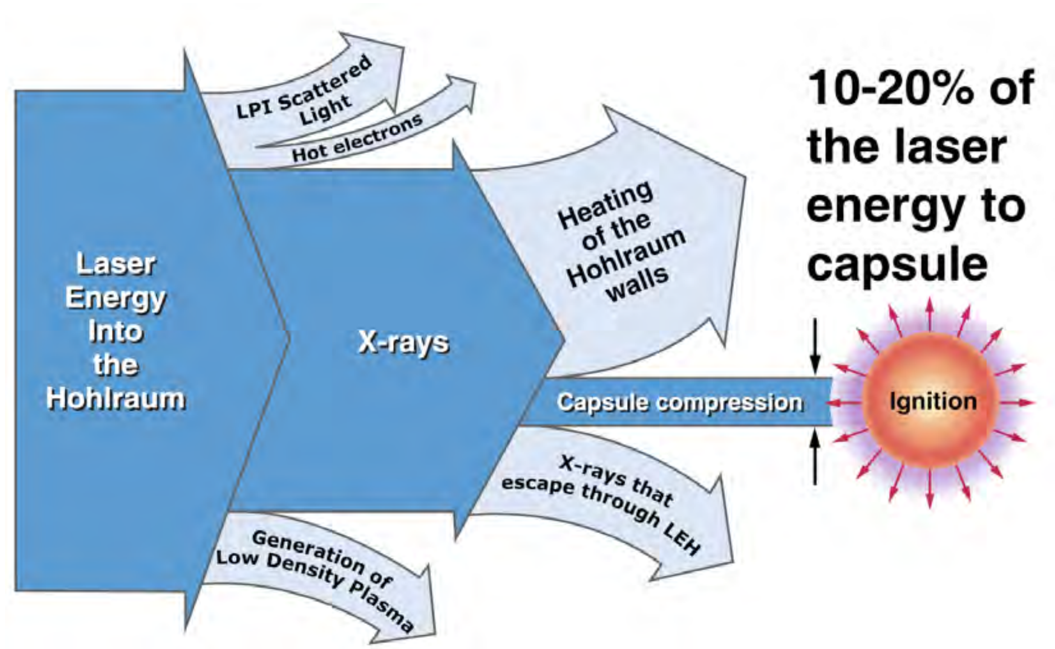
The energy gain "Q" is the ratio of the energy produced by fusion to the driver energy needed to achieve ignition.

The larger engineering challenge is producing ignition without "breaking the bank" in terms of energy. Energy is lost every time it is transferred from one form to another, which happens several times between the laser's power supply and the fuel. Some places where energy can be lost include:

- Powering the laser: the efficiency of converting electricity to laser light might be 1–20% depending on the laser and amplifier technology.
- Modifying the laser light, e.g. converting the laser light from the infrared part of the spectrum to a shorter wavelength: efficiencies of 50%-100%.
- Laser to x-rays (indirect drive): ~85% of the laser energy is converted to x-rays.
- X-rays to target (indirect drive): ~15% of the energy from the x-rays is deposited in the target.
- Laser to proton beam (in some direct drive approaches): ~10% laser energy is converted to protons.

The Sankey diagram from NIF below provides a great visual example. A rule of thumb is that the laser efficiency x Q needs to be at least 10 for ICF to be commercially viable.

The bottom line is that both demonstrating ignition and demonstrating a positive energy balance are needed for a successful fusion power plant.



Sankey Diagram showing how much of the initial laser energy (big arrow at left) reaches the capsule and contributes to ignition, and where it is lost along the way. (From Lawrence Livermore National Lab / [Image Source](#))

How Technology is Changing the Balance Sheet

Laser Technology

Most ICF simulations suggest that lasers with some combination of high power, short pulse length, accuracy over a micrometer area, and advanced pulse shaping are needed. These capabilities are all now within reach. Large laser systems (multiple lasers focused on one spot) that deliver high peak powers exceeding one Petawatt (PW) have been constructed at dozens of research facilities worldwide. Lasers are available that can deliver kilojoules of energy in microseconds (a millionth of a second), or fire pulses as short as femtoseconds (one 1,000,000,000,000th of a second).

Fusion research facilities built prior to roughly 2010 relied on flash lamp pumped lasers, which can only be fired a few times a day at best. New diode-pumped solid state lasers can reach higher repetition rates (up to 1–10 Hz for some lasers) due to advances in cooling. The efficiency is also dramatically increased: glass flash-lamp pumped lasers convert about 1% of electricity “from the wall” into laser light, while diode-pumped solid state lasers can achieve up to 20% efficiency.

The precision of laser optics has increased to heat a target smaller than a pinhead. Delivering the same amount of power to a smaller area increases the local temperature to achieve ignition.

One reason that relevant laser technologies have advanced so rapidly is their applications beyond the fusion community. Associated research on laser-matter interactions has also enabled generation of radioisotopes for positron emission tomography (PET), targeted cancer therapy, medical imaging, and the transmutation of radioactive waste. Each of these promising applications requires lasers with peak power of hundreds of terawatts (TW) to petawatts (PW) and with average power of tens to hundreds of kilowatts. [12]

Simulation and Controls

The other challenges that have prevented ignition from being achieved are subtle effects that lead to energy escaping the system: 1) non-symmetric laser illumination, 2) laser-plasma instabilities (LPIs), and 3) hydrodynamic instabilities during fuel compression. Advanced simulations and increased computing power have enabled scientists to model and predict more complicated interactions.

Technology Cost

This is the last key consideration—how have the costs of various components come down, and how might a fusion power plant be built to deliver energy at a competitive rate?

Magnetic Confinement Fusion

We previously discussed inertial confinement fusion, where fusion occurs in brief bursts, like a Supernova. In contrast, much of magnetic confinement fusion seeks to confine a plasma that burns steadily like the sun.

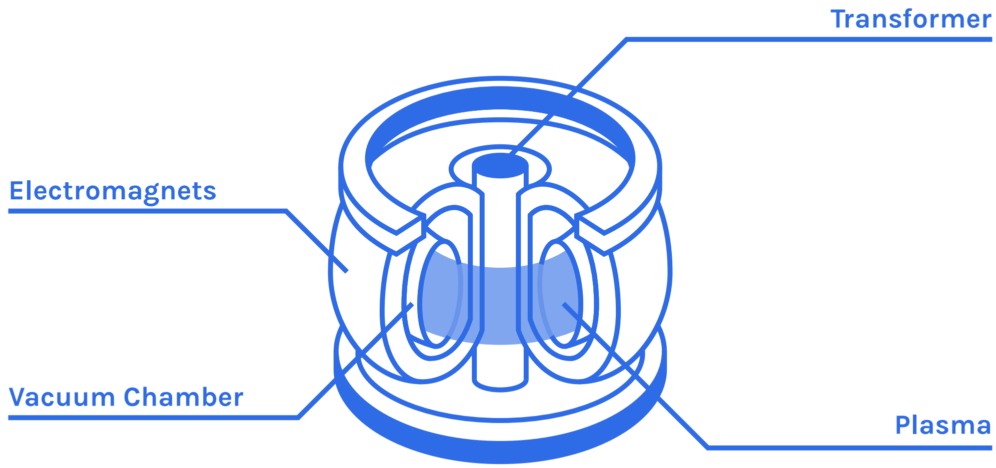
How Does Magnetic Confinement Fusion (MCF) Work?
In all types of fusion devices, we need to overcome the high energy barriers between atoms for fusion to occur. In MCF devices, the conditions for fusion are met by generating a plasma with a high electric current (lots of ions), confined to a small region (so they are very dense and close to each other), that is also very, very hot.

Most of the magnetic fusion devices built to date share these common design features:

Vacuum Chamber
In magnetic confinement fusion, the shape of the chamber is key. The most common shape is a donut-shaped metal chamber. The goal is to confine the 100 million degree plasma inside the donut, like the cheese in a stuffed-crust pizza. The metal donut has to be kept under vacuum so other atoms or molecules don't disrupt the plasma. Also, the chamber must be made out of materials that can survive getting slammed by high-energy neutrons during normal operation, and can contain a massive release of heat and energy if the plasma becomes unstable.

Magnetic fields
Around the metal donut are coils of wire - electromagnets - that produce strong magnetic fields. These coils, or solenoids, help "stiffen" the plasma and confine it to its donut-shaped track. Initially, these coils were copper wires, which constantly need power to produce a magnetic field. Today's designs use advanced superconducting materials, which are able to generate strong magnetic fields *with almost no power input* after they are initially charged. [13]

Other electromagnets help create an electrical current in the plasma that drives it around in a circle—these work similarly to an electrical power transformer.

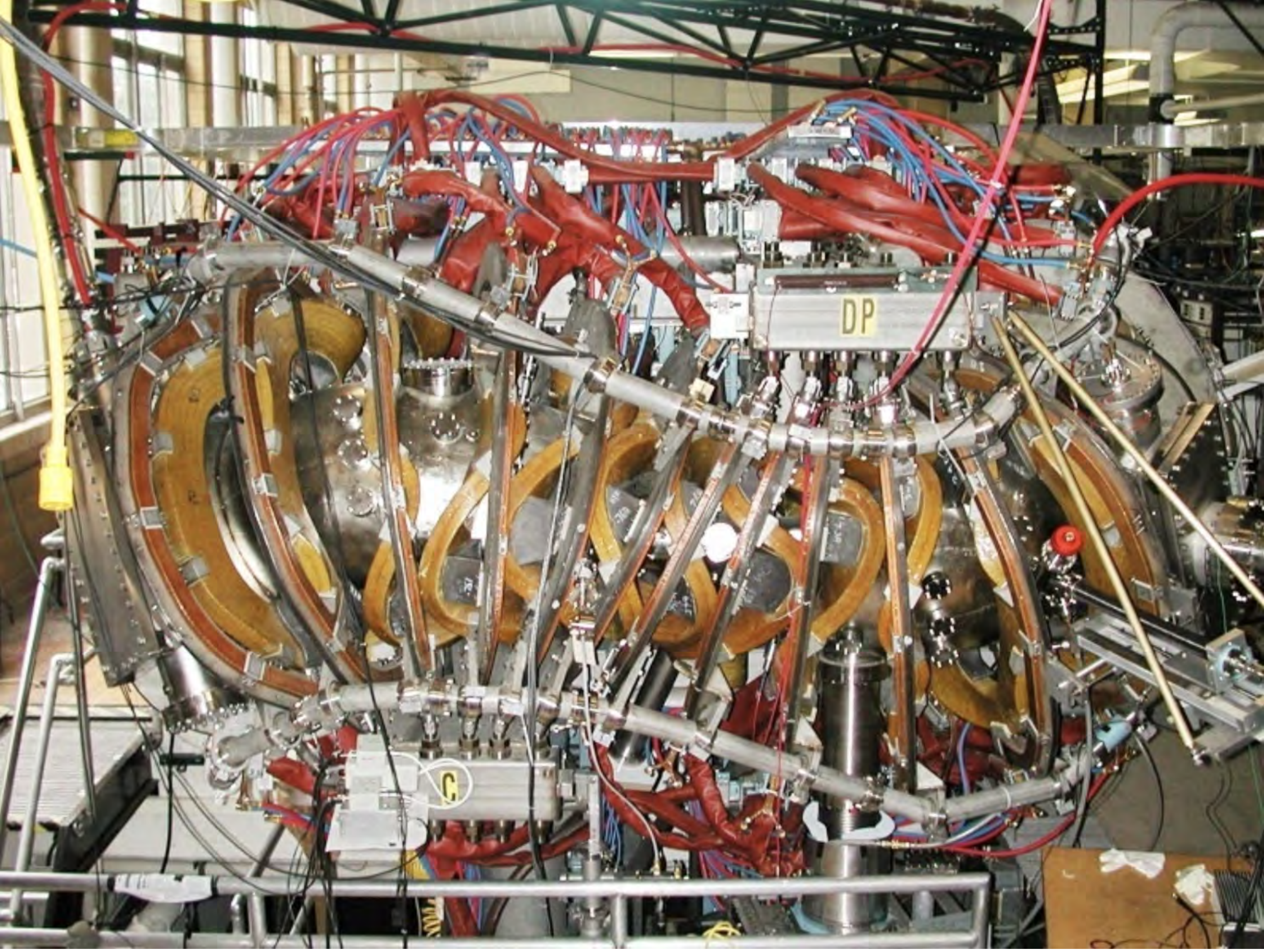


Tokamak Schematic
The plasma itself acts as a third source of magnetic fields. The electrical currents carried by the plasma create magnetic fields around it that "pinches" it into a narrower cylinder. When the magnetic fields generated externally by the coils are much greater than the fields generated by the plasma itself, the device is called a tokamak. [14] This is the most common type of magnetic fusion device.

Spheromaks and Field-Reversed Configuration (FRCs) are also MCF devices that are roughly donut-shaped, but don't require magnetic coils running through the center of the donut.

Completing the MCF managerie are Stellarators, which look like a cross between a donut and a mobius strip. Stellarators generate twisting magnetic fields that help confine the plasma, so that the magnetic fields produced by the plasma aren't needed. This makes the plasma more stable, but the windy electromagnets are hard to build.

Fuel
The atoms used to fuel fusion reactions are the same whether lasers or magnets are used. A mixture of deuterium (D) and tritium (T) is the easiest to ignite. Unlike inertial confinement approaches, for MCF devices the fuel to exists as a large volume of plasma rather than a tiny target.



An experimental stellarator with "twisted" electromagnets
Image Source: The HSX Team, University of Wisconsin-Madison

Importantly, the magnetic fields don't actually heat the fuel to cause fusion. They merely confine the hot plasma so that the temperature and density can reach the levels needed for fusion to happen.

Heating
To understand how the plasma is heated, we need to know that *a plasma contains a high fraction of charged particles- ions*. A plasma is essentially a soup of ions: the particles in a plasma have an electric charge, so they feel and respond to electric fields. A gas transitions to a plasma when a significant fraction of the atoms in the gas become separated from one or more of their electrons. For example, a deuterium atom has one proton, one neutron, and one electron. Once it is ionized inside a tokamak, the proton and neutron remain together as a positive ion, and the electron goes off as a negative ion. This soup of ions—the plasma—can now be controlled by electric and magnetic fields.

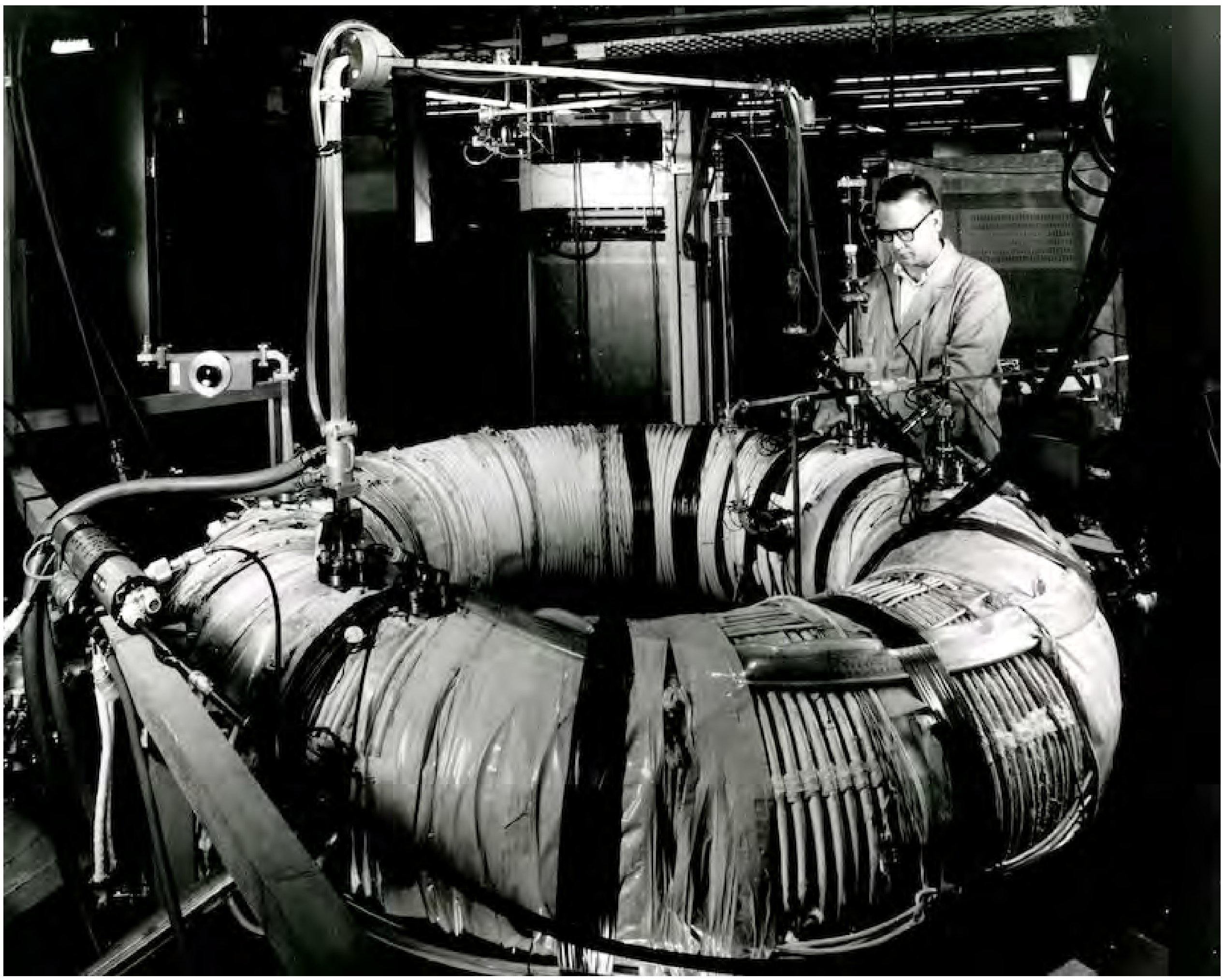
The plasma is heated with a method called **neutral beam injection**. Just like it sounds, beams of high temperature neutral particles (typically the same atoms as the fuel) are injected into the plasma chamber. Because these un-ionized particles have no charge yet, they don't feel the magnetic and electric fields that confine the plasma and zip happily in. Once inside the plasma, they collide with ions, give up their heat, lose their electrons, and become part of the plasma themselves.

Energy Conversion
For the fusion plant to generate power, the particles produced in the fusion reaction must be safely captured and their energy converted to electricity. Designing the lithium blanket to collect neutrons and breed tritium is a significant engineering challenge for all fusion concepts. In particular, developing suitable materials for the "first wall" between the plasma and lithium or other coolant is a significant challenge. This is especially true given the complex geometry and the need to maintain vacuum inside the region with plasma.

Another key element of tokamak design is the diverter, which sits at the floor of the vacuum chamber. It extracts heat and larger particles ("ash") produced by the fusion reaction, reduces plasma contamination, and helps protect the surrounding walls from overly high heat and neutron strikes.

In short, magnetic confinement fusion devices are highly complex. These devices have been developed and refined over decades.

Today's cars look very different from the initial Model-T, though some of the basic design features are the same. Similarly, magnetic fusion devices have also evolved significantly since the first research facilities in the 1960s.



An early magnetic confinement research device, circa 1967. Courtesy of the U.S. DOE
Image Credit

Current Status
Mainstream fusion has meant magnetic confinement fusion for much of the last 50 years. In the two decades following the 1973 oil crisis, several tokamaks and other magnetic fusion research facilities were built in the US, Europe, and Japan. Notable among these are the TFTR at the Princeton Plasma Physics Lab (now closed), JT-60 in Japan, and the Joint European Torus (JET) in the UK. The JET still holds the record for fusion output at 16 MW from an input of 24 MW of heating in 1997. While most of these devices are tokamaks, the Wendelstein 7-X MCF device was recently completed in Germany based on the related Stellerator concept.

Over time, magnetic confinement efforts and funding became focused on fewer, larger facilities. The pinnacle of this is the ITER (International Thermonuclear Experimental Reactor) project, which began in 2007 as a collaboration between the European Union, India, Japan, China, Russia, South Korea and the United States. (ITER also means “the way” in Latin.)

The ITER tokamak complex during construction in April 2018
By Oak Ridge National Lab [Image Credit]

Despite early delays, the first phase of ITER's construction is now more than half complete. It is now scheduled to begin experiments in 2025, and by 2035 it will be ready to conduct experiments with a tritium-deuterium mixture.[15] In particular, methods to control the plasma and extract the electricity-producing heat will be tested and developed at large scale. The learnings around materials development and energy extraction, even in the design phase, have benefited fusion programs, both public and private.

Research and development on MCF has led to breakthroughs in superconducting magnets, vacuum technologies, complex cryogenic systems, ultra-precise construction, and robotic material-handling systems.

Where is MCF headed?

Research facilities around the world, including ITER, also continue to advance our understanding of both plasma physics and how to engineer physical systems.

A 2019 report from the US National Academy of Sciences identified the key development needs to enable fusion as: "the materials and technologies needed to extract the heat and recirculate tritium and to promote the industrial development of very-high-field superconducting magnets. Innovations should [also] be encouraged and developed to simplify maintenance and lower construction cost." This is a significant shift from fundamental science to practical power plant considerations.

Framing development in terms of specific engineering challenges inspires optimism. Magnetic confinement fusion systems are undeniably large and complex. Many of the requirements around materials, welds, and maintenance are enough to give an engineer pause. However, progress in these areas has the potential to "lift all boats" — paving the way for a successful fusion plant, whether it is a direct successor of ITER or a totally different design.

Intermediate Fusion Concepts

While the two main strategies to achieving fusion: Magnetic Confinement Fusion (fusion with magnets) and Inertial Confinement Fusion (fusion with lasers) have dominated fusion efforts for decades, this is becoming an increasingly poor simplification. Today, there are a spectrum of “Other” possible fusion reactors between just-magnets and just-lasers, and a few that don’t fit easily into either bucket. [16]

Inertial confinement fusion relies on very dense plasmas produced within the target--so dense, the plasma can’t get out of it’s own way when it gets smashed by lasers. At the other extreme, the environment inside magnetic confinement fusion devices is under vacuum, and is much less dense than air. [17] Thanks to new simulation tools, many additional concepts have been imagined in the intermediate density range. Fusion devices that operate with plasmas more dense than MCF, but less dense than ICF, are called “Magneto-Inertial Fusion”.

Two examples of intermediate-density approaches that are being commercialized are magnetized target fusion (MTF) and stabilized Z-pinches. General Fusion’s MTF approach uses an imploding conductive liner to compress a “magnetized target” plasma, similar to how a piston compresses gas to ignite it in a diesel car engine. Zap Energy’s shear-stabilized Z-pinch uses a high speed plasma gun to form, compress, and heat a column of plasma to fusion conditions.

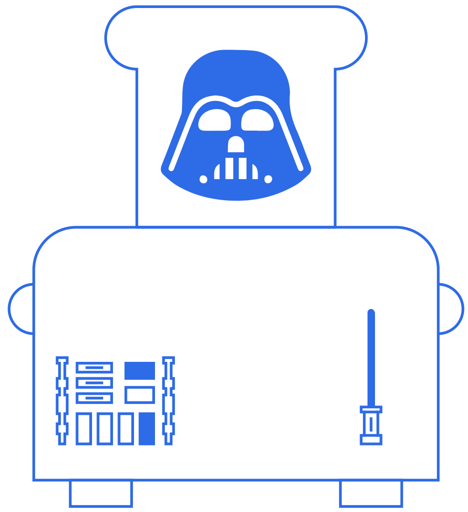
A third concept in the “Other” category are Mirror Machines, which use strong magnetic fields at each end of a tube as plasma “mirrors” to reflect the plasma back to the center. This approach is promising but hasn’t produced a private company yet.

Fusion Costs and Future Energy Markets

Given how far fusion technologies have come, when will fusion power first hit the electric grid?

When we will be able to run our toasters on fusion power? Recent progress from private companies suggests this could happen in 15 years or less.

Let’s explore why, and what the costs of this might be.



The first step to fusion power is getting to **net energy gain**, where the energy produced by fusion is greater than the energy needed to heat the plasma. We discussed some of the challenges to achieving net energy gain, or ignition in previous sections. The first fusion system to reach net gain will contain many first-of-a-kind (FOAK) components: giant lasers, magnets, materials that can hold a mini-sun, and all the controls and diagnostics to make them work. These systems may cost hundreds of millions or billions of dollars, depending on the design (more on this below).

It will not happen overnight. However, the race to achieve net energy gain contains a growing number of players, many of whom target net gain in just five years. This is a dramatic shift in the typical timelines for fusion projects from past government-led efforts.

The largest government effort, ITER (the international experimental tokamak project previously described), is currently scheduled to begin its first experiments in 2025. Deuterium-tritium (DT) experiments that could achieve net energy gain will start after 2035.[18] However, ITER doesn't include the back half of the power plant, which turns the heat from fusion into electricity. ITER will conduct experiments to optimize the design for DEMO, a larger tokamak fusion facility that is slated to generate electricity in 2050. [19] Fusion energy through the ITER program is currently at least 30 years away.

The timelines targeted by private companies and startups are much faster. Some have publicly announced plans to achieve net energy gain in 2025 or before. MIT-backed Commonwealth Fusion (which has designed a smaller, more compact tokamak) recently raised an additional $115mm to complete their concept and achieve net energy gain in 2025. The UK's Tokamak Energy also targets net energy gain midway through the decade, and first electricity to the grid in 2030.

Several inertial confinement (laser) startups including Marvel Fusion, HB11 Energy, and Innoven Energy have also emerged to leverage years of research at labs around the world. Magneto-Inertial fusion teams offer even more shots on goal. Within the next 5-9 years, one of these teams will demonstrate net energy gain.

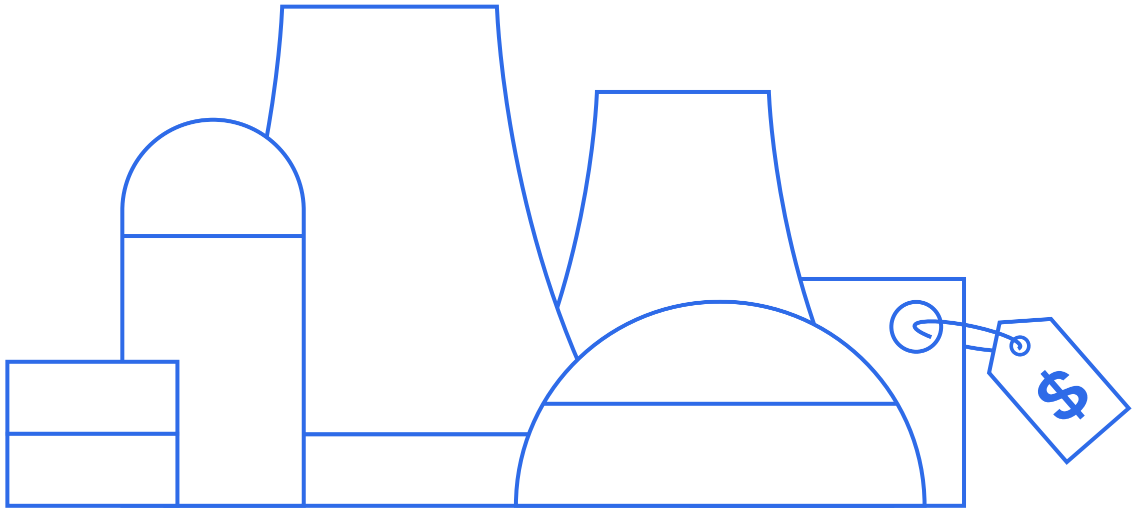
It will likely take an additional 5-10 years from net gain to getting electricity on the grid, assuming:

- The world funds enough fusion designs that one of them works.
- Regulators are able to play ball and create pathways for fusion companies to obtain operating permits.
- No more pandemics / giant meteors / other disasters push schedules back.
- The electricity produced is cost competitive.

I am optimistic that we will see the world's first fusion power plant by 2035.
The relevant math here:

5 years	+	5-10 years	=	10-15 years
to net energy gain		to complete the power plant		to fusion power on the grid

What Will Energy Cost in 2035?
When fusion power breaks onto the scene in 2035, will we want to pay for it? Or will prices for other sources of electricity continue to fall, making it difficult for fusion to compete? The question of what energy prices will be in the future is not an easy question—entire organizations and thousands of experts around the world are working on predicting the future of electricity markets.



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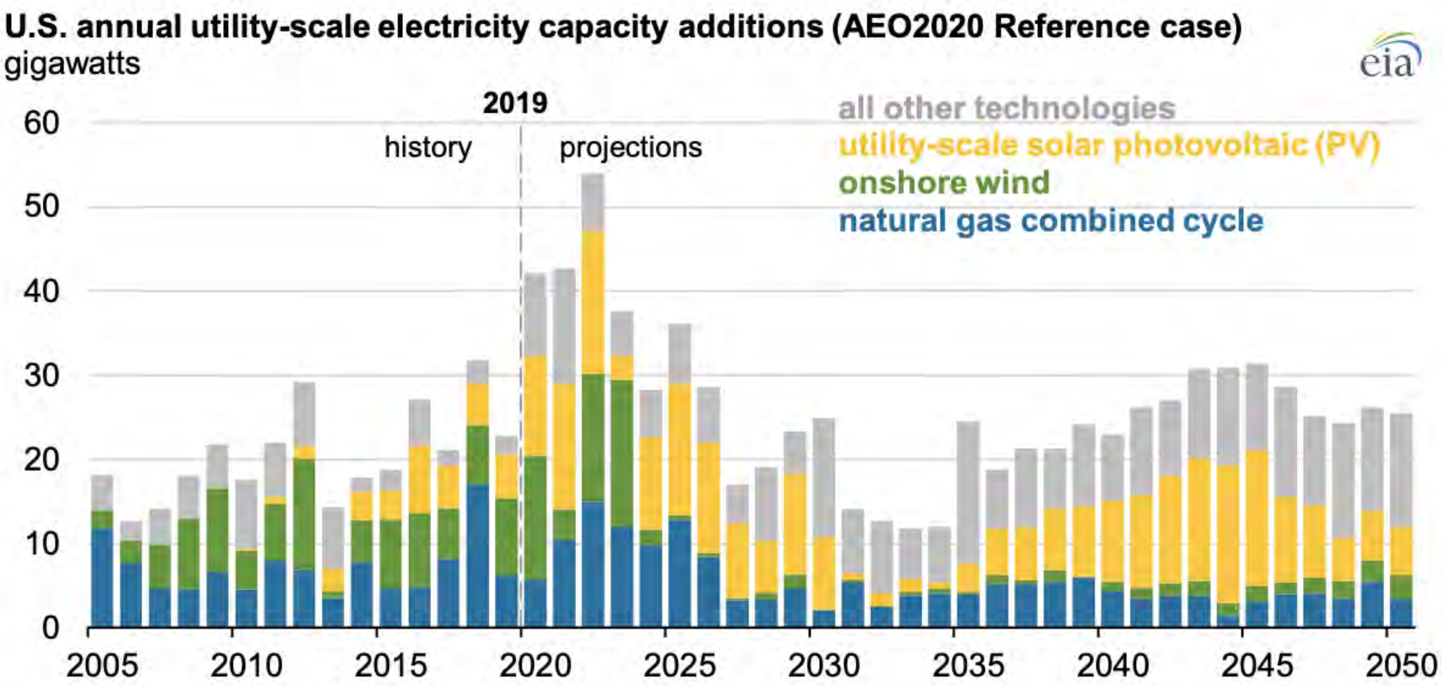
The easy answer is that *somewhere* electricity prices will likely be high enough to support fusion power. In 2019, the average retail price of electricity in the US was $0.11/kWh. In Hawaii, the average price was $0.29/kWh; in Louisiana, it was below $0.08/kWh). Electricity retail prices tend to be higher in western Europe and Japan—residential prices of over $0.25/kWh were reported in Germany, Denmark, Belgium, Italy and Ireland. The key takeaway here is the variability of electricity markets around the world.

Today in the US, we have about 1,100 GW (gigawatts, or billions of watts) of electricity generating capacity according to the US Energy Information Agency (EIA). The EIA assumes that US electricity demand will grow at roughly 1% per year on average through 2050. The additional capacity we need from 2030 to 2050 to cover this and make up for power plants retiring is roughly 20 gigawatts (GW) a year. For context, twenty gigawatts is about 25 natural gas plants [20] or 20 nuclear power plants.



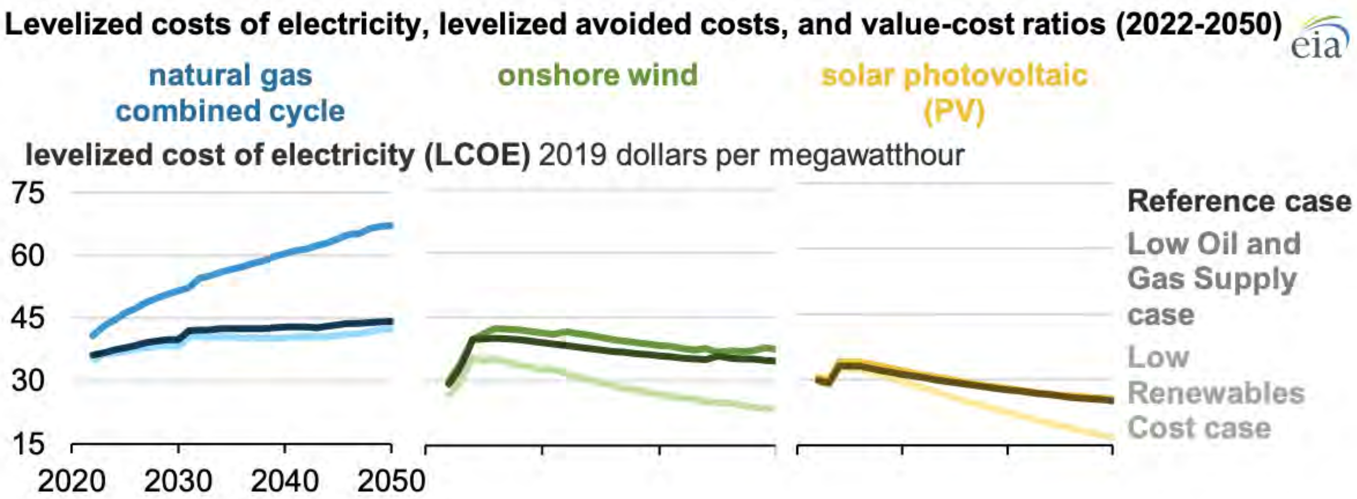
Source: U.S. Energy Information Administration, [Annual Energy Outlook 2020]

The US Energy Information Agency (EIA) currently predicts that most of this growth will come from solar and (to some extent) natural gas, based on an assessment of what will be most cost effective. This assessment uses a metric called the "[Levelized Cost of Electricity]" or LCOE to compare options for electricity production. The LCOE is basically the sum of all the money it takes to build the power plant and operate it for its entire life, divided by the amount of electricity it produces over those years. For the math lovers:

$$\text{LCOE} = \frac{\text{sum of costs over lifetime}}{\text{sum of electrical energy produced over lifetime}} = \frac{\sum_{t=1}^{n} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+r)^t}}$$

I = capital costs, M = yearly operations and maintenance costs,
F = fuel costs, and E is the amount of electricity generated.
Careful! There's a sneaky discount rate (r) in there.

Running with the EIA predictions (dangerous, but humor me), [21] the cheapest form of energy production in 2050 will be solar at $0.026/kWh and it will be dispatched whenever possible. Onshore wind energy will cost on average $0.035/kWh and electricity from natural gas will cost about $0.045/kWh. However, it is important to point out that the LCOE is NOT the retail price on your electricity bill. It does not include transmission and distribution costs, taxes, and marketing - it's just the cost of making the electricity.



To convert dollars per megawatthours to $/kWh, divide the cost in megawatt hours (MWh) by 1000.
Source: U.S. Energy Information Administration, [Annual Energy Outlook 2020]

How Will Fusion Power Compare?
Since no fusion power plants have been built yet, we have two options for estimating what fusion power plants might cost in the future. First, we can review the few engineering cost estimates that are available from public entities (governments) for fusion concepts. Where information is not available, we can look at the cost of projects with a similar scale and level of complexity (e.g. nuclear fission power plants), and extrapolate.

To demonstrate what this might look like, let's walk through a "back-of-the-envelope" estimate of the levelized cost of electricity (LCOE) for a fusion power plant. To complete this thought experiment, we will make some very big assumptions, and do things that the Advanced Research Projects Agency - Energy (ARPA-E) specifically tells us not to do. [22]

In 2017, the US ARPA-E, Bechtel and technology providers worked together to estimate the potential cost of a small fusion power plant based on four technologies developed through the ALPHA program. Each plant was designed to generate 150 MW of electricity, smaller than today's nuclear power plants. All designs generated roughly 500 MW of heat, and converted this heat to electricity with 40% efficiency. The estimated total overnight cost (TOC) for the power plants averaged $1.3B (in 2016 USD dollars), with estimates for each technology ranging from $0.7B to $1.9B. These costs assumed that each plant was the 10th plant built, e.g. that most of the kinks had already been worked out.

Say that Company A successfully demonstrates fusion and can build a power plant that produces 150 MW of electricity for $0.7B. We don't know how much it will cost to operate the fusion plant, but let's assume that operating costs are roughly 40% of the LCOE, as for nuclear power plants, and it will operate for 30 years. [23] The LCOE for this fusion plant would be $0.11/kWh. Considering EIA's predictions of about $0.03-0.045/kWh for solar, wind and natural gas in 2040, it is unlikely that fusion will be the cheapest source in unrestricted settings. Still, this LCOE may be economically attractive for small power plants in remote areas with low sunlight or access to other fuels (remember that Hawaii's retail electricity price is almost 3X the national average).

The simplest path to reducing the LCOE is increasing the size of the power plant to access economies of scale. Let's consider a larger example. Company A predicts that they can build a larger power plant that produces 1000 MW (the size of a typical nuclear power plant today) for $2.2 B. [24] At this larger scale, this rough calculation predicts an LCOE of $0.052/kWh for the same technology. In an unconstrained design space, this rule determines the size plant proposed by fusion companies. Extending the life of this plant to 40 years reduces the LCOE further by spreading out the capital cost over a longer period.

The breakdown of projected capital costs for a fusion reactor in the ARPA-E/Bechtel study are also interesting. In the four cases considered, the cost of the core fusion equipment - the chamber, magnets, lasers, fuel injection, and energy conversion to heat - makes up only 28-45% of the capital costs for fusion.

Cooling towers with large steam plumes show that all 4 nuclear reactor units at the Cattenom Nuclear Plant are running. Fusion power plants would likely have similar steam turbines and cooling towers. [Image Source]

The cost of structures and site facilities was also a large part of the costs at 21-28%. The steam turbine and electrical equipment represented 21-34% of these costs. If existing infrastructure could be used (e.g. from retired power plants), the cost of a fusion power plant could be reduced substantially.

Converting the fusion products directly into electricity without first making steam (to drive a turbine) would result in major cost savings.

This is a big reason that some fusion companies hope to use proton-boron fuel, even though it is harder to ignite. The proton-boron reaction produces atoms with an electrical charge—this means that some fraction of the energy can be converted into electricity directly.

For the sake of simplicity we have focused here on one recent and comprehensive fusion cost estimate that is publicly available, the 2017 ARPA-E/Bechtel study. A few other references for the potential cost of fusion plants are included in the notes for those interested. [25]

In reality, assessing the money and time needed to build the first new power plant or industrial process accurately is a hugely time-consuming and expensive process. For large projects like a commercial-scale power plant, companies would spend millions of dollars on front-end engineering and design (FEED) studies to answer these questions.

Doing the Work

Technical challenges clearly remain. We touched briefly on the need for advanced materials in the "first wall" between the plasma and the rest of the system. More work is needed to de-risk tritium breeding, and to design and optimize systems to convert fusion energy into electrical energy. Each design has its own unique challenges, which could be stronger electromagnets, liquid metals, or manufacturing inexpensive fuel targets.

Siting considerations and broader public perception are also important to begin working on now. In the past, people haven't wanted to participate in (or be sited near) technologies that they see has high risk. Nuclear fission is notoriously hard from a PR perspective. On the other hand, the ICF program at Livermore didn't have the same obstacles because the public were engaged and trust was built early. The fusion community needs to start early to engage and prevent the perception that fusion represents an extreme risk, like nuclear fission.

Regulatory pathways also need to be created to allow fusion power plants to safely operate. The US Nuclear Regulatory Commission (NRC) has developed new certification routes for new small nuclear fission reactor designs. This is an encouraging sign that they will be able to adapt and at least certify designs. Still, new licensing and inspection protocols will need to be developed.

For fusion to be widely adopted as a clean, reliable and safe source of electricity, we need to start thinking of fusion not just in terms of awesome science, but also in terms of power plants and the roadmap to get there.

Public Funding. To support the transition to power production, ITER and other government programs have focused more attention and resources on the engineering challenges associated with fusion. These include fuel production and handling, and materials for the "first wall" between the plasma and the energy conversion equipment. The US DOE's ARPA-E fusion program recently announced up to $30mm in funding through its GAMOW program targeting these areas. Another ARPA-E program, BETHE [26], is providing $30mm to increase the number and performance levels of lower-cost fusion concepts. (ARPA-E asks companies to show a path to costs of $5 per watt of power ($5/W) at the 400 MW power plant scale to make sure that the technologies they fund will be cost competitive.)

Building demonstration fusion systems requires significantly more capital - likely $50-$200mm. While some private companies have already raised these amounts, this is an excellent area for public-private partnerships, similar to NASA's COTS program that gave rise to SpaceX. In 2005, the Bush administration allocated $500 million over five years for the development and demonstration of Commercial Orbital Transportation Services (COTS) that it wanted to replace the Space Shuttle and budgeted the funds. NASA and each commercial partner agreed on fixed technical or financial milestones with success criteria to be associated monetary payments. This program was critical to the US's ability to maintain technical excellence and competitiveness in the manned space sector, and SpaceX has since flown many successful missions. As with space transportation, nuclear fission, defense capabilities, and DNA sequencing (e.g. Human Genome Project), the successful commercialization of fusion will provide technical and economic benefits that will vastly outweigh funding at a similar scale for the best demonstration projects.

Nuclear engineers at work (photo by C. Anderson)

Private Funding. The growing number of private fusion companies shows increased confidence from the private sector that science and engineering risks are being reduced. There is also a shift in the number and nature of institutional investors entering this space. Two oil and gas companies announced investments in fusion startups in the summer of 2020. Equinor invested in Commonwealth Fusion's $84mm Series D round, alongside Temasek, Breakthrough Energy Ventures, Khosla and others. Chevron invested in Zap Energy's Series A round. The backing of fusion technologies by mainstream energy companies represents a remarkable shift from the previous decades. Still, fusion companies must continue to reduce technical risk, set clear milestones tied to significant changes in valuation, and continue to meet them to justify continued fundraising events over the long horizon to full commercialization.

Even though there is significant work to be done to bring fusion technologies to commercialization, there is an increasingly real opportunity to unlock billions of dollars of low-carbon, reliable energy for hundreds of years into the future. The potential upside from both an economic and human perspective makes this area unbelievably exciting. Fusion could be the last energy source that humans will ever need.

Notes

[1] The amount of waste generated from nuclear power plants is surprisingly small. All of the high-level radioactive waste ever produced by the world's nuclear power plants would fit in a building 10 ft high and covering an area the size of a soccer field (Source: 2018 IAEA report, pg 39). As someone who has worked in nuclear power plants, I would happily live next to one. My family lived near the Beaver Valley Nuclear Plant in Ohio for years.

[2] There are many reasons for this, but insurance and regulatory costs play a significant role. More than 50 nuclear (fission) power plants are under construction in other countries, mainly China.

[3] The energy our sun produces comes from the fusion of hydrogen atoms to form helium (the second element in the periodic table). This happens in the sun's core, a dense ball of plasma (the state of matter that is hotter and denser than a gas!) that is at a temperature of millions of degrees C.

Convincing helium and larger atoms to fuse together takes EVEN MORE energy than fusing hydrogen. Scientists believe that carbon, oxygen, iron, and all the other heavier atoms were formed in the massive energy release accompanying a Supernova, or the death of a star. The building blocks for everything in our bodies were likely born in a star halfway across the universe (I just think this is beautiful).

[4] An isotope is an atom with more neutrons than usual. Hydrogen (1H) has only one proton and a molecular weight of 1. Deuterium (2H), has one proton and one neutron. Tritium (3H) has one proton and two neutrons.

[5] Fusion of a target containing 10 milligrams of DT fuel would release 3,400 MJ of energy assuming 100% "burn". If the lasers fire and fuse one target per second (a commonly assumed rate), this fusion plant would produce 3.4 gigawatts (GW) of heat.

[6] Specifically a phenomenon called plasma-block ignition, described in Hora et al. 2017. When a hydrogen and boron-11 fuse, three charged helium atoms (alpha particles) are produced. This takes advantage of the "avalanche" production of alpha particles to produce additional fusion events.

[7] The simplest way to achieve fusion is to blast the fuel with enough laser power to reach a temperature and density that satisfies the Lawson Criterion. The challenge is to deliver this energy quickly, before the fuel flies apart. This would require a very short (~picosecond) but VERY powerful laser pulse.

[8] "Fast ignition" strategies have been researched extensively, particularly at the National Ignition Facility (NIF) in Livermore, CA and the LFEX facility in Osaka, Japan. This approach uses a combination of 2 laser pulses. First, a long laser pulse causes an implosion and compression of the fuel—compressing the fuel reduces the amount of heat needed. Next, a shorter (fast) laser pulse induces ignition. This reduces the amount of energy delivered in each of the two steps.

[9] The longer pulse can be "shaped" to be more efficient, reducing the overall energy needed (smaller lasers). Pulse-shaping is like pushing a friend on the swing- in mid-swing, you start and stop pushing gradually, to give them maximum additional energy.

Even with pulse shaping and other laser beam manipulations, achieving uniform energy deposition is hard. Some approaches convert the laser energy (photons) into protons or electrons for the second fast ignition pulse. However, there is an efficiency penalty to pay for the increased beam uniformity; experiments on converting laser light to proton beams have shown efficiencies of roughly 10%.

[10] The shock ignition concept achieves ignition by accelerating the pellet shell to sub-ignition velocity, then igniting it with a converging shock produced by a high intensity spike in the laser pulse. A brief description can be found here.

[11] For more information about tritium breeding and the effects of neutrons on chamber materials, see this 2018 paper by Marek Rubel.

[12] Source: SPIE Conference Proceedings abstract

[13] Superconducting materials are called "superconductors" because they conduct electricity with zero resistance. This means that once an electrical current is started within a coil, there is nothing to stop it — it will persist forever unless something disrupts it. However, most known superconductors only have this property at very cold temperatures — near absolute zero (0 Kelvin, or -273 degrees C). They must be kept cold, or electrical resistance will become non-zero and the electrical current will be converted to heat. This is extra challenging when the superconductors need to be in close proximity to a high-temperature plasma.

[14] The name tokamak comes from a Russian acronym for a toroidal chamber with magnetic coils.

[15] The first phase of ITER's construction does not include tritium handling capabilities (tritium is radioactive).

[16] The previous ARPA-E program, "ALPHA" specifically funded fusion designs in this intermediate space, called Magneto-Inertial Fusion, and Z-pinch fusion reactor designs. Z-pinch fusion reactors use electric fields rather than magnetic fields or lasers to contain the plasma long enough to achieve fusion.

[17] To put some numbers to low and high plasma densities, ITER's plasma has an ion density of 10^14 ions per cubic centimeter (cm3)… not very dense. The National Ignition Facility (NIF), on the other hand, compresses targets to ion densities greater than 10^26 ions per cm3. For comparison, air has a density of about 10^20 atoms per cm3. Source: C.L. Nehl et al, Journal of Fusion Energy 2019.

[18] While the ITER tokamak will begin running basic deuterium fusion experiments in 2025, handling radioactive tritium requires specialized equipment and materials. The target for completing these upgrades is 2035.

[19] The ITER facility is designed to perform a range of experiments and measurements. The DEMO design will be larger but simpler, and will include equipment to actually convert the heat from DT fusion into electricity for the local electric grid. Another important task for ITER is to produce enough tritium for commercial facilities, and specifically for DEMO to use while starting up. Once a fusion plant is running on tritium, it can produce more through "breeder" reactions with other materials.

[20] The average size of natural gas plants in the US is ~800 MW. (Source: EIA)

[21] Source for graph: EIA

[22] The ARPA-E report clearly states: "ARPA-E and the technology providers understand that the report does not contain sufficient accuracy or detail to be meaningful in connection with any securities offering or other financing effort and due to the status of the technology development, the uncertainties as to time horizon in which any of these technologies could be commercially deployed, and the limited scope of the review, this report is not intended to be relied upon by any third party in making investment decisions."

[23] The distribution of capital costs and operating costs for nuclear power plants (and other electricity generation) was taken from Figure 1 in Hirth and Steckel, 2016. We've also assumed a discount rate (r) of 10%.

[24] This is where we break the rules a little. Let's apply the "6/10ths" rule to estimate the costs of engineering equipment for a larger 1000 MW facility, starting from our 150 MW power plant that costs $700mm. We project a capital cost of $2.2B. Starting from the average cost of $1.3B in the ARPA-E report gives a cost of $3.7B for a 1000 MW power plant.

[25] Other studies with estimates for fusion power costs:
[a] A techne-economic assessment based on a design for DEMO: ScienceDirect
[b] EPRI 2012

[26] The name of the program, BETHE (pronounced "beta") is an acronym for "Breakthroughs Enabling THermonuclear-Fusion Energy". It is also a nod to Hans Bethe, a German-American nuclear physicist (and Cornell professor — Go Big Red!) who played a major role in developing the atomic and hydrogen bombs. After the war, he campaigned with Albert Einstein and the Emergency Committee of Atomic Scientists against nuclear testing and the nuclear arms race, resulting in the 1963 Partial Nuclear Test Ban Treaty and 1972 Anti-Ballistic Missile Treaty (SALT I).