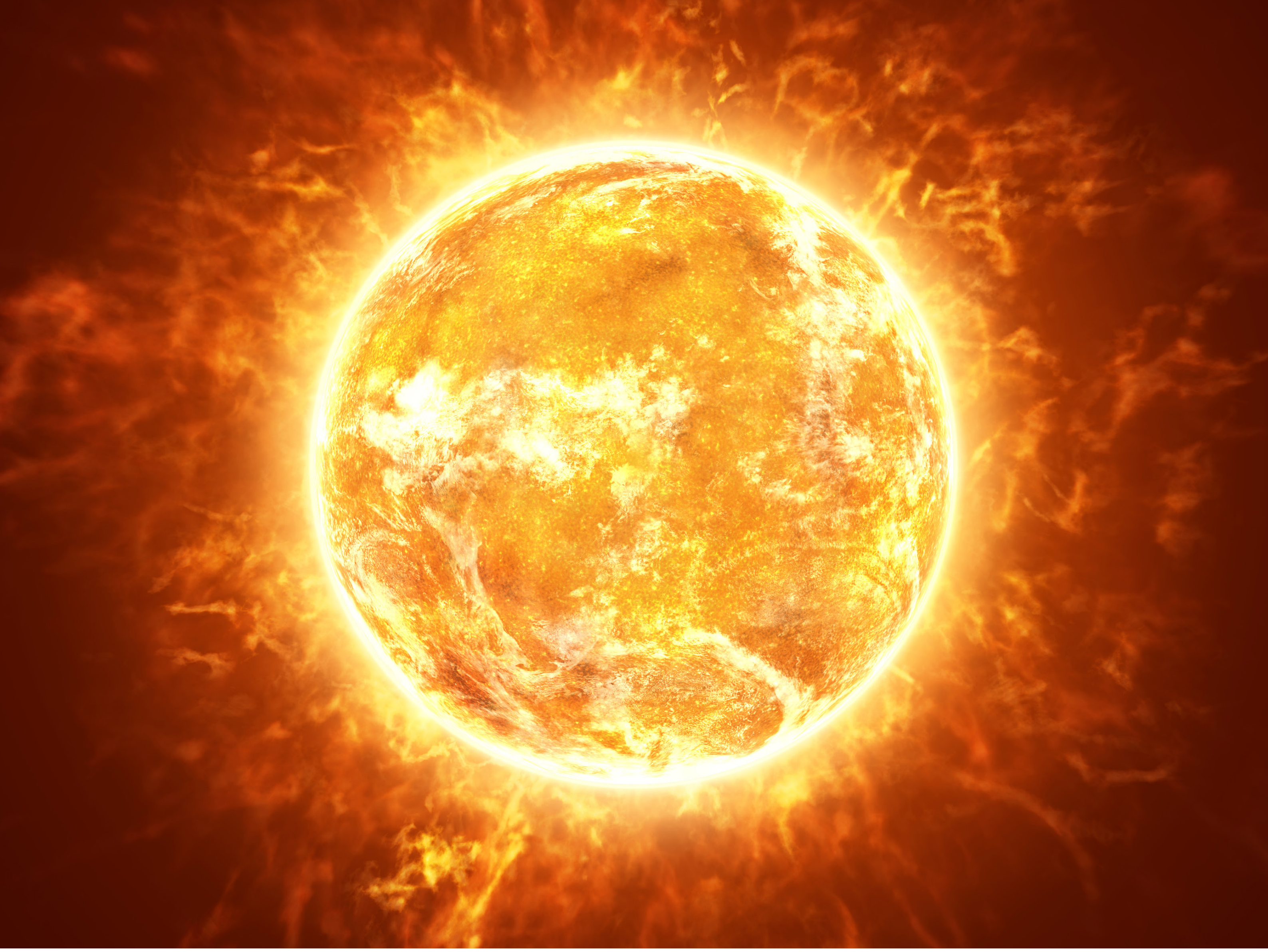

The next big bang in emissions-free energy

The private sector race to the nuclear fusion dream

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Arthur D Little

Content

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Executive summary

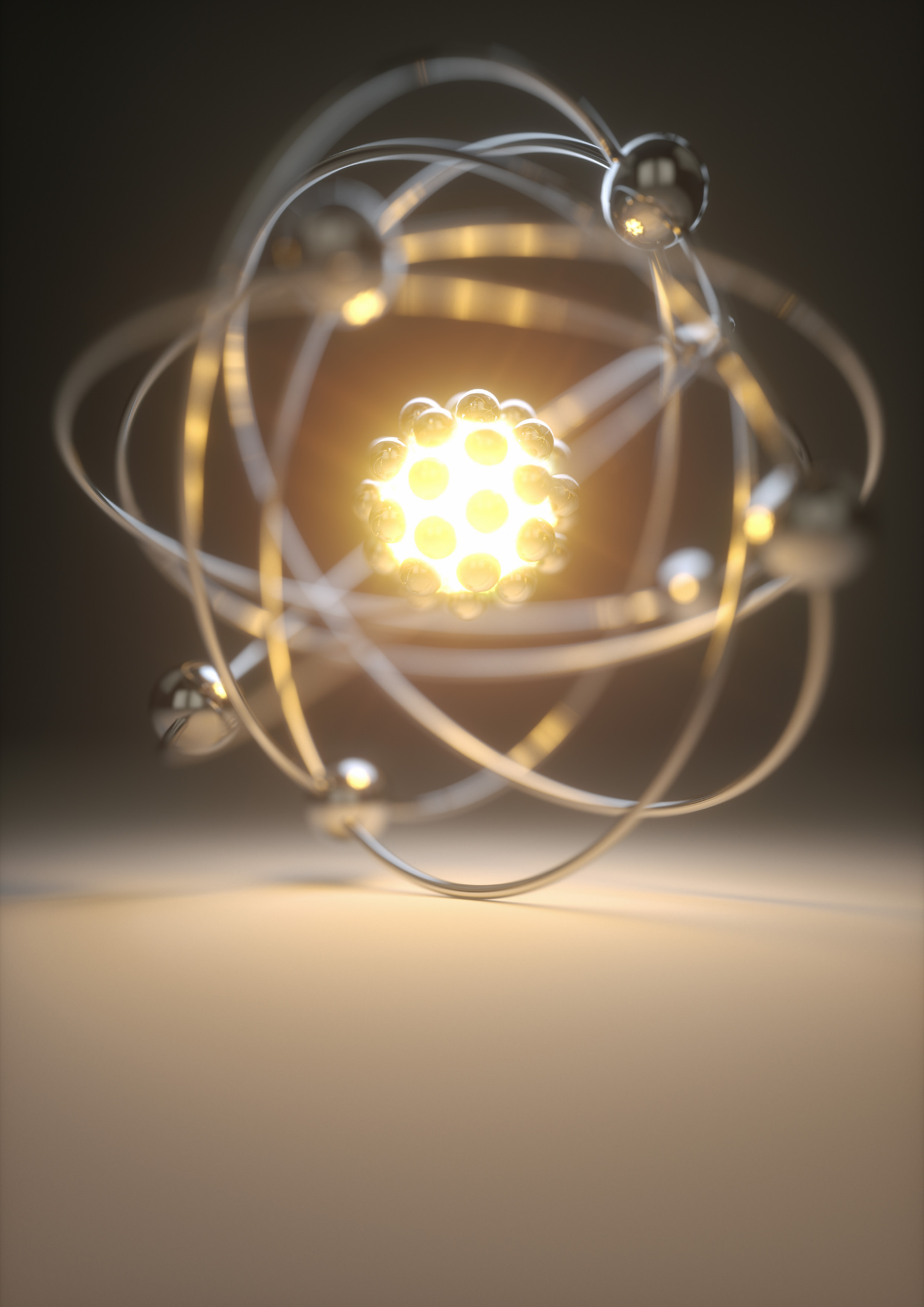
The energy industry is at a turning point. Despite extensive efforts, we have a long way to go before achieving a low-carbon economy. In addition to the belief in and unspoken importance of renewable energies such as wind and photovoltaic, nuclear power also provides low-carbon electricity. Notwithstanding often politically influenced discussions surrounding the disposal of nuclear waste and questions of safety, nuclear power holds the advantage of being a "clean" (low-carbon), relatively unlimited, source of energy. In fact, nuclear power can be used for electricity generation as well as heat production, making it a reasonable option to fight global climate change.

However, nuclear power has challenges competing with renewables and faces government restrictions that may prevent it from gaining greater footing. Safety fears and concerns over spent fuel disposal have led to several nuclear plants shutting down. Further, high up-front capital investments complicate financing, ultimately leading to hesitant investment decision making. Since the events of Fukushima in 2011, several countries, including Germany, Switzerland, and Belgium, have committed to phase out nuclear energy entirely. Still, countries continue to research nuclear energy. An example is Germany's Wendelstein 7-X experimental fusion reactor, which is operated by the Max Planck Institute for Plasma Physics.

Economists and decision makers wonder which technologies can hasten the transition to a "green" economy and meet the Paris Accord targets set in 2015. As we will explore in this Report, nuclear fusion appears to offer the potential to replace fossil fuels as a low-carbon, sustainable energy source.

While it is challenging to predict a reliable time horizon for when nuclear fusion will be commercially available, in this Report we provide a nuclear-centric perspective on the current energy-generation landscape. We discuss new nuclear technologies under development and the ways the private and public sectors are attempting to use nuclear fusion to profitably generate low-carbon energy. We conclude with thoughts for investors regarding the future of nuclear fusion.

Although nuclear fusion is not yet a mainstream source of energy, in recent years a variety of private companies, many backed by high-profile investors, have been established with the goal of making nuclear fusion viable in the next 20 years. Although several uncertainties still remain and the reliability of such ambitious timelines still needs to be proven, current market developments show a growing interest in developing nuclear fusion into a full-fledged industry sector.



1. The nuclear industry of today

The transition to low-carbon economies appears to be the primary driver of change in the energy industry for the upcoming decades. Many countries promote the use of low-carbon and renewable energy through subsidies and other incentives, while fossil fuels – primarily coal – are progressively being phased out. However, existing initiatives largely struggle to keep the pace expected to phase out CO_2-intensive energy sources and meet the Paris Accord targets.

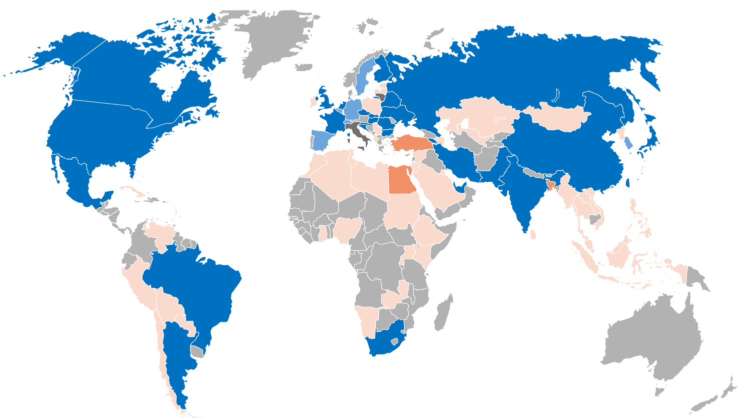
As with other technologies, nuclear energy poses both rewards and risks. On the one hand, nuclear energy is a low-carbon source of baseload energy. On the other hand, nuclear energy has shown occasional safety challenges, and the waste produced is nontrivial. For example, the Chernobyl, Three Mile Island, and Fukushima incidents demonstrated that nuclear reactors, when ineffectively enclosed or improperly protected from natural disasters, can have significant consequences for the public. Thousands of people were impacted by radioactive materials released by the Chernobyl and Fukushima power plants.

As Figure 1 demonstrates, countries vary in their approach to nuclear energy as well as in their response to these accidents. Some countries are committed to phasing out nuclear energy, while others are trying to develop nuclear energy for the long term.

Western countries vacillate between shutdowns and new builds

The most striking example of the trend toward nuclear energy phaseout among European countries is in Germany, which will complete phasing out its nuclear fleet in 2022, closing the remaining six operating units. Other European countries, including Switzerland and Belgium, have set similar nuclear phaseout strategies, although time horizons vary. While Switzerland envisages a long-term phaseout that will not occur before 2050, Belgium will begin closing its nuclear power plants in 2022. Phaseout policies have also been discussed and chosen outside of Western Europe, although not always with full commitment (e.g., South Korea). Despite this trend, a small number of countries (UK, France, and Finland) have been building new nuclear reactors. The US is building new reactors as well, extending lifetimes for 80 years, as well as pursuing new nuclear power plant (NPP) design technologies.

Figure 1: Country overview based on commitment to nuclear energy



Long-term committed nuclear countries	27[1]	Countries phasing out nuclear power	6[3, 4]
Newcomers with NPP under construction	3[2]	Countries that already phased out nuclear power	2
Countries considering entry into nuclear energy (policy discussion or planning)	44	Non-nuclear countries	113

1) Includes Croatia, which shares the Krško nuclear power plant with Slovenia; 2) The UAE and Belarus started operations of their first NPPs in 2020; 3) Excludes Taiwan, not acknowledged as a sovereign state; 4) Includes Sweden and South Korea, although their phaseout policy is still uncertain.
Source: Arthur D. Little analysis

Arthur D Little

Still, nuclear energy currently faces economic challenges to remain competitive. Natural gas, for example, is a more profitable source of energy in many markets. Likewise, coal, although it emits carbon, is a relatively cheap source of energy. Carbon emission costs will continue to negatively impact the competitiveness of coal in many countries. Nuclear energy also faces stringent safety regulations that decrease the profitability of nuclear plants. The difficulty of making nuclear power plants profitable, as well as the regulations they face, can cause premature shutdowns.

The new nuclear fleet

The scenario is significantly different in Eastern Europe, China, and India, as well as emerging markets and developing countries, where nuclear energy is being actively pursued. For example, nuclear newcomers like Turkey and Egypt have new power plant construction projects that could potentially lead to nuclear electricity in the coming decade. At the same time, Russia is showing strong commitment to nuclear energy by building new plants to replace older ones and systematically exporting its technology to other countries. Similarly, the Chinese and Indian nuclear fleets are continuously expanding to meet growing energy demands, grant energy security, and counter the pollution effects caused by coal power plants. Finally, a number of developing countries, including African nations like Nigeria, Latin American countries like Bolivia, and South Asian countries like Sri Lanka, have shown interest in the opportunity of nuclear power, which leads to policy discussions and, in some cases, to the development of more concrete plans.

Beyond present mature technology

Despite the wave of nuclear phaseouts and decommissioning, primarily in Europe, recent years have witnessed a renewed interest in nuclear technology. Still, public opinion highlights concern over the safety of nuclear reactors after the events of Fukushima, Three Mile Island, and Chernobyl, as well as the challenges posed by storing nuclear waste. In response to these concerns, private companies such as Bill Gates's TerraPower, as well as government agencies such as the US's Advanced Reactor Demonstration Program are investing significant resources to develop new nuclear technologies with three key objectives in mind:

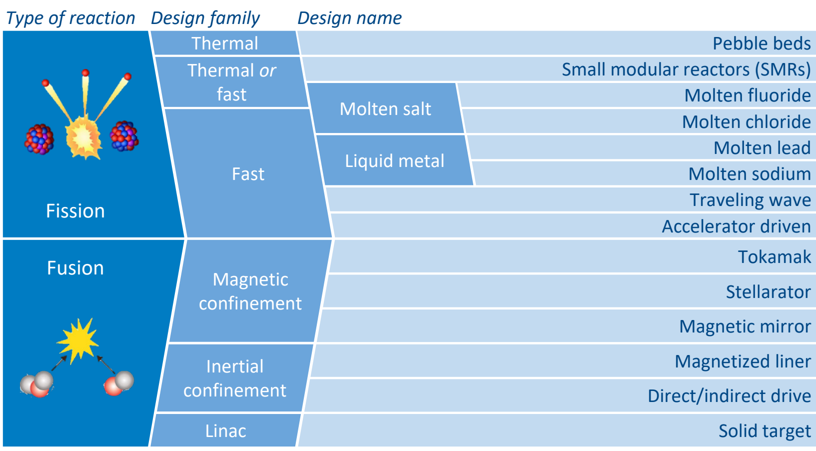
1. Further enhancing the safety of reactors, especially passive (self-protecting) safety.
2. Reducing the volume and longevity of nuclear waste.
3. Creating an economically sustainable (i.e., profitable) method of harnessing nuclear energy.

While recent developments in nuclear fission reactors promote designs with "walk-away safe" approaches and reduced radiotoxicity of waste, research is also gaining momentum in the area of nuclear fusion.

Nuclear fusion technology, although not currently commercially available, has the potential to overcome traditional nuclear safety issues and is characterized by short-lived nuclear waste. The next section presents an overview of nuclear technologies under development (both nuclear fission and nuclear fusion), which is summarized in Figure 2.

A broad understanding of both nuclear fission and nuclear fusion technologies can highlight the differences between each, demonstrating that nuclear fusion may avoid some of the potential downsides of nuclear fission. Nuclear fusion produces less radioactive waste than does nuclear fission and is generally considered safer because there is less chance of a nuclear accident caused by uncontrolled chain reactions. In a nuclear fusion power plant, if the fusion confinement mechanism failed, the plasma would expand and cool, stopping the nuclear reaction rather than causing the power plant to melt down.

Figure 2: Future developments in fission and fusion technologies (simplified)



Source: Arthur D. Little analysis

A brief overview of nuclear technology

Broadly speaking, nuclear technology is an extremely efficient form of heat generation, creating that heat by either splitting atoms (fission) or combining atoms (fusion). Nuclear technology works by changing the structure of hydrogen atoms, releasing their energy. This energy is used to convert water into steam, which then powers turbines, which finally power generators.

As readers may recall from basic chemistry, atoms are composed of a certain number of protons, neutrons, and electrons. The protons carry a positive charge, the neutrons have a neutral charge, and the electrons are negatively charged. The core of an atom, its nucleus, contains a great deal of energy, which holds together the positively charged protons and the neutrons. Nuclear power plants change the structure of the atom to release energy.

The number of protons in the atom's nucleus determines the chemical structure of the atom on the periodic table. A hydrogen atom, for example, contains one proton. ***Isotopes*** of hydrogen also contain one proton but have different numbers of neutrons. For example, hydrogen atoms with one proton and one electron, but no neutrons, are known simply as hydrogen-1 atoms. Hydrogen atoms with one proton, one electron, and one neutron are known as hydrogen-2, or deuterium. Deuterium is a stable isotope, meaning that it will not decay into another isotope. Hydrogen atoms with one proton, one electron, and two neutrons are known as tritium. Tritium is radioactive, meaning that it is not a stable isotope, and will decay relatively quickly.

Nuclear fission occurs when atoms are bombarded with neutrons. This bombardment causes the atoms to split apart, releasing energy in the form of heat. In the most commonly used approach, uranium atoms are targets for these bombardments and the resulting fission. The initial split causes the atoms' nuclei to break apart, which then splits adjacent atoms. The initial split causes the atom's nucleus to fly apart, which splits more atoms. The process is called a ***chain reaction***.

Nuclear fusion, however, relies on fusing two atoms together. Fusion reactors apply high pressure to light hydrogen atoms, forcing them to fuse together and release heat in the process. Because nuclear fusion technologies do not rely on chain reactions, they're less likely to be involved in nuclear accidents.

Several different types of both nuclear fission and nuclear fusion reactors are being developed. The aim for these technologies is to cost less to harness energy than to produce it. Until nuclear technology can compete with cheaper sources of energy such as natural gas, NPP operators will most likely choose to use nuclear technology only under specialized market or political conditions.

Below, we provide a brief overview of some of the nuclear technologies under research in order to acquaint readers with the difficulties of building nuclear power plants, as well as the range of potential technical solutions.

Nuclear fission technologies

Pebble-bed reactors

Imagine a graphite ball, the size of a tennis ball, filled with tiny particles of uranium. These graphite balls are known as "pebbles," and each pebble functions like a mini reactor, producing energy as the fuel fissions inside it. The pebbles circulate around the core of the larger reactor.

Pebble-bed reactors have an elongated design, with a large amount of surface area to promote cooling. They are also cooled by helium, rather than by complicated plumbing devices, which makes it harder for the cooling system to fail. When the cooling system is switched off, the reactor remains functional.

The pebble-bed reactor is constructed such that higher temperatures do not cause chain reactions, so the reactor doesn't melt when the cooling system fails. These reactors, however, are not without risk: the graphite pebbles may combust in the presence of oxygen. Pebble-bed reactors were originally designed in the 1950s in Germany, and the technology is still being developed.

Small modular reactors

Also under development are small modular reactors (SMRs), which are conceived primarily as a small version of current nuclear plants. Their main advantage relies on the implementation of proven technologies, scaled down and simplified to enable modular production in a manufacturing plant while increasing safety due to lower power densities. These changes result in a design that is more affordable to build, operate, and maintain.

Molten salt reactors

In the 1950s-1970s, Oak Ridge National Laboratory (ORNL) constructed and tested a new reactor concept known as a molten salt reactor. Molten salt reactors operate at lower pressures than do many other types of power plants, and thus do not require large containment devices. Molten salt reactors also produce less waste than many other types of reactors.

The ORNL design resembled a large bucket in which fuel was diluted in a liquefied salt. The molten salt absorbed the radioactive gasses from the fuel, reducing radioactive waste. The ORNL design, which is now being reevaluated as a potential answer to current energy challenges, does not need to pressurize the reactor and enables continuous feed or removal of fuel. This increases the efficiency of the reaction while at the same time allowing easy fuel removal and natural cooling during maintenance, shutdown, or emergency scenarios.

Liquid metal reactors

Liquid metal reactors, originally designed in the 1950s for submarines, require less space than many other types of reactors. They use metal as a coolant and – unlike many other types of reactors – can operate at low pressures. However, the metals used to cool them – often lead or sodium – can either corrode (in the case of lead) or become highly reactive if exposed to water (in the case of sodium). Thus, liquid metal reactors present both safety and operational challenges.

Traveling wave reactors

Most modern reactors require enriched uranium to operate and have a low fuel utilization. In fact, when the fuel is replaced, more than 96% of the residual energy has not been used. Fast reactors, such as traveling wave reactors, enhance fuel utilization. Such reactors can be fueled with natural and depleted uranium, thorium, or even spent fuel, and do not need refueling as they can generate their own fuel for decades. This can allow sealed core designs, in which the reactor is sealed and does not require recurring fuel inputs. Sealing the reactor increases safety but also decreases engineers' control of the systems, as the reaction is self-regulated. This design has the disadvantage of requiring special materials and/or advanced designs to withstand irradiation – or exposure to radiation – throughout the reactor's lifecycle, which is why extensive R&D is still ongoing. TerraPower, partially funded by Bill Gates, is currently conducting R&D on traveling wave reactors.

Accelerator-driven reactors

Accelerator-driven reactors were inspired by the possibility of having a core incapable of sustaining a chain reaction, with fission taking place only through externally provided neutrons. Such a design would remove the risk of a critical accident and could be fueled with natural and depleted uranium, thorium, or even spent fuel.

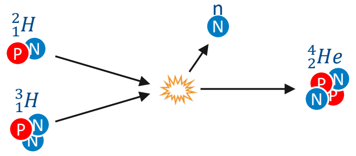
Nuclear fusion technologies

Nuclear fusion, unlike nuclear fission, fuses two nuclei together rather than splitting them apart. Fusing the nuclei releases energy. This is the process that powers the Sun, as well as all other stars.

Nuclear fusion requires very high temperatures, in which matter reaches the plasma state. Known as the "fourth state of matter," plasma is characterized by electrons stripped free of the rest of their atoms. The free-floating electrons allow energy to be conducted through plasma.

Nuclear fusion reactions use extremely high pressure and temperature to force two nuclei to fuse together and release energy. Two isotopes of hydrogen, namely deuterium and tritium, offer one of the most energy-efficient combinations of ignition conditions and released energy (see Figure 3). The left of Figure 3 depicts an atom of deuterium (the top atom) and an atom of tritium (the bottom atom). After they undergo the nuclear fusion process, they split into a single neutron and an atom of helium.

Figure 3: Deuterium-tritium fusion reaction



Source: Arthur D. Little analysis

The benefits of a Sun on Earth

Since the beginning of the nuclear era in the 1940s, researchers have discussed the idea of using nuclear fusion to generate energy, to "recreate a Sun on Earth."

Now more than ever, the ambition is driven by the fact that its achievement would represent a solution to the world's major energy problems. Nuclear fusion releases significantly more energy than nuclear fission and also avoids producing the greenhouse gasses that fossil fuels produce.

Another advantage of nuclear fusion as opposed to nuclear fission is fusion's lack of long-term radioactive waste. Fusion does not produce unstable nuclei that remain radioactive for millions of years; instead, it produces nuclei with short half-lives, which can be disposed of after approximately a century. This reduced radioactive waste hazard pairs nicely with the lack of meltdown risks, as an accident would destabilize the plasma and cause the reaction to shut down.

The challenges of building a Sun

The first roadblock for nuclear fusion on Earth comes from the extreme conditions required to trigger the reaction. The Sun is so massive and dense that its core is under intense pressure, creating conditions for nuclear fusion. On Earth, similar conditions must be achieved through other approaches, applying the three key parameters of temperature, density, and time.

For example, tokamaks are nuclear fusion devices that contain low-density plasma, heated to about 100 million degrees – hotter than the core of the Sun. The plasma is confined and stabilized, which allows nuclear reactions to occur. Although possible, maintaining the confined plasma under conditions that allow nuclear fusion is a difficult, costly task.

In addition to the challenge of maintaining the conditions necessary for nuclear fusion, a second crucial challenge that must be overcome arises from the fact that nuclear fusion reactors currently use more energy than they produce. It takes an enormous amount of energy to force the deuterium and tritium nuclei, which are both positively charged and thus naturally repel each other, to fuse. Nuclear fusion technology has not yet been able to produce enough net energy from the reaction for it to be commercially viable.

Finally, the most commonly pursued nuclear fusion reaction requires tritium, a radioactive isotope of hydrogen with a short half-life. To optimize its availability, tritium can be bred during nuclear fusion reactions, leveraging the neutrons produced as a side product of the reaction. This, however, leads to additional technical complexities of breeding and managing the tritium within the reactor.

To sum up, nuclear fusion represents the "holy grail" of carbon-free power generation. This technology, once fully developed and deployed, could mean the end of energy challenges for the foreseeable future. However, nuclear fusion commercialization struggles with various roadblocks that are difficult to overcome with current technology. Figure 4 provides a more systematic and overarching view of the major features of nuclear fusion.

Most common nuclear fusion approaches

Today, R&D in fusion energy has focused mostly on magnetic and inertial confinement, which represent different approaches to achieving the nuclear fusion conditions:

- **Magnetic confinement** leverages strong magnets to spatially confine low densities of fuel for long periods of time.
- **Inertial confinement** uses physical barriers to confine high densities of fuel for short periods of time.

Both technologies require high temperatures to ignite the reaction and release very large amounts of heat afterwards.

Magnetic confinement

Confining plasma in magnetic fields prevents the plasma from overheating the walls of its reactor. Imagine a giant donut-shaped device filled with superheated plasma. Inside the donut-shaped device, plasma is confined in specific magnetic shapes and travels in magnetic fields. Tokamaks and stellarators are two such donut-shaped devices that confine plasma.

Figure 4: Major features of nuclear fusion

Very high power output

- In a nuclear fusion reaction **two atoms** merge into a **single one**; part of the mass is converted into energy
- The energy density is extremely high: about **340 TJ/kg**[1]
- **Energy** release is **significantly** (orders-of-magnitude) **higher** than **fission**[2]

Very demanding conditions

- **Prohibitive conditions, equivalent** to those of a **star** must be recreated (e.g., temperature exceeding 100 million °C)
- Very high neutron energy represents a significant **challenge** for **materials, shielding, and magnets**

Sustainability and safety

- During fusion reactions, **no CO_2** is produced
- Fusion produces radioactive waste with **no high activity, long-lived isotopes** (reusable within one century)
- **No** danger of nuclear weapons **proliferation** or risk of **meltdown**

High costs

- **High technology** level and advanced materials to contain and withstand the fuel plasma make it **expensive**
- **Designs** that rely on **low energy densities** require **large machineries** and are consequently more costly

Fuel availability

- Typical **fusion reactions**[3] require **deuterium** and **tritium**
- **Deuterium** is **broadly available** and can be extracted from seawater
- **Tritium** can be **produced from Lithium-6** during the fusion chain reaction

Difficult to achieve and sustain

- **Hard to ignite** and maintain a fusion reaction without damaging the reactor components
- **Containment materials are a challenge** due to high energy released
- **Tritium breeding** and **processing** adds **complexity** to the technology

1) For the fusion reaction deuterium-tritium; 2) Compared to thermal nuclear reactors; 3) Other elements or isotopes (e.g., Helium) can be used.
Source: Arthur D. Little analysis

Inertial confinement

An alternative approach comes from inertial confinement fusion (ICF), which primarily is being pursued in the US. With ICF, the fusion reaction is initiated by heating and compressing the fuel, typically contained in spherical pellets. ICF research is being pursued at the US National Ignition Facility, which hosts the largest inertial confinement research device in the world.

Solid-state target with particle acceleration

Besides magnetic and inertial confinement, there has been research regarding several other approaches to reach and sustain controlled nuclear fusion. For example, another approach under study aims to create fusion reactions leveraging a solid target and a particle accelerator. Here, the solid target embeds high quantities of fuel atoms, while the accelerator drives a beam of high-energy fuel particles against it, enabling localized fusions.

2. Those who chase the Sun

See you in 50 years?

Scientists discovered the process of nuclear fusion in the 1920s but didn't begin attempts to replicate it until the 1950s. At that time, researchers stated that nuclear fusion was "50 years away." It has since then become a recurring observation within the nuclear fusion community that nuclear fusion is "50 years away and will always be."

But in 2021, are we actually 50 years away from nuclear fusion?

It depends whom you ask. On a global level, there are several players investing time, money, and resources to push R&D forward and to achieve nuclear fusion. There are two main categories of players:

1. **Publicly funded projects**, primarily of an academic or research nature. These are often experimental and have strong international involvement, supported primarily by government funds. The most famous of these is the megaproject International Thermonuclear Experimental Reactor (ITER).
2. **Private-sector entities**, generally startups, which set much more ambitious targets than their counterparts, often promising commercial nuclear fusion in 10-15 years.

Slow giants: ITER and its peers

ITER today is the result of an initiative that began more than 30 years ago. In 1985, the US and the former Soviet Union started to discuss the option of an international project to pursue nuclear fusion for peaceful developments. One year later, they reached an agreement, and the project was set in motion with the start of conceptual design works. In 2007, the ITER organization was officially established to build the world's largest tokamak in Saint-Paul-lez-Durance, France, with financial support from China, the EU, India, Japan, South Korea, Russia, and the US. It had the following objectives, which we have summarized from ITER's website:

- **Demonstrate the integrated operation of technologies for a fusion power plant.** ITER is a large-scale experimental program, designed in part to test and demonstrate a range of technologies in an integrated approach. Some of these technologies will include heating, control, diagnostics, cryogenics, and remote maintenance, which have not been tested beyond today's smaller-scale experimental fusion programs.
- **Achieve a deuterium-tritium plasma in which the reaction is sustained through internal heating.** Current fusion technologies have yet to achieve a self-sustaining plasma ("burning plasma"). This occurs when energy from the fusion process exceeds the plasma heating injected from external sources. ITER will be the first burning plasma, offering new scientific insights related to controlled fusion.
- **Test tritium breeding.** Tritium is one of the isotopes of hydrogen that will be used in the fusion process. ITER plans to test mockups of breeding blankets, called test blanket modules (TBMs), where sustainable tritium production may be developed. TBMs are specialized materials lining the dedicated ports in the vacuum vessel and are expected to create tritium when neutrons escaping the plasma interact with lithium.
- **Demonstrate the safety characteristics of a fusion device.** ITER plans to demonstrate control of the plasma and fusion reactions, seeking to showcase safe fusion energy production while verifying minimal impact to the environment.

ITER seeks to demonstrate the feasibility of using nuclear fusion as a power source rather than to harvest energy from the nuclear fusion reaction. Harvesting energy will be achieved by DEMO, the machine that will be developed after ITER, which will be designed either as a pre-industrial demonstration reactor or as a quasi-prototype and will be the last experimental step before an industrial-scale fusion reactor. Overall, the initiative is expected to demonstrate industrial-scale fusion electricity by 2050.

ITER is not the only project of its kind, although it is the most famous. Other facilities (e.g., Wendelstein 7-X in Germany) also operate or are being built to further develop the nuclear fusion research field. What unifies these facilities and projects is their "academic" and long-term approach to nuclear fusion, where optimization and development are seen as a priority over commercialization. In other words, these slow giants are focused on the advancement of technology rather than on the need to meet a market demand for nuclear fusion reactors.

Fast cheetahs: nuclear fusion startups

In the past 10 years, private startups have increasingly pursued industrial-scale fusion. However, there are some companies that have been established since the 2000s. This is the case, for example, with the Canadian General Fusion and the American TAE Technologies, founded in 2002 and 1998, respectively.

General Fusion (based in British Columbia), with more than 140 employees, was founded with the goal to bring commercial fusion to the market in the fastest, most cost-effective and practical way. Its approach to achieving fusion (i.e., magnetized target fusion) is based on the idea to continuously compress the plasma with an array of pistons, bringing it to fusion conditions. The company aims to have an operational 70% scale prototype in 2023 and a first nuclear fusion power plant by 2030.

TAE Technologies was founded with the purpose to develop and distribute nuclear fusion energy. The firm pursues a technology that works primarily with boron and hydrogen (proton-boron, or p-B11) rather than deuterium and tritium. For about 20 years, the firm has been pursuing nuclear fusion, working with private investors on a "money by milestone" model. This approach, the company claims, has ensured an efficient use of capital, disciplined project management, and focus on mission-critical elements. Based on TAE's estimations, the beginning of commercialization will be achieved later in the coming decade. Moreover, the strong technical know-how of the firm, currently backed up by more than 1,400 patents, has also expanded into spin-off opportunities in other fields, such as energy storage, life sciences, and electric mobility.

Besides these two firms, there are a large variety of startups founded more recently, such as Commonwealth Fusion Systems (founded in 2018), First Light Fusion (2011), and Renaissance Fusion (2019). All these firms share one factor: the pursuit of fusion energy that they claim is achievable in the short to medium term. Figure 5 provides an overview of a selection of nuclear fusion companies.

Gaining momentum

The aforementioned TAE Technologies, General Fusion, Commonwealth Fusion Systems, First Light Fusion, and Renaissance Fusion are just some examples of companies actively pursuing nuclear fusion, with ambitions to reach it faster than ITER. They are not alone, as tens of nuclear fusion companies, primarily listed on the Fusion Energy Base website, can be found worldwide. Figure 6 provides an overview of the number of companies founded per year and by country.

One clear message emerges from the chart shown in Figure 6: nuclear fusion startups are multiplying. In the first 10 years of the new century (2000-2009), five new companies had been established. The last decade, from 2010 until 2019, counts more than 20 new firms, with a vast majority of companies being founded in the second half of the decade.

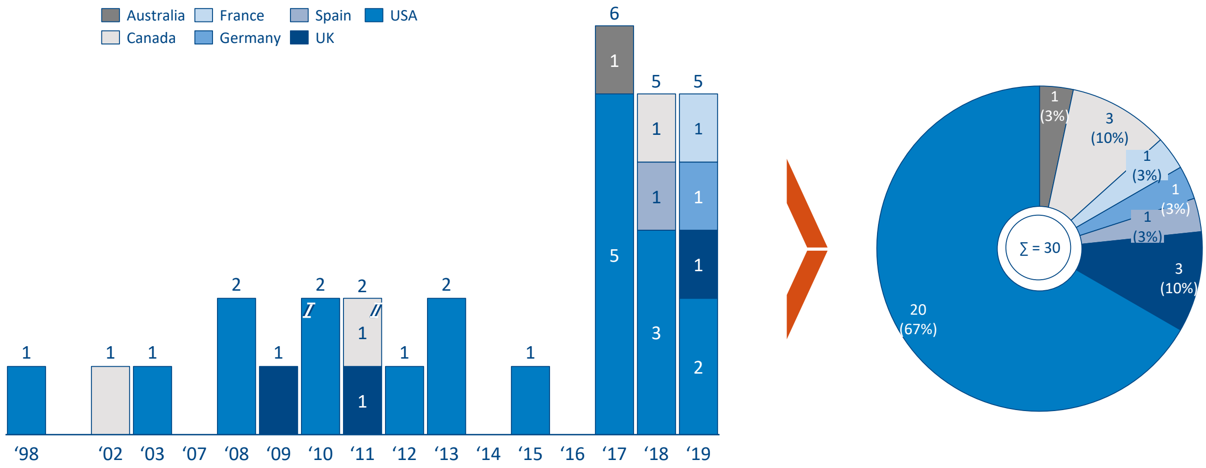
Another aspect highlighted by Figure 6 is the nationality of the nuclear fusion startups: most come from the US, followed by Canada (three companies) and the UK (three companies). Continental Europe is lagging behind from this perspective, with only three nuclear fusion companies identified: one in Germany (Marvel Fusion), one in France (Renaissance Fusion),

Figure 5: Selection of companies pursuing nuclear fusion

#	Company	Country	Foundation year	Employees (year)	Expected date for final publicly available milestone
1	tae technologies	US	1998	~180 (2020)	Late 2020s: start of commercialization
2	generalfusion	Canada	2002	~140 (2021)	Early 2030s: first commercial fusion power plant operational
3	tokamak energy	UK	2009	~160 (2021)	2030: fusion electricity in the grid
4	first light	UK	2011	>50 (2021)	2030s: fusion electricity in the grid
5	Helion Energy	US	2013	> 40 (2021)	N.A.
6	CTFusion	US	2015	<10 (2020)	2031: start commercial licensing
7	ZAP ENERGY	US	2017	>20 (2021)	Early 2030s: commercialization
8	Commonwealth Fusion Systems	US	2017	~120 (2020)	Early 2030s: fusion electricity in the grid
9	HB11 Energy	Australia	2017	<10 (2020)	2030: fusion electricity in the grid
10	Marvel Fusion	Germany	2019	>20 (2020)	End 2020s: commercialization
11	Renaissance Fusion	France	2019	~15 (2021)	2032: first fusion reactor connected to the grid

Source: Arthur D. Little analysis

Figure 6: Overview of nuclear energy fusion companies established between 1998 and end of 2010s



Note: Chart is intended to provide an overview of the most important companies and does not claim to represent a complete and exhaustive assessment of the global industrial landscape.
Source: Arthur D. Little analysis

and one in Spain (Advanced Ignition S.L.) – all of them founded in the second half of the 2010s. Although difficult to assess with certainty, the following may be seen as some of the contributing reason for this delay in the European nuclear fusion startup scene:

- There is a general lack of interest toward nuclear power in Continental Europe among new generations, leading to a lower number of students pursuing the career and therefore bringing fewer innovative ideas that could be turned into startups.
- The overall negative opinion of nuclear plays an additional role in the reduced market entrepreneurship. While the European countries are primarily shifting toward a greener economy, investors may have less interest to fund energy initiatives related to nuclear, even outside of traditional fission technologies.
- It may also be that nuclear fusion scientists and experts in Europe rotate more around the gravity center of academic nuclear fusion projects and the megaproject ITER (whose staff is 68.2% from Europe as of 2019) rather than pursuing new ventures as startups.

Unexpected investors

Startups pursuing nuclear fusion require funding, as they typically lack other income sources. Figure 7 offers a selection of fusion energy companies, including their received funds and relevant shareholders and investors.

The results show that many companies have successfully collected large amounts of funds to sustain their activities, such as TAE Technologies (more than US $880 million), Commonwealth Fusion Systems (more than $200 million), and General Fusion (more than $200 million).

A second highlight illustrated in Figure 7 is that the funding of nuclear fusion companies has been attracting high-profile market players and entrepreneurs, even from outside the energy industry. One example is Google, which has been involved both financially, via its parent company Alphabet's 2016 investment in TAE Technologies, and technically. Google is partnering with TAE Technologies to apply machine learning, data science, and advanced computation to drive a faster achievement of nuclear fusion.

Another interesting investment example comes from General Fusion, which both in 2011 and 2019 received funding from Bezos Expeditions, Jeffrey Bezos's venture capital vehicle. Together with other investors, the two investment rounds resulted in $19.5 million and $65 million in 2011 and 2019, respectively.

One more example comes from Commonwealth Fusion Systems. Besides large energy companies like ENI and Equinor, the firm received financial support from Breakthrough Energy Ventures, venture arm of a global group of high net-worth investors, funded by Bill Gates and including, among others, Jack Ma and Bezos.

Finally, Helion Energy has received funds from Mithril Capital, the global investment firm cofounded by PayPal founder Peter Thiel.

Reading about these small companies challenging gigantic projects like ITER and promising to deliver the nuclear fusion promise decades in advance may make leaders skeptical. However, some of the wealthiest men in the world, founders and/or owners of some of the most successful tech giants, appear to believe in these small firms, or at least trust them enough to be willing to invest money in them, looking for a breakthrough to change the energy world of the future and play a pivotal role in decarbonization.

Figure 7: Funds and examples of shareholders/investors for select companies pursuing nuclear fusion

#	Company	Collected funding [mln USD]	Year	Shareholders and investors (examples)
1	tae Technologies	> 880	2021	venrock, Wellcome, Google, NEA
2	Commonwealth Fusion Systems	> 200	2020	eni, Breakthrough Energy Ventures, equinor, Starlight Ventures
3	generalfusion	> 200	2021	Sustainable Development Technologies Canada, SET Ventures, bdc, Entrepreneurs Fund, Bezos Expeditions
4	tokamak energy	~ 200	2021	Legal & General Investment Management, Winton Global Investment Management
5	first light	> 60	2020	OSI Oxford Sciences Innovation, ipgroup, Parkwalk Investing in Innovation
6	Helion Energy	~78	2020	Capricorn Investment Group, Y Combinator, Mithril, arpa-e
7	ZAP Energy	~ 42.8	2021	Chevron, Fourth Realm, Energy Impact Partners, Lowercarbon Capital
8	CTFusion	~ 3.7	2019	arpa-e, W CoMotion, SBIR America's Seed Fund
9	Marvel Fusion	N.A.	N.A.	Blue Yard, in/ventures

Source: Arthur D. Little analysis

Building a brand-new ecosystem

Although the technology is not yet functioning, nuclear fusion is already becoming a full-fledged industry, similar to traditional nuclear fission. This can be seen, for example, in the establishment of an entire supporting ecosystem. Two examples are:

1. The aforementioned Fusion Energy Base, which gathers information on nuclear fusion projects and organizations.
2. The Fusion Industry Association, an international coalition that collects both fusion companies (members) as well as firms working to support nuclear fusion (associate members), such as those active in the superconductor industry.

As an industry, nuclear fusion also makes shared efforts to influence its surrounding environment. This is the case, for example, with the report "Fusion 2030 – Roadmap for Canada," developed by General Fusion together with University of Alberta, University of Saskatchewan, Alberta/Canada Fusion Technology Alliance, Sylvia Fedoruk Canadian Centre for Nuclear Innovation, and the Canadian Nuclear Society. This report was published as a lobbying effort to push the Canadian government to make nuclear fusion a national priority and shows how nuclear fusion, albeit not yet commercially achieved, is very active as an industry.

A timeline for commercialization

Fusion startups' competitive edge is that they claim to develop nuclear energy technologies more quickly than ITER – but how much more quickly?

In general, these startups aim to have commercially available nuclear energy by the beginning of the 2030s, but the specifics depend on the company.

Younger companies and firms with less funding tend to disclose less information publicly. Younger startups also tend to provide less structured information, sometimes disclosing to the public an expected commercialization year rather than a step-by-step milestones system.

Older startups, or those backed by larger funds, tend to provide more public information about their project plans, their technologies, and their new achievements. This is the case, for example, with Tokamak Energy and Commonwealth Fusion Systems.

Although each timeline is different, the general trend among startups is similar, with:

- A technology development/demonstration phase, generally starting in the first half of the 2020s.
- A commercialization phase, starting at the end of the 2020s or at the beginning of the 2030s.

In summary, these startups promise delivery timelines that are significantly more ambitious than ITER, which expects an industry-scale demonstration (i.e., not yet commercialized) by 2050. Figure 8 compares the ITER project's and select nuclear companies' publicly available timelines to achieve nuclear fusion.

Government and public perception of nuclear technology

The supply of nuclear technology facilities and research is increasing, but the demand for nuclear technology does not appear to be increasing as rapidly. In order for these nuclear energy startups to become profitable, they will need someone to purchase their products.

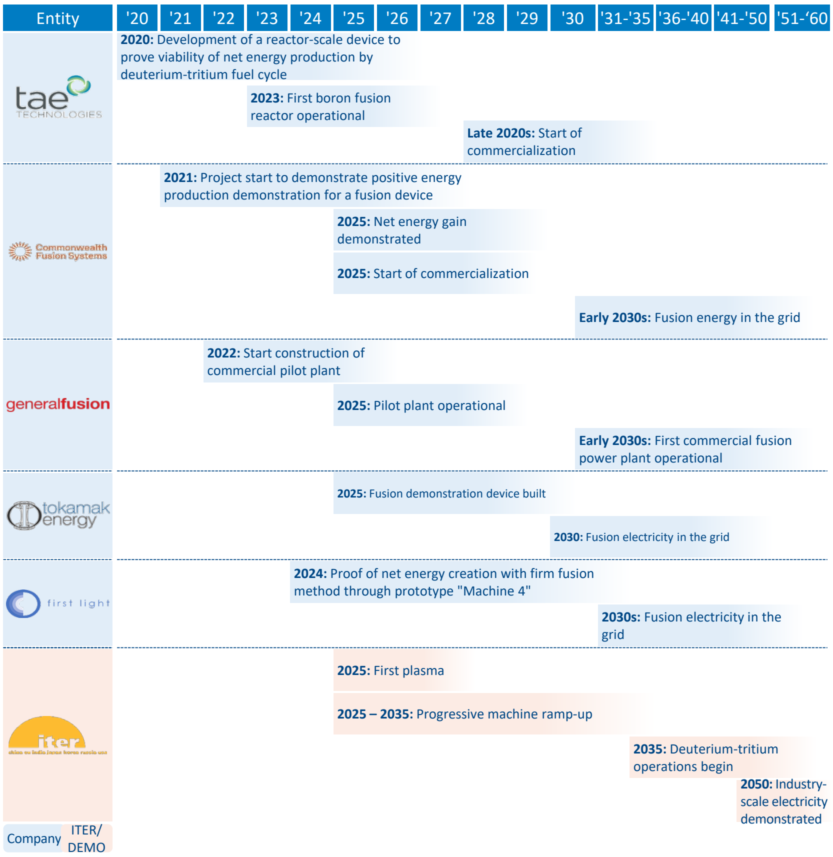
In order for investment in nuclear technology to be a profitable, long-term investment, the technology itself must become profitable. It must be able to compete with other energy sources such as natural gas. This could happen in at least two ways: (1) nuclear technology could advance so much that it becomes vastly profitable in the next 10-20 years; or (2) nuclear technology does not become profitable enough to compete with other energy sources such as fossil fuels on its own, but government regulations make fossil fuels relatively less attractive and nuclear energy relatively more attractive.

Governments might impose carbon taxes to reduce the profitability of fossil fuels and might subsidize nuclear energy (as they have already subsidized renewable energy).

The potential for government regulations to make nuclear energy seem either more or less attractive is an important factor that investors must consider when deciding whether or not to invest in nuclear energy. Investors should ask themselves whether or not world governments are likely to continue to promote nuclear energy or whether they will oppose the development of the technology.

As an example, the US government is currently sending mixed signals regarding nuclear energy. On the one hand, prominent government officials, including President Biden, have stated support for the goal for the US to achieve zero net carbon emissions in the next 20-30 years. Biden has promised $1.85 billion in funding for fiscal year 2022 to promote the Department of Energy's Nuclear Energy program. However, unified partisan support for nuclear energy is not present even among the Democratic Party, as revealed by former New York Governor Andrew Cuomo's closing of the Indian Point nuclear reactor in April 2021. The reactor had been producing about 25% of the state's electricity. Instead of switching to renewable energy,

Figure 8: Expected nuclear fusion commercialization timeline for selected nuclear fusion companies and for ITER



Source: Arthur D. Little analysis

New York ended up relying mostly on fossil fuels, which are still more cost-effective than renewables.

However, a carbon tax could change the profitability calculation. If the US government decides to tax carbon, this could make fossil fuels relatively less attractive. Biden, however, holds that carbon taxes are regressive because they impact the poor more than the rich. (That is because carbon taxes raise the price of products that are made of carbon, such as gasoline and electricity, which form a greater percentage of low-income people's budgets compared to high-income people's budgets.)

Positive byproducts of nuclear reactors

While we often think of radiation as a negative byproduct of nuclear reactors, it actually has several important functions not related to energy generation. For example, radioactive isotopes, also known as radioisotopes, are used in medical diagnostic procedures. In fact, some types of radioisotopes are relatively rare, so it would be valuable to increase the supply of such isotopes.

Unstable radioisotopes, which decay quickly, can be used as medical tracers to diagnose certain diseases. For example, once a patient is injected with radioisotopes, the isotopes will begin to decay in the patient's bloodstream. This rapid decay, when monitored by imaging devices, can show doctors whether specific bodily organs are receiving sufficient blood flow. As radioisotopes travel around the body, doctors can view the body structures such as organs and can detect the presence of tumors. Because they decay so quickly, radioisotopes do not have a chance to cause radiation-induced damage to patients during the diagnosis process.

Radioisotopes can also be used in medical treatments such as cancer treatments. Doctors use radioisotopes to target malignant, cancerous tumors. High concentrations of radioisotopes kill malignant cells, shrinking the tumors.

Medical isotope production using nuclear reactors has been ongoing for several decades, including at facilities in the US, Canada, France, Russia, and South Africa. Research continues into additional isotope production, using both reactors and other technologies such as particle accelerators.

Conclusion

Nuclear fusion is a hot topic for investors and scientists. Some believe it will not be used as an energy source until at least the second half of the century. Others claim that a faster approach exists, and that energy startups can actually bring fusion-based electricity to the grid in 10-15 years.

This latter opinion seems to have gained popularity in recent years, based on the number of nuclear fusion startups founded and on the high-profile investors they have attracted.

Without a crystal ball, we don't know when nuclear fusion will become a cost-effective source of energy. This, however, does not mean that investors should simply "wait and see" or "do nothing." Instead, prudent investors can stay apprised of news – regarding both technical developments in nuclear fusion technology, as well as developments in popular sentiment around such technology. Technical developments can provide investors with insight into the potential viability of such nuclear fusion in the long term. By staying informed of the technical developments, investors can form their own opinions regarding whether or not nuclear fission startups are overvalued, which can help them decide whether or not to invest in nuclear fusion. If investors deem that nuclear fission startups are overvalued, they may choose to invest in nuclear fusion instead.

Investors may also want to investigate industries that have the potential to grow through the positive externalities of nuclear energy. One of the most salient industries is the medical devices and diagnostics industry. Given that radioisotopes could be abundantly supplied by nuclear reactors, the medical devices industry has the potential to benefit from this increase in supply. Investors who are not ready to risk investing in nuclear energy may consider safer alternatives such as medical devices companies, which still stand to benefit should nuclear energy become widely used.

At the same time, we can expect existing startups to continue with their projects, generating more and more intellectual capital, know-how, and patents. This may also have positive spillover effects in other sectors, such as the life sciences. Investors may wish to investigate in sectors such as the life sciences, which stand to benefit should nuclear technology expand. At the same time, the nuclear fusion industry may continue to develop, and a progressively larger industry may form around the several fusion devices currently operational (97 worldwide), under construction (nine worldwide), and planned (27 worldwide), according to the International Atomic Energy Agency's Fusion Device Information System (FusDIS). This development may also lead to the public gaining more awareness of nuclear fusion, which may become acknowledged not only as an academic research field but also as an actual business and industrial sector. This could result in a growth of the sector even faster than currently expected.

In addition to the technical advancements in nuclear technology, savvy investors may wish to keep abreast of the public sentiment regarding nuclear energy. As we illustrated in this Report, certain divisions of the US government, as well as prominent investors, are financing and promoting nuclear technology. But there is not yet a sustained, large market demand for nuclear energy. If nuclear energy becomes a perceived requirement in a decarbonized future, market demand will increase, along with both private and public sector funding.

Nuclear fusion, rather than nuclear fission, could actually deliver the so-called nuclear promise of a safe, reliable, and economically convenient energy source capable to meet humanity's energy supply needs.

Overall, nuclear fusion does represent a significant opportunity for the energy industry and the race to decarbonize the world, and investors are aware of it. From an investment perspective, one could think of it as a lottery ticket: as the opportunity is uncertain, it is not reasonable to bet only on nuclear fusion as the solution to today's energy problems. However, the potential upside is so high that, even if the investment is risky and returns are not yet secured, investors searching for a solution to the energy problem of the modern era are willing to take the risk. From a policy perspective, governments may take the lead by investing in nuclear fusion research and development, just as many did with nuclear fission programs in the 20th century.

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