Think of nuclear power, and many imagine the worst. Atomic bombs, reactors melting down, radioactive wastes. There's no denying that the history of nuclear is fraught, and the dramatic and disturbing moments hard to forget. But for the most part, nuclear energy operates out of sight and out of mind, generating about 10 percent of the world's total electricity. This represents 29 percent of all the world's low-carbon power and 55 percent of the United States' low-carbon power. Nuclear reactors generate energy day and night, and produce no greenhouse gases. But overall, the growth of nuclear is slowing in comparison to other low-carbon sources like wind and solar.

By 2050, all 420 nuclear plants operating today must be replaced. We're not on a path to get there. Nuclear power plants are expensive to build, construction often takes longer than expected, and debates over how to handle radioactive wastes

rage on. What's more, public opposition to nuclear power is strong, especially in the U.S. But we're in the midst of a climate crisis, and many energy experts argue that despite a contentious history, nuclear has a key role to play in our energy future as a stable, always available source of power. As we replace coal, we really do need another form of what we call spinning reserve. You know, large power plants that when the wind isn't blowing or the sun isn't shining, that power is available. And nuclear is going to be the best solution for that. If you just believe in arithmetic, you need nuclear.

Some experts are working to upgrade existing nuclear power technology. That means designing safer and more efficient fission reactors, with the support of philanthropists like Bill Gates. But government labs, private investors and intergovernmental organizations are also devoting vast resources to what many consider the holy grail of energy: nuclear fusion. Good grief, the energy potential there is just enormous.

The energy that we need is going to be mastering this fusion. Nuclear fusion is the same process that powers our sun and every other star in the universe. And if we can figure out how to harness that power here on earth, it would be a huge game changer. Nuclear fission was discovered in late 1938 by a pair of German researchers. They found out that when you bombard uranium with neutrons, the nucleus splits, forming two lighter isotopes and releasing mass that gets converted into energy. The discovery paved the way for the development of the atomic bomb in the United States. And after the infamous bombings of Hiroshima and Nagasaki, concerns over nuclear proliferation spiraled as the global nuclear stockpile grew during the Cold War between the United States and the Soviet Union. But in 1953, President Eisenhower's Atoms for Peace program attempted to shift the focus of nuclear power toward peaceful energy generation, and much of the world started building nuclear power plants for civilian use.

Private industry quickly jumped on board, especially in the United States, and by 1991, the U.S. had twice as many operating nuclear power plants as any other country. If those all of a sudden went away and you had to make that electricity with fossil fuel, it would be like doubling the number of cars on the road. So our 100 nuclear power plants in the U.S. are helping us avoid, and have been for like 50 years, helping us avoid a significant amount of carbon generation. As of 2019, about 450 reactors worldwide operate in 31 countries. And some countries, such as France, Hungary, Slovakia and Ukraine, get more than half of their power from nuclear energy. But over the decades, a number of high-profile disasters have stalled the industry's momentum. In 1979, the partial meltdown and ensuing radiation leak at Three Mile Island in Pennsylvania cost about 1 billion dollars to cleanup. The disaster stoked public fears about nuclear power. Stricter safety standards were imposed. Reactors became more expensive to build and fewer were built. Fission is always also quite expensive, and because of the large amount of radioactivity in those machines, people are scared of it. So, the social acceptance of fission is not very good. The nuclear disasters at Chernobyl in 1986 and Fukushima Daiichi in 2011 led to further scrutiny of the industry, as concerns mounted over the long term effects of the radiation exposure. And then there's the battle over where to store nuclear waste. One proposed site, Yucca Mountain in Nevada, has been hotly contested for over 30 years. Yucca Mountain is unfit as a repository site for nuclear waste because of the impact it would have on national transportation. The current state of the industry remains mixed. Countries such as China, India and Russia are building new reactors at a fairly fast clip. But in the United States, more than one third remain unprofitable or face closure. Frankly, we're rusty. If you look at countries like China and Russia, we're being outnumbered by 30 to 1 on new builds. Only one new nuclear reactor has come online in the U.S. since 1996, as costs and construction times in developed economies have spiraled. The typical nuclear plant today in Europe costs well over 10 billion dollars and generally takes 10 years to build. The low cost of solar, wind and in particular natural gas, has meant that nuclear not only comes in at a very expensive proposition, but it also means that nuclear is not a very friendly player in the market.

Next generation fission technologies are much safer than reactors of the past, and some proponents claim they'll be cheaper too. The general public may still need convincing, but one idea has outlasted the controversy(пережить разногласия). The promise that someday, nuclear fusion will provide a better alternative. Scientists have been researching nuclear fusion since the 1920s, ever since they learned it's what powers the sun.

In a fusion reaction, extreme temperatures and intense pressure cause hydrogen atoms to fuse together, forming helium atoms. In the process, the atoms lose some mass which is converted into vast amounts of energy(огромное количество энергии). The reaction could produce four times as much energy as nuclear fission and nearly 4 million times more energy than burning coal or gas. Or another way to think about it is 2 pounds of fusion fuel is the same as about fifty five thousand barrels of oil. It doesn't contribute to greenhouse gases. The fuel is plentiful and can be found essentially everywhere in the world. The radioactivity would be short-lived. There's no possibility of a runaway reaction, so it's an inherently safe system. But after decades of research and billions of dollars, scientists still have not found a way to create a sustained fusion reaction(устойчивая реакция синтеза). That's created a not-so-inside joke among scientists that fusion is the energy source of the future and always will be.

Every time physicists think that fusion is around the corner, nature tricks them. That nature resists taking this large cloud of gas and compressing it to the point where you can get fusion out of it. When I talk to colleagues or like my parents or family, they make fun of me and say, "Oh yeah, you guys said fusion is going to be coming 50 years

from now, and that was 50 years ago. Where are ya?" But some think these questions and jokes overlook the real progress that's been made. Although we don't have fusion, over the last 30, 40 years, the amount of fusion that the prototypes make have increased by a factor of 10 to the four, 10,000 times. And this is actually a growth rate similar to the amount of transistors on a chip. The challenges is, until you get to the point where you build that first power plant, everybody thinks you haven't moved very far. Fusion has traditionally been the purview of government labs like Lawrence

Livermore and Oak Ridge. But more recently, a number of private companies have thrown their hat in the ring. This includes General Fusion, which aims to bring a commercial reactor to market in the 2030s. Amazon CEO Jeff Bezos is among the company's investors.

And then there's the large multinational effort that's underway in the south of France called the International Thermonuclear Experimental Reactor, or ITER, the project aims to create the world's largest and most powerful fusion reactor. While all of these players are competing for resources and funding, that could actually be a good thing for the nuclear power industry overall. The success of one company or one group or one organization actually grows the pie. It convinces more people out in business and in the economy to look at fusion as a viable alternative. And that attracts more investment for everybody. General Fusion, founded in 2002, operates out of a nondescript office park about 20 minutes outside of Vancouver. Unlike most government labs or academic institutions, General Fusion is focused on implementation over research. The company's goal is to build an electricity-generating fusion reactor in

the next decade or two. Jeff Bezos was an early investor and the company has now raised over 120 million, with about 90 million coming from private investment and 30

million from the Canadian government. General Fusion combines two common approaches in the industry: Inertial confinement(Инерциальное заключение), which subjects the fusion fuel to extremely high pressure for a brief amount of time, and magnetic confinement, which uses modest pressure for a prolonged time. When heated to extreme temperatures, the fusion fuel becomes a plasma, a state of matter similar to gas, except that it contains charged particles that allow it to conduct electricity and respond to magnetic fields.

Our compressor is going to be a big sphere about 4 meters across, 15 feet across on the inside. And into that big sphere, we are going to put liquid metal. And that liquid metal, we're going to spin around in a circle so it opens a hole. And into that hole we're going to put our fuel, which is hydrogen gas. It's preheated up to a few million degrees.

And then all around the outside of this sphere is a big array of pistons driven by compressed gas. So, they push on the liquid metal and they collapse the hole with this fuel trapped inside. And that collapse happens very quickly and compresses the fuel up to fusion conditions. The peak of the compression, the fuel ignites and gives a fusion reaction. That energy goes into this liquid metal. So, the liquid metal heats up, you take this hot liquid metal out, you run it through a heat exchanger and you boil water and make steam. And then the steam drives a turbine to make electricity and puts it out on

the grid. And we just keep pulsing and do that over and over again. Right now, General Fusion's main components, like its plasma injector, piston array and fuel chamber, all exist separately. Delage wants to integrate them into one large demonstration reactor, a

process he estimates will take about five years. A space roughly this size would fit a power plant that would be enough for a hundred thousand homes. And when the reactor goes online, Laberge says it will bring General Fusion's cost of power into competition with coal and renewables like wind and solar. At 5 cents per kilowatt hour, it's quite competitive, actually. Like it is cheaper than many other things. But it's not cheaper than natural gas. Laberge hopes it will eventually become cheaper though, a likelihood if the U.S. decides to implement a carbon tax. The energy market on the planet is a trillion a year. And so if we take a sizable chunk of that, we get a sizable fraction of a trillion dollars a year. But some industry experts believe that private companies like General Fusion are being overly optimistic with their timelines. In the past 10 years, there's been a lot of small industries coming in to say we can achieve fusion in five years, ten years.

I don't believe it. I think they've underestimated and not looked at the full challenge of a

fusion reactor. Nuclear fusion is hard. No research group or company has ever been able to reach the so-called breakeven point, at which the energy released from a fusion reaction is greater than the energy required to heat the plasma used in the reaction. This is not really an energy technology. It is basic research. Basic research has value. But to sell this as a technology that will solve our energy needs in the next 20 to 30 years is deceptive(обманчивый). We are just not that close. But basic research is the bread and butter of Lawrence Livermore National Lab. It's been researching fusion since its establishment in the 1950s. In 2009, the lab opened the National Ignition Facility with the goal of achieving breakeven(безубыточность) and ultimately igniting(в конечном счёте, воспламенение) a fusion reaction.

And by ignited we mean that it can be self-sustaining. It can propagate throughout all the fuel that's present in the implosion. Lawrence Livermore is pursuing inertial confinement fusion. That is, confining plasma at extremely high pressure for a very short amount of time, using high energy lasers to do so. We're standing in what we call our Target Bay, looking at our target chamber. The target chamber is a big ball about 30 feet across, and at the very center of that ball, we put a very tiny target about the size of the tip of my finger, and we irradiate that target with one hundred and ninety two of the world's most energetic lasers. Researchers at the National Ignition Facility and other national labs have access to enormous computing power, allowing them to run complex simulations that help them understand the exact conditions necessary to reach ignition. And so, based on our best simulations, they say that a facility of this scale is big enough to create this runaway reaction, if everything works nearly ideally. But clearly, getting everything to work perfectly in the real world is much harder than it looks on a screen.

The National Ignition Facility was based upon the promise of just that, ignition. After 10 years of trying, they haven't gotten anywhere close. And when they fail, they say, "All we need is a little bit more money and time!" And the critics are saying, "No, there's some fundamental problems here." So, it could very well be that neither the well-funded,

research-oriented national labs nor the scrappy, goal-oriented startups are going to solve the fusion puzzle. It might just take an international effort. The ITER project, originally known as the International Thermonuclear Experimental Reactor, originated nearly 35 years ago at the Geneva Superpower Summit. Now China, the European Union, India, Japan, Korea, Russia and the United States are all working together to build what would be the world's largest tokamak reactor, the donut shaped device used for magnetic confinement fusion. Currently under construction, ITER's tokamak reactor will be twice the size of the current largest machine and aims to produce 500 megawatts of fusion power from 50 megawatts of heating power. I do believe that this is more challenging than decoding DNA or putting a man on the moon. The literal challenge is beyond today's capacity. But Henderson says ITER is poised to surpass previous efforts simply due to the sheer scale of the proposed machine, which builds upon already established technologies. Unlike General Fusion's ambitions, the immediate goal of ITER is not energy production, though the project does have an eye towards eventual commercialization. We'll start building the actual tokamak itself, which is about 20 yards in diameter and about 20 yards in height. And that device should be completed around the 2024 period, and then

targeting to go nuclear in the 2035 period. So, by 2040, which seems a long way, we will have gained all the information that allows the next generations to build demos. Henderson hopes that these demos will achieve ignition, opening the door for industrial scale reactors that generate electricity for the grid. And that is literally where fusion will take off. It's not in our lifespan, but it is in our grandkid's or the great-great-grandkid's type lifespan. It's a grand vision, but even if ITER hits all its targets, how to translate that into a commercially viable reactor remains somewhat unclear. That's an entirely different problem. That'll take another 30 years at best. And whether the economics works out is another question. Henderson says it's impossible to say right now what a fusion reactor would cost or if the price point would be competitive. There is, however, a price tag on ITER itself. And while it's not cheap, it's not necessarily exorbitant(непомерный ) for an undertaking of this magnitude. ITER is going to cost roughly about 20 billion. It cost roughly about 120 billion in today's money to put Neil Armstrong on the moon. So, we're a fraction of that cost. And yet what we're offering is countless of generations a clean, basically limitless energy source. It's stupid we don't do this. Despite the project's obvious potential, funding for ITER can be intermittent and unreliable, as countries like the United States frequently change their contribution levels in tandem with their election cycles and energy budgets. Right now we're pretty much governed by the electoral 4 year or 2 year cycle. We need to be looking beyond that. Not everyone thinks fusion is so integral to our survival. Fusion isn't the only game out there. Fission is like fusion's ugly sibling. It's like no one wants to get involved with it. But that is the only technology that we have outside of solar and other sorts of renewables, that we can produce energy without carbon waste. Public opinion on nuclear fission remains split, but many within the industry say the controversy is undeserved. It's controversial for those who haven't studied it carefully. For those who have studied it carefully, it's not. You look at mortality rates per unit of energy produced and nuclear is the lowest of all. But there is a fear because of its origins. Many proponents of nuclear say to look back at the past to the accidents that happened is being naive about the innovation and evolution of technologies. Microsoft's Bill Gates is one of these proponents. He's intent on building safer and more efficient fission reactors to reinvigorate the industry. In 2006, he founded TerraPower, a nuclear reactor design company that's working on building new Generation 4 reactors. Most of the operating reactors around the world today, of which there's about 450, are Generation 2. Generation 3 plants are now being built out in the U.S., in China, in Russia. Generation 4 plants, they represent improvements in not just economics, but safety and waste reduction. So, the reactors that we're working on, they operate not just at lower pressures, which should be less expensive than today's reactors, but they operate at higher temperatures. When you move to those higher temperatures, you actually get a higher plant efficiency. Levesque also says TerraPower's reactors are "walk-away safe". That means that during emergencies, the plant will cool and stabilize itself without an operator present. Furthermore, Levesque says the plant produces 80 percent less waste and requires less uranium enrichment, allaying proliferation concerns. But getting new fission technologies off the ground is an expensive endeavor, so companies like TerraPower want government support, both to

build out their tech and to help them compete with cheaper power sources such as natural gas. The U.S. government does this all the time.

They did it in the case of hydraulic fracturing, they did it in the case

of wind and solar, and now it's time for the U.S. government to help demonstrate the next phase of nuclear technology as well. Levesque estimates that building TerraPower's first demonstration reactor will cost more than a billion dollars, ideally funded through a public-private partnership. I can't have my grandchildren, let alone my children, rely on fusion. This is something we've got to do because it's the one major system that we know we can build. It's a matter of how perfect we can make it, not whether it'll work. So, here's where we stand. Fission proponents(Сторонники) want to upgrade existing nuclear power plants and technologies. Fusion researchers say projects like General Fusion and ITER need more investment from both public and private sources in order to turn nuclear fusion into a reality. And climate change activists say the world needs to decarbonize, using the resources we have now, before it's too late. We need to turn to fission, turn to solar, turn to wind, turn to geothermal, turn to hydroelectric.

Do whatever we can to get off of the carbon addiction. Then, if the research and investment comes to bear, we can turn to fusion to support our rapidly growing population. I think fusion is actually an inevitable thing. I think we will solve this problem.

The key is to get it there as fast as possible. How soon we'll reach this fusion-powered future remains up for debate. The first demonstration will happen in about 10 years, I would think. By 2060 or 2070, the world is likely to be largely powered by fusion. Near the turn of the century, or maybe even a little bit beyond that. I think if the human race is still around in the year 2500 and we look back, I would wager that fusion plants will be there. However, these estimated timeframes may rely heavily on how much government decides to invest in fusion power. I think the question is political will. To what extent are our governments willing to spend the money to investigate these things? At this present rate and at this present level of will, I don't see it happening. If you were to ask me, "What is the most challenging thing about fusion?", I would not say holding some hot gas at 150 million degrees Celsius. I actually think it's our mentality. We don't think 5, 7, 12 generations down the road. A more realistic plan, a portfolio, is probably to concentrate on various renewables and work on improving standard fission. Where there's a will, there's a way. And through the process of building a machine like ITER, as well as building a machine like NIF, as well as building a machine like General

Fusion, we learn so that we can then apply that to the next time. Yeah, it goes beyond our generation. But sorry, I don't use that as an excuse.