Episode 7

The Case For All the Other Energy Sources

Packy

What do you think the pie chart of energy sources in the US looks like in the year 2050?

Casey Handmer

99% solar, maybe more. I think when people envision the energy pie chart for 2050, they consider what fraction of our current energy supply will be met by solar. But I'm also recognizing that our energy consumption by that point will have increased significantly, almost entirely due to solar. So that increases the total quite a bit.

I think it's quite likely that by 2050, the United States will have at least 40 terawatts of solar in production, which is just a staggeringly enormous number. So if I'm saying 99%, it's suggesting that everything else combined is about 400 gigawatts or so, which is also a pretty enormous number.

Bret Kugelmass

2050 is a hard number. Come on. That's too hard to predict.

But I can say in 2100, it'll be 300, maybe 500% nuclear.

Alex Epstein

For me, the obvious choice is fossil fuel, though it's not obvious to most people. I believe that for the foreseeable future, fossil fuels will remain uniquely cost-effective. They're affordable, reliable, versatile, able to power every type of machine, and scalable, able to do it for billions of people in thousands of places.

Angelica Oung

I think 40% renewable, 40% nuclear, 10% advanced geothermal, and 10% gas. That's as good as anybody can expect.

Meredith Angwin

There's no one thing that should be 100% on the grid, and that's my opinion. It just shouldn't be. I don't say we should have nuclear plants for everything, because I'm not happy with a grid that's 100% this or 100% that, even if it's my favorite kind of plant.

Julia

Welcome back to Age of Miracles. At the beginning of every interview, we ask our guests: What do you think the pie chart of energy sources in the US will look like by 2050? As you just heard, the answers we've gotten are all over the map. Some people, like Casey Handmer at Terraform Industries and Bret Kugelmass at Last Energy, think that one source will be able to carry us into an energy-abundant future.

Others, like us, think that there should and will be a mix. So today we wanted to talk to people about why they're excited about energy sources other than nuclear, although most of them are excited about nuclear too, and how it all fits together.

Packy

We have a great group today from all over the place. We'll hear from Meredith Angwin, the "Grandma of the Grid," who explains how our electric grid works, how different energy sources feed into it, and how we might make it more resilient. We hear from Mark Hinaman, who has spent his career as an oil and gas engineer and hosts a great podcast, "Fire2Fission," about transitioning to nuclear.

Alex Epstein, who you've met, is the author of "Fossil Future", a vocal supporter of the power of fossil fuels and overall an energy realist. We'll talk to Casey, who Julia just mentioned is the CEO of Terraform Industries, which is using solar to make synthetic fuels. He's doing what Isaiah at Valor Atomics is trying to do, but with solar panels.

Noah Smith, who you might know and love already, is the author of the popular blog "Noahpinion" and an outspoken solar and battery believer. Angelica Oung is a wind expert who finds herself more and more drawn to nuclear, and Eli Dourado of the Center for Growth and Opportunity, who co-wrote a classic piece on energy superabundance and tells us about geothermal, solar, batteries, and nuclear.

Across the board, the goal is more energy without fucking the planet. Our guests represent a number of different viewpoints on how we achieve that goal.

Julia

To understand where our energy mix is going, we need to start by breaking down where it is today. In 2022, humanity consumed over 160,000 terawatt hours of energy globally. For context, one terawatt hour is about enough to power 10,000 American homes for a year. Terawatt hours of consumption are not to be confused with terawatts in production. To get terawatt hours from terawatts in production, you multiply terawatt hours by the number of hours the source produces in a year, which for solar might be about 5 hours per day on average, and for nuclear might be close to 24/7/365.

So where is all that energy coming from? Oil is still our largest energy contributor at 30% of global energy consumption, followed by coal at 25% and gas at 22%. Next, surprisingly, is traditional biomass (things like wood, agricultural residue, animal dung) at 6%, mainly from developing countries. Then comes hydropower, also at 6%, followed by nuclear at 4%, wind at 3%, solar at 2%, biofuels at 1%, and all other renewables at 1%.

Packy

Despite all the drum banging and hand wringing about climate change, we've only managed to bring the combination of fossil fuels and dirty biomass down from 87% of global primary energy consumption at the turn of the millennia to 83% today. In absolute terms, our consumption of those fuels has grown from 122,800 terawatt hours in 2000 to 178,900 terawatt hours today.

Nuclear energy has actually shrunk as a percentage of energy from 6% in the 1990s and early 2000s to just 4% today. Worse, we're consuming less nuclear energy today than we were in 2000, 6,702 terawatt hours today, down from 7,322 terawatt hours then.

Julia

While the actual percentage of our energy coming from renewables is still very small, the growth rates have been steep. Wind has grown 59 times since 2000, from 92 terawatt hours to 5,487. Solar has grown a whopping 1,100 times from just 3 terawatt hours to more than 3,400. If you just extend that curve out, it's no wonder Casey thinks solar will be able to handle 99% of energy consumption in 2050, even at much higher total consumption.

That's the multi-trillion dollar, potentially existential question: What will the energy mix look like in the year 2050 and beyond? The United Nations Intergovernmental Panel on Climate Change (IPCC) suggests that to meet the climate goals in the Paris agreement and keep temperatures from rising more than 2 degrees Celsius, we'll need 70% to 85% of our electricity, or at least 50% of overall energy, to come from clean sources.

Climate activists and world governments have focused on renewables like solar, wind, hydro and geothermal at the expense of nuclear. But in mid-November this year, Bloomberg reported that the US is leading a push at the upcoming COP 28 climate summit to triple the amount of nuclear power capacity globally by 2050. They're also calling on the World Bank and other financial institutions to include nuclear in their lending policies, which wasn't possible before. If you were getting a World bank loan, it only could be for your solar or wind project. But nuclear wasn't included. This is a huge deal. Nuclear has been left out of COP discussions for years. The tides are turning.

Packy

They must be listening to Age of Miracles. Over the first five episodes of the season, we focused on nuclear fission: its history, why it's been so expensive to build, and why it's maybe not a big surprise when you hear that the deck is so stacked against it, like when they can't even get World Bank loans while solar can. We explored how to build large reactors more consistently and cheaply, and all the approaches entrepreneurs are taking to build new reactors that could be smaller, cheaper, safer, more efficient, and hopefully scalable.

But as we've told you before, while we do want to nuke-pill you, and we do think we need a lot more nuclear energy, we're not nuclear maximalists. We think the energy mix of the future should have fission, fusion, solar, wind, geothermal, hydro, synthetic fuels, and even good old-fashioned oil and gas. We'll cover each, starting with today's dominant contributor to global energy consumption: fossil fuels. Fossil fuels get a bad rap, but they too are a miracle.

Saying nice things about fossil fuels might get us canceled, but that's a risk we're willing to take. We want to live in an age of miracles, and the point of this podcast is to take a realistic look at what it's going to take to get there. It's impossible to imagine getting to where we are even today without fossil fuels. Without them, the world would be very different. Not just different. Worse. There would be no cars on the road or planes in the sky, no plastics, no widespread, affordable electricity powering homes and businesses, no advanced medical equipment that relies on precision engineering and components derived from fossil fuels.

Julia

We wouldn't have our current global food production capabilities, as modern agriculture heavily depends on machinery and fertilizers, both products of fossil fuels. Construction of buildings, bridges, and roads would be severely limited without heavy machinery and advanced materials like asphalt and concrete, which are also reliant on fossil fuels.

Our ability to communicate over long distances would be vastly reduced. The production of electronics, fiber optics, and even Internet infrastructure depends significantly on fossil fuel-derived materials.

I love the way Mark Hinaman puts it when we asked him about cutting fossil fuels out of our lives.

Casey Handmer

The common answer is, "You first."

Julia

Climate change is real, and we need to transition to cleaner, more abundant energy sources. But calls to just stop oil are misguided and unrealistic. People are gluing themselves to paintings and blocking traffic to fight something that has saved countless lives, improved standards of living across the world, and will continue to do so for the foreseeable future.

Yes, we want to slow and minimize the impact of climate change, but Alex Epstein, the author of "Fossil Future", thinks that above all else, we need to optimize for human flourishing, and fossil fuels help a lot more than they hurt.

Alex Epstein

I actually think that the main source of disagreement on energy policy is philosophical versus factual. In the book, I use primary sources and draw quite a bit on mainstream climate science. I don't offer new, radical climate science ideas of my own. Yet, the way I integrate the facts, which are almost all widely accepted, leads me to a conclusion totally different from the rest of the world. Part of it is that my goal when thinking about global policy and our environment is what I call global human flourishing. I want the world to be a place where humans have more opportunity to live long, healthy, and fulfilling lives.

One of my contentions in the book is that the way most people are taught to think about energy, particularly our energy leaders, is not optimizing for global human flourishing, but for an unimpacted planet. I think the dominant idea we have about our environment is that we should minimize or eliminate our impact. You can see this with the number one goal today: to eliminate our climate impact by 2050. That's what net zero by 2050 means. Why is that the number one goal? Why not empower 8 billion people by 2050? They're not saying, let's have 8 billion rich people by 2050. And they're not even saying, let's have the most livable and safe climate possible by 2050. They're saying, let's eliminate our impact on climate by 2050.

But if you think about what leads to a livable climate, it's hugely related to the availability of energy, because the natural climate is incredibly unlivable. The earth broadly is unlivable by our standards. Everyone used to be poor and die really early, and only a few people could do okay at all by our standards, often by exploiting others. So if you think about climate, it makes no sense to say our goal is to eliminate our impact on climate, because a lot of climate livability is having abundant energy so we can irrigate to alleviate drought, build sturdy buildings to be safe from storms, have storm warning systems, evacuation, heating, and cooling.

What I found in my research, which is fortunately now being publicized, is that we're far safer than ever from climate. A lot of that is energy that has come from fossil fuels. So this is just to set up that thinking through what your goal is in regards to energy in the world is really important.

Julia

Alex makes an important point that doesn't get brought up enough in climate conversations. Of course we want to keep the planet healthy and habitable, and we don't want rising temperatures to cause suffering and death, but we also want humans to flourish.

A livable, healthy climate is a prerequisite for human flourishing, but it shouldn't be pursued at the expense of humans by lowering the standard of living for people who rely on fossil fuels or blocking access to that standard of living from people who haven't yet achieved it.

Packy

Mark Hinaman told us something similar, that the net benefit of fossil fuels in terms of their impact on people's lives is why he works in the industry. Mark grew up in the oil patch in a rural Colorado town where his dad moved the family to run an oil and gas company. Mark and his brother worked with him from a young age, and he developed a love-hate relationship with fossil fuels in the process.

He actually swore that he wouldn't work in oil and gas, that he would work in sustainability. But during school, he took an internship as an engineer at an oil and gas company and came to appreciate the industry more. He's worked in oil and gas ever since.

Mark Hinaman

I remember being in a sustainable energy class, which I loved, and then I TA'd that class during my master's program. I remember chatting with the fellow TA about this. She asked, "But you're going into oil and gas, and it's causing climate change. Why is that good? How do you reconcile that?" Since then, I think the net public benefit that oil and gas provides is invisible to society because it's so rampant. It's in every aspect of our lives.

Everything we do, all the clothes we wear, all the food we eat - literally part of the food, the fertilizer is made with natural gas. And then how do we get it to us? There's nothing inherently bad or evil about utilizing specific energy sources. From a big picture, climate change is real and happening, but is it as bad as freezing to death in winter? Is it as bad as not having energy available?

The way I conceptualize it is the short-term net public benefit is significantly better and worth it than the long-term potential externalities. We have time; climate change is a slow and gradual process. Humans adapt quickly. We agree if we don't address it, climate change will be bad. But if you don't address putting food on your table, that's even worse.

Julia

Burning fossil fuels releases greenhouse gases into the atmosphere and contributes to climate change. That's a negative. But both Mark and Alex argued that you need to look at both the good and the bad, not just the bad, and weigh them against each other. Alex told us, fossil fuels come out looking pretty good.

Alex Epstein

The basic premise of the book is we should be thinking about global human flourishing. When considering energy technologies, we need to carefully weigh the benefits and side effects. With fossil fuels, we tend to only look at negative side effects, overstate them, and ignore our ability to use fossil fuels to neutralize and overwhelm those side effects. Drought is a perfect example.

Let's say we've contributed to drought over the last hundred-plus years of using fossil fuels. Yet the rate of death from drought has gone down by over 99%, thanks largely to irrigation and crop transport powered by fossil fuels. Livability with respect to drought has never been higher. If you only think about negative climate impacts and don't consider the ability to use fossil fuels to master climate, or the broader benefits of fossil fuels to agriculture and transportation, you'll make terrible decisions.

My basic premise is, if you carefully weigh the benefits and side effects of fossil fuels from a human flourishing perspective, you conclude that we need more of them in the coming decades, not less, and certainly not eliminating them. I go through how cost-effective energy is much more valuable than people think, and how fossil fuels are uniquely able to provide that on a scale of billions of people for the next several decades at least.

If you look objectively at the climate side effects of fossil fuels, the benefits are far more significant. We can expect that just as the world has become much better, including more livable climate-wise, than it was 100 years ago, we can expect the same thing to happen in the next 30 years if we're free to use fossil fuels and other forms of energy. If we're not, the world will dramatically regress, and everyone will be grievously hurt, especially the 6 billion people using very little energy right now, including 3 billion who use less electricity than a typical American refrigerator.

Anyone in the wealthy world needs to recognize that almost everyone is desperately poor by your standards, including energy poor. If you woke up in their shoes, you would think it was the apocalypse. So if most of the world is living in the apocalypse, then we need a lot more energy. And if you look at the current and likely future economics of different forms of energy, that means more fossil fuels.

Packy

One of the reasons I've had so much fun doing this podcast is that it's made me think more deeply about things I took for granted. As I have, I've changed my mind on a few things. I just assumed fossil fuels were bad and that we needed to get rid of them as quickly as possible. But I think fossil fuels might be caught up in some of the same trap as nuclear. Namely, we focus on all of the negative aspects instead of doing honest cost-benefit analyses.

And we fail to imagine solutions to the specific costs. Instead, we call to shut it all down. Mark pointed out that we've already come a long way with emissions thanks to good regulation, technological solutions, and hard work from men and women in the field.

Mark Hinaman

The idea that they're dangerous in the short term is true. The Clean Air Act regulates particulate matter, NOx emissions, and SOx emissions. People don't talk about that enough, in my opinion. We've done a lot to clean that up. The methodology we used to have to light these things on fire was much more rudimentary. We didn't have a lot of the emissions controls, and we have cleaned up a lot of those emissions. That being said, it's still not perfect.

But what comes to mind is school buses. I remember being a kid and seeing heavy particulate matter dumping out of school buses driving by. Everyone knew not to breathe that stuff in. It looked terrible. At the same time, people have seen images of cities in China or around the world pluming in particulate matter and pollution. Yet those societies are happy to exchange that for the value of the energy provided.

Now, why don't US cities adjacent to coal plants have these huge similar smoke plumes? We have emission controls on a lot of our combustion equipment. Similarly, it's rarer to see black smoke coming out of school bus tailpipes now because of better emission controls. I like to call attention to that idea also that there's been a lot of investment in solving these emission problems. We need to give credit to the men and women who have actually gone into these industries to help solve these problems.

It's one thing to complain about it and be a professor or have any other career outside the energy industry. But let's give credit to the people who have actually gone in and are working in these industries now, having an influence and a voice in how these companies operate.

Packy

Problems have solutions. One of my favorite examples here is Crusoe Energy, who I've interviewed on Not Boring Founders.

They're capturing stranded energy, like the methane being flared at oil and gas production sites and refineries, and using it to power crypto mining and AI data centers. We've talked about how power-hungry data centers are, and Crusoe is killing two birds with one stone to feed them.

One, capturing methane that otherwise would have gone into the atmosphere. Methane can be really bad when it gets into the atmosphere. And two, powering AI data centers that would have needed to use energy anyway.

Julia

Now, all of this isn't to say that we should just go on increasing our fossil fuel usage forever. Fossil fuels do contribute to climate change, and we do have clean sources like nuclear and solar that we should do everything we can to grow.

And Alex and Mark don't disagree.

Alex Epstein

I know I'm known as Mister Fossil Fuels, but I really don't think I have a pre-existing bias. I certainly didn't enter it with that. My bias is I want a lot of people to have a lot of energy now and in the future. I don't just want it in the future.

Julia

In "Fossil Future", Alex wrote down how he thinks about which energy sources are best suited to give people a lot of energy now and in the future.

His framework has four main pillars: affordability, reliability, versatility, and scalability.

Alex Epstein

The main criteria I talk about, all under the banner of cost-effectiveness, is ultimately what matters with energy. Can you use this in a way that's truly beneficial to you? If it's in any way cost-ineffective, you're not going to use it. I talk a lot in the book about what I call the "private jet problem". There are certain types of machines we would love to use because they're amazing. Private jets are an amazing thing, but energy, as well as some other production processes, is just not cost-effective for all of us to use private jets.

It's cost-effective for Tim Cook because his time is so valuable. If he wants to pay $50k or $75k to travel across the country to save a few hours, that's totally worth it. Or Taylor Swift, totally worth it. But for Alex Epstein, it's not worth it. I would bankrupt myself over time. Cost-effective is the core idea, and the elements of that are affordability - how much can a typical person afford? Reliability - to what extent are we able to use energy when we need it, in the quantity we need it? Both of those are crucial.

One interesting point is solar and wind naturally provide the exact amount of energy we need 0% of the time. When you use naturally stored forms of energy, or even manmade stored forms of energy, which unfortunately are usually really expensive, you can get the exact amount of energy you need when you need it. But natural phenomena that are flows never provide you exactly what you need. It's always too little or too much.

There's affordability, reliability, versatility - which is the ability to power all sorts of machines, including very difficult to power machines like large cargo ships and airplanes. This is a very underrated variable. People tend to conflate energy and electricity. But right now, only about a fifth of the world's energy use is electricity.

Usually, the most cost-effective thing is to directly burn hydrocarbons to create a lot of heat, whether it's for transportation or for some industrial or sometimes residential heat purpose. And then there's scalability, the ability to be affordable, reliable, and versatile for billions of people in thousands of places. Those are the four dimensions of energy benefit.

Packy

Thanks for listening so far. Hang on, we'll be right back after a quick word from our sponsors. Affordability, reliability, versatility, and scalability. In Alex's framework, fossil fuels and nuclear do well, but he doesn't give as much love to renewables.

My takeaway from talking to Alex and Mark, and frankly, to many other energy realists we've spoken to throughout the season, is that fossil fuels have been overly villainized and aren't going anywhere anytime soon, which is a good thing. They're incredible for humanity, but they're not the long-term solution. Fossil fuels' villainization has been a good catalyst to accelerate the electronaissance or energy transition by speeding up the development of energy sources that might be.

Julia

Renewable energy sources like hydro, geothermal, wind, and particularly solar, receive more public support and excitement. They let humanity pull energy from elements like water, wind and sun, which won't run out until the sun dies in 7-8 billion years. Combined, renewables make up about 12% of total energy consumption today and about 30% of global electricity consumption. The share of electricity has grown by 10% since 2010.

Renewables are growing quickly as they come down the learning curve and benefit from both government subsidies and a market push for more clean energy. We'll tackle geothermal, wind and solar, starting with geothermal, which may be the least understood energy source with the highest ceiling.

Eli Dourado, a self-described economist and regulatory hacker living in Washington, DC, and a senior research fellow at the Center for Growth and Opportunity at Utah State University, doesn't have a particular horse in the race. He's written about energy superabundance and writes on his website, "My fondest wish is that GDP per capita would reach $200,000 by 2050." Eli thinks geothermal has a lot of potential.

Eli Dourado

Traditionally, geothermal has been located at sites where boiling water is close to the surface. The first geothermal plant is in Italy at a place called Valle del Diavolo, or "Valley of the Devil," where it literally looks like hell because you can see boiling water on the ground. That's obviously a pretty niche source. As you say, California has this field called The Geysers. That is the biggest geothermal field in the world and provides maybe a gigawatt, but that stuff is pretty niche.

The real opportunity is to take all of the progress we've had in the last 15 years in the shale fields, with fracking and drilling, and just be like, okay, we're getting really good at this. Drilling costs have gone way down. We can make these geothermal formations anywhere we want. There's heat everywhere if you're able to drill deeply enough.

And then the other thing you need to produce geothermal steam is a rock formation that transfers enough heat to the water. Rock is actually not very good at transferring heat. It's pretty slow. So you need a high surface area to volume ratio, which means either a lot of fractures or a radiator-style design or some other way of collecting heat. And so we can construct these. The argument is at depth, if we can do that anywhere, then we have geothermal anywhere. It is a massive resource. It is bigger even than nuclear in terms of total thermodynamically available energy on the planet.

If we can get a replay of the gains we got in the shale fields, but with geothermal, you could have terawatts of geothermal energy in the United States in the next couple of decades. So it's a very big opportunity.

Packy

Geothermal is early relative to other sources. It powers 23% of Iceland's energy consumption. But across the globe, its current generation capacity of 16 gigawatts is so small that Our World in Data still includes it in the "other renewables" category.

As Eli pointed out, applying the drilling and fracking advances developed in shale fields over the last 15 years might help crack it open. Julia, it's been an amazing thing for our country.

Julia

Fracking was very controversial to start. People kind of freaked out - you're putting these fluids into the ground and suddenly we have all this new natural gas. But it's the reason carbon emissions have come down in the US over the last 20-30 years. It's an example of people in the oil and gas industry trying something new.

They were initially using fluids with some chemicals that weren't the best, but they quickly iterated towards something that is essentially water and sand, not actually harmful from an environmental perspective. They made a lot of progress, and it's been one of the reasons we've been able to bring our carbon emissions down. There's a lot more natural gas now that we're using across the country.

Packy

A couple of things I love there: one, energy abundance through innovation; and two, the history of technology as innovations happening in one field being applied to another. We're seeing that happen in geothermal. Recently, a startup called Fervo hit a milestone when it completed a 30-day test, which is the industry standard in geothermal.

They drilled down to 7,700 ft and then turned to drill another 3,250 ft horizontally - techniques lifted directly from the shale fields. Internal temperatures reached roughly 375 degrees Fahrenheit. Once they and others prove that it works using grant and venture dollars, they can move over to project financing and scale up, just like nuclear.

Julia

I'll make a plug here for an excellent book called "The Absent Superpower: The Shale Revolution and a World Without America" by Peter Zeihan. He also wrote "The Accidental Superpower," about why the US is so well-endowed with resources and benefits so much from that. This one talks about how the shale revolution, basically fracking in the US over the last 20 years, allowed us to become energy independent.

We weren't relying on international markets for energy, which is core to everything we do. You can imagine that allows us to pick and choose how we want to engage with the rest of the world. We don't have to show up in the

Middle East to make sure we get the oil we need because we don't have any other options and it being a source of tension.

Great read if anyone wants to learn more about the shale revolution.

Packy

We need to put up an Amazon referral link and start getting some revenue from all these plugs. That's amazing. And it brings up such a good point, which is one of the reasons we want energy abundance. We'll talk about that a lot in episode ten.

But when you control your energy, you control your destiny. It becomes one chip that you take off the table that you don't need to negotiate with. That's amazing with fracking, and we'd love to see it happen with nuclear, solar, fusion, and geothermal. I hope Fervo succeeds.

Julia

Quick aside on Fervo, by the way. It has the most stacked early-stage cap table in startup history. There are five angels who participated in the Series A: Bill Gates, Jack Ma, Richard Branson, Jeff Bezos, and Masayoshi Son himself.

Packy

Holy shit, what a lineup. All right, so now you have your target list for Antares' Series A.

Julia

I'm ready. Give me a call, Masa.

Packy

Do geothermal fans think it has a shot at producing most of the world's energy?

Like Casey believes solar can and Bret believes that nuclear can?

Julia

They don't. And the reason it can't is it's heat.

Casey Handmer

Geothermal doesn't get super hot. Super hot geothermal is considered about 400 degree steam at the surface. You get to about 500 degrees C temperatures in the rock, and then produce about 400 degrees C at the surface. That's about as hot as you're going to get.

If you want something hotter, you need nuclear, hydrogen, or natural gas. But there are a lot of applications that need 400 degrees C or less, including electricity generation, which you can do at that temperature or lower if you get creative with the turbines.

Julia

I love this point. It's obvious when you think about it, but important to spell out: not every source of energy is good for every use. It's estimated geothermal energy has the potential to meet 3-5% of global demand by 2050, and 10% by 2100. Take these estimates with a grain of salt, but they're useful for ballpark numbers.

Geothermal could be great for many things, especially as companies like Fervo figure out deep geothermal, and potentially traditional oil and gas gets involved in scaling it. I hope we see geothermal heating greenhouses and homes like it does in Iceland, and eventually reduce the need for coal as we drill deep enough.

Angelica told us she thinks we can get to 10% geothermal, and I'm rooting for that.

Packy

But oil, gas, and geothermal won't power the whole world, so we need to keep drilling or exploring other sources. Next up is wind. Wind is the energy source that excites me the least. It's intermittent and less predictable than the sun. It kills birds on land and whales offshore.

It takes a ton of resources to build and introduces a high maintenance burden. Wind farms are eyesores from miles away and require a shitload of land to build. You can move them offshore where the wind is more reliable and fewer people have to look at them, but then there are challenges with installation, connection, and maintenance. You need to run undersea cables to connect to the grid, and saltwater and rough seas increase wear and tear.

I get the beauty of pulling power from the wind, but in practice, I just don't get it. About 3-4% of total energy consumption in the world comes from wind. That's great, and it's been coming down the cost curves, but I still don't get it.

It was harder than expected to find a champion for wind to talk to us. I can name 25 people who champion nuclear on Twitter, a ton who support solar, but I couldn't think of one big wind advocate off the top of my head. Luckily, we found Angelica Oung, who has spent a lot of time researching and reporting on wind. She's a bigger fan of nuclear now, but we asked her to play the role of wind person, and she was kind enough to accept. She gives us the history and recent stumbles of wind.

Angelica Oung

The modern gigawatt-scale wind turbine wasn't the product of R&D; by a big company or the government. It started as a project in a Danish school, the Tvind School. This progressive school wanted to develop an energy source to show the world you don't need industrialized sources like nuclear or fossil fuels. They created this modern design, a wind turbine called Tvindkraft, in the mid-70s. It's amazing - you can still see it spinning in Jutland, Denmark. It has that modern trifoil shape of a wind turbine.

Since that initial breakthrough, the Danes have been the driving force in developing this technology. Now one of the biggest modern OEM turbine makers, Vestas, is from Denmark. Wind turbines started on land and got bigger over time. The amount of power produced is proportional not to the size of the turbine but to the swept area of the blades, so even a small extension of the blades results in much more power. Around the early 2000s, people got the idea to put them in the ocean. At first, this seemed insane due to challenging ocean conditions and difficult servicing. But they made it happen, and turbines kept getting bigger and placed farther into the ocean. This process is still ongoing. This is a crazy process that is still ongoing.

Turbines are getting bigger with almost every project. Offshore turbines have advantages: less NIMBYism issues and steadier winds, resulting in higher capacity factors (around 40% compared to under 20% onshore). For a while, costs came down steadily as the industry planned to go bigger and deeper, and it really looked like a linear progression where costs are just coming down.

But everything changed when the Russia-Ukraine war broke out. All of a sudden, the condition that enabled the industry to advance were reversed. They were counting on very steady commodity prices. We've had this cycle of commodity prices that delivered steady cost decreases. But then suddenly, the prices of their key commodities all went up 40-50%. Then, of course, cheap interest rates, which are almost like a lifeblood for the development of inexpensive renewable projects, stopped being a thing.

This revealed a lot of strains that were already existing within the industry. With a rapid increase in turbine size, the supply chains were really strained to the point where they're starting to creak and crack. When you pencil it out, it seemed really attractive to go from a 10-megawatt turbine to a 15-megawatt turbine. But when you start to install the thing, you realize we don't have enough vessels of that size, or these foundations are just so much more expensive to construct because they have to hold a bigger load. All these relationships of cost increases that are not linear started to reveal themselves.

Julia

In Angelica's telling, things seem bleak for wind, particularly offshore wind. Wind has been a public success story, right there on the chart next to solar, showing energy sources that just keep getting cheaper over time. But higher commodity prices and interest rates have opened up cracks in the story. Issues from within the industry itself, namely that huge offshore turbines need a lot more maintenance than expected, have also emerged.

And then taking stock prices, Orsted stock prices are down 50% on the year. We asked Angelica if there were bright spots, and her answer was pretty shocking.

Angelica Oung

What's interesting is nobody's disagreeing about the message, but people are split on what to do about it. On Twitter, when they see a headline like "Orsted stock crashing" or a big question mark on supply chain for the latest turbines, they think, "Bravo. It's time to stop with this offshore wind nonsense and do something like nuclear that we know works." But the wind people on LinkedIn don't think this is a problem for them as much as it's a problem for everybody. They think, "Our industry isn't profitable. So what are the governments of the world going to do about that?"

They'll say, "We wouldn't want offshore wind to become a luxury product. We wouldn't want these projects not to be built, which might happen if we stay unprofitable." In some cases, they'll simply say, "We need more support, we need more subsidies, chop chop." In renewables, they have enough social license that the offshore wind people feel they can do that and governments would comply.

I don't know if they're going to turn out to be right in the US, but in Europe, there's a huge amount of offshore wind in the goals because they're such a bulk source of renewable power. Europe can't reach its ambitious goals without offshore wind. Therefore, I think industry is correct in detecting that they have enormous leverage. "Make our business work for us or kiss your goals goodbye."]}},{

Packy

That is, pardon my Danish, fucking crazy. "Make our business work for us or kiss your goals goodbye." What Angelica is saying is that because the EU has climate goals to uphold, the wind industry believes the government must subsidize them, despite upside-down economics, if they want to hit those goals.

It feels like the tail wagging the dog and is the same kind of backward thinking that led Germany to shut down its nuclear and turn back on coal. Bad incentives, bad outcomes. The ideological pursuit is getting in the way of the real goal: to increase human flourishing.

Julia

Wind is a useful resource in very windy places, especially those that don't get a ton of sun. Denmark, the birthplace of wind turbines, gets more than half of its electricity from wind. Uruguay gets about 40% of its electricity from wind now, after droughts in '97 and 2007 caused blackouts due to the country's reliance on hydropower.

Larger economies like Ireland, the UK, and Germany get 35%, 24%, and 20% of their electricity from wind, respectively. When the wind blows and turbines don't break down ahead of schedule, wind energy can be very cheap. By levelized cost of energy, onshore wind is the cheapest source of energy at $.03 per kilowatt hour as of 2021, according to the International Renewable Energy Agency. This is compared to $0.05 per kilowatt hour for the next cheapest: solar and hydropower.

Packy

But levelized cost of energy has several issues: 1) It doesn't account for intermittency, reliability, or backup storage solutions like natural gas peaker plants and batteries required to ensure a stable energy supply. 2) It excludes many external costs, like environmental impact and health effects from pollution, and negative externalities, which to be fair, is a problem for a lot of measures of costs of things. 3) It ignores system integration costs like transmission and distribution infrastructure, which can be more expensive if the energy source is located far from people, like wind often is.

4) It makes assumptions on lifespan and maintenance, which seems to be a particularly big challenge for offshore wind turbines. 5) It doesn't consider location factors such as land costs and local environmental regulations, which can significantly increase the cost of energy generation. LCOE is kind of ballpark useful, but breaks down if you rely on it too much. That said, Angelica believes that while offshore wind is a bit of a disaster, onshore wind is actually slept on and something to sprinkle into the mix.

Angelica Oung

I actually think onshore wind is really slept on. Offshore wind became much sexier because there's more potential to spread out into the ocean when you don't have problems with NIMBYism and you get a better capacity factor. But the good thing about onshore is it's affordable because they've stopped progressing with the size of the platforms. For onshore wind, a lot of that has to do with transportation. You can't haul such big wind turbine components on the roads. For instance, the four-megawatt turbines have been standardized for a long time now. Vestas makes them, and they just keep getting better at it.

It's almost a little bit analogous to the SMR argument, because they're small and they've gotten so good at making them that they've really cut down on costs. If you're a country with a lot of land and you can sprinkle it with onshore turbines, I think that's a tremendous way to decarbonize. Of course, you have to manage intermittency, and you probably will need gas-burning plants as backup, but you'll be able to use that cheap wind to cut down on your use of gas.

I think, as with a lot of renewables, you can't make blanket arguments about what's good and what's bad. It depends on where you are. Are we facing a climate emergency or not? If you believe we're facing an existential threat for all human beings and other creatures on this planet, then maybe you have to take action somewhere. I think onshore turbines, if they're cheap and you have the land for it, are not a bad option at all.

Packy

I'm picking up a theme here. Both Eli and Angelica pointed out that geothermal and wind, respectively, can be useful pieces of the overall energy mix where they make economic sense. Neither is a candidate to power all of humanity's growing energy needs, and that's fine. Coming into the energy conversation from the outside, one thing that surprised me, but also didn't because humans are humans, is how tribal supporters of different energy sources can be.

Nadia Asparouhova wrote an excellent piece mapping out the tribes of climate that gives a good overview of the landscape. We'll link to it in the resources guide. The right way to think of each source is as part of a mix, each contributing where it makes the most economic sense, not falling so madly in love with any one that you let it blind you to reality. Angelica is a great model here.

Angelica Oung

Offshore wind was my first love in energy. It's like everything I do in life, if I'm going to be any good at it to any degree, I have to be in love with it. When I started covering offshore wind, I was fully in love. I thought the turbines were engineering marvels. I've always thought of the ocean as a very romantic place, and the idea of doing great things out there that will bring prosperity and stability to my country was tremendously stirring.

But I remember the first time I was checking how each of the projects were performing, and it was like zero, zero. I panicked and called up a very senior guy in the industry, head of APAC. I asked, 'What happened? What's going on with the projects? Why are they not producing any electricity?' He told me, 'Angelica, take a look on Windy, the app. It's below 4 meters a second right now, and those turbines don't produce anything at that wind rate.' I wanted to expose that very embarrassing detail about myself as a way of reminding people that it's possible for somebody to cover a subject as a reporter to the degree where they can just call up the head of APAC of one of the big companies in this subject, and not know that intermittency is just that brutal. When the wind isn't blowing, it doesn't produce.

That was when I realized that offshore wind, wind in general, is going to be more of a secondary solution for Taiwan's energy crisis. And we really do have an energy crisis. It's not just a decarbonization crisis, although, of course, we're trying to cut down on our carbon. It's an overall energy crunch. Some days, the state-run utility companies have to make calls to factories and ask them, 'Can you not run your machines this late afternoon? Because we're really tight.' No factory owner ever wants to get that call. They don't care if they're compensated three, four, five times the cost of the energy they forego. They want their lines to be working. They want their staff not to have to idle. So for me, this is already a power crunch issue.

And the problem with offshore wind is that due to the intermittency, it's not going to help with the power crunch because you can never rely on it. You'll always need 100% gas backup just in case the wind isn't blowing. So to me, that reduces their role to that of a fuel saver. Whenever the wind is blowing, you don't have to burn that gas, therefore you're saving fuel. Is that valuable? Yes, it's tremendously valuable. To the extent that you can get the price of offshore wind down, it can be a very good thing.

This is especially true for an isolated island grid like Taiwan, where you can't do the number one thing that people like to do to manage intermittency, which is to send it somewhere else that can use the power. The amount of variable electricity produced on the grid shouldn't go above 20% for an isolated grid like Taiwan. That's solar plus wind, and we're getting up there, and we're already starting to have to make a lot of expensive grid upgrades because of that.

That's when I had almost a mini existential crisis, because this was something that I was very devoted to. It very naturally led to my curiosity about nuclear energy. And the more I found out about it, the more I really asked myself, why aren't we using this already?

Julia

As we move on from wind, there are a couple of things to take away from what Angelica just said. At a high level, it's great to be passionate about understanding and supporting an energy source, but you should also be willing to look at the facts and change your mind when the facts call for it. The goal isn't to generate more wind per se, or more solar, or even more nuclear. It's to deliver energy where it's needed as cheaply and reliably as possible to support human flourishing.

The second thing, that variable electricity shouldn't contribute more than 20% to the grid, at least for an isolated island like Taiwan, is an important, nuanced point that merits a detour out of energy sources and into the infrastructure through which electricity runs once it's produced: the grid. We had the chance to talk to Meredith Angwin, known as the 'Grandma of the Grid' and author of the book 'Shorting the Grid,' to learn about how our electricity grid works, what makes it so fragile, and how she thinks about the energy mix in the context of delivering it to end users.

Meredith Angwin

I feel that people are going around with renewables saying, "that's all we need. We're going to have 100% renewables." And the answer is, there's no one thing that should be 100% on the grid, and that's my opinion. One of the things that bothers me is that prices go up as renewables get on the grid. This is because of the redundancy. You can't shut down that plant because the sun isn't always shining. You got to have it around.

And if you want that plant to stay around - this gets to be controversial - you have to pay it enough to stay in business.

Packy

This is the kind of stuff I was talking about when I ran through the drawbacks of using levelized cost of energy, or LCOE. Because wind and solar aren't reliable, backup plants - typically natural gas and sometimes coal plants - get two forms of payment. One is the energy payment per kilowatt hour. It's what you'd expect. Deliver energy and get paid - easy enough.

The second is capacity payment. Backup plants get paid just to stay online and at the ready whether or not they end up getting called on. That cost ultimately gets paid by the end consumer in the form of higher electricity prices.

Julia

The grid is a complicated beast. How does it work, roughly? It moves electricity from its source to end users. Electricity accounts for roughly 20% of global final energy consumption, according to Enerdata, up 3% since 2010. A large portion of the economy still runs on fossil fuels that haven't been converted to electricity. Think things like gas in your car.

The push to decarbonize is really a two-front battle: sources and uses. We've been focusing on the sources side, like nuclear, fossil fuels, wind, geothermal, and solar. But the other side is best defined by the race to electrify more of our economy. Electric vehicles are exciting because they can run on electricity, which can be produced by clean sources like nuclear and solar.

Impulse Labs is trying to electrify home appliances like stoves and move them away from gas. Heat pumps use electricity instead of oil to provide heat, etc. In some cases, there are efficiency gains in moving to electric-powered things, but the real decarbonization gains come from moving to electricity and then using clean sources to generate that electricity.

All of which ultimately means that we're going to put a lot more strain on the grid, which is why, to understand the different energy sources, you need to understand the grid. Here's Meredith to explain.

Meredith Angwin

The basics you need to know is that the grid is very different from a tomato. What I mean is, you can't tell one electron from another. When you buy a tomato, you could trace it back to the farm or greenhouse it was raised on, but you can't trace back electrons. They're just there. This makes the whole thing difficult to understand. You can't say, "We're not using Vermont Yankee power." When Vermont Yankee was putting power on the local grid, we were all using it, because there's no way to differentiate Vermont Yankee power from any other power. You can't really trace electricity the way you can trace other things.

Another thing about electricity is that it always has to be in balance. The amount produced and consumed have to be the same. Unlike tomatoes, which can be stored or moved, electricity must be used as it's generated. I wish I could take everybody to a balancing authority dispatch center where people keep track of predicted usage, what power plants they asked to come online, and then manage the changes. More might be used, less might come online, or wind turbines might be coming online more than expected. These people are constantly balancing it.

For example, when people said we were four minutes away from losing the grid in Texas in February 2021, it meant the system was out of balance. Demand was higher than supply, causing the frequency to drop, which can damage equipment. To fix this, they turned off some demand, leaving some areas without electricity, but bringing the frequency back online. If they hadn't, within four minutes, equipment would be damaged or shutting itself off, and the whole grid would fall apart. People don't know this. They think you just turn on the light and everything's fine. Yeah, if everybody's doing their job, the predictions are right, and there aren't any crises, it's going to be fine.

Julia

The challenging part about intermittent renewables like solar and wind is that they make predictions harder. That means needing to call on backup plants to come online quickly when the sun doesn't shine or the wind doesn't blow. It also means increased risk of having to turn off demand or of the whole grid falling apart.

It's a consideration that needs to be kept in mind when thinking about the right energy mix. That said, there are really smart people who have weighed that in their calculus and concluded that solar is basically all we're going to need.

Packy

Solar is really interesting because all of my techno-capitalist instincts scream, "This is it." I love the chart of solar cost declines and installation increases. I love the idea of just trusting the curves, just betting on solar to keep getting cheaper and powering more of our electricity.

Whereas geothermal and wind clearly fit into the "this can be a part of our future energy mix" bucket, solar's fans believe that it could do a lot more than that. Some, like blogger, economist, and fellow Turpentine podcast host (Econ102) Noah Smith, think that solar has won and that we don't need nuclear at all. We asked him to give us a brief history of why solar is doing so well.

Noah Smith

The first thing that happened with solar panels was that the government funded a lot of research into how to make solar panels better. For years, skeptics said we needed new, more efficient types of solar panels, like perovskites. It turned out we did not. Simple silicon did the trick, and there were many ways to make those panels more efficient. Until the mid-2000s, you see massive improvements in the technological efficiency of solar, mostly driven by government-funded research in the United States.

Then you see the switchover where solar panels don't get cheap yet, but cheap enough that people start to install more of them. The learning curve takes over as private companies scale up, leveraging economies of scale and learning by doing. Solar panels got insanely cheap, with some other factors too. Around 2010 or 2011, China massively subsidized solar panels, causing a brief dip in prices. But primarily, the factor behind solar panel cost decrease was learning curves.

Then you get all the harder stuff, called balance of system costs. You have to buy the land for solar power, get people to install and maintain it, and recycle it after its life. We're seeing cost improvements in almost all these things except land acquisition. But you see cost improvements in installation, and if you look at balance of system costs, they've been declining at a much gentler slope than the manufacturing. Panels are now dirt cheap, a commodity. You can get solar panels for free. They're too cheap to meter. But the installation costs have been going down steadily, though not as fast as manufacturing costs. The land cost is still the big cost and going forward, that will be the main continued barrier to making an economy based on solar.

Julia

It all comes back to learning curves. We'll come back to land costs shortly. But solar's learning curves have been nothing short of spectacular. It's exponential rates of improvement like this that inspire the founders we spoke to on episode four, who want to manufacture SMRs to bring them down their own learning curves.

Like you said, there are people who've seen that experts keep undershooting solar estimates and then have come to the realization that they should just trust the curve.

Packy

That's what Casey Handmer is doing at Terraform Industries, which is like the solar version of what Isaiah is doing at Valor Atomics, a company that we talked about in depth on episode five.

Casey Handmer

What Terraform is doing is asking the question, how do we build a synthetic hydrocarbon supply chain? With hydrocarbons, we have twin fundamental problems. They're too cheap, too wonderful, too amazing for overcoming global poverty. At the same time, there's not enough of them. They're scarce.

What we're trying to do at Terraform is not even all that hard. We're finding a way of converting solar energy, which is essentially unlimited on the scope and scale of what humans currently consume, into a synthetic hydrocarbon product. It's backwards compatible, essentially unlimited in availability, and does not use fossil carbon. So you can use as much of it as you want without increasing atmospheric carbon. The carbon is obtained from the atmosphere much the same way that plants do, just much more productively.

If we can get the costs down low enough to compete with drilling, we can displace drilling at the speed that we can ramp up solar production and decrease solar costs, which is staggering. It's like 10-15% cost reduction per year, 30-50% production increase per year, which is about as fast as any hardware manufacturing scale-up has ever occurred. That's super exciting. So we're pulling in that direction.

Packy

I think Casey is one of the smartest people I've ever met. He worked at NASA's Jet Propulsion Lab, writes one of my favorite blogs, and in his free time helped read the ancient scrolls as part of the Vesuvius challenge.

He's betting his whole company on solar and thinks that solar can provide 99% of the world's energy needs. His thesis is very much a "trust the curve" thesis.

Casey Handmer

First of all, I'm not necessarily the best person to give a history of solar or even its current state. But the good news is that no matter what I say, even if it was correct, it'll be wrong in a year's time anyway because the industry is still changing extremely quickly. For the last 10-20 years, all the adults in the room have been insisting that solar is going to flatline this year. No more cost improvements are possible. We've tapped it out completely, and every single year it's gotten cheaper. Every single year, they've deployed more. The so-called experts have been wrong for reasons that are actually pretty obvious in hindsight. But nonetheless, no one is updating on this and they're just assuming, "No, this is the year that solar will flatline." But actually, if anything, this is the year where solar has really taken off, which is kind of insane. There's this fabulous chart you can find of the retrospective predictions of solar deployment. And now the chart is really tall because it kind of blew off the top by about a factor of ten. As of this year, we think we're on track for between 450 and 480 gigawatts of solar deployed worldwide, which is a very large number. To put that in perspective, a 1 MW solar array consumes roughly five acres of land. You could think of an area a few football fields in size, and humanity is currently deploying those at a rate of about 1/minute. Last year we did about 260 gigawatts, the year before, about 180. So the year-on-year growth is 30-50%. Actually, I think this year versus last year will be almost 100% year-on-year growth, which is moving in the right direction.

If we think about a doubling time, how long does it take for the total deployments to double? I think when I started Terraform, that was closer to three years, and now it's less than two years. Just to put that in perspective, in order to completely displace hydrocarbons worldwide, we'll need about another factor of 1000 in cumulative growth. And 1000 is about 2 to the power of 10. So it's 10 doublings. And if a doubling occurs every three years, then that will take 30 years. If it happens every two years, it'll take 20 years. So 20 versus 30 years is 10 additional years of carbon emission into the atmosphere, which is roughly 400-500 gigatons of carbon. That's probably equivalent to half a degree or thereabouts of cumulative warming over a long period of time. And half a degree makes a really big difference in how many people ultimately get killed and seriously hurt. So I'm all on board with accelerating.

The really exciting thing about solar manufacturing and deployment is that roughly a quarter of solar deployment is occurring just within China. There should be a wake-up call for the rest of us. But there are dozens of companies producing solar panels, cells, and arrays, and there are different steps. If you look at the leaderboard of these companies over time, even though cumulative global production is growing 30-40% per year, these companies are switching places quite a lot. It's very volatile. Enormous investments are constantly being made in increasing production, building new factories, new technology, rolling out new building, and so on.

But the process from signing a piece of paper to having the factory in full production is longer than the critical timescale of the durability of a particular lead in this industry. So it's very hard to predict who will be in the lead in, say, five years' time. But that's also super exciting, because it means if you're an entrepreneur or an investor, and you think if you find the right team who's aggressive enough, if they can just maintain a 5-10% lead over the next best company, they could start from nothing today, and they could be the global leader in five years. I think that's super exciting. It's very hard to say who will be the major manufacturer in five or ten years, or even which exact technology they will use. But I think it is possible to say in the aggregate, roughly how much power will be produced at that point. Super exciting. Anyway, I'm getting fired up.

Packy

Noah thinks that China's big advantage, even more than its manufacturing capability, is that its government can just take the land that it wants and put solar panels on them.

Noah Smith

In China, they have no land acquisition costs because the communist party owns the land. They can simply declare, "This is now a solar farm," even if it was someone's home before. As a result, China is installing solar at breakneck paces. This isn't about subsidizing panels or cheap installation labor. It's about land. In China, they can put it wherever they want. America is installing solar power at a fast and accelerating rate, but nothing near China's pace. Europe is installing more, too. The main problem is our much more laborious process of land acquisition.

That's going to hit coal, gas, and nuclear, too - probably gas the least, because gas plants are really small. No one puts a giant security perimeter around a gas boiler until some dipshit decides to blow one up. Then maybe we'll have security perimeters on every gas boiler, just like we have to take off our shoes because of that one guy who thought he could make a bomb with his shoe. Worst terrorist of all time. Anyway, land is still the biggest barrier to solar power here. We're slowly solving it. There are lots of workarounds, like building on government land. The government owns more than half the land in the American West. We can build stuff there. We can build next to highways, where you already have the right of way. There's a lot you can do.

Ultimately, it comes down to a NIMBY problem to build solar, but that's going to hit pretty much all energy sources as well. We're solving that, but all the other costs got real cheap, and that's the main story of solar.

Packy

I agree with Noah on Richard Reed. I've actually whipped out a spreadsheet and tried to calculate the human life equivalence loss of taking shoes off in airport security lines. The worst. But his point on land costs is really interesting and much more relevant. Everything about solar has gotten really cheap, except for the land.

We have ways to get around that issue with enough will and government support.

Julia

Land use is something that comes up a lot when people talk about scaling up solar. Call me the NIMBY here, but I personally don't want to see mile after mile covered with solar panels if we have more space-efficient alternatives. The idea of painting the earth with rows of solar panels, which need maintenance and replacement, seems infeasible and undesirable, even if we did figure out how to get the land.

And in a place like the US, where we're so property rights oriented, it's going to be pretty hard to do. We asked Casey about land use, particularly in the context of producing enough solar energy to replace oil and gas, and he put it into context for us.

Casey Handmer

In terms of overall land use, it's instructive to think about what the land was before we got here, what it is now, and where it will be in the future. In the United States, huge quantities of land are used routinely for agriculture, forestry, grazing, and primarily for growing corn and soy to feed animals like cows. A little bit is used for biofuels - by "a little bit," I mean tens of millions of acres. The important thing to realize is that solar electricity, or even solar electricity being converted into chemical forms of energy, such as what we're doing at Terraform Industries, is about 1000 times more productive per unit area than biofuels or growing food to feed cows. You could easily imagine a future in 10 or 15 years where solar electricity is used to produce natural gas, gasoline, and other hydrocarbon products that fuel our economy. It could also produce synthetic starches, fats, and proteins to feed our animals so we don't have to spend 50% of the total surface area of the United States on a monoculture of corn and soy with crop dusting of chemicals.

Anything in that direction is a step in the right direction, because every marginal percent of land we can return to forest or open plains as it was before humans came to the continent in the first place is an enormous advantage. The second convenient thing about solar in the United States is that you don't need arable land to put it down. Most places where solar is being developed like crazy all over the world right now is land regarded as economically useless. For reference, something like 35% of Earth's surface area is essentially uninhabited desert or mountainous waste. We don't think about that much unless you spend a lot of time with geologists, because you just don't go there. Sometimes you see it out the window of a plane for 5 seconds. But if you've ever driven across Nevada, it takes a long time.

The nice thing about putting solar down on that land is that the impact is actually pretty low. Arguably, it improves the land. It increases its ability to retain water, reduces the temperature on the surface of the ground, and increases the ability of plants and animals to survive in this incredibly harsh environment. It's certainly less impactful than putting another factory outlet, building roads, urbanizing, farming, irrigating, or even having a dirt bike circuit there. Frankly, it does less damage to put a solar array out. And if you decide in 20 or 30 years that you don't want the solar array there anymore, it's relatively trivial to pull it out, dump it somewhere, and return that land to its pre-existing condition.

Packy

Another issue that comes up repeatedly is intermittency. The sun doesn't always shine. Sometimes it shines more than we need, and other times not at all. Today, we handle this by pairing renewables with natural gas peaker plants. They're called "peaker" because they come online quickly to meet peak demand.

This adds to solar's costs and means that solar isn't really carbon-free. But Noah thinks that's mostly fine.

Noah Smith

Gas peaker plants are fine. They're small and expensive because they idle most of the time, but they're fine. You don't need much of it. It's just a little additional. From the standpoint of "we must eliminate carbon entirely, we must have zero carbon in our entire economy" - well, that's never going to happen except in people's models. What's going to happen is we'll eliminate 90% of carbon and pull the rest out of the air with direct air capture, or 85% or something like that. People don't want to believe that yet, but a 100% decarbonized economy will not happen. Gas peaker plants are actually fine because they don't put out that much carbon. So from a climate perspective, gas peaker plants aren't going to kill our planet. They're fine.

By the way, one technological disadvantage of nuclear as a complement to solar is that you can't use nuclear as a peaker plant. Nuclear currently takes a long time to turn on and off. The current kind of nuclear we use takes a long time to turn on and off because the way we build nuclear plants is very dumb and stone age. Someday someone needs to invent a better way. And they will, but they haven't yet.

Julia

We'll come back to intermittency in a minute to discuss how batteries and solar might lessen the bottlenecks on the grid. But this idea that the way we design nuclear plants today is very stone age is one that both Noah and Casey brought up.

They both like the idea of nuclear, but see issues with nuclear plants as they currently exist. They literally both use the phrase 'stone age.'

Casey Handmer

At the end of the day, if you're boiling water to make energy, you can make heat however you want. You can use nuclear power, coal, or gas, but you're still boiling water.

It's Stone Age - oog make water hot, boil water, turn turbine.

Packy

Noah has a similar gripe with steam turning turbines and other things. We'll let him tell you, and then bring us back to intermittency.

Noah Smith

The fact that nuclear plants rely on a dampened chain reaction is kind of an L for nuclear power. In the 1940s, that's the best we could think of. But it's not the 1940s anymore. We're smarter now. We have ChatGPT. We can think of something better, and there are ideas that just need more research. We need more research funding for something better than a dampened chain reaction that boils water into steam and turns a turbine.

Anyway, nuclear plants can't be turned on and off easily, so you can't use them as peaker plants. You either use nuclear or solar plus a peaker plant - solar plus a battery, solar plus pumped hydro, etc. Peaker plants aren't going to kill us. They're just a little expensive because they don't get used most of the time. It's a gas plant you don't use often, which doesn't amortize well, but it's not big. So solar plus peaker is still pretty cheap because the peaker plant isn't particularly big.

That's fine unless you're crusading for zero carbon energy now. We just need to decarbonize most of the way as soon as we can and figure out the rest later. That's the smart way to do things. So, peaker plants don't scare me. There are actually two intermittency problems.

The first is night. Storms are just fancy night - a really dark cloud. Solar plants still work when it's cloudy. The sun shines through clouds. That's why you can still see outside. But sometimes you get a storm so dark it really does block the solar panel. That's just an unplanned night. If you have a battery that can store solar energy, it works for storms very well. Batteries don't leak much energy - about 15% over a whole year.

The other intermittency problem is seasonal storage. In winter, you're angled away from the sun, so you don't get as much sunlight. That is the tyranny of orbital geometry. The obvious thing to do is to build more solar. If you overbuild by a factor of 1.6, you can take care of all seasonal storage. When you can't get the land for that, you can build batteries to hold charge for seasons. It's just expensive because you use it very slowly.

No one I talk to is worried much about seasonal storage. It's really just night that everyone's worried about. As long as you have batteries that can get you through the night, intermittency is pretty much not a big deal.

Packy

I love Noah - saying the quiet parts out loud. But the point both Noah and Casey make is really important to understand. Solar produces electrons directly. Nuclear, as built today, produces heat that produces steam, which turns turbines to produce electrons.

They believe that difference in efficiency is a crucial advantage for solar.

Julia

He frames up intermittency and storage challenges well, too. According to Noah and many solar advocates, the solution to meet most of our needs is simply to overbuild solar panels. Thanks to learning curves, the more we install, the cheaper they get. So overbuilding is one route to deal with seasonality, when the sun shines less, but still leaves the challenge of nighttime.

For both seasonal and nighttime storage, or long-duration and short-duration energy storage, batteries are getting cheaper and more energy dense. Very cheap, energy-dense batteries would help alleviate some of the issues with the grid. Just store up solar energy and release it predictably when needed.

Meredith told us that for now, she's not ready to rely on batteries because they're part of what she calls the 'could grid.'

Meredith Angwin

There are a couple of grids. Let me explain what I mean by that. There's the grid you can see out your window, which has wires and poles. Somewhere there's a generating station, or maybe you have solar on your roof. It makes electricity, transfers it from place to place, and somebody uses that electricity.

Then there's the policy grid, which is about how people pay for electricity, what kinds they encourage, and what the problems are. And then there's the third grid, which I call the "could grid." My opinion is that most people don't know much about the physical grid, and it's hard work to find out about the policies.

But what people learn about is the "could grid." That's in the Sunday paper. There'll always be something about batteries coming, or offshore wind just about to start. It's all about what we hope to have in the future. There's nothing wrong with learning about that. We should. But you've got to know what's going on now, and that is hard to find out about.

So I felt that I should write a book about what is going on now and leave the interpretations of what is likely to happen within 15 or 20 years to somebody else.

Packy

The interpretation of what is likely to happen within 15 or 20 years is the multi-trillion dollar question, though. So we asked Eli to tell us about the current state of batteries and what we might be able to expect in the future.

Eli Dourado

We've made huge progress in batteries. Lithium-ion batteries have been an almost miraculous invention in terms of cost reduction over the last several decades. It's been orders of magnitude. Where we are today versus 30 years ago is just night and day. Batteries have massively improved. It does seem like they're probably running out of headroom for further improvements with current chemistries. We're down to below $100 for the cell level, and I don't think there's another order of magnitude improvement in the current chemistries. So we need new chemistries, probably, and particularly we need new cathode chemistries.

An interesting thing about batteries is that the cost declines come from two places. One is optimization. The major chemistry right now is nickel, manganese, and cobalt in the cathode. We've optimized it by changing the ratio of these materials, using more nickel and less manganese and cobalt, as nickel is cheaper. The other improvement is overall density. For any mass-manufactured product, your cost is a function of your materials. Higher density with the same materials means you can drive the cost down lower. That's what we really need: better chemistries that will drive the cost down much further, particularly cathodes.

There's a lot of people working on anodes, but cathodes are where we could really drive the cost down if we had a breakthrough. Lithium mining is going to be important. Mining for transition metals, increasing our nickel and cobalt stocks is going to be very important. Battery recycling turns out to be cheaper than mining new materials, so that could really drive the cost down in the long run.

I think there's definitely a world where it's less than 10% of current cost, maybe less than 5%, maybe even less than 1%. And higher density means you can do a lot more. You could have cars that can go 1000 miles, 2000 miles on a single charge. It means exciting things happening in electric aviation, cheap home batteries for consumers. It makes grid defection easier. So just huge possibilities if we can get the costs down.

Julia

We should probably take a second and explain here. A battery has two main components: cathodes and anodes. On your standard AA battery, the cathode is marked with a plus, and the anode with a minus. Batteries are filled with ions - atoms that have gained or lost one or more electrons, giving them an electric charge. In a lithium-ion battery, for example, the lithium ions have lost an electron, giving them a positive charge. When you charge a battery, the electric current from the charger pushes the ions from the cathode to the anode. When the battery discharges, ions move back from the anode to the cathode.

Improving cathodes can significantly reduce costs and enhance battery performance, as they often limit the battery's capacity and longevity. They're harder to innovate than anodes, but offer more potential for cost reduction and efficiency gains in battery technology. These improvements in batteries still exist in the "could" realm, a hard bet to make on something as crucial and fragile as the grid. But Eli imagines a world in which the function of the grid becomes decentralized.

Eli Dourado

I view batteries as more useful at the edge of the network than at the core. A home battery might be better than a grid battery because it can provide the same services, plus resilience if the grid goes down. In general, I think it's better to have batteries where the users are rather than where the power plant is. Maybe it's not an all-or-nothing thing, but I'd rather see batteries being ubiquitous all over the place. Then there are incentives to arbitrage different prices.

If we allowed the price on the grid to fluctuate and incentivized people to arbitrage for profits, that might be better than grid-scale storage. I'd like to see a lot of experiments with that. The problem with grid-scale storage is determining the storage period. Are you storing for four hours, eight hours, twelve hours, or six months? The way you invest differs based on those assumptions, because the optimal size of your battery farm is different for different usages.

I much prefer a world where we put batteries everywhere, allow the price on the grid to vary, and let people buy and sell on the grid. Then you don't need grid-scale storage.

Julia

Whether the batteries are centrally located or distributed across millions of homes, Casey put the battery conversation in terms of how much battery each person will need to make solar work at scale.

Casey Handmer

You can think of the total amount of batteries in a particular economy on a per capita basis. Roughly how many kilograms of lithium-ion per person does a country have? That's a pretty good proxy for their wealth. Then you can think, okay, in 2050, how many kilograms of lithium-ion batteries per person will we have? Probably less than a ton, but on that order. To put that in perspective, if everyone in your house has a car, you have a ton of steel per person just on the car, not including the house. If you live in a house, you've probably got five or ten tons of wood per person. It's interesting to think there's me, and then there's my ton of steel and my five tons of wood.

How many millions of gallons of water do you consume per year? It's just a fact of life that we need to dig stuff out of the ground and do stuff with it. The subtle point about batteries and storage is that if you have a bunch of solar and put additional batteries on the grid, those batteries make a shitload of money, and it also makes the solar make more money. If you have a bunch of batteries and add some solar, then both make more money. There's a harmonious factor going on here. More batteries increase utilization of your solar panels. More solar panels increase utilization of your batteries. Together, they're significantly competitive against any other form of grid stabilization or additional power provision later in the afternoon.

This has been the case for five years now. Even Texas has been installing batteries at a five, one, or ten to one ratio versus new gas turbine peaker plants. That's Texas, where gas is essentially free. Texans have many things, but they're not sentimental about value.

Packy

This is like trusting the curves squared. More solar creates more demand for batteries, which increases utilization of solar, and so on as the two tumble together down the learning curve. It's all about the money. Noah made a similar point, that Texas just cares about money, so you should watch what Texas is doing.

But he says it more colorfully.

Noah Smith

Texas will have a lot of stupid political rhetoric where someone says, "Batteries are Satan's energy. Batteries will make your kids gay." And then they'll say whatever. But then they're like, "My house has batteries 'cause it made me some money." That's the Texan attitude. Texans say the dumbest things in political speeches, absolutely unbelievably dumb.

But then the Texan business people just do whatever makes money and are super pragmatic. They'll build housing, any form of energy that works, invest in tech industry, whatever it takes. It's totally divorced from the silly rhetoric.

Packy

I think that's a good place to wrap up the arguments and move into analysis, because Noah captures the main theme of the Age of Miracles season. Not that batteries are gay, but moving from silly rhetoric to economics when determining which energy sources to bring online. On that front, there does seem to be a compelling case for solar. I'm not optimistic about offshore wind, but if batteries can get cheap and plentiful enough, the solar and battery combination is formidable. Honestly, after talking to Noah and Casey, I'm more solar-pilled than I was before. And that's after reading everything they've written on the topic. I want to trust the curves.

Of all the people we spoke to, they were the only ones who made me think twice about nuclear. It's not going to be wind. Geothermal will play a role. Oil and gas will and should continue longer than most people think. But everyone we spoke to, other than Casey and Noah, sees a big role for nuclear. Alex is working on nuclear policy. Mark has a nuclear podcast. Meredith is a nuclear fan, Eli thinks nuclear will be an important part of the mix. Angelica shifted from wind to nuclear. But Casey and Noah just don't think we'll need it.

It's almost like there are two camps: those who believe that solar and batteries will just get so cheap that nothing else matters, and those who believe that we'll need a mix, and that nuclear has an important role to play in that mix. After all these conversations, Julia, where do you come down?

Julia

I think both of us, Packy, are in the camp of needing a mix. We need everything included in the conversation. Most importantly, we want to see our energy consumption increase over time, because that's directly correlated with human flourishing. The abundance of energy is the most critical thing here. A few things I'll say. The fossil fuels conversations were really interesting for me. I think the narrative we've been internalizing for years is that fossil fuels are terrible, villainized beyond belief. But we haven't typically taken the time to do that cost-benefit analysis to say, actually, they give us basically everything comfortable about our lives.

The ability to go visit family across the country. It's short-sighted to say, "No oil, stop oil now." It's just not realistic. Packy, I think you and I probably have a little bit of a difference in terms of where we come out on solar. I'm still a little more skeptical that solar will become a majority source of energy for us. Two main reasons there. One is TBD where the costs go. You're already seeing the cost curve start to come back up again for solar. China has been subsidizing the costs of solar panels so they could dominate the market.

If that changes, or if we decide we want to produce those ourselves, especially if there's some sort of great power conflict that escalates, I don't think they're going to be as cheap as they are now forever. Then batteries, I think, is a toss-up. There's not necessarily evidence that batteries are going to continue to get so cheap that they'll just be ubiquitous everywhere. You talked about trusting the curve squared. You kind of have to believe two sets of things for that to be true.

And then the second thing on solar, and again, I'm going to come across as the total NIMBY here. We need to take a lot of land. I don't think I want to have states full of solar panels. I just think that's a rough way to go when we have alternatives that are much more space efficient.

Packy

Yeah, I think there are so many good points there. On the oil and gas point, I'm really conflicted about what I think the net impact of this whole thing is. Yes, I think we are definitely throwing oil and gas out after they've done so much for us. I also wonder if there's this weird rhythm to the universe where, if we didn't have this enemy to rally around in oil and gas, would we see the subsidies for solar? Would we see a renewed interest in nuclear? Would we see all this work happening in fusion? So even if all the individual actors are self-motivated, maybe the end outcome ends up being good and takes us from the spot where fossil fuels are amazing and they limit where we are on the Kardashev scale. And because we have this common enemy, we can unlock the technologies that move us to the next level.

To your point, we're going to need so much more energy. AI data centers, unless there are huge improvements in efficiency, are going to consume an absolute ton of energy. If we start having robots do more of our labor, they're going to use a ton of energy. And I don't think you get there on fossil fuels. And I think, to your point, we agree, you do not get there on only solar. Now, this is my insecurity coming across. Anytime I disagree with someone like Casey Handmer, I'm like, what am I missing here? Because that guy is just a thousand times smarter. But I do think, as we talk to other really smart people, as we start to get ready for the fusion part of the season, one of the things they say is that solar can get to 80% of the electricity that we use, maybe 80% of the energy that we use at some point, as more and more becomes electrified.

We talked to Ryan at Zap Energy, and you'll hear that conversation. It was really fun. But we asked him why he thought that solar couldn't get over 80% and it's actually something I've heard from a couple of fusion founders. Francesco at Proxima made a similar point. There's a study that Jesse Jenkins out of Princeton did that at about 70-80% of your electricity grid coming from solar power, it starts getting more expensive. Instead of getting cheaper, it gets more expensive for a few reasons. There's overbuild to meet demand, where you might not get sunshine all the time, or where you get winter. As Noah mentioned, you put in just 5-10 times more solar panels to do that, and that makes things more expensive.

There's land use, your point on the NIMBY side, but it's also just a ton of land. A solar farm needs 30 times more land compared to even fuel-based power plants. And then there's the transmission and interconnection. The land isn't just about not wanting these panels here, but as you put more panels, it gets further and further away from where the electricity ends up being consumed. More transmission and interconnection approvals are needed to make that electricity get back to where it's being consumed. That gets more expensive. As we know, NEPA is a disaster. And that just gets really hard to do to get all these projects approved.

So a lot of people think that it can't get above 80%. If we live in a world where it's 80% solar, 10% nuclear, 10% fossil fuels, and some geothermal mix in 10%, we have 110%. Well, we'll actually probably need 500% energy. So let's get all the way there. But that is a world that I'm excited to live in.

Julia

Absolutely. You make a great point about the pressure now put on our energy system to invest in things besides just oil and gas forever. We should be innovating and improving. You always need extreme people to help push that movement, which is fantastic.

As Mark brought up, the oil and gas industry itself got enough pressure that it has improved and cleaned itself up over time. If you think about the images of LA or New York City, places previously covered in smog with noxious fumes coming out of cars, we've made a lot of progress there.

Shout out to the environmentalists, because the Clean Air Act in the '90s, for example, really put pressure on industry to clean up. That's fantastic and shouldn't be lost on anyone. It's good we have this push and pull in the system.

Packy

I love when environmentalists do things I agree with, and I dislike when they do things I disagree with. But it's such a good point. I can get a little carried away saying, "Just get out of the way and let us build stuff." But you don't want a world with smog everywhere where you're not thinking about safety. It's a balance with all these things we're talking about, from the types of energy sources you use to how much you want to accelerate versus think about safety. All of that should be an appropriate balance.

Ultimately, at least in the West and even across the world, energy usage is starting to pick up again. The conversation is moving a little from conservation to using more energy. This was just this weird, dark period in human history where we had 50 years of energy kind of plateauing, but now we get to unlock this amazing foom of growth, and we do it in a clean way. Maybe it was all for the best.

Julia

Yeah, I'm a big states' rights person, and I love the idea of a place like Hawaii or somewhere else that's isolated saying, "Hey, we're going to run this experiment here. What if we decided to be 80% solar?" Would it work, I wonder? I just did a quick Google search, and it looks like Hawaii is just under 20% solar, which is much higher than a lot of other places, but their electricity is not cheap. I think it's the most expensive of all the states. Obviously, there's still a lot of shipped-in fossil fuels that they're using.

But it would be interesting to ask, could we make this our mission, to bring Hawaii to be one of these forward-thinking, majority solar places? Could they make that happen? I think it's fun that we'll be able to have this almost playground of different areas trying different strategies and seeing ultimately what plays out.

Packy

Yeah. To the points that Meredith and others have made, it's a risky experiment to run with electricity grids, especially in the middle of the Pacific Ocean where it's hard to get anything going. They also don't have deserts to just throw panels in the middle of nowhere. Land is scarce offshore.

As Clay told us, at some point we're going to be getting energy from space. Send that down to Hawaii. There's a lot of exciting stuff there. Is it time to turn our traditional opening question back on ourselves?

Julia

I think it might be the time.

Packy

I think it's the time. Julia, gun to your head, what do you think the pie of energy sources in the US looks like in the year 2050?

Julia

Okay, I'm going to start with electricity, if that's cool, because I think it's a bit more manageable to wrap your head around. Today, we're just under 20% of US electricity from nuclear. I think we should be able to double that by 2050. Of course, I'm a believer and an optimist. There are many reasons to believe that's going to be very hard to do. We talked a lot about Vogtle and the issues with getting gigawatt-scale nuclear power online. But I think there are enough people rallying around it, whether you're on the left and it's climate change driven, or you're on the right and it's national security or energy security driven.

Together, they can help the industry break through financing issues and over-regulation. If we can get there, I think we can start a big nuclear renaissance. I think we're going to continue to build a lot more solar. There are rooftops all over the country welcoming solar. We actually have a fairly sunny country compared to many others, especially our southwest. I think we'll see more wind going in in little pockets and areas. So I imagine those go up and maybe get to another 20% total across those.

We'll continue to keep our hydro online. So what are we at? Like almost 50, 60%? And then I think the rest will be majority natural gas and maybe a little bit of oil and coal. Packy, what do you think?

Packy

I think we're pretty much aligned. I think we're going to build a lot more solar. If 50% of our electricity or more comes from solar, that's awesome. I'd love to see that, particularly given how much electricity I think we're going to consume by 2050. I think three to five times is probably a dramatic underestimate of how much electricity we'll need to consume by then. So let's say 50% comes from solar. I'll back you on the 40% nuclear. The rest will be a mix of wind, natural gas, probably not much oil or coal, I hope, for the electricity grid.

I think electricity is just going to be a much bigger piece of the overall energy consumption pie by 2050. For things we use fossil fuels for today - planes, industrial - I hope a lot of that comes from synthetic fuels, using either solar or nuclear to pull carbon from the air and turn it into fuel. There's something really beautiful about that idea. It also has the added benefit of creating an economic incentive for carbon capture that's not government subsidy dependent. I'm going to say that 20% of our fuel mix will come from synthetic fuels. I know that's an over-optimistic estimate, but let's be over-optimistic.

Or has this whole conversation been pointless and we'll be powering everything with fusion energy by 2050? Fusion has a lot of people excited. Governments around the world, and at least three dozen legitimate private companies are working to bring fusion onto the grid, but it's still very early.

Over the next few episodes, we'll tackle fusion energy, its history, and current state and future. We'll be talking with experts, researchers, founders, operators and investors to try to answer the question: when will we see commercial scale fusion and what will it mean for humanity when we do?

Julia

Stay tuned for our next episode where we start the dive into fusion energy. I can't wait.

Packy

I can't wait either. I'll see you there.

Julia

See you then.

Packy

Thank you for listening and watching to this episode of Age of Miracles. If you like what you hear, please rate, subscribe and share. If you're feeling really generous, tell us what you think in the comments.

Plus, we have a ton of resources and references in our resource hub if you want to go deeper, and we've linked them all in the show notes below. See you next week.