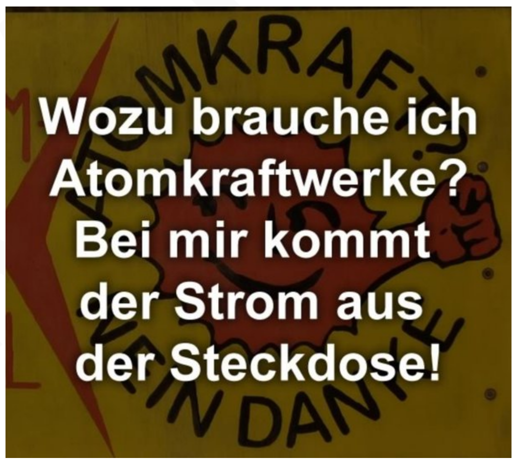
Chapter 11

Leaving Fossil Fuels

Even after record years for green energy, the world today still runs approximately 85% on fossil fuels. We shall thus start the technology part of our book with an introduction to the advantages and disadvantages of coal, oil, and natural gas vis-a-vis three important clean alternatives: hydrogen, nuclear power, and batteries (most likely charged by wind and solar farms). We will also caution to keep a cool head when it comes to taking in all the propaganda. This caveat applies both to clean-energy objections from the fossil-fuel side and overly exuberant and unrealistic technology forecasts from the clean-technology side.



A popular German bumper sticker from the 1980s: "For what do I need nuclear power plants? At my place, electricity comes out of the socket!" Beneath: "Nuclear Power, No Thanks."

1 Ongoing Growth

Start by reviewing the relative shares of humanity's energy consumption in Figure ??. More than 90% of the world's energy consumption today are fossil fuels. Add dirty biomass, and the number is above 95%. Without extensive use of fossil fuels — and almost surely for many more decades — we could no longer plant, fertilize, harvest, and feed the world's population. Energy use is not primarily about plastic bags. It's primarily about the basics. It's about keeping billions of people alive.

The scale of the energy transition poses huge challenges. If humanity simply wanted not to increase fossil-fuel consumption further — too modest a goal — then clean energy will "only" have to cover the future increases in energy needs. Nevertheless, as we explained in Chapter 1, where we also mentioned that nameplate power and fossil-fuel inefficiency in the conversion to electricity are roughly similar, this still means that clean energy will need to grow by a factor of 15 *within the next 30 years*. In numerical terms, that translates into an increase from a measly 8 PWh to 117 PWh, with about 110 PWh just to prevent increases in fossil fuel use. If humanity also wants to retire coal, it will require growth of 150 PWh, a factor of 20. If the goal is to retire all oil, gas, and coal, it will require 240 PWh, a factor of 30. The latter two numbers represent real growth rates between 9% and 12% per year. Think about what it would take to increase anything by a factor of 30 — say, your income or bank account.

Right now, clean energy is growing by about 15% per year — but it's easy to grow from a low base. Growing at 12% per year consistently over thirty years is not impossible, but it's a tall order. Doing it much faster seems both economically and physically impossible.

2 Fossil Fuel Advantages

Fossil fuels have taken over the world because they have some important advantages. You should understand them first. Besides the sheer challenge of replacing such large amounts of energy, it is also the case that fossil fuels are different from clean replacements — their energy is better in some respects, worse in others.

The most important advantages of fossil fuels are:

1. An existing infrastructure to collect fossil fuels, send them to the desired destination, and use them efficiently (especially in highly-developed countries). This includes wells, storage facilities, refineries, distribution networks, and devices that run on fossil fuels, such as cars, ships, trucks, planes, heaters, factories, and furnaces.
2. Abundant availability at low cost, even after figuring in logistics costs.
3. Low shipping costs for gas (pipelines) and oil (tankers), but not for coal.
4. A high energy density for oil and gas, both by weight and volume. This is important not only for shipping, but also when used to power engines. Airplanes, cars, and trucks simply perform better when light and small.
5. A good safety record, with limited potential for disasters.
6. Near-perfect efficiency when burned for heat. However, fossil fuels have poor efficiency when generating electricity or producing kinetic energy.

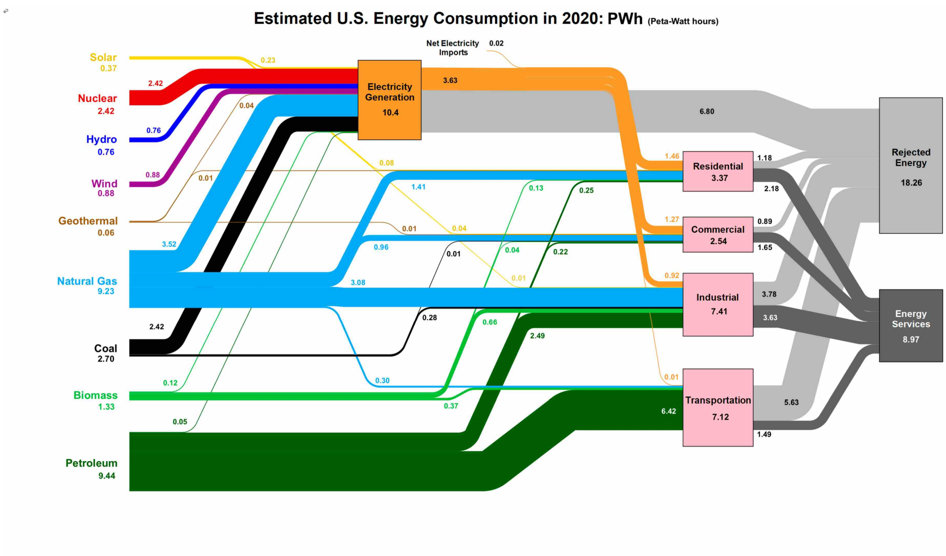
These characteristics need to be judged relative to those of the clean alternatives available — principally hydrogen, batteries (charged from wind and solar), and nuclear energy.

We will discuss technologies in more detail in the next chapters, but for now, let's outline how clean energy differs from fossil fuels.

Figure 1 is a beautiful visual representation of U.S. input and output energy flows. The far left side lines up primary input energy. The far right side shows the outputs.

First, the "good news" from the perspective of clean electricity as a substitute. Two-thirds of all the primary energy inputs today, mostly from fossil fuels, end up as waste heat without ever providing any services. This is the case even for electricity generation This means that it should not be too difficult and expensive to replace fossil fuels with cleaner sources for electricity

Figure 1. Flows of Energy Through U.S. Economy (ca 2020).



Note: Two-thirds of all energy ends up as waste heat.

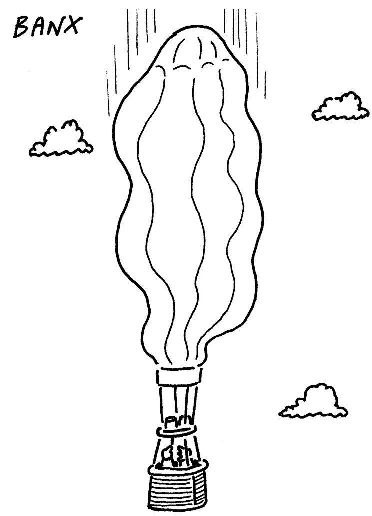
Source: LLNL Flowcharts 2020.

generation. The same holds true for transportation, where almost 90% of the fossil fuel energy only produces waste heat instead of kinetic energy.

Now the bad news. Fossil fuels are intrinsically superior in generating heat. This is what our one-trick ponies do well. And heat production accounts for at least half of residential and commercial use, and much industrial use. Yes, electricity can also generate heat, but it will have to be incredibly cheap to compete with near-ideal chemical heat sources.

3 Hydrogen

Hydrogen is the energy carrier that is the closest potentially-clean substitute for other fossil fuels. It contains energy in the form of chemical bonds. It is so similar that it can even use most of the existing natural gas pipeline infrastructure (with some alterations to reduce corrosion). But hydrogen is not exactly the same.



We've reduced emissions by 78%!

First, there are differences in energy density. Hydrogen is lighter but requires more space (even in liquid form). It can store almost 40 KWh per kg, which is about three times higher energy density *by weight* than oil and gas (and eight times higher than coal). Great! However, hydrogen can store only 2.8 KWh per liter. This is only one quarter the energy density *by volume* of oil and one half the energy density of gasoline. Not so great.

Despite drawbacks, hydrogen has an almost assured future: It will likely become the preferred clean fuel for airplanes. Airplanes have no grid connection and weight matters. However, the necessary increase in fuel tank volume will require airplane and power train redesigns.

If you feel queasy about flying in a hydrogen airplane, this is probably because you have watched the 1937 Hindenburg disaster. A spark ignited leaking hydrogen and caused a massive fire. It has given hydrogen a bad rap that it has never overcome. Yet with modern technology, hydrogen can be just as safe as fossil fuels. The real problem was not even the disaster (airplanes have had many worse disasters) but the spectacular film record. Even this footage was misleading. Most casualties on the Hindenburg were from people jumping out of the gondola. Hydrogen burns quickly and upward from its envelope. The gondola, where the passengers were located, was below the envelope. Passengers who simply waited until the gondola descended walked away scot-free.

As of 2021, hydrogen has "only" one major practical drawback, but it is deadly: for the same amount of energy, when created from clean sources via electrolysis (rather than from natural gas), hydrogen energy costs about ten times more than natural gas. Over the next 30 years, the cost differential is likely to decline from this factor of ten to a factor of two.

Even if hydrogen becomes economically viable compared with natural gas, it will still likely not be used in all the same ways. Fossil fuels are a cheap way to store massive amounts of energy that will eventually be turned into electricity. That is, fossil fuels today are mined, then stored and finally burned when needed. Without a breakthrough technology,[1] the round trip (make hydrogen from electricity, store hydrogen, make electricity from hydrogen) will remain more expensive than the alternatives of either using batteries, or storing heat.

Therefore, we can predict that in this century hydrogen will be important in transport applications that have no close access to the electric grid (specifically, airplanes and ships), but not in utility-scale electric energy storage less than one day or in automotive transportation. If electricity generation continues to drop in cost into the next century, hydrogen could eventually become worth catalyzing. Unfortunately, we won't be around to find out if our prediction will come true. Perhaps a good approach is first to focus on reducing the price of clean electricity, then to focus on the cost of electrolysis, and only thereafter to invest in uses of hydrogen.

We will return to hydrogen production and uses in Chapter 11.

[1] H2Pro is promising a generational leap — great progress but probably not enough. Other processes could improve on catalysts. We hope our skepticism will turn out to be incorrect. However, there are also issues with containing hydrogen, which can ironically then contribute to global warming.

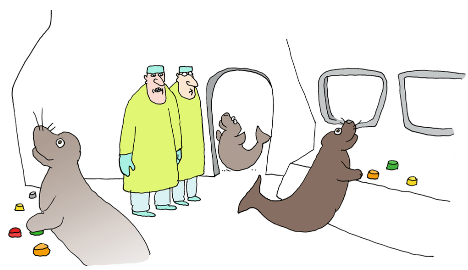
4 Nuclear Power

The next clean alternative is nuclear power, the ultimate Promethean fire. Uranium and thorium are powerful and dirt-cheap energy sources, but they also have serious drawbacks.

➤ Safety

Nuclear plants may be among the safest plants ever designed by engineers, but they have such exceptionally catastrophic potential that safest may not be good enough. Despite extensive regulations, there have been major nuclear accidents about every 30 years. (Chernobyl was the worst.) The estimated rate has been 1 core-melt down per 3,704 reactor years. This actual rate is far higher than what engineers had designed the plants for.

You can see that this is a problem when you start counting: there are about 500 nuclear power plants operating in the world today. This means one meltdown every 8 years or so somewhere on the planet. The odds are better-than-even of having one such accident in the United States about every 25-30 years.



To prevent human error, the power station only employs trained seals.

We can even assess the extra expected accident cost that we should attribute to existing nuclear reactors. Over-the-envelope estimates for the cost of the Chernobyl meltdown range from $200 billion to $800 billion, for Fukushima meltdown about $500-$800 billion. With about 400 nuclear plants in the world, economists should budget about $5 billion for expected damages — roughly doubling the construction cost per plant.

joke

What's the most terrifying word in nuclear physics? Oops!

It is also likely that the wider public (and some experts) will always doubt whether nuclear plants can be trusted. (And this adds further political risk, too!)

Think about the construction incentives when not everything can be triple-checked and inspected. In practice, Contractor shortcut and profit motives will trump extremely-low-probability accident fears, so every screw needs to be triple-checked. But who checks the checker? We cannot forget John Glenn's famous quote: "I felt exactly how you would feel if…you were sitting on top of 2 million parts — all built by the lowest bidder."

Despite excellent engineering arguments about how safe nuclear plants are or can be, it remains plausible that future unknown unknowns will cause new types of unforeseen nuclear accidents. Each accident will be a little different and then engineers will fix the problem — but potentially catastrophic once. Our failure to advance nuclear technology — instead having been stuck in a time warp in which iterative improvements were impossible due to regulatory-cost reasons — may have had good intent but has not made nuclear plants safer over the long run.

Somewhat ironically, the public has been more forgiving of coal plants, which have been much more harmful. They kill thousands of people with their relentless pollution every year — but they do so with more consistency, less individual-death attributability, and most importantly, with less bang on the evening news.

➤ Regulation

Good regulation of nuclear plants is difficult. Regulators are on the hook if something goes wrong (as they should be), but they get no reward when the plant is running. In the United States, no new nuclear plant has been *both* designed *and* built since the inception of the Nuclear Regulatory Commission (NRC) in 1975.[2,3]

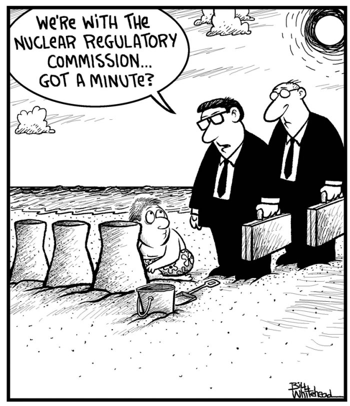
The Nuclear Regulatory Commission has imposed not only stringent and smart restrictions (good), but also many stringent and stupid restrictions (bad).

[2] Unlike the FAA, which has an official mission to help airplanes operate, the only mission of the NRC is to protect the public and environment. Zero plants is clearly safest. A highly biased perspective appears in the American Action Forum. It still is interesting reading.

[3] By 2022, 66 nuclear reactors with pre-1975 designs had come on line in the United States, the most recent in 2016. No new designs were both approved and built since 1975. This may be changing. In November 2021, Terrapower announced its intention to build a completely new design in Wyoming — a first in decades. Estimates are that it could come together for under $1 billion for an 0.5 GW power plant — about half the power of a typical nuclear power plant but only about 10-20% the cost and with more intrinsic safety.

It is an excellent question whether the current regulatory approach and thicket of regulations have been making plants safer by adding more safeguards, or less safe by making design iterations so expensive that improvements have not been worth inventing and installing. Our view is that if a new design itself is passively cooled and intrinsically not subject to the risk of a meltdown (and ideally also to chemical explosions), then a different regulatory regime should apply. In this different regime, small alterations should no longer require year-long reviews. Is bureaucratic reform possible under the scrutiny of a hostile press and public? We don't know.

Although the unfriendly approach of the NRC has contributed to the high costs in the United States, the slow demise of nuclear power cannot primarily have been the NRC's fault. We know this because companies have also not been racing to install nuclear power plants outside the NRC's jurisdiction, either.



➤ Nuclear Waste

The public is also concerned about the nuclear-waste disposal problem. However, this problem is solvable. It was created in large part by stupid government commitments. For some reason, governments had promised to take care of the waste, thus giving nuclear power operators little incentive to reduce it. It is cheaper for nuclear plant operators just to mine new dirt-cheap uranium and hand the spent fuel to the government. Yet much of this nuclear waste could be reused thousands of times more with reprocessing in breeder reactors. (This is not magical, because the waste remains highly energetic). Of course, new breeder reactors are no longer being built, either, making reprocessing not only expensive but also currently impossible.

➤ Economics

But ironically, the biggest threat to nuclear power is no longer actual safety, perceived safety, poor public relations, excessive regulations, or radioactive waste disposal — although all of these have contributed to nuclear energy's malaise. Instead, the biggest threat now is economics.

By the time we'd lobbied the government, got planning permission, raised capital, put the job out to tender and built it, we didn't need it any more!

It takes about 10 years and $10 billion to build a traditional nuclear power plant — and construction costs have always seemed to run many times over projections. Thus, the only way nuclear power plants would likely be built nowadays would be with guarantees by electricity regulators that they will buy power from new plants for decades at a committed price that covers the construction costs — itself recouped from taxes on captive consumers.

The more basic problems are (1) the low price of natural gas in many countries; and (2) the looming potential of cheap clean energy. Who wants to invest their own money into a $5-10 billion nuclear plant that will take 5-10 years to build and then needs to earn money over a 30-year lifespan? The invention of better, clean energy storage could obsolete the plant before construction is even finished. It would turn it into a "stranded asset." And this is ignoring the political uncertainties if the electorate demands the shutdown of all nuclear plants after a nuclear accident somewhere in the world (as happened in Germany).

But what if clean-energy technological progress stalls? The world's 500 nuclear plants are on average over 30 years old. Most will shut down within our lifetimes. Extending their lifetimes, with stricter safety inspections and guidelines, should be under active consideration. The choice of how long to operate plants has no clear safety cutoff. Where is the line? If mid-age nuclear reactors are operating at a rate of one core meltdown every 3,704 years, should we shut down old-age plants at one meltdown every 3,600 years? Every 3,500 years? (Or maybe we should shut them all down!)

➤ Newer Designs?

The existing nuclear power plants are at the end of their lives. Could we design and build a newer generation of better, safer, and cheaper nuclear plants?

All new plant designs face one big hurdle: First Of A Kind (FOAK) plants and nuclear plants specifically are much more expensive than Next Of A Kind (NOAK) plants. We won't fully understand new designs until we have built a FOAK. But safety considerations need to be paramount, which drives the cost of such FOAK nuclear plants to uneconomic levels.

Intrinsically Safe: New designs would have to improve safety by two orders of magnitude. Even nuclear fusion plants, despite their completely different physics, are *economically* really just like nuclear fission plants. (Uranium fuel costs have always been trivial.) Fusion differs primarily in that it immediately turns off when disturbed even slightly, which thus renders fusion intrinsically perfectly safe.

To be two orders safer, better fission reactor designs should probably no longer be based on active pressurized water cooling that can lead to a chemical explosions and radioactive contamination when cooling fails.[4] The newest operating plants such as the Westinghouse AP1000 have passive emergency cooling, which is already much better than earlier designs. Fourth generation pebble bed reactors do not melt down (or release radioactivity) even if all active cooling breaks down. Gravity will disperse the pebbles which will end the nuclear fire. China just put the first such reactor into service.

Smaller Reactors: An important problem is that countries often need energy "yesterday" (or at least asap). China is building coal plants rather than nuclear plants not just for employment and cost reasons. Instead, coal plants can be built within 4 years, while nuclear plants take about 10 years. China needs energy *now*.

Yet, perhaps there could be a nuclear alternative. Many countries are now working on smaller reactors that could be mass-produced and shipped on trucks. Small nuclear reactors have already been used on military ships for decades, but they do not suffer from the problem that hazardous material could fall into the wrong hands. Nevertheless, just in the last two years, small reactors have made good progress:

[4] Contrary to popular perception, nuclear reactors cannot explode like a nuclear bomb. Instead, they can explode chemically when they are not appropriately cooled, because their heat then generates flammable hydrogen as a byproduct. Once the hydrogen explodes, the core can melt down and becomes like a "dirty bomb" — which is not really a bomb in a conventional explosive sense, but a source of highly toxic pollutants that are difficult to contain.

- The DOE is funding companies to develop 1–10 MW reactors that could always stay on their trucks and drive to where they are needed. Think about this: 1,000 trucks could power a small U.S. state!
- The NRC has approved a more traditional but (first) smaller, modular, and potentially factory-mass-producible NuScale reactor for civilian use.
- Britain started the approval process for a new kind of nuclear mini-reactor built by Rolls-Royce — one could say the "Rolls Royce of nuclear reactors."
- France has announced its own prototype small modular reactor, again with the goal of being able to mass-produce them more cheaply in the future.

This is just a selection. There are also other promising tiny and safer nuclear power designs on the horizon.

➤ Our View

Worldwide, the construction of traditional nuclear power plants has slowed to a crawl. In the United States, since 2000, only one new reactor has come on line. Construction is only a little more active elsewhere around the world.

Yet nuclear plants could play an important role in reducing global emissions — if they were only a lot safer and a lot cheaper. Without top-to-bottom changes in *everything* — from regulatory processes to mass production to safety to operations to nuclear waste handling — it's not likely to succeed at large enough a scale. This is neither a lament nor a rejoice. It is simply our factual assessment.

Reasonable experts can and do disagree about whether new plants will live up to the promise. Bill Gates believes they will, while the Union of Concerned Scientists thinks otherwise.

Let's keep our fingers crossed that some new designs will prove to be safer, cheaper, better, and produce less waste. The world could surely benefit from better clean base-power technology. But let's also not be too eager and blue-eyed about what will prove to be a tough road ahead.

5 Batteries

We will discuss wind and solar power generation (and energy storage) extensively in the next chapter. They are already the cheapest sources of power today. Their Achilles heel is that they generate power not on demand but only when nature cooperates. Fortunately, batteries can be charged by wind and solar power when electricity is cheap and abundant; and discharged on demand when electricity is expensive and scarce.

anecdote

> Abraham Lincoln, 1860: "Of all the forces of nature, I should think the wind contains the largest amount of motive power ... Take any given space of the Earth's surface, for instance, Illinois, and all the power exerted by all the men, beasts, running water and steam over and upon it shall not equal the 100th part of what is exerted by the blowing of the wind over and upon the same place. And yet it has not, so far in the world's history, become properly valued as motive power. It is applied extensively and advantageously to sail vessels in navigation. Add to this a few windmills and pumps and you have about all. As yet the wind is an untamed, unharnessed force, and quite possibly one of the greatest discoveries hereafter to be made will be the taming and harnessing of it."

Batteries are intrinsically completely different from chemical and nuclear energy storage. They cannot store energy in every chemical or atomic bond. Thus, they have low energy density. Even the best lithium batteries provide only about 0.25 KWh/Kg and 0.5 KWh/L (compared to 12–15 KWh/Kg and 5–11 KWh/L for oil and gas). For transportation, this limitation is partly compensated for by the fact that electric engines have 90% (or more) efficiency compared to 25% for combustion engines. Similarly, for grid-based and near-grid-based electricity storage, the low energy density of batteries is not very important. Their high input-output efficiency makes up for it.

However, for some applications, batteries are as wrong an economic solution as hydrogen is for electricity storage. The least suitable application is heat. Burning fossil fuel for heat is too efficient and cheap.

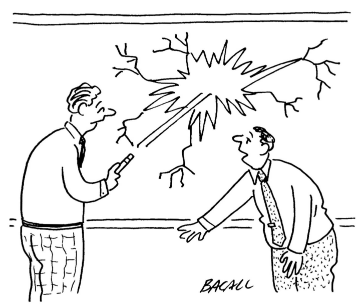
However, even if fossil fuels were banned, batteries would still not be the right solution. The alternative to storing electricity in batteries and making heat later is making heat first and storing the heat in thermally isolated containers. The latter is far cheaper and more easily scaled. This is not only the case for home heating, but also for industrial furnaces.

The second and greater problem with batteries is a central subject of our next chapter: their fixed cost structure. More energy storage for batteries means manufacturing more batteries. This is expensive. In contrast, more energy storage of fossil fuels simply means a larger tank. This is why there is only about 100 GWh of battery storage on the U.S. grid. That's enough to power the U.S. electric grid for about 10 minutes. To cover just ordinary days (and without growth of demand) will require at least 50 times as much capacity. If the world were to electrify transport and heat, too, it would probably require 100 to 200 times as much capacity. Currently, batteries are too expensive to take over electricity storage at this scale.

6 How To Read Technology Forecasts

At this point, you are probably as enthusiastic about wind, solar, and battery technology as we were when we started writing this book. (We still are, but a little more cautiously so.) A lot of pundits are painting an exciting energy future ahead. Not a week passes without more great news on some invention. And the progress of clean-energy technology has consistently outperformed even its most optimistic predictions. But before you buy into all the clean-energy propaganda, let's take a step back and explain why you should remain excited in general but not in the specifics.

For example, Agora is one of our favorite battery technology candidates. It already has a prototype for a CO2 consuming "redox flow" battery, whose emissions are primarily bicarbonates. These are costly chemicals used widely in industry. Agora could revolutionize the world. What could possibly go wrong? Plenty! The devils are in the details, and there are many details before the technology can be mass-deployed — if ever. Foreseen or unforeseen problems could throw a wrench into the gears (though batteries have no gears). Agora could fail to solve the toxic bromine byproduct problem. The owning partners could fall out among themselves and litigate rather than develop. Or the founders or CEO could be incompetent. Or their sales department could be incompetent. Or the money could run out in the height of a financial crisis. Or another battery technology could obsolete them before they can even start. Or government regulation and red tape could kill them. Or an accident, possibly with great publicity, could set them back. Or electricity demand could stagnate. Or lithium car batteries could last virtually forever and simultaneously back up the grid. Or some other countries could wait for the first Agora product, disassemble it, reverse-engineer it, and produce it more cheaply in mass. (Litigation over property could well take decades to resolve, by which time Agora could be bankrupt.) More concerning, Agora is a technology firm, and they will need global manufacturing partners and chemical commodity partners. And so on.



Maybe you should replace the super platinum-iridium-cadmium batteries in your laser pointer with ordinary alkaline batters?

The right way to think about Agora and other battery technologies is that even the most promising truly new technology (i.e., that is not just a small improvement on existing lithium batteries) has perhaps a 1-in-10 chance. (A 1-in-10 chance of revolutionizing the world is no small feat!)

However, the future for humanity is far more promising than just Agora. There is not just Agora, but maybe two dozen battery developers with innovations of various kinds. Any one of them has only a small chance of success. But one or two of them will almost surely hatch.

Put differently, we would not put all our eggs into Agora's baskets. But we would take a bet that within 10–20 years, today's conventional Lithium batteries will either last 10,000 cycles and be an order of magnitude cheaper or they will no longer be the dominant form of utility-scale electricity storage.

7 The Politics of Defending Fossil Fuels

We just advised caution about clean-energy propaganda. We would advise twice the caution about better-funded fossil-fuel propaganda. The fossil-fuel industry and its employees are not taking the clean-energy transition in magnanimous resignation.

Their most prominent approach has been to support surrogates who sow FUD ("fear, uncertainty, doubt"). The goal of their campaigns is to discourage customers from buying into newer and better alternatives. Historically, the fossil-fuel industry has not just been prolific in providing energy, but also in spreading misinformation — the subject of Michael Mann's book *The New Climate War*.

Today's fossil-fuel proponents are delighted when they can raise environmental objections to wind, solar, and nuclear power. Although some of their objections are correct and indeed require consideration, they are mostly red herrings. Many of them are misinformation spread by fossil-fuel funded and NIMBY groups with equally misleading names, like Citizens for Responsible Solar. Let there be no doubt, though: There are no intrinsic show-stoppers preventing eventual large-scale deployment of clean energy. And wind and solar are the least environmentally harmful energy source ever available to humans. Let's go over a few of the objections.

Energy Density

Their most important objection to wind and solar is their low intrinsic energy density. It is true that physics limits the area density of wind turbines to about 3 Watts per square-meter and the equivalent area density for solar cells to about 10 Watts per square-meter. (There is room to improve this solar number. Moreover, there is plenty of space. Offshore wind alone could probably provide enough power for the entire electric grid of the United States, though at a higher price.) Because of the low energy density of wind and solar power, critics note that to provide 4 PWh of energy (the current annual electric energy demand of the United States) would require an area twice the size of Massachusetts — about 20,000 square miles. This observation is true.[5]

[5] Actually, fossil fuels only provide about 2.5 PWh of these 4PWh, and even the area for 4 PWh is overstated, given newer and more efficient solar cells.

Source: Bill Nussey, 2018, at freeingenergy.com. Note how small Massachusetts is in comparison to Western states. Requiring even this large an area is not a problematic constraint. There is more than enough space all over the United States. (And either sun or wind are in abundance almost everywhere on the globe.) Note that because of transmission costs, placing so many solar cells in Nevada would not be anyone's first choice.

However, keep the size of the problem in mind. This area would supply the entire electric energy demand for the entire country. Figure 2 shows the required area in a more appropriate perspective, courtesy of Bill Nussey. The Mojave desert alone could meet the entire electricity generation demand of the United States.[6] Of course, Nevada is not the best spot for all of the U.S. electricity generation given the costs of transmission.

Comparing the estimated required 20,000 needed square miles, Nussey also points out that the oil & gas industry leases about 40,000 square miles from the Federal Government (though they do not even use it all!), that about 13,000 square miles are impacted by surface mining, and that about 30,000 square miles are used to grow corn for ethanol. Agricultural land in the United States covers about 900,000 square miles, about 45 times the 20,000 square mile area. Furthermore, wind farms can be built on land that can still be used for agriculture and are even more efficient in mountainous terrain; and solar

[6] Of course, environmentalists will object that lizards' and turtles' habitats will be adversely affected, but until the environmentalists can present a better constructive electricity alternative, these concerns should not be enough to stop construction, merely enough to modify specific plans. It is also not clear whether the extra shade won't be of natural benefit to many species.

farms are optimally located in areas where there is little agriculture or forests. Suitable locations exist almost everywhere even near major population centers in most countries.

Nevertheless, although doubling or tripling the 20,000 square mile area to cover 4 PWh of electricity would still not be a problem, the United States consumes a whopping 30 PWh in primary energy (i.e., all energy, not just in electricity). Electricity is a higher-quality source than fossil fuel if it has to be converted to kinetic energy, but it would still require an area more like 100,000 square miles (five times the square in the area), *plus* a requisite area for energy storage, to transition all power to clean electricity. This is a taller order than just transitioning electricity generation — but it is not impossible.[7]

Many similar surrogate objections are variations on the theme that the required scale is just too large — for example, a recent variation on this theme claims that the United States would have to build one new solar and wind installation every other day. This assertion seems frightening — until you realize that 7 new power plants per U.S. state per year sum up to 350 power plants. It's one new plant per year for every 1 million people. The United States is a big country.

Fortunately, all of this is a tall order that we do not even need to contemplate for at least another decade or two — area density and growth will not be limiting constraints for decades. Instead of focusing on the debate how much the world should, could, or need to ultimately cover, smart governments should instead focus on how to best improve the grid and develop wind and solar generation in order to move the needle now.

[7] Deserts can similarly provide most of China and Africa (and to a lesser degree India) with power, although with high transmission costs. China has the potential to meet 13 times its electricity demand with solar power.

Scarce Ingredients

Another objection from the fossil-fuel lobby is that wind and solar farms require resources and energy to build and install and this is bad. Ars Technica (2021) has a wonderful rebuttal of a typical set of fossil-fuel shill claims trying to knock clean technology.

One version of this argument is that many clean-energy technologies need more rare raw materials (such as lithium, nickel, graphite, cobalt, and rare earths) than the world is producing now. This objection is, in fact, correct.

There will be battery price fluctuations related to shortages of ingredients for today's battery chemistries. It likely won't be lithium, which is actually the cheapest part of the battery, but cobalt and nickel used for anode and cathode. But these shortages should be temporary.

From an economic perspective, cobalt (and nickel) just happen to be the best materials at the moment. For almost every needed ingredient for batteries, there are already many alternative materials on the horizon — manufacturers are simply using the chemistries that are cheapest at the moment. This is especially the case for stationary utility-scale batteries that exist in labs but still have to be developed and deployed.

The world has also just not needed these materials in large quantities for a long time, and it will take a while to find and open new mines. Here, the free market and profit motive will work wonders. In the long run, ample natural availability of ingredient elements, mass production, and competition will almost surely continue to drive down battery prices. Mining companies are already exploring actively for new sources.

The skeptics have one good point, though — a mine in the US can take 7–10 years to approve, more if faced with well-funded NIMBY (not in my backyard) lawsuits. They can effectively delay and sometimes outright stop the transition. But this is a self-inflicted wound that could be treated. We will come back to how to handle this concern appropriately in our final chapter.

Recycling

Still another version is that turbines and panels will have to be retired at the end of their lives. These claims are again true. The green industry has not yet worked out how to recycle its devices — the industry has been busy and has not yet built enough wind, solar, and battery devices even to worry about large-scale recycling.

Although it is true that mining materials for wind, solar, and batteries will have adverse environmental consequences, for comparison, a lot more mining is required to keep fossil-fuel plants going. The desolation and pollution spawned by many coal, oil, and natural gas fields are comparably devastating. In comparison, if worse comes to worst, at the end of their lifespans in 30 years, we can just bury turbines and solar panels in shallow graves or landfills. Unlike coal, oil, and gas infrastructure, obsolete turbines and panels are not hazardous waste. Even lithium batteries are comparably harmless.

But it probably won't come to this. When there are enough end-of-life installations, someone will probably find a new use for them. In 1990, there were three billion car tires in disposal sites (over 1 billion in the United States). There are no more tire mountains today, not because the environmentalists raised the alarm, but because used tires are now a valuable raw material for the construction of cement, flexible surfaces, etc. In fact, used tires are expensive now.

More likely, industry will be able to reuse some and discard other parts. And in any case, there are no externalities that could not be priced into the construction and disposal of clean energy — especially if the United States were to institute a fossil-fuel tax and sensible environmental regulations.

In a cosmic view, recycling objections to clean energy should even be welcome. Thinking about these issues early on is a good idea. For example, there will indeed be environmental impacts associated with the transition. How else could the world provide the energy for 8 billion people? Companies could build solar cells, windmills, and batteries designed for easier recycling, especially if the government forced them to take back the residuals at the end of their lifespans. (The race to recycle is already on.) The government could also plan better in terms of where and how to foster specific clean-energy solutions.

Unfair Competition

An even sillier claim is the complaint about unfair competition and subsidies to clean energy. Although it is true that clean energy is now subsidized in many locales, the sum-total does not remotely come close to the subsidies that the fossil-fuel industry has enjoyed for over a century and is continuing to enjoy. As already mentioned, the IMF (itself no anti-capitalist green institution) has assessed the worldwide externalities and subsidies to the fossil fuel industry at more than $5 trillion per year.

In any case, ultimately, the transition will be unavoidable. At current extraction and usage rates, fossil fuels other than coal could be depleted in about a century.

8 The War on Climate-Change

Given news coverage of public concern about climate change, is it the case that the world is now at war with climate change? Allow us to be cynical for a moment. Who exactly views climate change as a coming apocalypse? Climate change seems to be primarily a niche concern of middle- and upper-income people living in richer countries. By and large, most people go on with their lives instead of thinking about future generations. For most, the national soccer team or personal relationships seem more important. The press is mostly an echo chamber. It writes what its audiences want to hear and audiences self-select. Most of the audiences of climate-change websites are the people who are already concerned. And even most of them have other more immediate problems to worry about.

Table 3. Annual GDP, Spending, and CO_2 Removal Costs, ≈ 2020

		In Trillion-$	Per Person
Global	GDP	$ 84.71	$10,870
	Health Spending (9.9%)	$ 8.40*	$1,078
	Defense Spending (1.5%)	$ 1.98	$254
US	GDP	$ 20.94	$63,480
	Health Spending (17%)	$ 4.00*	$12,200
	Defense Spending (5%)	$ 0.78	$2,380
	... minus RU ($0.062) and CH ($0.252)	$ 0.46	$1.400
5 $GtCO_2$ (US) Removal Cost @ $50/$tCO_2$		$ 0.25	
15 $GtCO_2$ Removal Cost @ $100/$tCO_2$		$ 1.50	
30 $GtCO_2$ (World) Removal Cost @ $200/$tCO_2$		$ 6.00	

Explanations: The figures are approximate. Per-person numbers are based on a global population of 7.8 billion and a U.S. population of 328 million (2020). For perspective, the per-person per-year emissions of India are 1.5 tCO_2, of China 7.5 tCO_2, and of the US 15 tCO_2. The global average is about 5 tCO_2. Key Sources: OECD, SIPRI, and OECD.

Table 3 shows where government spending actually goes. As a whole, Western countries are not putting their money where the media's mouths are with regard to climate change.

Take the United States, for example. We emit about 5 $GtCO_2$ per year. There are plenty of opportunities to remediate or switch technologies to remove at least the first tonne of CO_2 at $50/$tCO_2$ or less. Multiply 5 $GtCO_2$ by $50/$tCO_2$ and you get a total cost of about $250 billion per year, or about $750 per U.S. citizen.

Yes, $750 per person per year (or $3,000 for a family of four) is a lot of money, especially considering that the median income is only about

$35,000/year per capita and $63,000/year per household. But $750/year is also only $2 a day. And it is "only" about one-quarter of our military budget. The fact is that countries are not at war with emissions. They are at (a low-flame) war with one another.

We share the obvious wish to redirect the world's military spending to better causes. But, for better or worse, as we explained in the previous chapter, the world is not a decision-maker. Thinking in terms of global welfare is a conceptual error. Countries are the decision makers. And realistically, they will not redirect their military spending towards environmental spending.

As of 2021, American energy-related spending remains small and almost incidental. Not surprisingly, the U.S. Armed Forces spend more on nuclear weapons than on clean-energy technology. But the same is true even for the so-called Department of Energy! The National Science Foundation did offer modest support, but much of that spending funds university overhead rather than specific energy projects. Clean-energy R&D could sure benefit from more funding administered in a better fashion.

But the fact is that our voters and politicians have spoken, and they do not view climate change as the apocalypse. They prefer to support their militaries rather than the war on climate-change. And even if the current U.S. or any foreign administration is willing to direct more funding to environmental issues, the next administration may not be. And, at the rate that our voters' views can be changed, we may get around to committed large-scale pollution fighting in, say, 100 years. By that time, clean energy will likely be so cheap that voter intervention will no longer matter.

The United States is by no means alone, either. Take Germany, among the most environmentally conscious countries on Earth. (The European Union in general is the world exception.) With the Green Party in government and without any enemies on its borders, Germany's typical green spending is approximately $12 billion, about 25% of its spending of $50 billion on its military.

Go beyond Europe and the rich West, and there is almost no spending on green initiatives and lots of spending on militaries. And as we explained in Chapter 2, the world's most urgent task now is to convince China, India, and Sub-Saharan Africa to curtail their emissions growth. The United States and Europe are no longer enough.

Thus, our recommendation for realistic environmentalists is this: Advocate moving on actions that we can take *in our own countries here and now*, that have a good chance of winning and maintaining political support *in our own countries here and now*, and that are likely to have staying power *in our own countries and beyond here and now*. Let's leave the Utopian proposals to later.

Realistic solutions should be such that, once implemented, it will be cheaper and more convenient to continue with them and not to return to the old fossil-fuel way of life in the next electoral cycle. Again, this means focusing on low-hanging fruit. And the sweetest fruits are those that require only getting a process started, without having to pay forever to keep it going — in other words, let's convince our governments to view themselves as catalysts rather than cops.

Conclusion

Don't believe everything you read. Clean technology is exciting. However, it is not yet ready to fully take over the world. If activists want to change the world for the better, they should push the most intelligent and effective policies for and within each country. The most obvious one is accelerating clean technology research and development for countries' own sake (and surreptitiously for the world's sake).

The immediate next steps are really all that activists should care about right now — *moving the needle now*. Let's worry about the grander proposals for full decarbonization only after we have made good progress on the first steps.

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