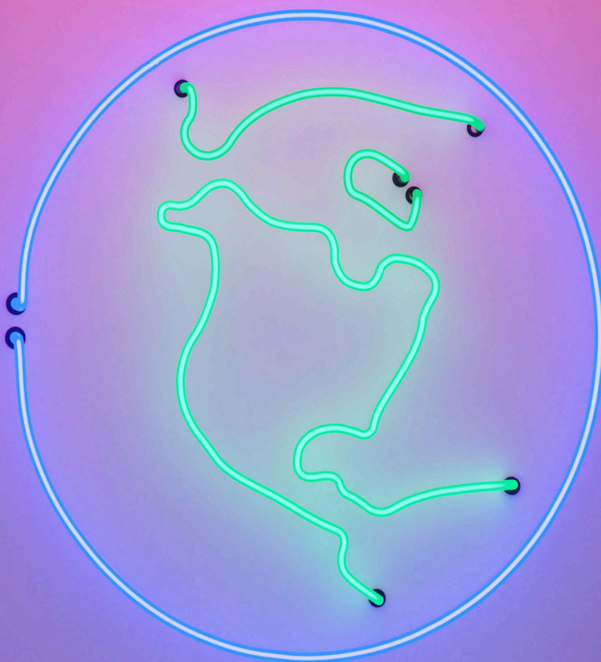
REWIRING AMERICA



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WITH

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REWIRING AMERICA

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A Field Manual for the Climate Fight

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with more than a little help from

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Thank you Arwen, for everything.
Especially for Huxley and Bronte, who give me hope and purpose.

This is an emergency as serious as war itself.

—Franklin D. Roosevelt

We're not alone. Good people will fight if we lead them.

—Poe Dameron

Americans will always do the right thing — after exhausting all the alternatives.

— Abba Eban (maybe)

Rewiring America

In this book we approach the climate emergency from a new angle. We look for solutions, not barriers. We outline pathways to success.

We don't begin with the question of what is politically possible, but ask what is technically necessary to make a climate solution that is also the best economic pathway for a country. We need mobilization of technology, industry, labor, regulatory reform, and critically, finance.

We tackle the thorny question: *"what is the best climate outcome we can achieve?"* We prioritize things that are *shovel ready*, meaning they can be deployed today and don't require unknown years of research and development to become a reality — we simply don't have time for that. This makes our solutions sound like we have *THE* answer, which we don't, we are just emphasizing a path forward based on the things we already know how to do. Inevitably there will be a small amount of clean–up from new inventions for the remainder of our emissions. Looking at it this way, we see a no–regrets pathway that is most easily summarized as **electrify everything ... now**.

We lean on data and an unprecedented analysis of the U.S. energy economy that allows us to look at the consequences of electrifying everything. Will our lives change? The surprising answer is not a lot. Those things that will change are for the better: cleaner air, cleaner water, better health, cheaper energy, and a more robust grid. We can have pretty much all of the complexity and variety of the American dream, with the same–sized homes and vehicles — and we'll need less than half the energy we currently use. This is a success story that casts aside trying to "efficiency" or "deprive" our way to zero emissions.

How do we ensure the lowest cost of energy while electrifying everything? First, we have to rewrite the federal, state, and local rules and regulations that were created for the fossil–fueled world and are preventing the U.S. from having the cheapest electricity ever. Then, we have to finance our transition to a zero–carbon energy system with a low–interest "climate loan." We have precedents and mechanisms for doing this; the U.S. pioneered public–private financing in the past that can help us get the job done today.

The consequence of getting the technology, financing and regulations right is that we can save every family in the U.S. thousands of dollars a year and create the good new jobs every economy needs.

We will need to triple the amount of electricity delivered in the U.S. and we'll discover that the moonshot engineering project we need is a new grid with new operating rules, more like the Internet. We must have "grid neutrality."

The industrial mobilization required will mean an effort similar to WWII's Arsenal of Democracy in size, speed, and scope.

For a world looking to bounce back from a pandemic and economic crisis, there is no other project that would create this many jobs. An analysis shows that there are tens of millions of good paying jobs that will be created in every zip code, suburb, and rural town in the country.

It is by no means easy, but it is still possible. But not for long. Billionaires may dream of escaping to Mars, but the rest of us ... we have to stay and fight.

Here's the field manual.

Contents

1 A glimmer of hope

- The technical path to decarbonization is simply this: we must electrify (nearly) everything.
- We need a near 100% adoption rate of decarbonized solutions. It is the big purchases that count far more than the little ones. Your next car needs to be electric, your next furnace a heat pump, and you need solar on your roof. This is your personal zero–carbon infrastructure.
- We must create new financing mechanisms — "climate loans" — so that everyone can afford to be part of the solution.
- Electrifying everything will require nearly four times as much electricity. It needs to be generated, transmitted and stored with "grid neutrality," where households, businesses and utilities operate as equals.
- Fossil fuel subsidies must end, but equally importantly we must eliminate the rules and regulations that artificially inflate the costs of renewable energy and clean solutions.
- We can only decarbonize on schedule for 1.5° C/2.7° F – 2° C/3.6° F with a wartime–like mobilization of industry.

This field manual is your action plan to fight for the future. A lot of people, including many politicians, activists, academics, and scientists, have given up. Sometimes I feel despair, too, given the widespread inertia and denial about climate change. But I refuse to give up. We have to fight not only the fossil fuel interests but the people who think we can't change politics in time to save the future. As an engineer and an expert in energy systems, I can squint at the data and see a way forward to keep carbon emissions down to a point where the earth will remain livable and beautiful for future generations. If we do it right, we'll all save money and we'll create millions of good new jobs and revitalize our economies.

In this handbook, I'm going to map out a viable path to averting a climate crisis. It's not the *only* path, but I can illustrate it in enough detail to reassure us all that we don't have to turn the world upside down to achieve it. We have one last chance to address climate change, one glimmer of hope, and we must act now. We can no longer afford to wait. If we are to keep global warming under 1.5° C/2.7° F – 2° C/3.6° F — if we are going to avert certain climate disasters — we must now play endgame decarbonization.

Endgame decarbonization means never purchasing machines or technologies that rely on burning fossil fuels ever again.

My glimmer of hope comes from knowing that many of the barriers to a clean energy future are systemic and bureaucratic, not technological. We have the technical means to address climate change, to have cleaner air and a verdant future without giving up our cars and comforts of home. People have come to believe we need a miracle to address climate change; instead we just need hard work. They have been told it will be too expensive (if we do it right it will save us money). They say it will cost jobs (it will create millions of them). Most people believe it will require them to have less (it doesn't have to).

There are obviously a lot of barriers to accomplishing this plan. The politicians who ask for my help as a scientist start with "what is politically possible?" not with "what is technically necessary?" I tell them what is necessary and they tell me about the barriers. As naïve or implausible as it may sound, we have to figure out how to remove all of those barriers — one at a time, and then hopefully many at once. We have to change what we currently believe is politically possible. If what is politically possible is the extent of our ambition, we are doomed.

Fortunately the younger people striking for climate change haven't given up, and thank goodness for them, and for others who are doing their part. This book is for those of you who have hope — and are willing to fight. I aim for this book to give you a blueprint of demands so that our entreaties to politicians may be detailed, and our requests of business leaders specific. They failed to provide a road map to the future we want, so now we must give it to them, and urgently.

I have challenged myself to give you a very detailed answer to what is **technically necessary,** based on the best, most comprehensive data we have. If we know what is technically necessary, then we can get creative with the questions of how to make it politically possible, and how to pay for it.

As my bioengineer friend Drew Endy sometimes quips, "For the first time in human history we have the technology for nine billion people to prosper on this planet, but our politics and institutions haven't caught up."

Unlike COVID–19 — at the time of this writing — climate change has a vaccine *now.* That vaccine is **clean energy infrastructure.** We know what that looks like: massive electrification with wind turbines, solar cells, electric vehicles, heat pumps, and a much expanded electrical grid, with Internet–like neutrality, to glue it all together.

Incredibly, as I will lay out in this book, **if we make the commitments to electrify our infrastructure at the scale required, we will lower the energy costs for all Americans**. This is especially true if we can accompany the project with an appropriate set of financing mechanisms — loans, incentives, subsidies — that will make the future affordable for everyone. We have the clean energy solutions we need to keep our levels of carbon emissions low enough to enjoy a clean, green, and prosperous future.

I still have a glimmer of hope. But to turn that hope into a reality for the future, we have to ask and answer some critical questions, which will be the focus of this field manual:

What is the urgency? Carbon dioxide emissions from human activities are heating the earth to dangerous levels that will harm unimaginable numbers of people, ruin economies, spark wars and mass migrations, decimate species, and damage the environment — if we don't act now. "Committed emissions," fossil fuels slated to be burned by machines that already exist, make the situation more urgent than is generally realized. For any chance of hitting our climate targets, we need an almost 100% adoption rate of decarbonized energy solutions starting right away. This means we need to immediately scale up ready-to-go solutions — and not hope for miracles or solutions we haven't developed, such as cost–effective technologies to suck CO_2 out of the air. See Chapter 2.

What can inspire us? The plan we outline in this book may sound so audacious as to be nearly impossible. Yet on climate change, that's where we find ourselves — having to achieve the impossible. If we look to historical examples of America taking on daunting problems and succeeding at them, we can begin to see the pathways that can turn the impossible into the inevitable. See Chapter 3.

How should we change our thinking about climate change? We must understand that unlike previous energy shortages, this isn't a crisis that can be solved with efficiency and simple improvements to current systems; it requires transformation. Hidden in our historical energy use patterns is great news — we can completely decarbonize without drastically changing our lifestyles or giving up the things we know and love. The clean energy future is just plain better. See Chapter 4.

What do we have to do? Over the past 40 years, government agencies and scientists have collected all of the information we need to address climate change. Based on our understanding of energy datasets, we know what we have to do: electrify (nearly) everything. On the supply side, we need massive deployments of wind and solar, which are already cheaper than natural gas and other fossil fuels for producing electricity. Hydrogen and biofuels won't be playing starring roles, except in certain applications (like biofuels for air travel). On the demand side, we need a huge roll–out of electric vehicles, heat pumps, and energy storage. See Chapter 5.

Where will our energy come from? Mostly, the sun and other renewable energy sources. People fear a future that they can't imagine. We outline the basic physics of energy supply to paint a picture of how we will power the future cleanly in Chapter 6.

How will we make it work 24/7/365? People don't like it when their lights go out, so how do we make sure this system provides the reliable energy we have come to know and love? See Chapter 7.

How are we going to pay for it? Perhaps a better question is, "at what interest rate?" because that's how we can finance climate infrastructure. All of the technologies for decarbonization have high up–front capital costs, and low lifetime fuel and maintenance costs. America solved finance problems that looked like this when we invented auto financing in the 1920s, the modern 30–year government–guaranteed mortgage in the 1930s, and rural electrification during the New Deal. We need something analogous today. We also need to pay for the past: We can fight the fossil fuel companies until the end of both of us, or we can figure out how to thank them for a century of service, pay off our debts, and engage with them in the fight for our future. See Chapter 8.

How do we rewrite the rules? We have a legacy of regulations written for a fossil–fueled world. People broadly understand the problem with subsidies for fossil fuels, but more importantly, and less obviously, we need to eliminate the regulations that artificially increase the price of doing the right thing. We need to write simple rules that encourage the best energy system we can build. See Chapter 9.

What about the economy? The COVID-19 crisis has caused the unemployment rate to be the highest since the Great Depression. Now, like then, and more like World War II, we can create new jobs with massive investment in infrastructure — this time, clean energy. If we make the switch to a decarbonized economy, we will gain millions more jobs than we will lose in the fossil–fueled world. See Chapter 10.

What about...? There is a lot of hope pinned on various audacious ideas — some optimistic, some just crazy. There is lingering anxiety about things we love, like meat and flying. In the interest of keeping the body of the book short we argue against getting too excited about most of these things in Chapter 11. We embrace a principle of "Yes, *and...*" Yes, these things are on the table *if* you can make them work, *and...* let's do all of the things we *know* will work now, as we can't wait for miracles.

How can I make a difference? Everyone can contribute their personal efforts and skills to a war–scale mobilization effort. The only way we're going to win the battle against climate change is to keep fighting. Always demand more. We lose the battle against climate change one compromise at a time. When politicians set targets for 2050, you need to demand targets for 2030. When industry says they will transition via natural gas, you need to reply that there is no more time for natural gas (and there's nothing natural about it). When people say that it doesn't matter what they do because China or the Russians or India or Brazil won't do it, you need to respond that we will show other nations the way. We can afford no delays due to despair. Despair must be channeled into hope, and hope converted into action. See Chapter 12.

Who am I? I'm a scientist, engineer, inventor, and father who wants to leave my kids a better world. I'd also like them to feel the sense of awe for our planet and its creatures that I have been lucky enough to enjoy. I'm in this fight with all I've got. The data convince me that it is still rational to have hope — but not for much longer. We can win big against this climate emergency, but this is our last chance. If we win —– *when we win*, because there is no other option — we'll be much better off than before. We'll not only have a better future for our kids, we'll create new jobs and the U.S. will remain the economic powerhouse in the world that it was through the latter half of the 20th century.

It's a climate emergency. Join the fight.

2 1.5 degrees?

- ☞ We must shoot for a target of 1.5° C/2.7° F , which at this point is very, very difficult.
- ☞ Our situation is worse than most commonly reported emissions trajectories conclude. They assume we'll achieve rapid "negative emissions" later this century by somehow pulling CO_2 out of the air. We shouldn't bet on things we don't know will work.
- ☞ Committed emissions — fossil fuels slated to be burned by machines that already exist — already take us past 1.5° C/2.7° F . This means we need early retirement of machinery — something people are reluctant to do.
- ☞ Industrial mobilization will take time. Even if we committed to doing this today, it will take a heroic effort and a number of years to bring our production of the appropriate technologies up to scale.
- ☞ We now live in a permanent state of climate emergency where we must always agitate for faster and more ambitious action.

The science on climate change is clear. Scientists have written a large body of work on global warming and can predict the future climate from estimates of our carbon emissions so far. We aren't going to waste any more time debating the deniers, or give you a laundry list of the future disasters we'll endure if we don't address climate change intelligently right now. We know, with certainty, that we are hurtling toward multiple environmental and human catastrophes.

It would be easy to write another doomsday book on climate change. Instead we are going to show you a clear path to a better world in enough detail to bridge the imagination gap. This is where our hope is, based on science and what is technically possible.

But first, let's look at why the time line for action is more urgent than you think.

We must act now

It has to be now — not ten years from now, or even a month from now. We have arrived at the last moment where we can shift global energy infrastructure without passing a 2° C/3.6° F temperature rise. We still have the opportunity to address climate change in a way that will make the future better.

The 2016 Paris Agreement[1] aimed to avert climate crisis by keeping global temperature rise this century to 2° C/3.6° F above pre-industrial levels while pursuing efforts to limit the temperature increase even further, to 1.5° C/2.7° F .[2] In 2018, the Intergovernmental Panel on Climate Change (IPCC), a United Nations group of scientists who summarized the worldwide findings on climate change, concluded that meeting the Paris target of 1.5° C/2.7° F would be possible, but would require "rapid, far-reaching and unprecedented changes in all aspects of society."

That is true.

The report predicted that "we have 12 years"[3] to halve human emissions by 2030 to stay on schedule. That was then; now we have only ten. But having ten years to cut our carbon emissions in half doesn't mean we can wait a few years before we start making the far-reaching changes we need to solve the climate

[1] *Paris Agreement*. United Nations Treaty Collection, 12 December 2015.

[2] The targets 1.5° and 2° were political as much as they were technical, and in some respects chosen because they are round numbers (at least in celsius). For even with these emissions targets we have significant chances of not hitting the climate stabilization we would like.

[3] The report was issued in 2018, so the original headline was we have 12 years, but we didn't really do anything to improve the situation in 2019 and 2020, so now we have 10 years.

emergency.[4]

1.5° C/2.7° F of warming is the IPCC's aspirational target for climate change. I would love to live in a 1.5° C/2.7° F world – we might actually save some of my favorite Australian coral reefs. I believe it's important to do even better so that we avoid the worst losses of the 6th great extinction.

But 1.5° C/2.7° F is very hard. It's absolutely worth shooting for, but very, very hard. This target does not consider at least three practical problems.

The first is that since 2004 the IPCC has allowed significant negative emissions by carbon sequestration to be used in models of 1.5° C/2.7° F . But at the moment, while those technologies would be nice, they don't yet exist on a workable scale, and there are strong arguments that they will never be cost–effective.[5] We cannot rule out a breakthrough, but we also shouldn't model it in as a done deal. We must consider that as a single man–made substance, humanity produces more CO_2 than it does *all other materials combined*. In 2019 the US manufactured around 6.5 billion tons of agricultural products, fossil fuels, metal ores and non-metallic minerals. In the same year we emitted 6.7 billion tons of CO_2 .[6]

We can't rely on fantasy technologies to reach our climate goal (or to argue that we can continue to burn fossil fuels because someday we may be able to suck the CO_2 out of the air). We must aim to hit 1.5° C/2.7° F to 2° C/3.6° F with technology that works *today* — which we have, and will do the job, if we employ it right away.

If we exceed our emissions targets, we will face tipping points[7] in climate change where we won't be able to stabilize the climate at all. Given what we know about climate feedback and sensitiv-

[4] The best mantra of what we should do is Rockstram et.al. "Halve emissions every decade." I think we can do even better. *A roadmap for rapid decarbonization.* Rockström, Johan, Owen Gaffney, Joeri Rogelj, Malte Meinshausen, Nebojsa Nakicenovic, and Hans Joachim Schellnhuber. 2017. Science. vol. 355, no. 6331. pp. 1269.

[5] https://doi.org/10.1073/pnas.1012253108

[6] https://www.researchgate.net/publication/326686200_The_politics_of_anticipation_the_IPCC_and_the_negative_emissions_technologies_experience, https://www.american.edu/sis/centers/carbon-removal/upload/carbon-removal-debate.pdf

[7] As Lenton et.al. highlight in their recent paper, the more we learn, the more that the tipping points look sooner and more drastic. https://www.nature.com/articles/d41586-019-03595-0

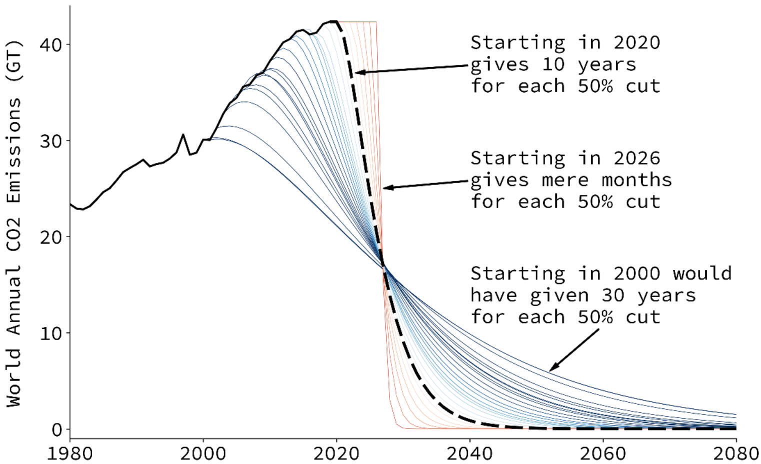

Figure 2.1: *Mitigation curves required to hit a 1.5° C/2.7° F world, redrawn from Robbie Andrew's data. As we can see we have NO time left to begin before any chance of the climate targets we need to hit slip beyond our reach.*

ities, such as more rapidly melting glaciers, the effects of deforestation of the Amazon, methane emissions from Arctic tundra, and carbon releases from fires, we are already precariously close to such a tipping point. Every year we wait — whether hoping for a political revolution or a technological miracle — has dire consequences to the timeline and the health of our planet. This climate response emergency is expressed best in the analysis and charts of Zeke Hausfather[8] and Robbie Andrew[9] which we redraw in Figure 2.1.

Here's how to look at this chart.[10] If we had started this grand project in the year 2000, we could have hit our 1.5° C/2.7° F target by halving emissions every 30 years. If we start now, in 2020, we have to reduce at a phenomenal rate, halving every 10 years.

[8] *UNEP: 1.5°C climate target 'slipping out of reach'*. Zeke Hausfather. Carbon Brief. 2019.

[9] *It's getting harder and harder to limit ourselves to 2°C*. Robbie Andrew. 2020

[10] You might note a trend with our graphs and charts — that they look a little cartoonish — that is by design. For the general reader we want to help you see the trends, and discern the consequence of those trends, not labor over whether the mathematical function of a decarbonization scenario is sigmoidal or linear. There is a trend to believe that more data or more resolution means more knowledge, but what we need to act on here are the big trends, not the tiny details.

If we wait just four more years, we have to halve in less than a year, and after eight years it's gone completely. **We simply must start NOW!**

Committed emissions

The second reason the notion that we have ten years to hit our 1.5° C/2.7° F target is difficult has to do with **committed emissions**, those that are locked in because we have *already* invested in a piece of infrastructure that will emit carbon dioxide throughout its useful life. An example is the car sitting in your driveway that burns gasoline but is too new to trade in for an electric vehicle.

Fossil–fueled power plants built today will emit CO_2 for 50 years or more unless we shut them down. A gasoline–powered car or gas furnace purchased yesterday will probably discharge CO_2 for 20 more years. These committed emissions[11] may already take us past 1.5° C/2.7° F of warming and closer to the edge of 2° C/3.6° F . That should sober us up, because it means that even if we made perfect climate decisions on every purchase from now on we will shoot past our target.

Let's reflect on that for a moment. We have left this fight so late in the game that now every time we retire a fossil fuel–burning machine, it must be replaced with a decarbonized machine. That's for everything that uses energy, by everyone, everywhere, whether an individual, a power company, or a corporation, to be a decarbonized solution[12]

This statement, while dramatic, doesn't mean you have to run out to buy a new EV today. It means that the next time you need to retire a machine, it should be replaced with a solution that doesn't emit CO_2 . It means that when your car finally dies,[13]

[11] *Committed emissions from existing energy infrastructure jeopardize 1.5°climate target*. Tong, D., Zhang, Q., Zheng, Y. et al. Nature 572, 373–377 (2019).

[12] In theory this calculus would change a little if you retired the heaviest emitting coal plants before their end of life, but it only buys you one more gasoline burning car, not two, nor substantively change the fact we need to eliminate ALL fossil fuel burning machines.

[13] *Consumer Reports* says the average life expectancy of a new car is 8 years and 150,000 miles of travel, though well maintained cars can last much longer — I have a 1963 Land Rover moving into its 400,000th mile — but with a new engine.

you have to replace it with an electric one. The same goes for your water heater, your furnace, your stove, and your roof. Start saving today. Similarly the natural–gas electricity generation plant that was built in your town in the mid–2000s won't be retired tomorrow, but at its end of life, which is probably 2040 or 2045. Start lobbying today.

100% adoption rate

Every time a car reaches retirement age, there is only a small chance the replacement will be electric. If one in ten people buy an EV, then we say the adoption rate is 10%. Because machines like your car have long lifetimes, we can't afford those slow adoption rates anymore. We need everyone buying electrical vehicles. We need everyone purchasing a power plant to choose solar instead of natural gas and wind instead of coal. Across the board we now need adoption rates of 100%. **This is what we mean when we say we are now playing end–game decarbonization.**

Let me state something that will make a lot of people very uncomfortable:

A 100% adoption rate is *only* achieved by mandate. The invisible hand of markets is definitely not fast enough; it typically takes decades for a new technology to become dominant by market forces alone as it slowly increases its market share each year. A carbon tax isn't fast enough, either. Market subsidies are not fast enough. The best we can do is early retirement of our heaviest emitters in combination with a mobilization of industry that enables 100% adoption rates.

Consider that electric cars still only represented 2% of sales of US vehicles in 2018[14] — 15 years after Tesla was founded and 20 years after GM shut down the production of its first electric car, the EV1. We need electric or emissions–free vehicles to be 100% of vehicle sales as soon as is physically, and industrially, possible.

Water heaters last 10 years. Refrigerators, 12; clothes dryers, 13; rooftops, 15; furnaces, 18; cars and trucks, 20; thermostats,

[14] 5% in California in 2019

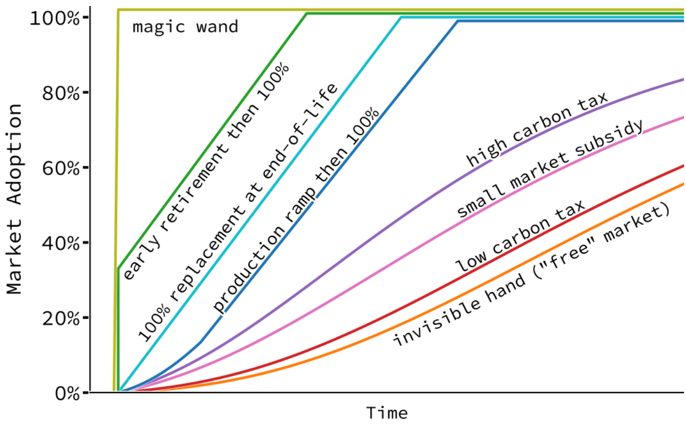

Figure 2.2: *Market adoption is the measure of penetration of a new technology. With 100% adoption of clean energy technologies we could be living carbon-free. The rate at which we get to 100% adoption will determine what global climate change we will get. We can contextualize different mechanisms for motivating increased market adoption where the "invisible hand", or a purely free market, is the slowest, and a magic wand that overnight changes all of our infrastructure to clean is the fastest.*

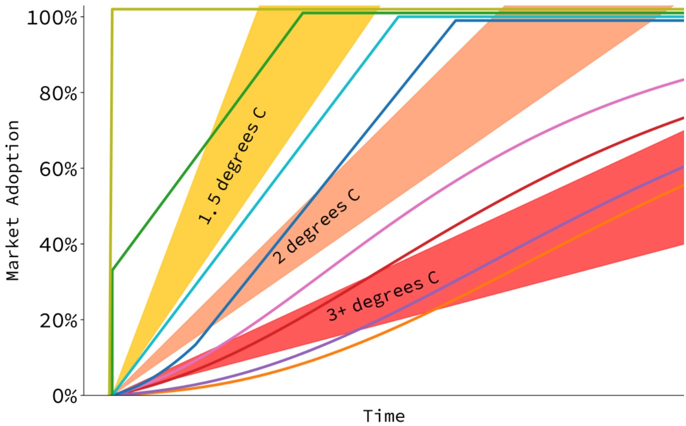

Figure 2.3: *The adoption rates we achieve will determine our fate. To hit a target of 1.5° C/2.7° F to 2° C/3.6° F now requires near perfect execution of the most rapid adoption possible — massive mobilization of decarbonization. There is no 'free market' adoption mechanism that can hit the targets we need to hit.*

35; power plants, 50.[15] No matter how effectively we may sway the market to buy green technology, we are unlikely to decarbonize faster than the curve dictated by the natural replacement lifetime of existing machines. That's why we'll need incentives such as buy–back programs and subsidies to swap out fossil fuel–burning machines for electric ones as soon as possible.

We can buy ourselves a little extra time if we shut down the most polluting infrastructure before it ends its natural life. This is why people advocate for early retirement of fossil fuel power plants, particularly those that burn coal. But consumers, utilities, and other organizations will require extreme motivation to retire their fossil–dependent infrastructure early because of their sunk costs. You aren't going to give up your gasoline–burning car unless there are enough incentives out there to make it easy for you to replace it with a new electric vehicle.

The challenge of 100% adoption presents a giant conflict that we need to address right up front: the "free market" as we know it is not up to the task of keeping us below 2° C/3.6° F and has absolutely no chance of 1.5° C/2.7° F . We can see this in Figure 2.3. It may sound like this is a giant screed for government intervention; it is not, I am merely stating what is technically necessary. If your toilet was broken and you called me and asked me what to do, I wouldn't tell you "the free market will fix that;" I'd tell you to call a plumber. That is where we're at on climate change: no amount of hope in free market solutions can change the fact that it is now too late to rely on the free market to act fast enough. We need to call the plumbers (and electricians, and engineers, and manufacturers) to fix our infrastructure now.

This is not to say that businesses and the market don't have roles; they are critical. But in emergencies, ideologies must be put aside. When Mother Nature arm–wrestles with the invisible hand,[16] she will always win. The conclusion of this urgency is that we need every player to act and do their bit. Individuals,

[15] *Study of life expectancy of home components*. National Association of Home Builders / Bank of America Home Equity, 2007, and *By the Numbers: How long will your appliances last? It depends*. Consumer Reports, 2009.

[16] As our friend and economist Skip Laitner says, the free market needs an invisible foot to give it a swift kick in the ass now and then.

governments, businesses and the market — we need every tool in the box, and we need them working together.

A third hurdle between us and a 1.5° C/2.7° F target is the time required to ramp up the industries necessary to create the solutions. If we just look at electric vehicles, batteries, wind turbines, and solar modules, they need 4X, 16X, 12X and 10X increases in production capacity. This is two or more doublings of the current capacities. Even with something akin to the U.S.' WWII production ramp–up, but this time globally, this would take five or more years to achieve.

Finally, if large economies that are heavily invested in fossil fuels, such as Russia, Brazil, Nigeria, Saudi Arabia, and others take decades instead of years to also adopt these plans, we lose any chance of 1.5 or even 2 degrees. Diplomacy, trade pressures, global treaties and better economics of the clean alternative will all be required to push these countries to the right answer.

So how do we hit 1.5 degrees from here?

- We need the fastest possible industrial mobilization of the biggest national emitters.
- If we invest heavily in science we might enable negative emissions technologies.
- If we achieve early retirements we have the chance to pull ourselves closer to 1.5° C/2.7° F than 2° C/3.6° F .

In order to have any chance of reaching 1.5° C/2.7° F , we must now employ an "endgame" decarbonization strategy. That assumes an aggressive WWII–style production ramp–up of three to five years, followed by a prolonged deployment period that replaces all deployed fossil equipment at their retirement with a 100% adoption rate. This includes supply–side generation technologies as well as demand–side technologies like electric vehicles and building heat electrification. Early retirement of our heaviest emitters (coal–fired electricity) would help.

It also means the other major manufacturing nations — China, Germany, Japan, and South Korea — must follow suit in short order, and we will have to convince nations that are unlikely to decarbonize quickly due to their fossil reserves and politics (eg. Russia, Saudi Arabia, Brazil, Nigeria).

We have a chance to hit 1.5° C/2.7° F . Just barely.

If we succeed, decarbonizing our country and switching to clean energy will create jobs in every zip code: in manufacturing, construction, installation, infrastructure, agriculture, and forestry. This is a chance to revitalize our cities, rejuvenate our suburbs and reignite our rural towns. We can rebuild a prosperous and inclusive middle class, as we enjoyed after World War II, with tens of millions of good new jobs that are vital and proud. If we do it right, everyone's energy costs will go down. Everyone has a role to play in the war effort.

We now face a climate emergency as challenging as all of our other 20th century emergencies combined. It requires mobilization with extraordinary speed and resources. Without doubt you are worried, scared, or worse. That's reasonable, but we can't do nothing, and as we'll find out, this is also a vast opportunity to improve our world.

3 Emergencies are opportunities for lasting change

- ☛ We can look to prior emergencies to understand what we need to do to boldly avert climate change.
- ☛ We need to take all the actions all at once to decarbonize on time.

The U.S. (and many other countries) botched the response to the COVID-19 pandemic. Climate change is a larger, more insidious version of a similar problem that stems from disregarding science until it becomes an emergency. We need to bend the curve as per Figure 3.1. We may have failed with COVID-19, but there is no need to fail on climate — the U.S. has successfully fought many other emergencies in the last century, making a difference with both our individual and collective actions. Whether the threat was to the wilderness, prosperity, democracy, civil rights, technological superiority, national security, public health, or the hole in the ozone layer, in each case, we faced a strong enemy — and we won. It's worth a moment to reflect on how we did it, for inspiration and guidance.

Let's also look at this list to understand the tools we can use from history to help fight our climate crisis.

Saving the wilderness

In 1903, the naturalist John Muir realized that many of America's wild lands[1] — "temples of nature,"' he called them — were

[1] A fabulous little book on the history of National Parks is *The National Parks: America's Best Idea*, by Dayton Duncan and Ken Burns (Alred A. Knopf, 2009).

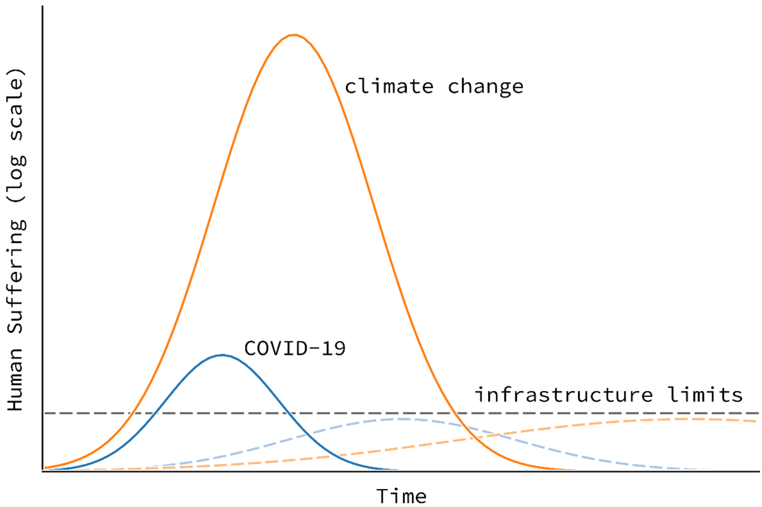

Figure 3.1: *Flatten the curve! Climate change has similarities to COVID. We must act long before we see the worst of the effects and to prevent overwhelming our infrastructure limits – with COVID, a few weeks in advance; with climate change a few decades.*

being stripped for logging, mining, and development. If the destruction continued, those wild places would be gone. They urgently needed to be protected before they were forever destroyed. He convinced President Theodore Roosevelt to come camping with him in Yosemite, roughing it for three days while he impressed upon the president the need to create protected public lands to preserve our natural resources for future generations. (I love the idea of a president who would go camping as an example for the nation!) It worked: During his presidency, Teddy Roosevelt signed into existence five national parks, 18 national monuments, 55 national bird sanctuaries and wildlife refuges, and 150 national forests.[2]

We have it in us to preserve our natural world for future generations to enjoy.

[2] *100th Anniversary of President Theodore Roosevelt and Naturalist John Muir's Visit at Yosemite National Park*, National Park Service Press Release, 2003.

The New Deal

Between 1933 and 1939, President Franklin D. Roosevelt, working with Congress and advisors, enacted a series of programs, public works projects, new jobs, and financial reforms to help Americans recover from the Great Depression. One was the modern long–term, government–backed home mortgage, which allowed many people to buy homes, and anchored an enduring and stable middle class. Mortgages and low–interest loans are important in the context of the climate emergency, because while clean energy sources produce almost free electricity when they're up and running, they require up–front cash. You have to have the spare capital to put solar panels on your roof in order to enjoy long–term savings. Fixing the climate will require "climate loans" that will make it easier to buy electric cars and electric home heating units rather than continue to rely on fossil–fuel powered machines.

Another New Deal program that may be a model for how we can finance electrification today was the Rural Electrification Act of 1936, which provided federal loans to install electrical systems to rural areas in the U.S. The Electric Home and Farm Agency (EHFA), helped rural Americans finance purchases of electric appliances, such as refrigerators, ranges, and hot water heaters. EHFA ultimately financed some 4.2 million appliances, at a time when there were around 30 million households in the U.S.[3]

Innovative financing plans can pull us out of a crisis and build a strong basis for a more prosperous citizenry.

The mobilization for World War II

In 1940, after Hitler's troops marched into France, the situation in Europe — and for democracy — seemed dire. Britain's Prime Minister Winston Churchill entreated FDR to join the war.

Initially, the U.S. was in no shape to take that on. Coming out of the Depression, the country was in an isolationist mood, and

[3] *The Electric Home and Farm Authority, "Model T Appliances," and the Modernization of the Home Kitchen in the South.* Michelle Mock. The Journal of Southern History. Vol. 80, No. 1. February 2014

the military was under–equipped and disorganized. In 1939, the U.S. military ranked 18th in the world, just edging out Holland. As Arthur Herman recounts in *Freedom's Forge*, the U.S. Army's fighters and resources were so far behind Hitler's that Brigadier General George Patton had only 325 tanks to the Germans' more than 2000 — and he had to order nuts and bolts for them from the Sears and Roebuck catalog. Practice war games held that year were so shabby that the Army used ice cream trucks as stand–ins for tanks.

But Roosevelt responded with agility to the threat of fascism, creating an industrial infrastructure capable of out–manufacturing Germany in a new type of war that would be won not just with soldiers, but with airplanes, tanks, jeeps, guns, bullets, boats and bombs. Roosevelt partnered with industrialists to build the armaments we needed to get the job done, fast. The U.S. government drafted a list of critical munitions and offered capital plus a guarantee of a 7% profit to industrialists who would turn their engineering know–how and factories to producing a military arsenal that could fight Hitler and save democracy. The profit was sometimes ridiculed as "patriotism plus 7%" by the New Dealers, but it worked.

Building on American mass production of cars, the "Arsenal of Democracy" was the linchpin of winning the war. In 1939 the U.S. had only 1700 aircraft, and no bombers. By 1945, the U.S. had some 300,000 military aircraft, 18,500 B–24 bombers, and an arsenal big enough to support the Allies and defeat the Axis. Today, with the right financial incentives, we could transform our current industrial machine to produce the zero–carbon infrastructure we need. Indeed, it is an opportunity for us to modernize our industrial infrastructure and manufacturing base to again lead the world.

The WWII manufacturing build–up created over 16 million new jobs, including jobs for women, adolescents, retirees, African–Americans, and others historically left out of the workforce. No jobs program before or since has been as successful at putting people to work. After all the smoke had cleared, WWII investments in manufacturing continued to sustain American prosperity for decades. At the height of the Great Depression, U.S.

unemployment was over 24% (recently, the COVID-19 pandemic put unemployment at the highest rate since then). Over nearly a decade of New Deal programs, joblessness stubbornly remained above 14%. With the wartime production effort, in 1944, unemployment was 1.2%.[4]

In 1940, the U.S. population was 132 million, and the GDP was $100 billion. Between 1939 and 1945, the U.S. spent $186 billion producing the war materials critical to the success of the Allies. The GDP doubled in the next three years (1940–43). Today, the US population is 330 million and the GDP is $21 trillion. If we were to spend in the same proportions today, it would be equivalent to $39 trillion. The good news is that the effort to decarbonize should cost ***comparatively less than the financial commitment required to win WWII.***

To get to carbon zero, we have to fight World War Zero.[5] Even if the situation right now seems mired in inertia and political paralysis, we have to act. We've done it before — and not only did America win WWII with the Allies, we created jobs and technologies that ensured our long–term prosperity. Winning War Zero is possible; as we'll see, it's a problem of will, not technology.

We are capable of ramping up industrial production at an astonishing rate — fast enough to make the technological changes we must in order to meet a crisis.

The space race

On October 4, 1957, the Soviet Union surprised President Dwight D. Eisenhower and the U.S. by successfully launching Sputnik I, the world's first artificial satellite. The beach ball–sized Sputnik set off the US–USSR space race, and launched new political, military, technological, and scientific developments.

Immediately after Sputnik, the U.S. created a series of nimble young science agencies to avoid future surprises and to chart

[4] These figures are complicated a little because around 10 million people went off to war, but they were more than offset by new entrants to the formal workforce such as women.

[5] With apologies to John Kerry, who may have coined this term—it's a great summary of what we need—a wartime effort to get the economy to zero carbon emissions.

a path forward, including the National Aeronautics and Space Administration (NASA) and the Defense Advanced Research Projects Agency[6] (DARPA). These agencies have gone on to make astounding technical advances in artificial intelligence, stealth technologies, microelectronics, surveillance, and communications — including the prototypical communications network ARPANET, which evolved into the worldwide Internet as we know it today.

President John F. Kennedy leveraged Eisenhower's agencies to launch a technical project so ambitious that it now defines scientific and engineering ambition: the moon shot. On March 25, 1961, he declared a dramatic goal: to land an American on the moon within the decade. On July 20, 1969, the U.S. Apollo 11 landed on the moon — Neil Armstrong's small step, and our "giant leap for mankind." These space efforts gave humanity a vision beyond our own tiny planet, to place us as a species in the larger context of the solar system and the universe.

In today's dollars, the Apollo program cost $150 billion. Currently the U.S. government only spends about $3 billion annually on energy and climate technologies.[7] A 10–, or 50–fold increase in spending on saving the planet seems reasonable.

We can invest massively in science and technology to solve audacious problems — to succeed and to beat the competition.

The civil rights movement

The civil rights movement fought the slower–moving, more deeply–rooted, and more human emergency of institutionalized racism in the U.S. A succession of courageous activists, from Rosa Parks and the Freedom Riders to those who participated in the 1963 March on Washington, in which Dr. Martin Luther King, Jr. proclaimed "I have a dream" for racial equality, helped change discriminatory laws. The Civil Rights Act was passed in 1964, the Voting Rights Act in 1965, and the Fair Housing Act in 1968.

[6] DARPA started out as ARPA, the D– for Defense– was added in 1972

[7] The Department of energy has a budget of around $30bN, the great majority is spent on Nuclear deterrent, stockpile and security. The DOE invests heavily in fundamental science, and only a small fraction, around 3bN in energy technologies that are likely to make an impact in the near term. *FY 2020 Budget Request Fact Sheet*. U.S. Department of Energy. March 11, 2019.

Since then, we've seen the election of our first black president, Barack Obama, and other gains in diversity and inclusion. The Black Lives Matter movement in response to racist police brutality has resulted in what may be true lasting changes in discriminatory policing, hiring, and day-to-day attitudes about race. But discrimination, racism, and violence against people of color continues to be a deeply pervasive challenge in the U.S.

Civil rights activists have been — and continue to be — a model for many activists, notably for LGBTQX rights, and an inspiration for climate activists — the youth who are rising up and demanding their right to their future. Today's climate activists understand how the devastating global effects of climate change disproportionately affect people of color. The civil rights movement still hasn't fully achieved it's early aspirations which speaks to another analogy to climate - it's a long road requiring continual pressure.

People, together, can change the course of history with their collective activism. It requires bravery and direct action.

The 1973 energy crisis

Late in 1973, President Richard Nixon addressed the nation about "The Energy Emergency," warning about our reliance on foreign oil. The energy crisis demanded an ambitious response. He created science–based agencies to study and solve environmental problems — The Energy Information Administration (EIA), the Department of Energy (DOE), and the Environmental Protection Agency (EPA). Much of our deep understanding of our energy and climate crisis sits in the wheelhouses of these agencies that were bought into existence through three consecutive presidents: Nixon, Ford, and Carter.

Back then, the problem was that we were importing 10% of our energy from foreign sources, so we could reasonably count on figuring out how to use fossil fuels 10% more efficiently to solve the problem. That's how we got CAFE efficiency standards and Energy Star appliances — and a now outdated sense that we can solve energy problems with efficiency alone. While the '70s energy crisis was about the 10% of our energy system that used imported oil, the current crisis is about transforming close to 100% of our energy system to clean electricitiy.

Today, we need to stop using fossil fuels altogether; we can't "efficiency" our way to carbon zero.

We understand our energy needs and strategy now because America pioneered collecting comprehensive energy data in the 1970s. We need to invest further in our existing federal technology innovation system and data collection to develop the technologies we need to get to carbon zero at scale, and on time.

Smoking, a public health crisis

In 1964, U.S. Surgeon General Luther Terry dropped a bombshell on the American public: smoking causes lung and other types of cancers, and the tobacco industry misled consumers by hiding the dangers of cigarettes. At the time, 42% of adult Americans smoked regularly. The Surgeon General mounted a public campaign against smoking that included health warnings, advertising bans, and a public awareness campaign of smoking's dangers.[8] Since then, the rate of smokers has dropped by more than half, to 18%. The *Journal of the American Medical Association* (JAMA) estimated that over that period, our crisis response to the smoking epidemic avoided 8 million deaths.[9]

Climate change also poses a grave danger to human health. The World Health Organization has estimated that meeting the goals of the Paris Agreement could save 7 million lives worldwide per year by 2050, just by reductions in air pollution, which cause asthma and other respiratory illnesses.[10] The EPA estimates that the higher concentrations of ozone in the air due to climate change may result in tens of thousands of additional ozone–related illnesses and premature deaths per year by 2030 in the United States.[11] Global warming will also result in heat strokes and other heat–related deaths.

[8] *History of the Surgeon General's Reports on Smoking and Health.* CDC, 2019.

[9] *Tobacco Control and the Reduction in Smoking-Related Premature Deaths in the United States, 1964-2012.* Theodore R. Holford, et al. JAMA. 2014; 311(2):164-171.

[10] *Health benefits far outweigh the costs of meeting climate change goals.* WHO, 2018.

[11] *Climate Impacts on Human Health.* U.S. Environmental Protection Agency, 2017.

A concerted public effort can turn around a public health crisis and rein in companies that promote ill health, whether Big Tobacco or Big Fossil.

Ozone depletion and refrigerants

After scientists figured out that we had a large hole in the ozone layer that protects us from harmful UV radiation, nations came together to agree to the Montreal Protocol in 1987.[12] They signed an international treaty to phase out the chloro–fluoro–carbons (CFCs) that were in most refrigerants at the time. We have amended the Montreal protocol many times, including the most recent Kigali amendments.[13] It is a great example of international cooperation in the face of an emergency. We mention heat pumps frequently in this book; just like refrigerators and air conditioners, they use refrigerants and could be disastrous for the atmosphere if it weren't for the fact that science figured this out. The future of refrigerants involves "natural" refrigerants like supercritical CO_2 that have comparatively miniscule greenhouse gas impact.

Nations came together to stabilize a complex geological system through collective action. Science identified the problem, engineers created solutions, and politicians created the right regulatory environment.

Today's climate emergency

☞ **Like preserving the national parks**, we have an opportunity to save beautiful wild places — and the whole planet — for our children.

[12] *Montreal Protocol.* Wikipedia.

[13] It probably wasn't all altruism - Dow was making less money off CFC's in the 1980s, so started to support the Montreal protocol to phase out CFCs, in favor of HFCs, which it does have a patent on. (*There's money in the air: The CFC ban and Dupont's regulatory strategy*, Business Strategy and the Environment, Vol 6, 276-286 (1997)) Now, in the 2010s, the same story repeats itself, with chemical companies (DuPont, Chemours, Honeywell) funding the Kigali amendments to the Montreal protocol, which phase out HFCs, because they have new patents on HFOs (*A monopoly like none other.* Chandra Bhushan, 2016). They're also trying to resist deployment of natural refrigerants which are competitors to HFOs (*How a Dupont spinoff lobbied the EPA to stave off the use of environmentally-friendly coolants.* Sharon Lerner, The Intercept, 2018).

- **Like the New Deal**, this crisis will take innovations in financing, require public works projects and create employment.
- **Like the World War II mobilization**, we must turn to industry to transform infrastructure, and accelerate the wartime production we need to solve an urgent problem. If not done voluntarily, this may require federal mandate through emergency powers.
- **Like the Space Race**, we must commit to ambitious timelines and massive investment in science.
- **Like civil rights**, the response through legal channels has been far too slow and must be supplemented by direct action and social movements that don't let up in creating the political pressures for change.
- **Like the 1970s energy crisis**, we must look to data to guide our action.
- **Like the public health crisis that is smoking**, we must use a combination of incentives — regulation, pricing, public awareness, and availability — to decarbonize.
- **Like the Montreal Protocol,** we should lean in to international policy–making that will address this crisis.

But the climate crisis we face today is in many ways different than these previous crises. This time the *enemy* — fossil fuels — is integral to our existing economy. This time, because of the lag–time in climate response, we need to act long before the worst impacts are felt. It is for these reasons that climate change has been described as a "super wicked hard problem".[14]

Our reward for this work — besides saving the planet — will be abundant cheap energy, quality jobs, improved public health, and a new era of prosperity. **We must be bold again.**

[14] Wicked hard problems are even defined as a special category of almost impossible tasks.

4 2020s thinking

- It's not the 1970s any more, and we're not facing a '70s energy problem that can be solved with efficiency.
- '70s thinking champions efficiency where transformation is what is necessary.
- '70s thinking focuses us on lots of small decisions and distracts us from the big picture.
- '70s thinking muddles thermodynamic efficiency with behavior change efficiency.
- '70s thinking leads to a narrative of deprivation.
- '70s thinking was about doing less bad, not about doing a lot more good and building good into the way we do everything.

We are stuck in a way of thinking about the environment that dates back to the 1970s. This mindset can be succinctly summarized as, *"If we try extremely hard, and make many sacrifices, the future will be a little less fucked than it might be otherwise."*

To address climate change, we need a new narrative that is both more honest about the task at hand and more broadly engaging than a story about sacrifice. It can be a story about what we have to win — a cleaner electrified future, with comfortable homes and zippy cars — which is better than nightmares about what we have to lose. We have a path to decarbonization that will involve changes, to be sure, but not deprivation. The 2020 mindset says: *"If we build the right infrastructure, right away, the* *future will be awesome!"*

The language of sacrifice associated with being "green" is a legacy of 1970s thinking, which was focused on efficiency and conservation. The 1970s began with Earth Day (April 22, 1970), and was a decade defined by two energy crises over oil imports. The air[1] and water quality[2] problems caused by our energy production were coming to the fore, in part because of groundbreaking books like Rachel Carson's *Silent Spring*[3] and the burgeoning environmentalist movement they inspired. The answer to these problems became a story about conservation: use less fossil fuel, turn down the thermostat, buy smaller cars, drive less. This is the era that gave us the mantra *Reduce! Reuse! Recycle!*

This approach translated to more fuel–efficient (but still petroleum) cars and better insulated homes (but still heated with natural gas). The emphasis on efficiency ever since the '70s is reasonable, since almost no one can defend outright waste, and almost everyone agrees that recycling, double–glazed windows, more aerodynamic cars, more insulation in our walls, and industrial efficiency will make things better. But while efficiency measures have slowed the rate of growth of our energy consumption, they haven't changed the composition.

We need zero carbon emissions, and you can't "efficiency" your way to zero.

The '70s emphasis on efficiency was also confusing, in that it conflated different types of efficiency. You can make a big car more efficient with a more efficient engine, or you can buy a smaller car that is more efficient because of its smallness, or you can use cars less. One of these efficiencies is thermodynamic efficiency; the other two come from behavior changes. Environmentalists have focused more on behavior–change efficiencies — which are fine, as far as they go — but we will gain a lot more with big technological changes. Rather than make a more

[1] The clean air act was passed in 1970 (Evolution of the Clean Air Act, U.S. Environmental Protection Agency.)

[2] United States. Federal Water Pollution Control Act Amendments of 1972. Pub.L. 92-500, October 18, 1972

[3] *Silent Spring* was in fact about pesticide use, but it inspired the awareness of the impacts of human activity that define the environmentalist movement.

efficient fossil–fuel–powered car (thermodynamic efficiency), or drive it less (behavior efficiency), it makes most sense of all to make an electric car powered by renewable energy.

2020 thinking is not about efficiency; it's about transformation.

Nearly half a century after President Jimmy Carter's famous[4] comments about wearing sweaters (which are oddly similar to what Nixon said six years before him[5]), we know efficiency fixes are not enough. While we have made more fuel-efficient appliances, and paid a lot of attention to "greening" our small, daily purchases, we haven't done much to solve our larger carbon problem. And even if energy efficiency did work, we haven't shown any inclination to drastically cut our consumption since the '70s.

We're also never going to get outright support for decarbonization if people believe it will lead to widespread deprivation — which many people associate with efficiency. We won't address climate change if people remain fixated on and fighting about losing their big cars, hamburgers, and comforts of home. Americans won't agree to anything if they believe it will make them uncomfortable, or take away their stuff.

We need to stop focusing on efficiency — and on the demand side of the energy equation in general, which says that if we just use less, we will need to supply less. Nor can we simply address changing the supply, swapping out different fuels to power the same machines. We need an entirely new paradigm, which isn't mired in our '70s notions of supply and demand, but realizes that the two are intimately connected. We need to decarbonize supply at the same rate as we decarbonize demand, and that means powering electric machines with zero carbon electricity.

It's 50 years later. We must play endgame decarbonization.

End-game decarbonization means electrifying everything — changing the infrastructure in our lives, rather than our habits.

In this 2020 paradigm, we need to think bigger. We need to change our mindset from the efficiency environmentalism of the 1970s to a transformation mindset appropriate to the 21st cen-

[4] At least famous to old people, hippies, nerds, and wonks.

[5] Transcript of Nixon's Speech on Energy Situation, New York Times, Jan. 20, 1974.

tury.[6] Let's stop imagining that we can buy enough sustainably–harvested fish, catch enough public transport, and purchase enough stainless steel water bottles to improve the climate situation. Let's release ourselves from purchasing paralysis and constant guilt at every decision we make.

Instead of efficiency, massive electrification is the first and biggest win for addressing climate change. If the electric car in your driveway is powered from the solar on your roof and in your community, and your heating system runs on electricity generated at a far–off wind farm, then you have made the small number of critical decisions that eliminate the large majority of emissions from your life.

What this means is that instead of changing our energy supply or demand, we need to transform our *infrastructure* — both individually and collectively.

Infrastructure is more than just dams, roads, rails and bridges. Where 20th–century infrastructure largely emphasized a supply–side view of the world, the 21st–century infrastructure encompasses the demand side as well. It is not just the roads that matter, it's the vehicles on them and the batteries inside those vehicles. It is not just where the transmission lines go, but what is wired up at the end of them: the water heaters, ovens and stoves, heat pumps, and refrigerators. It's not just you being connected to the grid, but also to everyone around you.

Infrastructure is about big decisions, not little ones. If we focus on fundamentally rethinking our infrastructure, doing the right thing will be baked into the world we inhabit. You just need to make four or five big decisions well — think of them as your personal infrastructure. These are purchases (or investments) that are made roughly every 10 years: what's in your garage, on your rooftop, and heating your house. Make them well and you can pretty much forget about the day–to–day hand-wringing. These infrequent decisions are the ones that lock us into using either a lot of energy, or a little, and

[6] Efficiency proponents will counter that if you make the thing more efficient first, then you will need less electricity. That is true. I will then counter argue that electrification has a bigger immediate win, is more politically palatable, and that we should look at this problem from all sides to make the most progress.

into spewing carbon dioxide, or not. **If we design our personal infrastructure right, we will be able to live our lives without sweating all the small things.**

If we are to succeed in beating climate change:

- Everyone's next car, and every subsequent car, should be electric. (Of course, public transit, bicycles, electric bicycles, electric scooters, or anything that isn't powered by fossil fuels are even better options). Try walking.

- Everyone should install solar on their roofs at the next opportunity, whether that be a retrofit, replacing shingles, or buying or building a new house. You should be installing enough solar to power your electric vehicles and electrified heating systems, not just the small solar systems of today that only accommodate your existing electrical load.

- Replace furnaces and gas or oil–fired heating systems with electric heat pumps.[7] Additionally it is wise to insulate and seal homes so that they need less energy. If you are replacing your flooring, it is a perfect time to install radiant heating systems.

- Choose the most efficient induction stoves, electric refrigerators, dryers, heat pump water heaters and dish and clothes washers that are available.

- As lives become increasingly electrified, there will come a moment (quite soon) where a small home battery[8] will make economic sense to install as a backstop to personal energy demands as well as to make the grid more robust.

Of course we can't get to a zero–carbon world purely by making personal consumer decisions — we critically need government and industry. But the easiest emissions for us to eliminate

[7] The average furnace lasts 15 years

[8] We don't need to argue, in the spirit of "yes, and" there will also be grid connected batteries. The point being there is enough storage required for everyone to participate. Cost will be the ultimate decider, and i"m going to bet we'll do more storage closer to the end use because then transmission and distribution costs will be less significant.

as individuals are those we directly control as everyday consumers, and these decisions address roughly half of our total CO_2 emissions.

These are choices we all need to make. Think about the potential of our personal infrastructure at scale. By connecting our vehicles and homes to the larger grid we enable the neighborly infrastructure of the 21st century.

It's 2020, and time to see our way to a clean, electrified world.

- 2020s thinking is about transformation and endgame decarbonization.
- 2020s thinking understands that your personal infrastructure determines the big picture of how much carbon you (and we, collectively) produce.
- 2020s thinking will lead you to conclude we need to electrify everything.
- When we electrify everything, it creates more efficiency gains than any 1970s thinking could ever do.

5 Electrify!

- We can't just swap out fossil fuels for similar fuels just because they feel familiar.
- We can't keep burning fossil fuels and assume we can suck CO_2 out of the air and stuff it back into the earth or oceans.
- We have to electrify (nearly) everything.
- When we electrify everything, we realize we need about half the energy of the old world.

OK, so we can't use fossil fuels. How will we do the things we want to do?

When people imagine switching to zero–carbon energy, they often think about simply swapping fossil fuels for another "familiar fuel." If you had a gallon–sized gas container, you'd like to just fill it with something else that is zero–carbon yet powers the same lawnmower, or a familiar–looking car.

That's why people think a lot about net–zero–carbon fuels. Biomass, ethanol, switchgrass, sargassum — there are lots of names for things that absorb CO_2 out of the atmosphere as they grow and emit it when they burn. Couldn't these fuels could be used in our machinery with minimal changes to life? Sounds good.

Similarly, people talk about making hydrogen or a synthetic fuel like ammonia or ethanol with properties like gasoline or natural gas. Again, it sounds easy, but it requires using more renewably or nuclear–generated electricity to create the fuels than you would need to simply power an electric car straight from the grid. Hydrogen vehicles are the canonical case of this silliness. The idea is to make a unit of electricity, lose 25% of it converting it to hydrogen, and lose another 25% of it in a fuel cell that converts it back into electricity that drives the wheels. All for the convenience of having a familiar fuel to fill a familiar tank.[1]

The biofuel route imagines we can make a similar amount of fuels with biomass, but the problem is that there just isn't enough to go around. To create the amount of biofuel we'd need to power our lives, we'd have to burn a quarter of all the biomass that grows on earth each year, every year, with devastating environmental consequences. At best, it can make about 10% of our fuels.[2]

The synthetic fuel route imagines we make carbon–free electricity using solar, nuclear, wind, and hydroelectricity, and use that electricity to make the molecules of our familiar fuel. This is a game of compounding inefficiencies.

Imagining that we can just swap one fuel for another keeps us in the 1970s' world of lots of machines with low thermodynamic efficiencies. It also keeps us tied to the massive inefficiency of burning enormous amounts of material. We move more tons of fossil fuels than any of the other things that humanity produces — more than all of our agricultural products, more than all of our metals and ores. Imagining that we will build an industry that can manufacture this amount of alternative fuel on the necessary timeline is absurd.

The other "familiar fuel" strategy is carbon sequestration, imagining that we'll use the same fossil fuels, suck the CO_2 out of the atmosphere, and bury it. Again, the tons of CO_2 humanity produces every year is more than all of the other material flows we use *in total*. There is no dump large enough to stick it in, even if it wasn't a thermodynamically awful idea in the first place.

[1] Actually all hydrogen now used in hydrogen vehicles is a byproduct of natural gas, which just perpetuates our current problem, and is part of the reason these fuels have been cynically over–promoted as a solution.

[2] *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy*, U.S. Department of Energy, 2016.

What do I mean by a thermodynamically awful idea? Carbon sequestration imagines that we would create *even more* energy — about 20% more — with fossil fuels, just to capture the CO_2 produced by those fuels, then use yet more energy (still!) to compress it and bury it — and hope that it stays buried, something that isn't guaranteed. Given that renewable electricity is already cost–competitive against fossil fuels, it is fairly obvious to those who think about energy a lot that the cost of carbon sequestration will kill the economics of fossil fuels.

All of these ideas are cynically promoted by people who wish to keep profiting off fossil fuels, burning your children's future. Don't let them divide us by confusing us.

We don't just need to change our fuels; we need to change our machines. We need to use 2020s thinking to reimagine our infrastructure.

At the highest level, and at the risk of repeating myself, any realistic plan toward total decarbonization is simple: **electrify everything.** When we replace everything in our lives with electricity, cars will be zippier, the air in our cities, suburbs, and homes will be cleaner, our appliances will be better, the streets will be quieter, and our carbon–consciences will be clear.

We have the technology we need, today, to solve climate change. And when we electrify everything, as we'll soon show, we will eliminate more than half the energy we think we need!

Where does all of our energy go?

Fortunately, the U.S. government has been collecting comprehensive energy data since the Nixon administration. We sat down with all of the data (Figure 5.1) on the total amount of energy we use, and begin a thought experiment, asking "what happens if we electrify everything?" Some interesting things jump out, as we detail in Figure 5.2.[3] Right away, we find out we need less than half of the energy that we think we do, which makes the task of generating it with renewables twice as easy. Here's how.

[3]We've spent years assembling high-resolution data on this topic. See it on the web at www.departmentof.energy

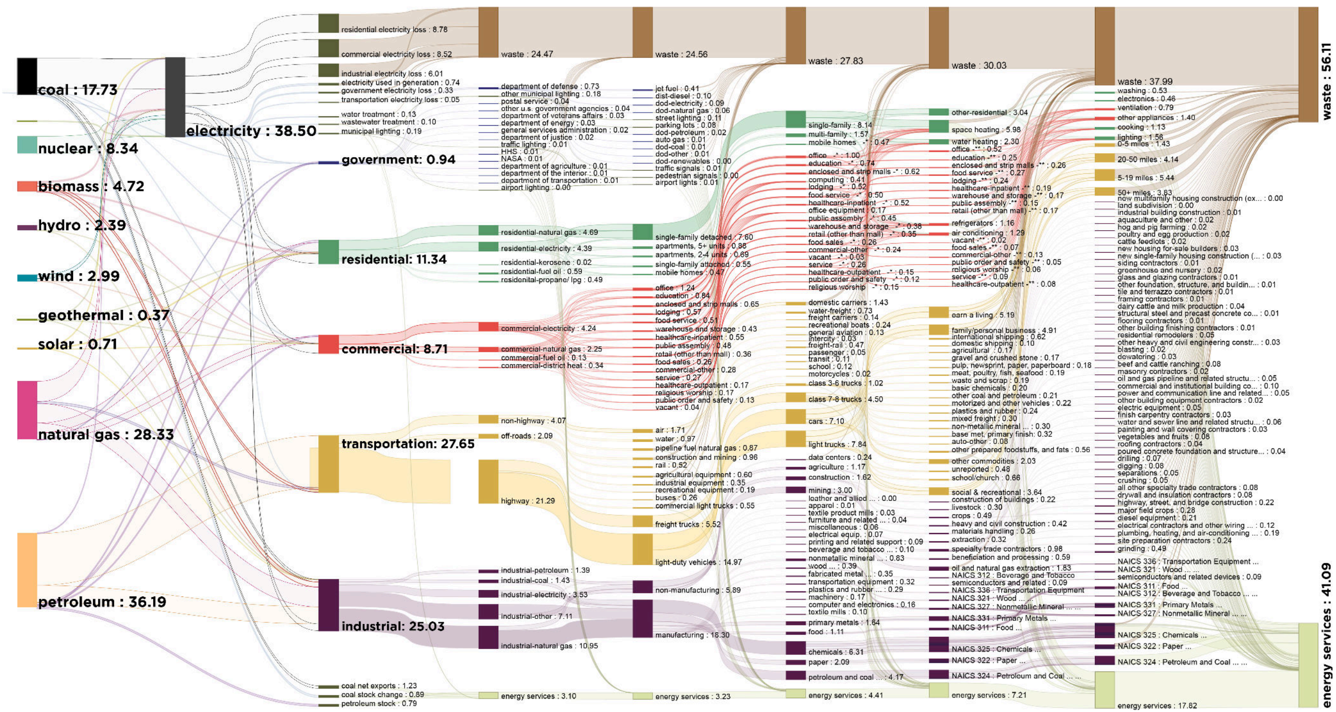

Figure 5.1: *More energy data than you can poke a stick at. All U.S. energy flows integrated from EIA data, RECS, MECS, CBECS, and NHTS. All units are Quads (Quadrillion BTUS / year) but as the U.S. uses approximately 100 quads, they can be conveniently thought of as percentages. Yes, the small print might be too fine to read, so try looking online at:* `www.departmentof.energy`

Make clean electricity — save 23%

We can eliminate almost a quarter of the energy we think we need if we stop burning fossil fuels to generate electricity.

In a power plant today, fossil fuels are burned to generate heat, which is used to make steam, which is used to spin a turbine, which is used to create electricity. Physics tells us that using heat to generate electricity is subject to inescapable limits on efficiency. Those limits are set by the laws of thermodynamics, which dictate that a machine that converts heat to electricity will lose half or more of the energy involved in doing the conversion.

Carbon–free, non–thermal sources like solar and wind — while also subject to the laws of physics — don't involve so many conversions from one type of energy to another.[4] Because of this, generating electricity with renewables would eliminate approximately 15% of the primary fossil energy we currently think we need to run the economy.

Other "savings" in the amount of energy we think we need come from a couple of longstanding accounting curiosities associated with fossil fuels, which have caused us to over–estimate the primary energy for both hydroelectricity and nuclear energy.[5] If we correct these accounting errors mired in fossil–fuel

[4] Today when we use fossil fuels we are harnessing a long train of energy conversions: Solar energy from long ago was converted to a bio–fuel, which over geological time became a fossil–fuel, which was burned to become heat, which evaporated water to become steam, which spun a turbine to become motion, which through electromagnetism became electricity, wasting a little or a lot of energy at each step along the way. When we use solar, a photon from the sun strikes a semiconductor and liberates an electron due to the photoelectric effect (thanks, Einstein).

[5] In the 1970s, concerns about scarcity and drought led us to calculate the primary energy of hydroelectricity to be the amount of fossil-fuelled power that would need to be added to the grid to replace a hydro facility lost to a drought. Because the average efficiency of fossil–fuel -fired electricity generation is only around 30-40%, this resulted in an overestimate of the primary hydroelectric resource, which has persisted in the accounting practices to date. Strangely, in calculating hydro energy, we take the capacity of the hydro facility, and multiply it by the average inefficiency of our fossil fleet — which means we over–report by a factor of 3. Such are the oddities of a world literally defined by fossil fuels. The second accounting curiosity comes from how we measure primary energy in nuclear–generated electricity. The U.S. elected to use light–water reactors for its nuclear electricity plants, in part because of the security and safety issues of the resulting waste. In this type of reactor, only about 1-2% of the energy in the fissile material is extracted; however, dangerous or weaponizable isotopes are avoided. We could have used breeder reactors like France and Germany do, generating more fissile material than consumed, but these create an even more difficult set of safety and security issues. Instead of using the

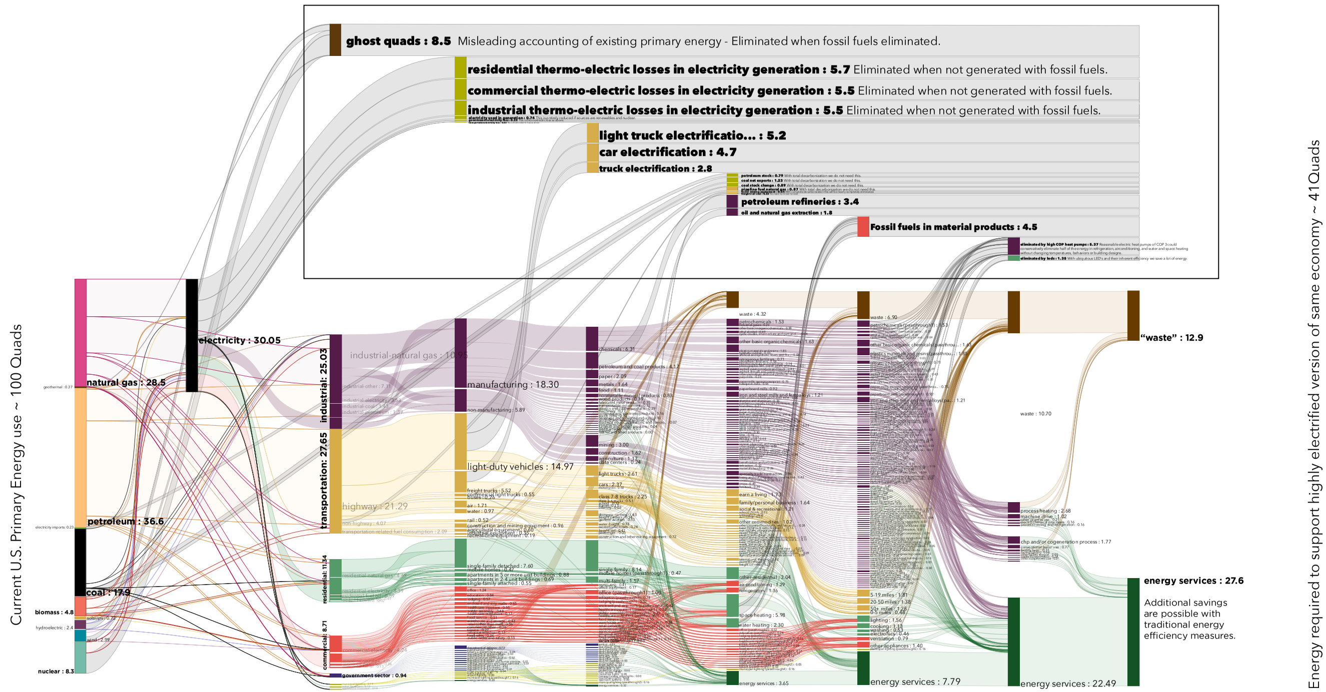

Figure 5.2: *A highly electrified, decarbonized U.S. energy sector roadmap showing where the massive efficiencies lie in electrification.*

thinking, we see that roughly 8% of the energy we think we need was never really there. Together, the savings from thermodynamic efficiency and proper accounting total around 23%, just for switching electricity generation to carbon–free sources.

Electrify transportation — save 15%

Electrifying transportation is the next big energy win, saving us around 15%. [6] Gasoline car engines, which make up the overwhelming majority of vehicles today, are even less efficient than power plants in converting fossil fuels into a useful activity.[7] By the time the energy in the fuel has been turned into the motion of the vehicle, the efficiency is only about 20%. The heat you feel on the hood of your car after a long drive is the waste heat. (You can fry an egg on your engine block — in old Land Rovers people learned to put a Dutch oven in the engine bay and cook a stew as they drove!) If we electrify all cars and trucks, we will eliminate most of that waste heat and cut the amount of energy consumed in moving those vehicles by a factor of three.

Electric cars have gone mainstream, are dropping in cost, charging faster, and are expanding in performance, range, and options. At their current rate of improvement, we are only a few years from electric vehicles with a 300– to 400–mile range. We already have vehicles with enough range for nearly all purposes except for extreme road–trips or extraordinarily long days. It is not a matter of if, but when. If all road vehicles were electric and powered by non–carbon sources, 15% of all of our primary energy needs would disappear.

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conversion efficiency of nuclear fuel to useful energy to measure the efficiency of nuclear plants, the DOE decided to use the "heat rate." This, in effect, is just the thermodynamic efficiency of the steam turbine at the output end of the power plant, and ignores what happened in the reactor. In the context of figuring out how to decarbonize America, choosing heat rate to define the efficiency of a nuclear plant ignores the 98% of the fuel we don't use and simply isn't a useful definition. It makes us think there is more waste in the energy system than there really is, and doesn't highlight that we have other technological options for harnessing nuclear energy.

[6] As a former colleague, Wes Herman, pointed out many years ago, and as the guy he went to work for, Elon Musk, has turned into a very real business.

[7] For reasons of convenience when LLNL determines which energy is useful and which is waste, they assume a blanket efficiency for cars of 20%. They just take the amount of fuel you put in your tank, and assume 1/5th of it works to push you in the right direction.

Eliminate finding, mining, & refining fossil fuels — save 11%

A huge and largely unseen amount of energy is used to discover, mine, refine, and transport fossil fuels. In a zero–carbon economy, we won't need to expend that energy, which saves us more than 11%. Oil and gas extraction consume nearly 2% of U.S. energy flow. Piping around natural gas (1%), running coal mining equipment(0.25%), moving the coal from the mine to the power plant via rail(0.25%),[8] and refining crude oil into gasoline and diesel (3–4%) consumes around 8% of the national energy supply. Other savings come from accounting for stockpiles, stock–changes, and exports of fossil fuels, bringing the total savings to 11%.

In all likelihood, the energy savings of eliminating fossil fuels is even greater, as we haven't considered the fuel for tankers delivering gasoline from refineries to gas stations and the energy that goes into building all of the mining and shipping equipment that are necessary for this massive heavy industry. Remember, we move as many tons of fossil fuel as we do of any other commodity category.

The thoughtful reader might argue that these savings will be offset by the energy required to build the windmills, solar cells, batteries, nuclear plants, grid, and electric vehicles that will replace the fossil fuel industry. But the energy used in their construction and operation is likely a significantly smaller percentage of the future energy economy than fossil fuel processing is today. Estimates vary, but wind and solar provide approximately three times higher energy return on investment than fossil fuel power plants.[9]

[8] Nearly half of all of the tonnage of stuff that is moved by rail is coal. (Roughly) the other half is grain. We move a few cars and pieces of machinery and a small number of people, too.

[9] Historically, energy return on investment (EROI) of fossil fuels has not included electricity generation, making the EROI look artificially inflated. When this is taken into account, renewables beat fossil fuels hands down. For example, see *Estimation of global final-stage energy-return-on-investment for fossil fuels with comparison to renewable energy sources*. Paul E. Brockway, Anne Owen, Lina I. Brand-Correa, and Lukas Hardt. Nature Energy, Volume 4, pages 612–621 (2019).

Electrify buildings — save 6–9%

Electrifying the heat used in homes and offices is another huge opportunity for savings in the new energy economy. For low–temperature heat (i.e. thermal energy that is hotter than human skin but cooler than boiling water), we have an astounding and well–developed technology called heat pumps that significantly outperform the old ways of doing things.

Today heat and hot water for homes and offices is usually created by burning natural gas or fuel oil, or by running electricity through a resistive heating element. Heat pumps work on a different principle, using electricity to move and concentrate thermal energy from an abundant source (e.g., the air or earth outside) into household appliances and HVAC equipment. This difference allows them to operate more efficiently, supplying more than three times as much heating or cooling per unit of energy input as conventional approaches. If deployed at scale in the U.S., these devices would cut another 5–7% of the total energy required.

LED lighting wins us another 1–2%. LED lighting, like electric cars, has matured greatly in quality, performance and availability in the past few years. Lumen–for–lumen, LEDs use one fifth the energy of traditional lighting technologies. What's more, they last for tens of thousands of hours and require much less frequent changing of the bulbs. Integrated controls and occupancy sensors for switching off lights when they aren't needed can extend these savings further. A wholesale commitment to these technologies can save us another 1–2%.

Accounting for fossil fuels we don't burn — save 4–5%

Fossil fuels that get turned into our day–to–day materials currently get counted as 4–5% of our "energy use." Rather than being burned to provide power, they are transformed into familiar products. A common example is black top roads, which are partly made out of bitumen (asphalt), a byproduct of the oil refining process. Bitumen is also a component of 85% of the rooftops (asphalt shingles over plywood) in America. Plastics are made using feedstocks derived from natural gas. Carbon from coal is used to turn soft iron into carbon steel. Most of the carbon from these materials isn't released into the atmosphere as CO_2 so their energy content is not relevant to today's climate conversation. While we should track and count their use, it should be in a resource assessment of material flows, emissions, and sustainability constraints, not in terms of their impact on the energy economy.

With certainty huge energy savings are possible in industry by electrification, but we don't even need to account for those here to see the enormous benefits.

Same comfort, same conveniences, half the energy

When we add up all of those savings, we find we only need 40% of the primary energy we use today.

Well, that is pretty remarkable.

We can cut the problem down by more than half with no efficiency measures other than electrification. No thermostats were turned down, no vehicles were downsized, no homes were shrunk. Not only that, but electrification is a "no–regrets" option — we can also deploy other strategies like behavior change, and the things we typically call efficiency, and see even further gains. That's why electrification is the only real strategy for decarbonization — and why it will release us from a paralysis of "what to do?"

There are too many people who quote too many numbers about the future with too much confidence. Yes, I can state that we probably only need 42% of the primary energy we need today, but that is overly granular. The population will grow a little bit. We'll invent some cool new pastimes that use a bit more energy (electric–powered paragliding anyone?) and we should be seeking to elevate everyone's quality of life, which typically requires an increase in energy consumption. It is easiest to just say that we'll only need half the energy we use today if we electrify everything. What a win.

Winning the war against the climate crisis will also mean a cleaner, more positive future. Our houses will be more comfortable when we shift to heat pumps and radiant heating systems that can also store energy. While it may also be desirable to downsize our homes and cars, at least in the U.S. it isn't absolutely necessary. Our cars can be sportier when they are electric.[10] Household air quality will improve, as will our health, since gas stoves raise our risk of asthma and respiratory illnesses. We don't need the ever–impossible switch to mass rail and public transit, nor mandate changing the settings on your thermostat, nor ask all red–meat–loving Americans to turn vegetarian. No one has to wear a Jimmy Carter sweater.[11] And if we sensibly employ biofuels, we don't have to ban flying.

In short, the future will be quite recognizable in terms of the sizes and shapes of the major objects in our lives — cars, homes, offices, furnaces, and refrigerators. They'll just be electric. There is no need to fear this future, and there will be cost savings and health benefits to embracing it — oh, and we'll address climate change appropriately at the same time.

[10] But driving faster is never safer because the kinetic energy goes way up, so our electric cars won't really be faster and safer at the same time!

[11] But if you like cardigans, by all means wear one!

6 Where will we get all that electricity?

- ☛ There are enough renewables to easily meet global energy demands.
- ☛ Solar and wind will be the biggest suppliers.
- ☛ Hydroelectricity is critical, especially as a battery.
- ☛ Biofuels matter, especially for things like air travel, but don't solve every problem.
- ☛ Nuclear is not necessary but is very useful.
- ☛ Our land use patterns are critical if we are to harness enough solar and wind energy.

To electrify everything, we'll need more than three times the amount of electricity that we currently produce. Today, the U.S. grid delivers, on average, 450 GW of electricity. If we electrify nearly everything as we described in the last chapter, we'll need somewhere between 1500 GW and 1800 GW. That's a lot. If we use solar, it's more than we can fit on all of our rooftops, and more than we can erect over our parking spaces (See Figure 6.2). If we added wind turbines in all of the corn fields in America, that would supply about half of what we need.[1]

The good news is that we need have no shortage of energy.

[1] This assumes a power density of wind of 2 W/m^2 based on standard turbine spacing in wind farms (*Sustainable Energy - without the hot air*. David JC MacKay, page 33.), and the total acreage of corn, America's largest crop, of 90 million acres (*Feedgrains Sector at a Glance.* U.S. Department of Agriculture, 2020.). Of course, adding wind turbines and their supporting infrastructure can't be done without taking land from crop production, but this gives a sense of scale.

The amount of solar radiation that makes it through our atmosphere and into our earth systems — 85,000 terawatts (TW)[2] — far surpasses the approximately 19 TW that humanity uses.[3] The U.S. uses approximately 20% of that, 3.5–4 TW of primary energy.

As we can see in Figure 6.1 the sun is the primary source of almost all our renewables — energy that can be replenished. The major player is **solar**, abundant wherever the sun shines. The sun heats the air and creates **wind** that can be harnessed with turbines. The winds whip up **waves** that can be captured by wave power generators. The sun evaporates water, which becomes clouds and rain, filling rivers that can be tapped for **hydroelectricity**. As your feet know when walking on hot sand on a summer beach, the sun also heats the ground. This "ground–sourced" **geothermal heat**[4] can be harvested year–round by a technology called "heat pumps" to keep buildings at an even temperature. The sun is also critical to photosynthesis, which creates biomass (wood, algae, grasses, forestry and agricultural waste, food waste, human waste, and other biological matter) which can be converted to **biofuels** to supply energy to hard–to–decarbonize sectors like long–haul aviation. (In fact, all of our **fossil fuels** are just very old biofuels that have been buried and concentrated over time.)

Which energy sources will we use?

Given our needs, we'll have to make electricity wherever we can — understanding that some sources are easier, cheaper, and more convenient than others. Some places have better wind, some have better solar, and some don't have enough of either

[2] A terrawatt (TW) is a trillion watts, or about the same power as ten billion incandescent lightbulbs.

[3] The PFU database of Grubler and his colleagues is a fabulous resource for global numbers. `tntcat.iiasa.ac.at/PFUDB`

[4] Confusingly, this kind of geothermal energy differs from what people commonly think of, which is a closer relative of geysers and volcanoes and hot springs, and similarly rare. Geothermal energy is not derived from solar, but is actually remnant heat left over from the formation of the earth, with a little heat generated from radioactive decay thrown in for good measure. This creates extremely hot rock, which is accessible by drilling, and can be used to create steam, driving a turbine to create electricity. Fracking technology can be appropriated to access more of this resource (in fact the U.S. possesses an amazing amount at the 5-10km depth), but this technology is still far from being proven cost effective.

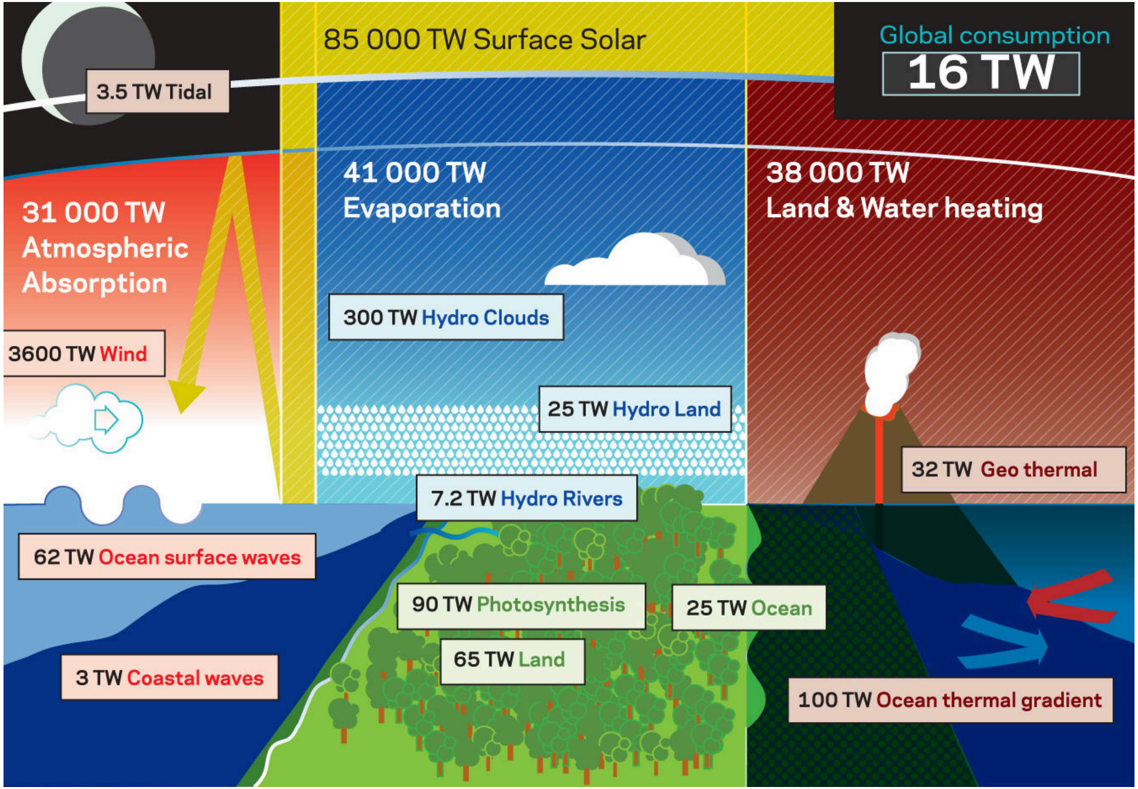

Figure 6.1: *Our adoption rates will determine our outcome.*

and will need some nuclear. Where there are rivers, hydroelectricity, which provides nearly 7% of electricity in the U.S. today, will be critical. Where there are oceans, wave and tidal power will help at the margins. Offshore wind is likely to be the big producer from the oceans.

Solar, wind, and nuclear are the resources we have that far exceed our demands. Solar and wind are the cheapest, and have fewer complications than nuclear energy. Some scientists, such as Mark Jacobson at Stanford, argue that an all–renewables strategy can supply our energy needs globally.[5] This bold claim has sparked some controversy (and a lawsuit), but if we allow some nuclear energy and use tricks to smooth out daily and seasonal variations (described in Chapter 7), the claims of Jacobson's critics evaporate. We're blessed with enough zero–carbon energy to meet our needs and even expand our wants — we just have to harness that energy sensibly.

Nuclear energy isn't renewable — there is a finite amount of fissile material in the world (primarily types of plutonium and uranium).[6] Estimates vary between 200 and 1000 years, depending on what portion of the supply it will meet, and whether we stick with light water reactors that don't produce weaponizable by–products, or whether we move to breeder that do. While we could get by without nuclear energy, it is available to us, and useful in places that don't have enough area to support wind and solar infrastructure.

Regardless of the minutiae of exactly how we decarbonize, solar and wind will do the heavy lifting. The no–regrets pathway to quickly transform our fossil fuel–powered world to a world powered mostly by electricity is a combination of a majority of renewables (solar, wind, hydro, geothermal) with moderate nuclear and some biofuels as a backstop.

The exact balance of those things will vary geographically, and can be determined largely by market forces and public opinion about how to use land. The details and balance of power[7] will be determined by how well we use storage to iron out the

[5] *New Mark Z. Jacobson Study Draws A Roadmap To 100% Renewable Energy*, Cleantechnica, 2018.

[6] *How long will the world's uranium supplies last?* Scientific American, 2009.

[7] Energy nerds are always good for an energy pun!

variability of renewables as will be discussed in Chapter 7.

How much land will we need to use?

Our landscapes will necessarily look different when we make this switch to renewable energy. Solar panels and windmills will become pervasive in our cities, suburbs, and rural areas. To power all of America on solar, for example, would require about 1% of the land area dedicated to solar collection — about the same area we currently dedicate to roads or rooftops (See Figure 6.2). Our rooftops, parking spaces, and commercial and industrial buildings can do double duty as solar collectors. Similarly, we can farm wind on the same land we farm crops.

As we've seen, to electrify everything we'll need to generate 1800GW. To generate all of that with solar would take about 15 million acres of solar panels.[8] To harness that with wind energy alone would take around 100 million acres planted with wind turbines.[9]

Some people talk about the size of the solar cell we'll build in the center of the Arizona desert that will power all of America. But that's not actually how this job will get done. The installations will be everywhere, so it is more illustrative to compare the amount of solar and wind we need to other ways humans use land. Because it is a lot of land required, it is worth looking at surfaces and activities that can do two jobs at once.

Let's first look at solar. In Table 6.1 we see the U.S. acreage of rooftops, roads and parking spaces — all places where we could install solar panels.[10] That totals 21 million acres. If we were to use all solar, we would need nearly 15 million acres for panels to produce all our electricity needs – more than two-thirds of all our available roofs, roads, and parking spaces. Clearly, we will need to be putting solar panels wherever we can fit them.[11]

[8] This assumes a real fill fraction of 60%, a capacity factor of 24%, and a cell efficiency of 21%. Thus, to get 1800 GW we need 15 million acres, or roughly a megawatt per acre.

[9] wind math

[10] Obviously, there are details about how to effectively use these land areas for renewable generation, but these are merely meant for comparison. For instance, solar paving of roads gets a lot of attention, but isn't a great idea due to the dirt and abuse of driving cars on top of solar cells. Better to think about lofting panels over roads and filling the medians.

[11] There is a camp of environmentalist that believes we'll power the world with distributed solar, but the

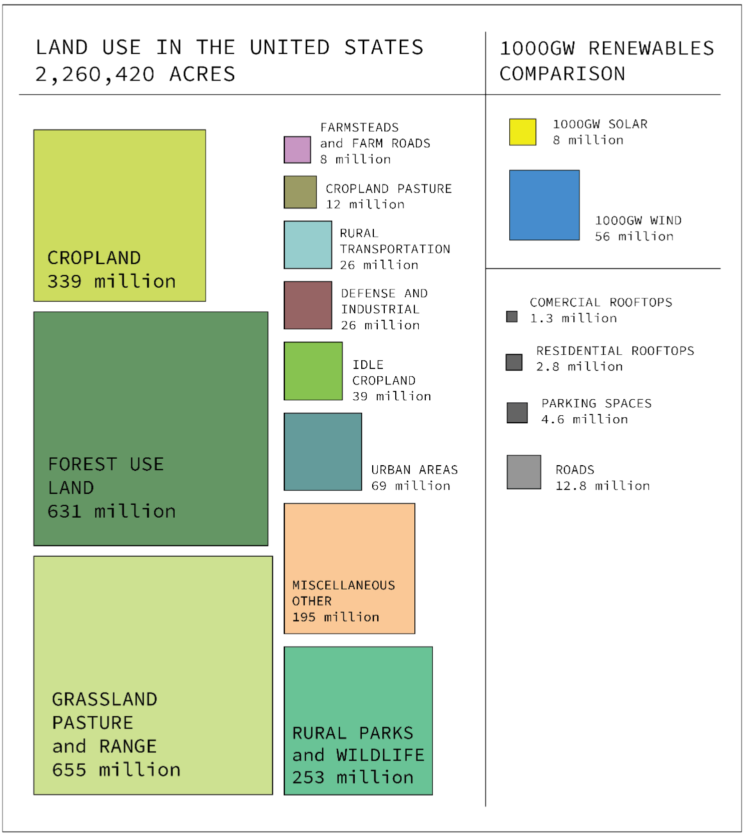

Figure 6.2: *Illustrative areas of the U.S. land use, including reference areas for renewables. Thanks to Kirk Von–Rohr*

Human–Built Thing	Million acres
Commercial Rooftops	1.2
Residential Rooftops	2.8
Roads	12.8
Parking Spaces	4.5

Table 6.1: *Estimates of land area occupied by our 6 million commercial buildings, 120 million homes, 8.8 million lane–miles of roads, and 1 billion(!) parking spaces.*

Human Land Use	Million acres
Cropland used for crops	339
Idle cropland	39
Cropland pasture	12
Grassland pasture and range	655
Forest-use land	631
Rural transportation	26
Rural parks and wildlife	253
Defense and industrial	126
Farmsteads and farm roads	8
Urban areas	69
Miscellaneous other land	195

Table 6.2: *From United States Department of Agriculture, Economic Research Service. Major Land Uses.*

But we also have to recognize that we'll need industrial–scale renewables to complement those we install in our communities.

Fortunately, we can also rely on abundant wind resources in the U.S. Let's take a look at where we can put wind turbines. Again, they can do double duty, harnessing wind on agricultural and rangelands, among others. Let's look in Table 6.2 at our overall land use in the United States, and how it's broken up.

Right away we can see that we have plenty of cropland where we can also put wind turbines. Idle cropland is ideal for turbines

numbers tell a simple story that we'll need all of the distributed energy we can harness AND we'll need industrial installations of solar and wind as well.

(and perhaps for generating income for farmers). We also have massive amounts of grassland pasture and range, where we can place wind turbines. If we set aside land used for urban areas, transportation, defense and industrial, rural parks and wildlife, and forest-use land, we still have about 390 million acres we could use for wind turbines. Some places will be more amenable to wind than others — because of prevailing winds and politics.

There can be no "not in my backyard" with solar and wind energy. Consider that fossil fuels are pervasive and pollute everyone's back yards — in the air, the water, the soil. Over the decades, we have learned to live with a lot of changes in our landscape, from electricity lines and highways to condos and mini-malls. We will also have to live with a lot more solar panels and wind turbines. The trade-offs will be cleaner air everywhere, cheaper energy, and, most importantly, that we will be saving that land and landscape for future generations. We will have to balance land use with energy needs. But we can see that we are blessed with vast land resources in the U.S., enough that a combination of solar and wind will give us plenty of energy to electrify everything.

Nuclear

Nuclear energy can work, but 50 years of debating it have passed and we still haven't agreed on the best way to handle proliferation and waste issues. It's not "too cheap to meter," as was once predicted;[12] in fact, it is likely more expensive than renewables.[13]

Nuclear has been a reliable source of baseload power, though. Baseload is the most reliable resource that you are least likely to lose or turn off. Experts now frequently argue about just how important baseload is[14] (In fact, we will discuss this in detail in Chapter 7). We likely need less baseload power than

[12] *"Too Cheap to Meter": A History of the Phrase*. Thomas Wellock. 2016

[13] The exact costs depend on who you ask. For instance, operating costs of a particular plant can be impressively low. On the other hand, many think the costs should include military and disposal expenses necessary to maintain a safe nuclear fleet, significantly increasing costs. There are many more examples of such conflicts, leaving the true costs a matter of considerable debate.

[14] *Dispelling the nuclear baseload myth: nothing renewables can't do better*, Mark Diesendorf, 2016.

people think, and perhaps none at all, because of 1) the inherent storage capacity of our electric vehicles, 2) the shiftable thermal loads in our homes and buildings, 3) commercial and industrial opportunities to load–shift and store energy, and 4) the potential capacity of back-up biofuels and various batteries.

The approximately 60 nuclear facilities and 100 reactors in the U.S. already provide roughly 20% (about 100GW) of all our delivered electricity (around 450GW.) The problem is that nuclear plants take decades to plan and build. In 2016, Watts Bar unit 2 was connected to the grid.[15] It was the first new reactor in the U.S. since 1996.[16] Only a relative handful of new plants are being planned. Quickly scaling up nuclear power would be difficult.

Another problem is that nuclear power plants use river or ocean water to cool down, which ends up heating the water to levels that are deleterious to the fish and plants. 40% of water in the U.S. passes through the cooling cycles of thermoelectric power plants — this ultimately would limit the amount of nuclear power we could deploy using current technology.

We could build nuclear plants faster. We could make them cost less by changing the regulatory environment.[17] We could develop next–generation technologies. We could use mass production techniques and economies of scale to lower their cost. But that's a lot of what–ifs. It is unlikely that we'll collectively achieve the conviction to build much more nuclear power before the combination of renewables with battery storage proves itself to be far more cost–effective.

Nuclear power is so fraught with problems that Japan shut down its plants. So did Germany. China is also slowing down on nuclear technology. This isn't because nuclear doesn't work (it does) but because the socio–political–ecological–economic question marks that surround nuclear make it a long, hard road. And it's far more costly than solar.[18]

[15] Unit 2 took 43 years from beginning of construction to grid connection (*Watts Bar Nuclear Plant*, Wikipedia.)

[16] *U.S. Nuclear Industry*, U.S. Energy Information Agency.

[17] The interest rate on the money borrowed to build a nuclear plant can amount to a significant cost addition.

[18] The DOE itself has set targets of 5c/kWh for rooftop solar, 4c for commercial solar and 3c/kWh for

Still, it's unlikely we'll eliminate nuclear energy in the U.S. for reasons of national security. Unless we completely disarm, it's unrealistic to imagine the U.S. pulling out of nuclear power altogether. In order to address climate change, we'll likely mildly increase nuclear (fission) power capacity in the U.S., but it probably won't become the dominant energy source for all the reasons we've explained. In other countries with very high population density or a lack of renewable resources, nuclear or imported renewables are the only realistic options.[19]

Yes...and

We'll need a diversity of energy sources, so stop anyone who tries to tell you about *the* answer. We can move past the arguments about how to decarbonize by embracing "Yes, and ... " Yes, and ... if we can make them work at scale, we should use: renewably–generated liquid fuels like ammonia, airborne wind energy, low energy nuclear reactions, cold fusion, and whatever might come from these creative lines of thinking. Yes, and ... if cheaper biofuels, a synthetic fuel, or hydrogen, work out as storage mechanisms, they can come to the party.

"Yes, and ... " allows for technological advances in carbon sequestration or fusion or something even more incredible to emerge — if we invest in the right R&D, and get a little lucky. As we have said, it's too late and too dangerous to rely on miracles. Any precious capital going to these other projects is not going to the zero–carbon solutions that we know work. "Yes, and..." avoids arguments that distract from the main players in decarbonization while allowing that other technologies can all make small, but vital, contributions.

There is no physics that says that we can't do it all with renewables. There are only cynical or specious arguments. The biggest barriers remaining have the same origin: inertia, the stubborn insistence of the incumbent way of doing things. This

utility-scale solar by 2030. DE-FOA-0002064 FY19 SETO FOA Mod 00002

[19] All this probably leaves you wondering where I sit on nuclear. If I were king of the world I would do without it and live more simply. Given that I can't enforce that on my fellow humans, pragmatically I think we'll do some nuclear. I think it would be irresponsible to add a ton more nuclear without a lot more investment in improving the technology and the waste processing and security.

manifests as fossil fuel subsidies and massive misinformation campaigns. It's also buried in old ways of doing things, like the state–sponsored utility monopoly, giving low–interest rates to big projects instead of to consumers who need to swap their gas heaters for solar and heat pumps.

There will be trade–offs. More nuclear means fewer batteries but more public resistance and most likely higher costs. More solar and wind means more land use. What we cannot afford are plans that make no progress because we are wasting time arguing over these issues before we begin, or because we are over–investing in things that can't scale up sufficiently.

The real test should be, "Is it ready today to go to scale?"

We need to act now.

7 24/7/365

- Renewables are intermittent, but complementary to each other.
- Everything that can store energy should store energy.
- Everything that can move its demand to match supply will need to do so.
- In electrifying sectors that were previously not electrified, it becomes easier to balance the grid.
- We'll need to share electricity with our neighbors and borrow it back from our friends.
- We'll need to expand long–distance transmission infrastructure.
- Just as with fossil–fuel infrastructure, there are big cost benefits to over–building capacity.
- We critically need "grid neutrality" to ensure our 21st–century infrastructure works at its best.

We've established how much energy we need, where it can come from, and that it will make us all more comfortable without giving up anything except bad air, corrupt politics, and dirty water tables. As you'll see, if we can finance it appropriately, it will also be far cheaper (Chapter 8) and will provide millions of new jobs (Chapter 10). **So why aren't we already adopting the electrification of everything as fast as we can?**

People who resist decarbonization often have vested interests in continuing to burn fossil fuels. Others just don't like change. These dinosaurs often wrap their opposition to renewables in a critique that they are intermittent, expensive, and unreliable. They say renewables are fatally incompatible with always–on, 24/7/365 electricity. Since renewables have outputs that fluctuate — with day–night cycles, weather patterns, and the seasons — the concern is that supply won't be able to keep up with demand, causing brown— or black-–outs.

It's true that we have come to expect that when we press a button, the car starts, the stove cooks, the lights go on, and when we turn the faucet, the shower is warm. Reliability was built in to the 20th–century grid as part of a grand bargain giving a monopoly to corporate utilities in exchange for their assurances of 24/7/365 reliability and service to the under–served. This deal worked pretty well through the 20th century, but left us with a mixed bag of incentives that are neither motivated to decarbonize nor to innovate rapidly enough to address climate change.[1] Rural electricity co–ops serve another significant portion of U.S. consumers and have their own set of challenges that likewise are slowing our progress towards the better world our children deserve.

This field manual is about outlining the pathway to "yes" so we can all go fight for it, and in enough detail to quiet the plethora of naysayers. So let's look at the tricks we have to make the grid we need work 24/7/365. This is the hardest problem remaining in decarbonization. It's not go–to–the–moon hard, it's organize–billions–of–things–to–work–together hard.

We earlier found out we are going to need 1500–1800GW of electricity to power America carbon–free, and that we *can* get the majority of it from renewables. It is worth reminding yourself that this means generating and delivering 3–4 times as much electricity as we currently do. This is not a tune–up of the old grid, this is a demolition and rebuilding with new 21st–century rules and Internet–like technology.

The challenges begin at home. Our needs for energy throughout the day vary. Most homes require more energy in the morn-

[1] See for example https://appvoices.org/2018/10/17/the-problem-with-monopoly-utilities/

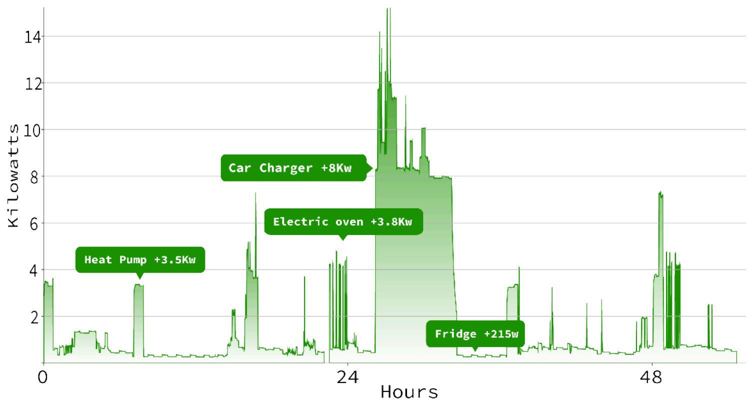

Figure 7.1: *A trace of the energy demand of a single electrified house, where the intermittent operation of appliances cause large spikes.*

ing (for showers, laundry, breakfast) and even more in the evening (for lights, heating/cooling, food prep, dish washing, and entertainment). Demand drops during the day when people are out — though it rises in offices and industry.

When we leave our homes for the day, many of us go to our jobs, in industry or commerce, and consequently we take our loads with us. We turn the lights off in our homes but turn on the computers and cash registers and production lines. Taking advantage of this can further balance our loads and match them to renewables.

While we are out of the house a few things still stay on, such as the fridge's compressor, some lights and always–on devices like cable boxes, wireless routers, and clocks and timers. We have a big load lump in the morning, a lull in the middle of the day, and a bigger lump in the evening that falls to a trickle overnight.

A version of the 24–hour load–balancing problem is well illustrated in my own home. I installed a monitoring device to look at all of my electrical loads. My home isn't fully electrified (yet) but the heat is electrified, the stove and oven, and the car. I haven't yet electrified the water heater, and we don't yet have solar on the roof (I am waiting a year or two more until I need to replace my shingles to make it more cost effective). The load data can be seen in Figure 7.1. This illustrates the very real on–the–ground challenge of electrifying everything. The electric car, the heat, the oven, all of these devices are very high instantaneous loads. They also are not applied very intelligently in my current house, and so don't line up with either daytime solar, or with low–cost grid–electricity periods.

Added to hourly variation in demand, there are also daily differences caused by weather fluctuations and larger seasonal variations; we use more heat when it's cold and more air conditioning when it's hot. We drive a little more in the summer, and in the winter we use more electricity because we're indoors more.

Right now, depending on where you live, these various energy demands are powered by some combination of natural gas, electricity, propane, firewood, and oil. Electrifying them all solves the carbon problem, but it does introduce tremendous load variability.

Smoothing out demand minute to minute, hour to hour, day to day, and month to month will require all of the ingenuity we can muster, which fortunately is quite a lot.

We have existing ideas that will solve most of the problem, and we'll also see that our connectivity to each other is critical, as averaging effects, geographical effects, and the ability to lean on each other's generation and storage capacities is the only realistic way to get it to all work out.

Batteries, batteries everywhere, and not a drop of oil to drink

We'll need a lot of storage, mainly in the form of batteries. Everyone knows this, but we need to think bigger about what batteries are.

We will have to create lots of storage for renewable energy. In our fossil–fueled world, we already have vast storage facilities, so it's something we already do at scale. Natural gas is stored in giant underground caverns.[2] The U.S. strategic petroleum

[2] America has around 4 trillion cubic feet of natural gas storage capacity. https://

reserves in Louisiana and Texas contain hundreds of millions of barrels of oil.[3] Most coal plants stockpile enough coal for a month of generation.[4] These energy storage systems are required to balance supply with demand in the face of fluctuations, whether it be a cold snap, a compromised pipeline, or an oil embargo.

The most straightforward approach to supplying reliable electricity is to build storage infrastructure where we can deposit extra electricity when we have it, and withdraw it when we need it.

Chemical batteries, like the cylindrical AA's you immediately imagine when you think of a battery, can store electricity directly, but they are quite expensive. Their costs have been falling quickly, though. Lithium ion battery prices were above $1000/kWh of storage capacity in 2010, fell to $150/kWh in 2019, and are projected to be $75/kWh by 2024.[5] Large-scale deployment of batteries is becoming a realistic possibility. Chemical batteries are best at ironing out the short–term or daily variation in electricity. They're excellent at storage on the order of one hour, one day, or one week, but they won't help us store energy for winter, as they would be prohibitively expensive if we only charged and discharged them once a year.[6]

Given that batteries are currently expensive, and will never be free, we should think about all of the other things in our everyday lives that will have batteries or can be used as batteries. The batteries in electric cars will represent an enormous storage opportunity. If all of our 250 million vehicles were electrified, they would have the capacity of about 20 terawatt-hours (TWh), enough by themselves to balance out the daily fluctuations of

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`energyinfrastructure.org/energy-101/natural-gas-storage` which is roughly a month's supply. The infamous Porter Ranch gas leak in Southern California, from such a storage facility, released more greenhouse gases than the Deepwater Horizon accident, the largest oil spill in history.

[3] That's only about 30 days of U.S. consumption, a testimony to how much oil we use!

[4] Data from *Monthly Energy Review*. U.S. Energy Information Administration, 2020. and *Today in Energy: Coal stockpiles at U.S. coal power plants were at their lowest point in over a decade*. U.S. Energy Information Administration. 2019.

[5] My battery–bullish friends think about this as the energy singularity, the moment when batteries cost less than grid transmission. I'm a tad less bullish — it will change energy economics in a very fundamental way, but we will still need the grid and all of the other tricks in balancing it.

[6] It would take 1000 years to get the benefit of the capital investment!

our new electrified world.[7] Given that our cars like to be out and about, we wouldn't need to use all of their capacity, but the grid will benefit hugely from their contribution.

Besides our car batteries, our 120 million homes and 5 million commercial buildings have an enormous number of hot water heaters, refrigerators, and HVAC systems, all of which can be used to store energy. This type of battery is thermal energy storage, where instead of storing electricity directly, it is converted to heat (or cold) in our refrigerators or HVAC systems. In this future where we'll have excess (solar) energy in the middle of the day, storing that away to keep our refrigerators cold, and homes warm overnight is critical. People already run water heaters when electricity is cheap and store the hot water for later use.

We need to find and use as many of these opportunities as possible. For instance, an inexpensive thermal storage system the size of your clothes washer and dryer could store an additional 25kWh per household — about another 3 TWh of electricity across the U.S. There are already companies that sell ice–storage systems for air–conditioning. Freeze the water when energy is cheap, and use that coldness at the hotter times of day when electricity is more expensive.

We have other types of batteries. Pumped hydro is a form of mechanical battery. These systems use electricity to pump water uphill when the wind is blowing or the sun is shining, then let it run through a turbine to generate electricity on the way back down when the sun is down and the wind is still. Pumped hydro is cheap, and can work with our existing hydroelectric infrastructure. Right now, 95% of our grid–connected battery capacity is pumped hydro. It is good for short and mid–duration storage, but falls short on seasonal storage. There are other mechanisms that can store energy: flywheels, compressed air, and hydrogen. For a multitude of reasons they are highly unlikely to be the major players in grid–scale storage, so we'll talk about them later, in Chapter 11.

Using bio–fuels to bridge seasonal gaps can also be signifi-

[7] Assume each battery is 80kWh, enough for around 2-300 miles range, 250 million of them is 20TWh

cant. Take wood, the best–known biofuel. We used to measure energy in cords, a 4ftx4ftx8ft pile of lumber. Common wisdom holds that a house needs three cords of wood for the winter with a good wood–burning stove. With minimal management the average acre can sustainably produce one cord per year, with some effort, 1.5. There'd be no winter storage problem at all if we had 5–6 acres of forest each (but there might be an air quality problem). As my dear old friend David Mackay said: "For forest–dwellers, there's wood. For everyone else, there's heat pumps."[8] I'm not proposing going back to firewood,[9] but our waste streams from agriculture, sewage, food waste, and forestry waste could be a battery that easily bridges the summer–winter divide if we were to store it for that occasion. It is a resource equivalent to about 10% of our current energy supply. Just how much bio–fuels become part of our seasonal battery will come down to details of technology, economics, and policies.

Using all of our varieties of batteries, on the grid and behind the meter, is what is necessary to make 24/7/365 a reality.

Still, contemporary lithium batteries only last around 1000 cycles. They can be pushed a little further, but even then, the cost is still high, about 10-25¢/kWh for *each storage cycle*. It's important that we double or triple battery cycle life. This will happen and make the storage cost for each cycle mere pennies.

The energy game will change forever when the combined cost of rooftop solar and battery storage can beat the cost of the current grid.[10] In some markets this moment is already here, or very near. Remember that the average U.S. cost of grid–based electricity is 13.8¢/kWh. If rooftop solar achieves the price point it has in Australia, (6-7¢/kWh) and if batteries achieve a price point of around the same 6-7¢/kWh per storage cycle, then we will have arrived at that moment when our battery storage can beat the grid on cost, and in a way that can be built out incre-

[8] David MacKay, *Sustainable Energy Without the Hot Air*, page 153.

[9] Though that can be a carbon neutral form of winter heat if done correctly, though probably not at national scale!

[10] My battery–bullish friends think about this as the energy singularity, the moment when batteries cost less than grid transmission. I'm a tad less bullish — it will change energy economics in a very fundamental way, but we will still need the grid and all of the other tricks in balancing it.

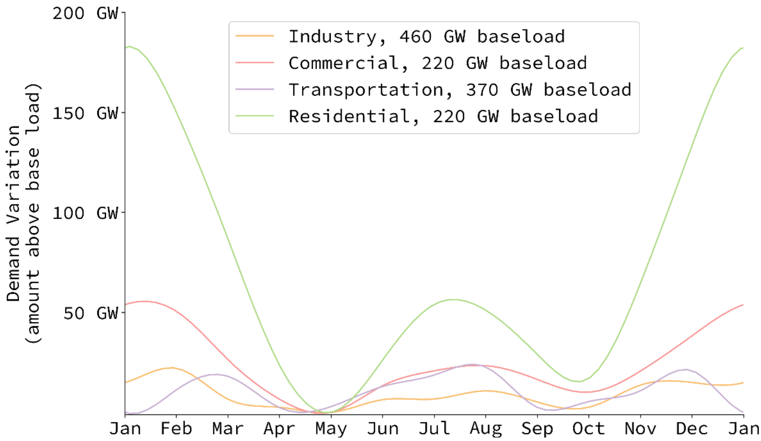

Figure 7.2: *Seasonal load fluctuations. In residential and commercial buildings we see extra heat in the winter and air conditioning in the summer. We drive a little more in the summers. Industry is consistently using energy all year round trying to maximize its use of capital plant*

mentally without massive investments. If we halve the capital cost of batteries one more time, and double the cycle life, we will be in that future. It is only a matter of time. If we move faster in this direction, we will bring the future forward and have a better climate outcome.

Storage is not the only pathway to matching supply and demand, and not enough by itself. Two other techniques are demand–response, and over–capacity, and both will likely be cheaper again.

More electrification begets more electrification

In the same way the Internet gets better with more users, balancing the grid gets easier the more things we electrify. When we electrify everything, we are electrifying the transportation sector, the commercial sector, and the industrial sector as well as our homes. These sectors are even larger users of energy than our homes, and just as averaging the loads of all of our homes makes it easier to electrify everything, so too does electrifying all sectors, and linking them to our new 21st–century grid.

We can look at each sector individually, and the annual variations in the loads. We show this in Figure 7.2. The swings are particularly wild in the residential and commercial sectors, which is understandable because the variations are mostly the variations in heating loads — heat in the winter and A/C in the summer. We can also see that we drive a little more in the summer (yay roadtrips!) and that industrial loads are basically flat across the year as industrialists like to keep their capital equipment running at full capacity.

We need to contemplate the very important links between energy and culture and society. Because coal plants were difficult to shut down, we let them run all night. We had to make electrical loads after dark to consume that energy.[11] The lights in our homes were not enough. So we reacted to cheap power at night by creating night shifts in heavy industry so that industry could consume that power. In a solar–and wind–powered world we will have the opportunity to rethink some of these decisions (I don't know a lot of people who love working the graveyard shift).

The big loads in industry that can be shifted will help a lot. A huge amount of energy is used in the cold chain. This is the set of refrigerated warehouses, vehicles, and other storage depots that keep our giant food supply cold and fresh. This load is shiftable without compromising any of the food; we just choose when to run the compressors that keep the system cold and manage the temperatures more carefully as though in an icebox. In every sector, everything that can be a battery, everything that can shift a load, should.

Even our steel mills and aluminum smelters will be critical and shiftable large loads that can be moved to match supply. Together, the U.S. steel, paper, chemical, and food/beverage industries consume about 6 billion kWh per day.[12] That is the equivalent of 50kWh per household — a huge home battery. These industries can still produce the same amount of goods in the long–term, but match their major loads to the available

[11] Contemplate how this is partly responsible for what Las Vegas is today!

[12] *Manufacturing Energy Bandwidth Studies.* U.S. Department of Energy, Advanced Manufacturing Office, 2013.

energy supply. When there is ample energy, they can over–produce goods. It is often cheaper to store products than it is to store electricity directly. We already warehouse summer grains so that we can eat bread in the winter. We could expand this seasonality to our durable goods, offering companies cheap electricity so they can make hay when the sun shines.

Demand response: balancing the loads

A typical house currently uses around ∼25kWh of electricity every 24 hours. If you electrified the two cars in the driveway and they drove the approximately 13,000 miles per year of an average car, then their combined constant equivalent load would add an additional ∼20kWh. Electrifying everything currently driven by natural gas — hot water and space heating, cooking — represents a further ∼30kWh load (provided it's done efficiently with heat pumps; otherwise it's closer to ∼80kWh). Electrifying the whole household roughly triples the amount of electricity it requires — and can eliminate all the gasoline and natural gas. While this might initially seem like a problem, adding thermal loads and connecting electric vehicles to the house provides greater opportunity for these machines to take turns sucking up some sunshine. This technique is called "demand response."

Many residential and commercial loads are flexible — for example, swimming pool pumps that don't care what time of day they run. By networking these devices, their demands can be timed to when the supply can accommodate them. Further, by networking across multiple houses we can ensure we don't turn them all on at the same time. The peak loads exerted on the grid can be significantly reduced, increasing reliability and offering savings in transmission and distribution.

Averaging loads over many households smooths out the demand even further. You and I do our laundry at different times, we commute at different times, and we shower at different times. We all cook and eat on slightly different schedules. Adding all these loads up has an averaging effect. There is still an evening peak and an overnight lull, but collectively they are smoother and more manageable than it is for any individual. Smart controls on most of our appliances will allow them to coordinate such that our loads won't collide, our dishes will get done, our homes will be warmed, and we won't even notice it seemlessly happening.

Your wind, our sunshine, your nuclear, our hydro

We'll need lots of long–distance transmission so that your sunrise powers my breakfast and my sunset powers your late night TV.

If I have 10 wind turbines in California, there are days where the wind won't blow, and I don't make much power. If I have 10 in California, 10 in Idaho, 10 in Texas, and 10 in North Carolina, on any given day I have an excellent chance that they collectively are producing power. Similarly, if it is overcast in Virginia the sun is probably still shining in Florida and New Mexico. The bigger the geographic region we connect to the grid, the higher the likelihood that we can produce power *all* of the time. The contiguous states span four time zones, broadening the solar window. East Coast sunshine can help the mid states through the early morning rise in demand. Late afternoon Californian sunshine can power the last demands of the evening peak in Chicago. The evening breezes over the plains can get California through the night and help the East Coast rise.

Long–distance transmission of electricity was necessary in the 20th century because we had a hub and spoke model of electricity. Giant generating plants at centralized locations connected via transmission and distribution lines to our homes. A new grid, with widely–distributed renewables needs this long–distance transmission even more. Keeping some of the 20th–century generation technologies can make things easier. There are currently around 100GW of nuclear electricity feeding the grid. This baseline resource can fill in gaps everywhere. Expanding its capacity could ease supply anxieties everywhere further — but is predicated on transmission that goes further and carries more electricity.

Moving energy in quantity from north to south, from east to west, makes the 24/7/365 problem just that much easier. It gets easier again if we share with our international neighbours. Canadian wind and Mexican sunshine. Just like the Internet, the more connected we are, and the bigger the wires, the better it gets. The grid already has major interconnections that cross time zones and state boundaries. We don't need to imagine new magical technology here, we need to commit further to the things we know how to do already.

Abundance!

Here's a radical idea for you. We have become so intoxicated with efficiency, reductions and scarcity in the conversations about the future of energy that we've forgotten to imagine a world where there isn't scarcity, there is abundance. This abundance is overcapacity, and it's something used in the current energy system; it is going to be one of the cheapest ways to provide safe, clean, reliable energy in our renewable future, too.

Natural gas "peaker plants" in our existing energy system are an example, generating electricity only during peak times. They spin up, for instance, in the late afternoon to meet the demand for the evening peak. They don't operate all day, so in that sense, they are under–utilized. They are an overcapacity. Another (less obvious) instance of overcapacity is the nation's automobile fleet. Suppose we could perfectly utilize all of our cars, all the time. That would mean we would need far fewer cars to meet our needs. But because our needs to move ourselves and our stuff are variable, that perfect utilization is impossible (though ride–sharing services are working towards this). Right now, if we ran all of our car and truck engines at full power at the same time, it would represent something like 40TW of generating capacity. In reality, our cars only use about 1TW of power, on average, so we are something like 40 times overcapacity.

So here's the idea: Given that wind and solar–generated electricity are now the cheapest energy sources, often penciling out at 2-4¢/kWh, instead of fretting the winter minimum, let's just design the system to meet that minimum, and have an oversupply and overcapacity the rest of the year.[13]

[13] We are not the only people thinking about this radical idea: https://www.wartsila.com/energy/

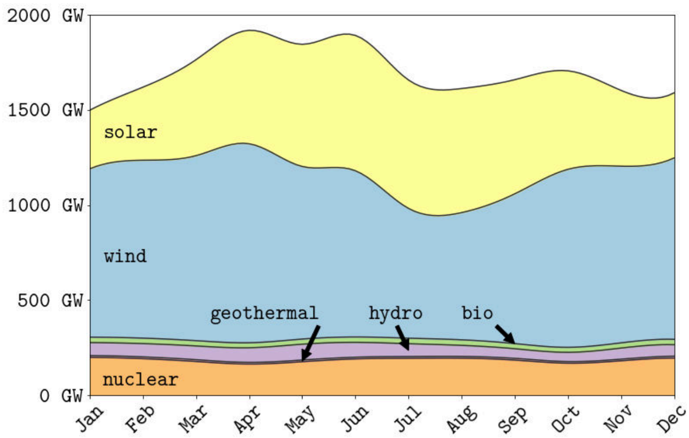

Figure 7.3: *Electricity supply, simple future model*

We crudely modeled the surpluses and shortfalls over the year of an energy system where all sectors are electrified and connected, and the patterns of wind and solar generation we already see on the grid are scaled up — this is plotted in Figure 7.3. To reliably provide enough electricity for all demands, all year long, we'd only need to overbuild our supply capacity by about 20%. At 2-4¢/kWh for grid–scale electricity, that would only increase the cost of our generation capacity by 0.5-1¢/kWh — a much cheaper option than any of the batteries we have discussed above. Given that we know a pathway to 6 or 7¢/kWh electricity on our rooftops, and industrial wind and solar at around 4¢, it doesn't strike me as crazy that we'll add an extra 20% for the peace of mind it will bring.

To make all of these tricks work in concert, which is enough to solve the problem, the critically missing thing is a grid that can tie it all together.

towards-100-renewable-energy/atlas-of-100-percent-renewable-energy/

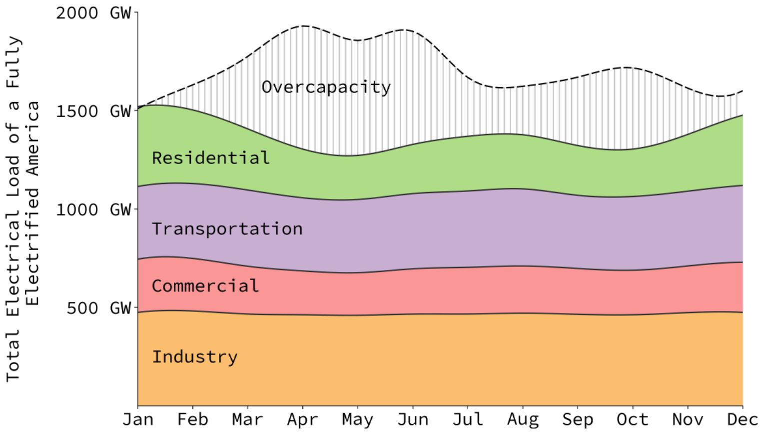

Figure 7.4: *Electricity demand projected into the future for a highly electrified economy. We employ a simple model of the future to predict the year round cumulative loads of an economy with widespread deployment of electric vehicles and electrified heating systems. The big variations seen in individual sectors largely cancel each other making the storage problems less challenging.*

A 21st–century grid

In 1973 and 1974 a small group of researchers working on ARPANET, the precursor to the modern Internet, designed a set of protocols commonly called TCP/IP that determined how information would flow over the network. They invented the unit of information called a packet. The great innovation was a protocol that ensured that all packets on the network were treated equally, no matter what data they contained, where they came from, or where they were headed — now known as "net neutrality." This architecture was explicitly designed to scale and to adapt to changing technology, and it did, growing from a small academic and military network into the modern Internet, which comprises billions of connected devices that send and receive uncountable packets across it.

It should be our goal to enable a similarly decentralized electrical network protocol that allows the rapid movement of "packets" of electricity between billions of connected loads and uses them as needed for storage and balancing.[14] People have implemented such systems on a small scale, often calling them micro–grids, but fully electrifying the U.S.'s energy system will require creating a decentralized network of all the energy supplies and loads in a plethora of overlapping and connected micro–grids.

We could get to a point where we can truly share at scale all of the demand–response possibilities, and all of the storage and battery opportunities in all of our homes and vehicles. Small amounts of storage everywhere add up to the giant battery we need.

Right now, if you have solar panels, you may sell some of your energy back to the grid, but often with caveats such that you can only sell back as much as you use so the accounts balance to zero at the end of the month. We need to make it universally possible for householders to be able to connect as much solar and storage as they like and to be able to offer the vehicles and appliances as part of a nationwide, connected demand response possibility. It needs to be more innovative than time–of–use pricing and more flexible than net–metering. We need a grid that treats everyone connected to it as both a supply and a demand, and as a load–shifter, and as a battery.

Lets start demanding **grid neutrality**. Join the board of your rural co-op. Write your representatives. Get elected to a state utility commission.

[14]The analogy breaks down here as the Internet can be purely digital, whereas managing the flow on the electricity grid isn't about managing discrete packets but rather voltages.

8 How are we going to pay for it?

- The scale of a project to decarbonize the U.S. is sufficient to drop the cost of renewables by half, so that they trounce the cost of fossil fuels.
- With fossil fuels you save now and pay later; with renewables, you pay now and save later (including the planet). If we can loan ourselves the money at the right rate — a "climate loan" — the economics will start saving us money today.
- The 8000–lb carbon gorilla in the room are the proven reserves sitting as assets on the balance sheet of our fossil companies. If we fight them until the end, it will indeed be the end, for both of us. With a mechanism for them to fight alongside us, we both have a chance.

Okay, we have the technology to create a carbon–free future. How are we going to pay to make the switch? It seems sacrilegious to discuss costs when considering the future of our planet, our species, and the majestic and beautiful creatures and plants we share the earth with. It's dismal to have to justify the "economic cost" of doing the things that will make our future better. But we can sharpen our pencils and show you how, in fact, it will save everyone money.

We have the opportunity to solve climate change *and* make energy cheaper in the future.

Electricity is cheap, and getting cheaper

Already, generating clean electricity is extremely cheap, and getting cheaper, and some of it will be cheaper still when it's behind the meter — provided we don't screw up with the wrong rules and regulations, which we will talk about in Chapter 9.

When energy nerds compare the prices of different types of energy, they talk about the levelized cost of energy (LCOE). This is how much a particular technology costs per kilowatt hour (kWh) when all lifetime costs are taken into account (such as building, operating, and decommissioning a plant). The asset management firm Lazard, which tracks LCOE to guide investments, has data showing how much cheaper renewable energy sources are compared to fossil fuels.[1] The latest report places utility–scale solar at ∼3.7 ¢/kWh and wind power at ∼4.1 ¢/kWh. Compare this with natural gas, which clocks in at ∼5.6 and coal at ∼10.9. *The future is here and the cheapest generation sources are renewables*[2].

These impressively—low LCOE numbers refer to utility–scale installations. Oddly though, rooftop solar can be cheaper still because if you're generating electricity yourself you don't have to pay for distribution. We haven't yet realized this potential in the U.S., but Australia has lowered the cost of rooftop generation so much that their "behind the meter" energy — the energy they generate on their own rooftops, without relying on a utility — is cheaper than the cost of distribution alone from a centralized plant. The average cost of distribution in the U.S. is about 8c/kWh — higher than the 6–7c/kWh which is LCOE of rooftop solar in Australia. We can't make all of the energy we'll need in the future this way, but we can make an awful lot.

A friend and fellow Aussie expat, Andrew "Birchy" Birch, wrote an influential piece about replicating the Australian model of rooftop solar in the U.S. He showed how the dominant por-

[1] *Lazard's Levelized Cost of Energy, version 13*, Lazard, November 2019.

[2] Far back in my family tree were people who introduced coking coal to Australia. My first real job was in the Australian steel industry, which depends on coal. I appreciate my ancestors and the marvels coal has given the world, but it is time to stop using it both economically and environmentally. Incidentally, I have ancestors on my other side who helped build all of the light houses in Ireland, another technology that gave us the modern world, but is largely unnecessary now that we have GPS and better maps!

tion of the costs in the U.S. are "soft costs," or those not directly tied to a piece of hardware. These include permitting, inspection, overhead, transaction costs, and sales.

In the U.S., a solar installation happens like a custom home construction project, requiring several layers of design, specification, and oversight for each piece. Each step of the project must be evaluated and approved, a cost is incurred, and over the course of the process, these really add up. Taxes, overhead, and other indirect costs mean that consumers in the U.S. are paying close to or above $3.00 per Watt. I have colleagues — Todd Georgopapadakos, Mark Duda, Eric Wilhelm — who are working on a set of relatively simple technologies that can make this process more like installing a consumer appliance like a water heater or electric dryer. If you can automate many of the inspection and approval steps that currently happen, it drastically lowers the cost.

In Australia, rooftop solar installs at under $1.20 per Watt. In Mexico it is around $1.00, and in Southeast Asia, it is below $1.00. This is proof that the right building codes, training programs, and regulations can get the soft costs down (there are also differences due to relative labor costs in each country).

Renewables are going to get even cheaper again thanks to technology innovations and production scaling.

For instance, a company I co-founded with Leila Madrone in 2011 is working on making solar energy ever cheaper. Sunfolding makes the tracking component of industrial solar systems — the device that makes sure the solar panel follows the sun across the sky to harvest as much energy as possible. We replaced expensive motors and gearboxes with technology about as complicated as an inflatable beach ball, reducing the component and installation costs per watt by a dozen pennies or so. Those pennies matter — and help add up to solar's dramatic cost reductions. In 2020, our technology is now included in projects offering 25–year power purchase agreements (called PPAs in the biz) at just 2¢/kWh!

Wind and solar are getting cheap so quickly that it's even hard for innovators to keep up. In 2006, I started a kite–powered wind energy company called Makani Power. The idea was to produce wind energy at 3–4¢/kWh, cheaper than natural gas and 5–6 times cheaper than other wind–powered electricity at the time. The project was truly awesome, building wings the size of 747s, tethered by a giant cable, that flew in circles at 200mph, undergoing 8 Gs of acceleration while producing megawatts of electricity. With investments from Google the company followed an exciting development trajectory to make our technology a reality, culminating in an offshore deployment and demonstration in Norway in 2019 in partnership with Shell.

In the meantime, however, the wind industry at large also made historic strides, and is now routinely deploying turbines at 4–5¢/kWh. In 2020, Makani shut down due to this evaporated advantage. The technology and execution were sound, but the industry found its own way to slash costs, just by the improvements that come deploying at massive scale. Despite the fact that Makani's technology didn't win the cost battle, it was part of an enormous movement and ecosystem of global innovators responsible for driving down costs and making wind, solar, and batteries competitive with fossil fuels.

Currently, about 250 GW of wind and 125 GW of solar are installed around the world. To reach the fully–electrified version of the world we want, we will need about 10-20 TW of electrical power.[3] That means the cumulative production of solar panels and wind turbines still has to grow ten–fold or more. Many readers will be familiar with Moore's Law — the trend of computer power halving in cost every 18 months. A similar scaling law, Swanson's Law (named for Richard Swanson, the founder of SunPower) states that solar gets 20% cheaper with every doubling of production capacity as we find in Figure 8.1. These technology learning rates translate into real changes. We have to double production quantities a few more times each for wind, solar, and batteries.

As these stories illustrate, the solar and wind industries are improving, getting cheaper and cheaper as innovations overtake the field and as production ramps up.

Pause on that thought for a moment. If we commit to wind

[3] Add a baseline source. The exact number depends on how world population grows, and what quality of life is enjoyed by what percentage of humans.

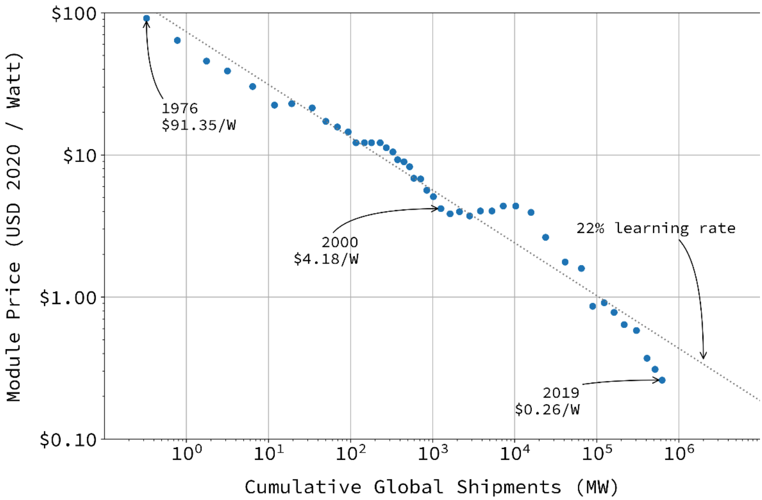

Figure 8.1: *Learning curve of photovoltaic module price. Data from Terawatt-scale photovoltaics: Trajectories and challenges. Haegel et. al., Science, 2017, the IEA Photovoltaic Power Systems Programme (PVPS), and NREL's Solar Photovoltaic System Cost Benchmarks.*

and solar at sufficient scale to address our clean energy needs for climate change, that commitment alone will likely halve the cost of renewables — another nail in the coffin of fossil fuels.

All of this represents a rare opportunity for industry, small and large. We need start–ups to innovate, but we critically need big companies to seize on these innovations and scale them up. Start–ups can't get the job done in time, big business struggles to innovate. We need everyone to work together.

Cheap electricity makes everything else cheaper

When electricity is cheap, that makes a lot of other things in your life and home cheaper, too. For instance, if you drive a 25 mpg gasoline–powered car and gas costs $4/gallon, that's 16¢/mile. A 300 Wh/mile electric vehicle using 6¢/kWh electricity will cost only 2¢/mile.

Despite the cheap (and dirty) "natural" gas that fracking has given us, electricity would be cheaper to heat most of our homes, too.[4] At average U.S. prices, home heating costs \$11.20/MBTU.[5] Using a heat pump with a coefficient of performance (COP) of 3 [6] and 6¢/kWh electricity, that's just \$5.80/MBTU. As natural gas likely won't get any cheaper, this electric advantage is only growing as thermal storage and demand response are used to increase COP. That's not to mention the advantages clean electricity has given the adverse health effects of fracking in our communities and burning methane in our homes.

Let's put this in context and see what these savings mean for an average American household.

Currently, as visualized in Figure 8.2 the average household spends \$2,734 annually on transportation fuels, \$1,572 on electricity, and \$433 on natural gas.[7] For the sake of round numbers, let's call that \$4,700 per year for the energy to run our lives. Now let's see how much we can save by making the switch to zero–carbon infrastructure.

In this thought experiment, we will provide our electricity needs through rooftop solar, our heating needs with heat pumps, and our transportation needs with an electric car. This is as though we use Australian solar policies, German heat pump policies, and Californian EV standards.

Let's start with the capital costs. We'll need about 15kW of solar. Let's assume we catch up to Australia's rate of \$1.20/W to cover the panels and their installation — that's \$18,000. A typical American home might require a heat pump with 2.5 ton capacity. Assuming when you retire your natural gas furnace, you can upgrade to a heat pump with thermal storage for a difference of about \$5,000. To estimate the cost difference of upgrading to electric when we replace our car, we just use the cost

[4] https://rmi.org/insight/the-economics-of-electrifying-buildings/

[5] Million British Thermal Units

[6] A heat pump can move energy from one place to another. How effectively it does this is the ratio of energy used to the amount of heat moved. A heat pump with a COP of 3 is typical for a good heating unit which means that it uses one unit of electricity to move 3 units of heat from outside of your home into your home.

[7] The costs of electricity and natural gas come from the EIA's Residential Energy Consumption Survey (e.g., Table CE2.6). The costs of transportation fuels come from the U.S. Bureau of Economic Analysis, "National Income and Product Accounts", Table 2.5.5. Personal Consumption Expenditures by Function, 2019.

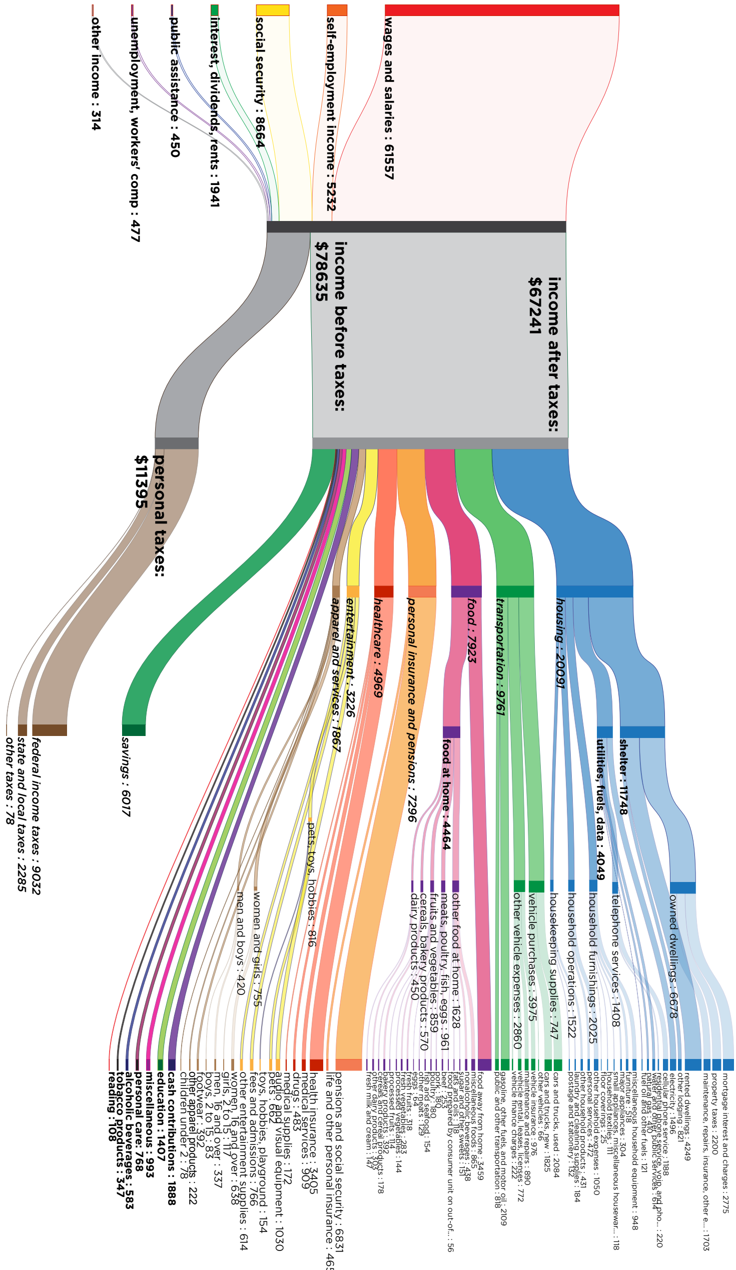

Figure 8.2: *Average spending by category in a US household.*

of the battery (as you are buying the rest of the car anyway). Following the learning curve of lithium–ion batteries, costs will soon be $75/kWh. For a range of 350 miles, we need 100kWh, which will cost $7,500. The average American household has two cars, so that's $15,000. Finally, let's add a $5000, 70kWh home battery to balance the rest of our daily supply and demand.

All told, this is an outlay of ∼$40,000, certainly outside the reach of all but the wealthier Americans. But, if we appropriately finance this capital like a mortgage, say at 3.5% interest over a 20 year term, that's a ∼$232 monthly payment, or about ∼$2800 per year. **Given the current average $4700 per year spent on energy, that's a household discount of ∼$1,900 per year for saving the planet!**

We could thumb wrestle over whether the price assumptions I have used are correct, but that's not what is important here. The interest rate has the exponential effect. Compounding interest gets you in the end.

The three card trick I just pulled is this: (1) I give you a wholesale cost of electricity with Australian rooftop solar, (2) I let you benefit from your wholesale electricity in price arbitrage against retail gasoline and retail natural gas, and (3) I give you the best interest rate in the world — the U.S. home mortgage interest rate.

The household example illustrates what should be a major talking point of every conversation about how to decarbonize: If done right, fixing the climate crisis can save everyone money. If we simply multiply our $1,900 per year savings by the 120 million households in the U.S., we get a savings of $230B per year across the country. **We need to remember the simple mantra: clean electricity is cheaper than fossil equivalents.**

There is a catch to this good news. As we've observed, these clean energy technologies have higher up-front costs and lower ongoing costs, and the challenge is paying for the up-front capital. Climate change doesn't care about your household budget or economic circumstance, and unfortunately this means a disparity between rich and poor in incentives and access. A wealthy household can afford to capture the potential savings from decarbonizing by electrifying everything. They can afford the up–front capital costs of solar and electric vehicles and hydronic heat pump heating systems, because they have access to easy credit and probably can pay for a lot of it in loans against the equity they have in their mortgage already. At the other end of the spectrum, low–income families need the economic savings of decarbonization but can't afford to pay for the up–front technologies. Lower–income families would benefit enormously from the lower household costs of a decarbonized, electrified life. The problem is, they very likely don't have access to the capital to pay for it. **We simply won't solve climate change if we don't figure out how to help everyone afford the future.**

How to pay for clean energy for everyone

During previous emergencies, the first question wasn't, "How can we pay for this?" The first question was, "What do we need to do?" You don't fight a war because you can afford it — you fight a war because you can't afford not to. We can't afford not to fight the war on climate change. We also can't afford not to electrify everything, because if we do it right, it will save us all a huge amount of money.

When people talk about the total cost of solving climate change, it sounds enormous, often in the trillions. This is exactly the wrong way to approach it. We should think about how much money it will *save* us. We must ask ourselves the question, "What market conditions, and at what interest rate, can we make solving climate change save us money?" We must then write the regulations and build the institutions and policies that make that possible.

Up until now, the early markets for clean energy have been developed in places and circumstances where the economic benefits were glaringly obvious. Australia figured out residential rooftop solar because, with low population density, the grid is so spread out that retail grid electricity is expensive, due to distribution costs. South Australia proved out grid–scale batteries because it was cheaper than building out new gas plants. California led the world in electric vehicles because the air pollution

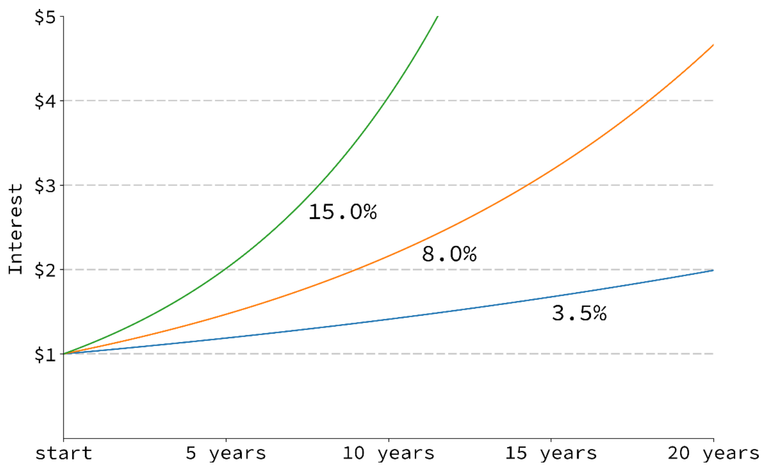

Figure 8.3: *effects of varying interest rates*

in Los Angeles and other urban centers made the need for clean vehicles obvious. In recent years, China scaled this up even further because of even worse air quality issues. Western Europe and Japan mastered heat pumps because of limited domestic natural gas and the need for inexpensive heat.

If we put together a global recipe of the best of all of these measures, and apply massive scales of manufacturing, and eliminate unnecessary regulatory costs, we have a path. But all of these technologies share two things in common: high up-front costs and low operating costs. The goal becomes selecting an interest rate to finance the up–front costs that makes these technologies pay for themselves over time.

Recall that switching to all renewables will cost the average household about $40,000 in the U.S. Very few people have enough cash to pay for a project like that. As illustrated well in Figure 8.3 if we have to pay for it on a credit card, solving climate change will be very expensive — credit card interest rates hover at 15–19%. If we use the common financing options available for solar today, we'll be paying around 8%. If we can pay for it with a government–backed, low–interest rate loan at something like mortgage interest rates of 3.5–4%, it will be affordable for nearly everyone. These may sound like small differences, but consider a solar purchase that is paid for over 20 years. If we could borrow at a mortgage rate of 3.5% we ultimately pay about double the original price. If we borrow at a common rate of 8%, we pay 4.5 times the purchase price. Don't even think of buying it on your credit card.

A mortgage is really a time machine that lets you have the tomorrow you want, today. We want a clean energy future and a livable planet, so let's borrow the money.

The key to rapid decarbonization will be to create the same kind of public–private partnerships and innovative capital financing strategies that have long underpinned America's economic engine: loans. We must invent the "climate loan," a low–interest financing option to help consumers afford the capital investments for 21st–century decarbonized infrastructure. Green banks are emerging to finance utility–scale infrastructure, but we need to be more audacious. Our climate loans need to be available as retail financial products, so we can all afford the personal infrastructure that builds solving climate change into your everyday life.

America's lifestyle has been built on loans; the car loan and mortgage were both 20th–century American innovations. America and indeed the modern world would not be recognizable without these financial instruments that help the bulk of the population afford big–ticket capital items.

Creating a climate loan in response to the climate crisis has clear historical precedent. The modern mortgage market was shaped by the federal government's intervention in another time of crisis: the Great Depression. During the Depression, property values plummeted, and about 10% of all homeowners faced foreclosure. The government stepped in during Roosevelt's New Deal, when Congress passed the Home Owners' Loan Act of 1933,[8] which created the Home Owners Loan Corporation (HOLC) to provide low–interest loans for families at risk of default. As a result, hundreds of thousands of homeowners were able to

[8] Henry Ford wouldn't allow his cars to be purchased on debt because of his religious beliefs. General Motors' Alfred P. Sloan recognized the market opportunity of making cars affordable to the masses by inventing auto-financing. This American financing innovation was the precedent for the modern American home loan.

pay off mortgages, and the program actually turned a slight profit, defying expectations of massive loss of taxpayer money.[9] This program gave rise first to Fannie Mae in 1936, and Freddie Mac in 1968, and created the lowest–cost debt pool and largest capital market the world has ever seen. Significantly, African-Americans were left out of these opportunities, increasing structural inequalities based on racism in the U.S. *Financing our clean energy infrastructure is the opportunity to do this again, and to do it more equitably.*

Under the New Deal, another program offered low–cost federal financing support — for electrification. The Electric Home and Farm Agency (EHFA), originally an offshoot of the Tennessee Valley Authority (TVA), helped provide financing for the purchases of electric appliances — refrigerators, ranges, and hot water heaters. Its focus was rural America (especially the Tennessee Valley), and it was part of an effort to expand the domestic market for electricity consumption.[10] Manufacturers that wanted to participate had to produce standard–issue, low–price appliances subject to EHFA approval. Consumers would then select an EHFA–approved appliance and purchase it on an installment credit contract from the dealer, backed by the U.S. Treasury. The terms were 5–10% down (much lower than any other installment credit offered at the time) and 36–48 month terms at 5% interest. The offer was available only to consumers who got their electricity from companies that charged rates that were acceptable to EHFA. The program ultimately financed some 4.2 million appliances, at a time when there were around 30 million households nationally .[11]

For the purposes of climate stability, and a more robust energy infrastructure, the U.S. government must be just as audacious in financing zero–carbon capital. Tomorrow's infrastructure will necessarily be more personal and distributed, so it's time to help homeowners access the capital they need to contribute to this

[9] *Home owners' loan act (1933).* The Living New Deal.

[10] Another New Deal program, the Rural Electrification Program, helped underwrite the installation of basic electricity circuits throughout rural America. The standard installation was a 60Amp, 230V fuse panel with circuits for the kitchen and lighting, with an outlet and a light in each room.

[11] *The Electric Home and Farm Authority, "Model T Appliances," and the Modernization of the Home Kitchen in the South.* Michelle Mock. The Journal of Southern History. Volume 80, No. 1, February 2014.

national effort while also reaping the long–term savings in their home.

When we electrify everything, everyone will have a personal infrastructure that will not only take energy from the grid, but give some back. Balancing the grid of the future — as we learned in the previous chapter — relies on leaning on our collective batteries and load–shifting opportunities to make it all work at the lowest cost. The grand consumer bargain is that the U.S. government should guarantee your cheap loan for your electric cars, and your electrified home, in exchange for being able to connect it to our collective national infrastructure that will make the loads balance for everyone.

Clearly, developing financing methods and institutions for this type of infrastructure, including bond measures, public–private financing, and regulated utilities, can significantly aid adoption. We need to be there with finance, product, and policy, at every one of Americans' consumer purchasing decisions. We also need financing that works for landlords, and for shared infrastructure for people who don't want to, or can't, own a car or a house. If done right, innovative low–cost financing will be the most effective way to ensure equity and universal access to cheap, reliable energy in the 21st century.

As a result of the COVID pandemic in 2020, interest rates internationally have dropped close to zero. This is a remarkable turn of events, and at exactly the right moment — if we decide to use these historically low interest rates to finance the small number of things and infrastructure that will decarbonize our future lifestyles.

How to pay for the past

We've seen how financing can aid the adoption of zero–carbon energy sources, but we must also think carefully about the economic ramifications of the transition away from fossil fuels.

Digging holes in the ground costs money. Finding the one with oil or gas in it costs more money. Not unlike what we have just suggested for decarbonization technologies, fossil fuel companies spend a lot to find fossil fuels, and only recoup those investments slowly over time. This business model requires borrowing money to dig the holes, and when they borrowed that money, the asset they pledged was the oil coming out of their next well.[12]

In the context of the proposed transformation of our energy infrastructure, lingering debts like these are called stranded assets, and they're a big problem. Stranded assets are resources that once had value but no longer do, usually because of a change in technologies, markets, or social habits.

Currently, it is estimated that the total value of fossil fuels that aren't even dug up yet is tens to a few hundred trillion dollars.[13] Despite the fact that no human has laid eyes on these fossil fuels, they appear as assets on energy companies' ledgers. Climate scientists agree that burning those reserves would compromise the 1.5 degree warming limit — indeed to stay under that target, we must not burn a third of the oil, half of the gas, and 80% of the coal in that asset pool.[14] Because these fuels are already financed, however, they are already traded like any other form of money. People who own those assets are going to struggle against giving them up. If you had $10 trillion dollars in the bank, would you relinquish it without a fight?

We're living in an economic carbon bubble built on these fuel reserves. If we ban oil and gas companies from extracting these assets, their stocks would crash. That would affect tens of millions of individuals who (perhaps unknowingly) hold these and related stocks in mutual funds and pension plans.[15] A 2018 study in *Nature Climate Change* estimated that as much as $4 trillion would be wiped off the global economy by stranding fossil

[12] Though that can be a carbon neutral form of winter heat if done correctly, though probably not at national scale!

[13] (1500GT CO_2 in the ground) × (∼0.4 T CO_2 per barrel) × ($50 per barrel marginal profit) is ∼ 200 trillion dollars. Exactly how many tons of proven reserves are in the ground, and what price we should pay to leave it there is a contentious enough topic that it deserves its own book much longer than this one. Saudi oil can be produced at around $10 a barrel. Most American fields are unprofitable below $30. We chose $50 because it makes the math simple.

[14] *Manufacturing Energy Bandwidth Studies*. U.S. Department of Energy, Advanced Manufacturing Office, 2013.

[15] Imagine that we replace all natural gas and oil heating with electric heat pumps, enjoying the 3X efficiency win of electrification in the process. Further, we replace gasoline-powered vehicles with electric equivalents, enjoying the same efficiency benefits of electrification.

fuel assets.[16] By comparison, a loss of only $250 billion triggered the crash of 2008 (remember "toxic assets"?). Stranding fossil fuel assets would not only affect energy stocks, but investments in other industries and equipment related to fossil fuel, from gas stations to pipelines to oil tankers. Like the 2008 crash, the rippling effects of such an event could be catastrophic.

Clearly we can't just pull the rug out from underneath the industry that gave us modernity. We need a plan.

Could we divest from fossil fuels?

An activist investment movement, promoted by many liberal–leaning universities, and gaining steam, is known as "portfolio divestment." Investment portfolios that join this movement sell off all of their stocks in fossil assets.[17] The idea is that if enough people sell these assets, we'll slowly starve the fossil fuel industry of the precious capital they need to keep digging, drilling, and pumping.

Divestment (also known as disinvestment) can work, and is not without precedent. In the 1980s there was a widespread movement to divest from South African businesses involved in apartheid. In 1986 this divestment campaign was even written into law in the U.S. as the Comprehensive Anti–Apartheid Act. Ronald Reagan tried to veto it, but the Republican–led Senate over–rode him.[18]

Unfortunately, there are still too many buyers who will purchase fossil fuel assets from the groups who are divesting them. Given enough time, divestment may work. In no way do I discourage these efforts, but the urgency and inevitability of climate change demands that we move faster, and with a more

[16] Using data on utility scale solar and wind plants from *Monthly Energy Review.* U.S. Energy Information Administration, 2020., we can extrapolate to construct a hypothetical zero-carbon electricity supply. We include 50 times more solar capacity than we currently have and 30 times more wind. We also double the current nuclear and hydroelectric supplies.

[17] I find the hypocrisy that we want to divest from fossil companies, but we don't divest from automotive companies or appliance companies, frustrating. Given their size, 1-2% of global emissions come out of the tail pipes of products a single company like Toyota or Ford make. Maybe this is because fossil fuel companies kill the minks, whereas automotive companies just wear the coats?

[18] *Sanctions, Disinvestment, and U.S. Corporations in South Africa.* Richard Knight.

guaranteed result. Because divestment is a conflict–based strategy, we'd have to fight every inch of the way, instead of coming up with an amicable solution with wide support.

Stop fighting and start collaborating?

In navigating this precarious scenario, the best strategy may be to treat the owners of these assets, the fossil fuel industry, as friends rather than enemies. After all, they did provide us with reliable vehicles and warm homes for a century. Rather than make deniers and fighters out of these companies, what if we engage them as allies to build the decarbonized future? Today's fossil energy companies are extremely good at financing capital–intensive businesses. They have enormous teams of smart and competent people who are good with shovels and trucks. They speak infrastructure as a native tongue. Those people could be just as happily employed building decarbonization infrastructure. Why don't we thank them for having done an incredible job bringing us the energy we so obviously have enjoyed using? And then invite them to be a driving force in our mobilization of a cleaner world.

The major roadblock is the stranded assets, keeping our friends tied to their old industry. So what if we buy them out? It probably wouldn't even be that expensive. We could negotiate. We don't have to buy them out for the full value of their assets, because they would only make a slim profit margin (around 6.5%[19]) on them anyway. Let's round it up to 10% to be generous: 10% of 200 trillion dollars is 20 trillion. This is a relatively small fraction of the 100 trillion dollar annual global GDP. For that price, we could buy back the land and fossil fuels underneath them (and perhaps make an international collection of national parks for perpetuity?).

As a result, the fossil fuel companies would wind up with a huge amount of clean capital they could invest in the new energy economy and the new infrastructure of the 21st century. Yes, they would be winding down their operations for

[19] *Oil Company Earnings: Reality Over Rhetoric*. Forbes, 2011.

a decade or two, but they would be optimally positioned to capitalize and operationalize the new energy economy, generating jobs and economic opportunity. Their margins would increase, as they build infrastructure spanning supply and demand–side technologies, and they could leverage the initial capital investment to build businesses with valuations far exceeding that of their stranded assets.

Admittedly, this is a bold idea, but consider it a token of the type of thinking we must embrace to solve our climate crisis and its inherent conflicts. Business as usual will not cut it. You may be an economist, activist, or fossil fuel company executive who is fuming at my naïvete right about now, but hopefully it has triggered a better idea that might be the ultimate grand compromise to engage our biggest energy companies in the biggest energy infrastructure build–out ever to occur.

9 Rewrite the rules!

- Fighting climate change involves the long, hard, tedious work of changing thousands of regulations.
- We don't get to zero with efficiency standards alone.
- Australia is proof that rooftop solar would be the cheapest energy if only we got rid of outdated regulations.
- Building and electrical codes need to be updated to support clean energy technology rather than be in conflict.
- We must end all fossil fuel subsidies.
- We desperately need grid neutrality, a collection of protocols and rules of the road for the new grid that encourage businesses and individuals alike to maximize the amount of generation and storage they connect.

It is not obvious, but one front line of the fight for fixing our climate is the collection of hundreds of little regulatory barriers preventing the future we need. It would be awfully satisfying if marching in the streets and buying electric vehicles were all we had to do to arrest climate change in its tracks. But winning the fight for our future isn't about marching on City Hall. It's about walking in to talk to your representatives or, better yet, getting yourself voted in so that we can make local building regulations, state utility regulations, and federal financing regulations align to support a carbon–free future.

I have always believed that rules and regulations should have expiration dates. Most laws shouldn't last longer than 20 years, because given enough time, humans figure out how to corrupt or work around any set of rules or regulations. Nowhere could this be more true than in the burning of fossil fuels.

The old way of doing things is embedded in legislation and dinosaur thinking everywhere: building and electric codes that aren't friendly to solar, home, and vehicle electrification. Similarly, we have backwards–looking utility regulations, road rules, gasoline taxes, homeowner association charters, and tax incentives that all pervert the energy market away from what we need to do. We will solve climate change if we don't let the bureaucratic crud and mental laziness of 100 years of writing regulations for a fossil–fuel–based economy get in the way of a green decarbonized future for our children.

Vehicles

Australia tried to support its domestic car industry by putting high import taxes and higher luxury vehicle taxes on cars from abroad. Rather than elect to innovate, perhaps in electric vehicles, Australia chose to try to protect its fossil–fueled car industry. Today it's still expensive to buy an electric vehicle in Australia because of these taxes — a Tesla is twice the price. Instead of sticking with those regulations, Australia should incentivize its car market to make EVs the cheapest, not the most expensive. This strategy has worked in Norway, where electric cars now make up 60% of new car sales and sale of new fossil–fueled cars is on track to be cut to zero by 2025.[1] Ironically, Australia's policies didn't even save its auto industry; the last Holden Commodore[2] rolled off the assembly line in 2017.

In the U.S., CAFE fuel standards were devised to motivate American automobiles to consistently become more fuel efficient. That's a great idea. But as with any set of rules, over time enough lawyers can be thrown at them to find loopholes and work–arounds. Light trucks were placed in a different cate-

[1] *Norway and the A-ha moment that made electric cars the answer*. The Guardian. April 19, 2020.

[2] a red one

gory, with different fuel standards than vehicles, and because of that, SUV and cross–over vehicles were born, effectively killing off the market for sedans and shorter, more aerodynamic (and hence more efficient) cars. Efficiency standards are a great idea in theory, but they, too, can be bastardized.

Gas taxes were a reasonable idea to help pay for roads. But America kept them too low for too long. They have been held at the same value, in cents per gallon, since 1993, making the tax proportionally lower and lower every year. This results in badly maintained roads — which many of us literally feel every day. It also encourages larger and heavier gas–guzzling cars which sadly deteriorate the roads even faster. One of the reasons Europe and Asia have smaller, more energy–efficient cars is that they have higher gasoline taxes, which increase the cost of driving. Some people wonder what will happen to these tax revenues when we have a majority of electric cars. If we were wise, we would tax vehicles by the mile, and by the ton. Something similar already exists with car insurance that charges by the mile. This should encourage lighter, more efficient vehicles that will be driven less. Car companies would be rewarded for lighter–weight vehicles. We can only hope.

In New Zealand, there's tax to pay when a company gives a car to an employee — it's a reward for employment, so it's taxed. Unfortunately, an exception was made for utility vehicles, under the logic that if it's full of tools, then it's not the vehicle you use to pick up the kids and go shopping. So all company cars are now "utes" (which is kiwi for truck), whether or not the employee actually needs it, thus evading the fringe benefit tax. This loophole only just got repealed, but is typical of the type of perverse incentives we create everywhere that impact our energy ecosystem and carbon output.

Even some well–meaning regulations and incentives need to be scrutinized. The early electric car tax credit of $7,500 was meant to incentivize people to purchase clean air vehicles and build the electric car industry. Because early EVs were expensive, this looked like a subsidy for the rich. As we move forward to our decarbonized world it is worth remembering once again that we don't win unless we all win, and designing regulations and incentives that work for everyone is critical. An awful lot of "incentives" are tax deductions or tax breaks. You need to have a pretty high income before you can take full advantage.

Rooftop solar

As we've seen in the cost difference between rooftop solar in the U.S. and Australia or Mexico, regulations are a serious impediment to widespread rooftop solar installation. Recall that when you buy solar on your rooftop in Australia, it costs $1.20/W, but because of regulations, permitting, inspections, and high sales cost, that price is $3/W in the U.S. The underlying hardware is incredibly cheap, with modules (assemblies of solar cells) selling internationally at 35¢/W (with believable pathways to 25¢/W). Solar energy is not expensive. The regulations surrounding solar make it expensive.

Some of these regulations are so old as to be museum pieces. In San Francisco, you can't put solar modules all the way to the edge of your roof — you have to set them back 4ft. I have been told this is because of the fires that followed the 1906 earthquake in San Francisco, which were more damaging than the earthquake itself. It's incredible to think that at that moment in history, the majority of home lighting came from tiny little fires in your house connected by gas lines.[3] When the earthquake hit, the gas lines leaked, the gas filled the houses and rose to the top because methane is lighter than air. Fires sparked up everywhere. Subsequently, firemen insisted on building codes that allowed them to vent the building by punching a hole in the roof.[4] San Francisco's lots are small, typically 25′ wide and 80′ long. Houses can usually only stretch 45′ into the lot. The roofs are tiny, and if you eliminate 4′ around all the edges, you lose 44% of the area that could be generating cheap solar electricity.

The origin story may not be exact, but the point is valid: we have building codes all over the country that are in conflict with building our best, clean–energy electrical systems. Similarly, our electrical codes, speed limits, fire codes, health and

[3]Gaslighting as a climate change problem has existed for a century!

[4]One of the reasons fireman carry an axe!

safety codes, environmental laws, and pollution standards were all written for our old fossil–fueled world. We have an opportunity to lower the cost of our new electrical world by sending in an army of lawyers and citizens to clean up and rewrite the codes to optimize for a safer and lower–cost energy system.

An example of progressive building regulations that are looking toward this future are the California[5] and San Francisco[6] requirements for the inclusion of solar PV in new construction. Critically, the California building codes consider the impact on housing affordability — ensuring that the requirement actually decreases the cost of home–ownership and passes these savings to the residents. But we only build new homes at the rate of about 1% of U.S. housing a year. Critically we won't solve climate change unless we make the rules and regs and incentives apply to upgrading and retrofitting existing homes.

Another example that gets a lot of press are natural gas connection bans, first on newly-built homes in Berkeley,[7] but now becoming a national movement, including regulations in Massachusetts[8] that also remove natural gas lines when undergoing major renovations.

Fossil fuels

In 1913, the first U.S. oil industry subsidy was written into tax code. Called the Revenue Act, it allowed oil companies to deduct oil in the ground as capital equipment, writing it off as a tax deduction. It began as a 5% per barrel deduction and now stands at 15%, amounting to billions of dollars annually. This is only one of many ways we subsidize the very thing that is threatening our beautiful world.

A bonding requirement is a deposit that the government requires of oil and gas drillers before they can drill. President

[5] *2019 Building Energy Efficiency Standards*. California Energy Commision. 2020.

[6] *Bulletin No. 11: Better Roofs Ordinance.*. San Francisco Planning Department: Bulletins & Policies. 2019.

[7] *Berkeley became first US city to ban natural gas. Here's what that may mean for the future*. Susie Cagle. The Guardian, July 23, 2019.

[8] Full disclosure — my friend Lisa Cunningham is an architect and was instrumental in leading the fight in Massachusetts. See *Prohibition on New Fossil Fuel Infrastructure in Major Construction* and *The Gas Industry's Bid To Kill A Town's Fossil Fuel Ban*. Chris D'Angelo. HuffPost, Dec 16, 2019.

Kennedy set these bonds at $10,000 and they haven't been updated in the 50 years since. The bonds are so low that they encourage irresponsible operations, particularly for fracking, including groundwater contamination.

Must–run contracts are often used by fossil fuel plants to gain monopoly. They argue that they must be allowed to run their coal plants — at the expense of other electricity plants that might be cheaper, like solar. The logic behind this is that otherwise, the coal plants won't be economically viable enough to provide a "reliable grid" when they are needed. Let that be so, let the economics of renewables shut them down. Obviously we are at a threshold where we should provide extra scrutiny over any such contract, as we should any regulation, incentive, tax, subsidy, or rule that advantages fossil fuels.

Electrical codes

National electrical codes are a good idea, and are largely written to ensure safe practices. But once again, they were written for a world gone by and for yesterday's technology, not tomorrow's. They need to be conservative, but we should push to have them embrace the future ever faster. As an example, we currently have codes for the load center — that's the giant breaker box between the grid and your house — that require it to be sized as though every single load in your house were turned on at the same time. If we electrify everything and triple the load in your house, the peak loads are going to be gigantic, and this quickly goes from a cheap and simple box to a heavy, expensive one. Installing solar as a retrofit already requires nearly half of homes to replace their load center. Given that we know how to make switchable circuits, and the fact that we can manage our peak loads with those switches, we could instead write codes that embrace cheaper switching breakers.

Unions are not guiltless in creating impediments to the future. The electrician's union is apparently largely responsible for the requirements of wiring to be housed in hard conduit — those metal tubes that snake around your basement and on the side of your house. New "soft–conduit" options exist and have been deemed safe in many applications and in other countries. We could embrace new technologies and ways of doing things that would lower our energy costs, too. A decarbonized future will need more forward–looking union practices.

Grid neutrality

Fully realizing the savings of electrification requires minimizing the cost of the grid, making how we regulate the grid critical. We've already brought up the idea of grid neutrality, where people could share energy like they do information on the Internet, democratically. This will not only help our problem of intermittency, but reduce the cost.

Net metering,[9] where solar panels and other home renewable energy sources are connected to a public-utility power grid and surplus power is transferred back onto the grid, isn't good enough. Since electricity is generally purchased back at the wholesale rate, rather than the consumer rate, it doesn't encourage you to maximize your own solar capacity or share your storage assets. It's a bit like a tax credit; it's only useful if you pay a lot of tax.

Time–of–use pricing[10] isn't good enough either; it breaks the day into chunks at different prices and then you choose when to use energy. Not everyone has that choice, and the coarseness of the rate schemes limits adoption.

In a grid neutrality system, households and utilities would be treated the same, and be allowed to buy and sell without limit from each other. Only through this arbitrage can we realize the most savings (in both dollars and Watts). It would be like the Internet, where I can give the Internet as much information as I want, take as much information as I want, and even create businesses.

The utilities don't love this idea, especially those that are trying to protect their natural gas business as well. Remember that

[9] Net metering is a mechanism that allows a consumer to sell back excess electricity to the grid. See *Net Metering*, Solar Energy Industries Association.

[10] Time-of-use rates for electricity vary over daily or yearly cycles, charging more during high demand and less during low demand to help balance the grid. See *What are TOU rates?* California Public Utilities Commission.

"we the people" regulate the utilities, so we don't need to fear them. We can control them; we just need to express our collective will. Utilities will say that they are necessary to provide guaranteed access to low–cost energy to the poorest households. I counter that we can lower the cost of energy to those households if we write the rules of the road correctly. We can guarantee access by other means. The utilities wish to maintain the monopoly that we granted them. They should work with us for a climate–friendly future or we should take their monopoly away. Utilities have a fabulous and giant role to play in solving climate change, but it is not in preventing households from generating and sharing electricity for themselves and with each other.

There are thousands of examples of rules and regulations that undermine the climate action we need today. This is the very front line of the fight we have to save the beautiful world that we want and need. There are good groups working on these regulations, either writing new ones or overturning old ones.[11] There's no such thing as too many people working on fixing these impediments to our future. The lawyers and politicians need jobs, too, so let's get them involved in fixing climate change.

[11] A good example is the Environmental Law Institute of Columbia University and Widener Law School, who have published the Legal Pathways to Deep Decarbonization.

10 It's the economy, stupid

- The coronavirus pandemic, and the resulting high unemployment, is an opportunity to rebuild a zero–carbon economy.
- Decarbonizing America on the time frame required to beat a 2–degree target will create tens of millions of jobs.
- The majority of jobs that are created will be distributed throughout the economy, and there will be high–paying jobs in every zip code.

I wish that decarbonizing for the sake of having a better place (planet) to live would be enough incentive to get it done. But people are rightfully cautious about the impacts this decarbonization might have on the economy. A lot of people have portrayed the idea of decarbonizing America's energy system as being bad for economic growth, particularly for people who work in traditional energy industries. Any proposal to transform the world by overhauling the energy sector needs to reassure people that they won't lose their jobs — or even better, that they will get new jobs that pay more and are more satisfying.

So far we have outlined a path that can save everyone money tomorrow, but people need jobs today. As we write this, during the 2020 novel coronavirus pandemic, the unemployment rate is higher than it has been at any time since the Great Depression. There is a solution to this tragic challenge. The good news should be shouted from the rooftops: a rapid transition to a clean energy economy will create millions of better–paying jobs. Probably the only project of sufficient ambition that could put everyone back to work in this terrible employment environment is decarbonizing America's energy system. These jobs will be highly distributed geographically and difficult to offshore.

Why does clean energy create more jobs than fossil fuels?

Simply put, clean energy technologies require more labor in manufacturing, installation and maintenance than fossil fuel technologies. It takes more people to install and keep a wind farm running than it does to drill a well and keep it pumping to produce the same amount of energy over time. Renewables get their fuels for free, whereas fossil fuels cost money. It takes more labor and maintenance to access those free renewable fuels.

What do people do all day?

In order to have a smooth transition to zero–carbon energy, we have to bring along the people who work in the fossil fuel industry. But they aren't as many as you might guess. The Bureau of Labor Statistics (BLS) maintains excellent publicly available data on jobs in their "Current Employment Statistics" monthly reports. We arrange it in Figure 10.1 as a tree map that breaks down the big categories into increasingly small ones — answering the question that Richard Scarry sought to answer in his famous children's book *What Do People Do All Day?*.[1]

What stands out is just how few people are directly employed by the energy industry — about 2.7 million of the 150 million (pre Covid–19) workers in the U.S. The largest number of people employed in fossil fuels are the nearly one million working in gas stations. But we need to remember convenience stores also sell us hot dogs, cigarettes and lottery tickets, so we probably shouldn't completely categorize them as energy industry employees; convenience stores sell 80% of the gas in this country.[2] Next, we can see just how few jobs there are in coal mining

[1] Richard Scarry, *What Do People Do All Day*

[2] https://www.convenience.org/Research/FactSheets

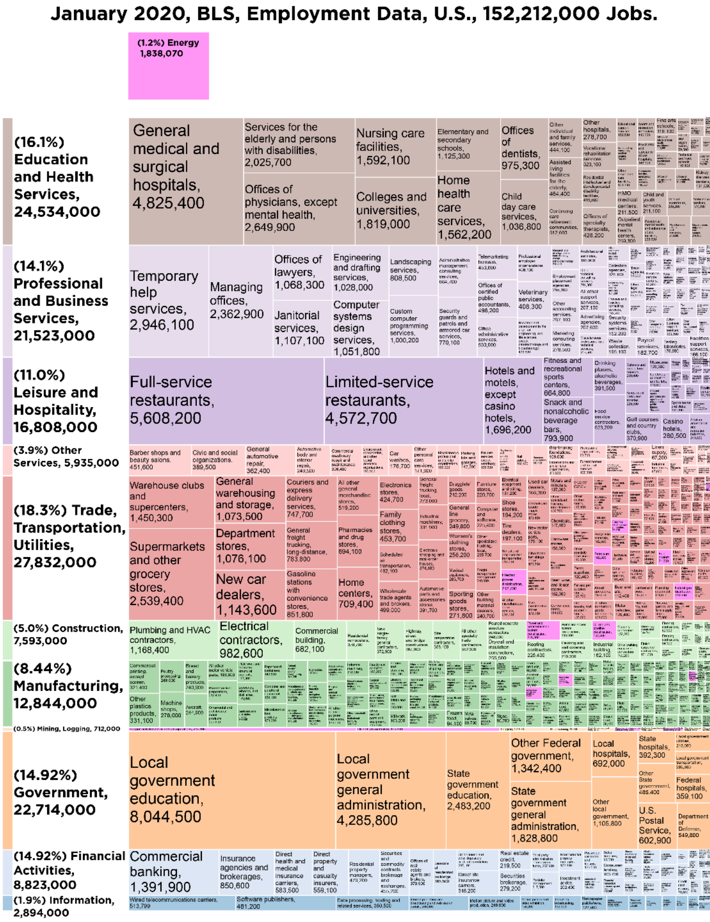

Figure 10.1: *All US jobs, Pre-COVID-19. Data from the Burueau of Labor Statistics' Current Employment Statistics. Get out your glasses!*

— around 50,000 — and compare that, say, to the 450,000 people who work in hair styling and barber shops, the 370,000 who work in golf clubs, or the more than 10,000,000 who work in restaurants. There are more accountants than all the people in the entire "energy industry." It's not a big slice of the economy at all.

How many new jobs will we have in our clean energy world?

There are many ways to calculate the number of new jobs, and while estimates vary widely based on methodology, just about everyone agrees the answer is "a lot." My friend Jonathan Koomey warned me that calculating jobs in the energy sector is a fool's errand. I went on that fool's errand in a white paper, "Mobilizing for a Zero-Carbon America: Jobs, Jobs, and More Jobs."[3] I found a new friend, Skip Laitner, an economist used to such calculations, to help me be a fool.

Our estimate of jobs comes from understanding how much energy we currently use in the U.S., and how much renewable energy we would need to produce to power our lives at the same level of comfort we enjoy today (cars, heaters, push-button conveniences) — all of which we've described in previous chapters. We've used this understanding of our energy needs to build a "machines–up" account of decarbonization, counting each specific piece of equipment required to make the transition: solar panels, heat pumps, electric dryers, and electrifying equipment that can be used for energy storage such as hot water heaters and electric vehicles. Then we figured out how many jobs it will take to create all these new electric things.

Economists estimate job creation by starting with a cost estimate. We use our estimate of the cost of all the machines we need to build to figure out how much money the whol project of decarbonization will cost. Economists then draw from historical data the number of jobs created per million dollars spent, for a variety of industries. These jobs include direct, indirect, and

[3] https://www.rewiringamerica.org/jobs-report

induced jobs.

Direct jobs are jobs that are concretely and specifically in energy. Indirect or supply–chain jobs are the jobs associated with servicing the direct jobs. A direct job might be installing natural gas pipelines or solar panels, and an indirect job related to that is making the steel for the pipes, fiberglass for wind turbines, or the valves and pumps for the pipeline. Induced jobs are the jobs that are created in a community around the direct and indirect jobs — the people employed in the restaurants, schools, local retail stores, and other facilities who support the people in the direct jobs. The woman installing wind farms gets a handsome pay check that she'll spend a good portion of in her local economy employing butchers and bakers and LED makers.

To create our beginning cost estimate we made a list of what we need to build. Remember, we will need something like 1500GW of new (clean) electricity capacity on the supply side. That will mean millions of miles of new and upgraded transmission and distribution to get the electricity to the end user. On the demand side we'll need to electrify our 250 million vehicles, 130 million households, 6 million trucks, all of our manufacturing and industrial processes, and 5.5 million commercial buildings covering 90 billion square feet. From those numbers we can estimate how many batteries, heat pumps, induction stoves, electric cars, water heaters that will need to be manufactured and installed.

We count up how much everything we just described will cost, in comparison to the things they replace. This gives the relative cost of decarbonization vs. business as usual. We divide that amount of money by the ratio of direct jobs per million dollars spent for our zero–carbon economy. Similarly, we can multiply out the number of induced and indirect jobs. For example, $1,000,000[4] spent in construction creates 5.38 direct jobs, 3.87 indirect jobs, and 10.22 induced jobs. That's nearly 20 jobs created per million dollars.

That gives us the gross number of new jobs. Then you have to subtract out jobs that will be lost with the new activity, in-

[4]2017 dollars; economists have to adjust everything for inflation.

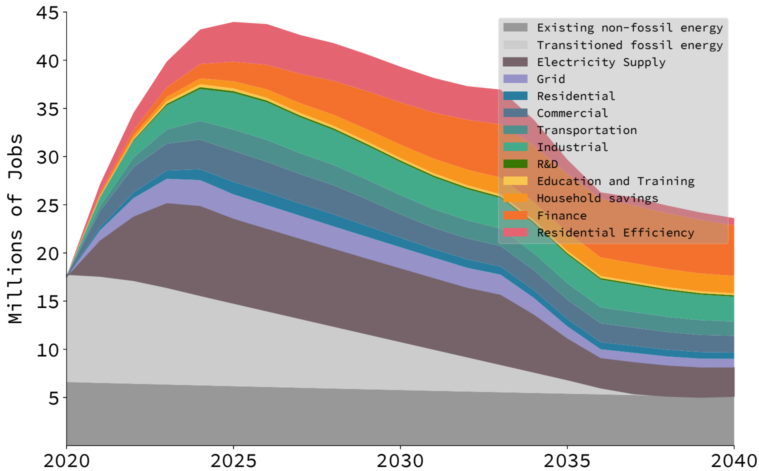

Figure 10.2: *Total jobs in energy through 2040 with a winding down of fossil fuels and decarbonization effort commensurate with a 2° C/3.6° F target. The "efficiency" jobs (pink stripes) are optional, and not necessary for decarbonization and not included in our total job count.*

cluding their indirect and induced jobs. We have to phase out coal mining and find jobs for those 50,000 miners, but we don't phase out the 2,500,000 jobs in the auto industry, as they'll be redirected to electric vehicles and other net–zero carbon vehicle options.

We assume that we will have a massive wartime mobilization period up front (3–5 years) to get our production capacity up to scale, followed by a 10–year period of deployment. This is in line with an emissions trajectory for a better than 2° C/3.6° F world. On the demand side we replace things at the rate implied by the natural lifetime of the incumbent technology. For example, when your water heater kicks the bucket at 11 years, we replace it with one powered by a heat pump. To make the transition to renewables happen will add a lot of jobs in finance, R&D, and training, which we include.

Figure 10.2 summarizes the output of this model. At its peak, the model projects that this rewiring of America will create more

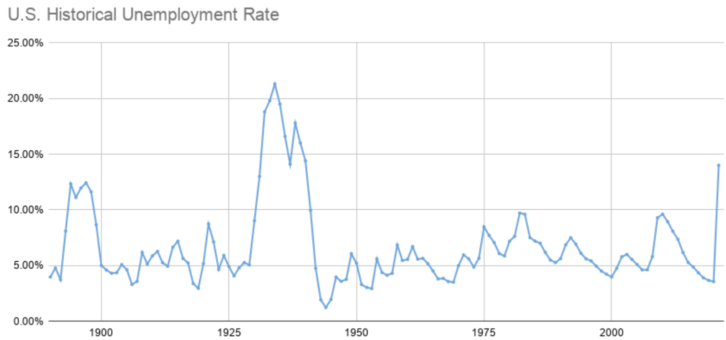

Figure 10.3: *Historical rates of unemployment in the U.S. including the recent Covid–19 spike in unemployment.*

than 25 million new jobs. There are around 12 million jobs currently in the energy industry (including all of the indirect and induced jobs, to be fair to the accounting). You can see over the course of 20 years that the existing fossil jobs transition to new clean energy jobs, and that the end result after the rapid buildup is a sustained 5–6 million job increase over what it is today.

What does history have to say about this?

Creating this many jobs, and doing it in quick order with a massive mobilization is not without precedent. As we've seen, we did something quite similar in WWII. Winning the war for the Allies had a total cost to the economy of around 1.8 1939 Gross Domestic Products (GDPs).[5] Transitioning to a completely decarbonized energy system probably has a cost closer to just one 2019 GDP of $22 trillion — a comparative bargain to save the world.

Last time unemployment was this high, during the Great Depression, we stimulated the economy with the New Deal, which, while it created jobs, wasn't enough. Figure 10.3 shows us that at the height of the Great Depression, U.S. unemployment was

[5] In 1940, the U.S. GDP was $100 billion. Between 1939 and 1945, the US spent $186 billion producing the war materials critical to the success of the Allies.

over 24%. FDR's public works and jobs programs made real progress starting in 1935, but it wasn't until the war that the job situation changed significantly. Once the mobilization of American industry to manufacture war materials for WWII kicked in, unemployment was down to 1.2%. Unemployment was so low that for the first time, women and African–Americans were employed in large numbers in high–paying jobs. The productive capacity we built for that wartime effort created not just jobs then, but for decades afterwards.

We can take a retroactive look at the wartime production known as "the Arsenal of Democracy."[6] Our projections that look enormous are not dissimilar in their effect on the economy as what was seen in WWII. There was a 60-70% expansion of manufacturing employment, a more than doubling of manufacturing output and massive increases in construction and raw materials production required to feed this activity.

WWII production statistics show the economy–wide benefits of such an audacious project: An 18.3% increase in the labor force, a 63% increase in manufacturing employment, a 52% increase in Gross National Product, and a 58% increase in consumer spending. The war analogy is not perfect, but it helps us understand that if we shoot for a victory against climate change with a wartime–style mobilization of our industrial productivity, we stand to benefit enormously economically, and in terms of jobs and consumer well–being.

But wait a second ...

Our numbers are suggestive, not gospel, and almost certainly on the high side. This is so far outside business as usual that it's challenging to arrive at accurate estimates. The historical data of jobs per million people are based on periods where the economy was fairly normal. This would be such an enormous stimulus program as to render a lot of that econometric data "iffy" at best. What you can conclude is that there will be a huge number of jobs — many, many more than we might lose.

[6] *Freedom's Forge*, by Arthur Herman (Random House, 2012) and *Wartime Production Statistics and the Reconversion Outlook*, War Production Board, Oct 9, 1945

The economist's method underscores a sharp conflict in any of these job estimates — you create more jobs by spending more money! This was why the various announcements of the Green New Deals sounded like an ever–increasing race to spend, spend, spend. If you want the biggest headline about jobs, you just spend more money.[7] This is in conflict with making energy cheaper, which should be our other goal. Making energy cheaper means getting efficiencies of scale and lowering the job count required to do every task. Balancing employment and cheap energy is critical.[8]

Another historical perspective can help us with this conflict. In the 1950s and 1960s, America went from a majority 6–day work week to a 5–day work week! The productivity improvements that came from automation after the industrial revolution were sufficient to give us more leisure. I don't know a lot of people who want to give up their 2–day weekends. So for me there isn't a conflict between creating more jobs and creating cheaper energy. Let's just automate the work, and lower the cost of energy as much as we can, and then make every weekend a 3–day long weekend as well! Yay for robots.

Another funny aspect of doing this detailed analysis was underscored by calculating the job situation around LED lighting. LEDs are now so cheap, and last so long, that they save a ton of money. This means that finishing the project of converting much of America's lighting to LEDs will save money, which to the economist, destroys jobs. Think of the headline "LED lighting destroy jobs — it's un–American!" Except of course, we Americans like our energy cheap.

How much?

The Green New Deal announcements came with sticker shock, because these vague plans just had a top line number of "it'll cost 20 trillion." They made it sound like a bad, expensive deal

[7] If you'd like to re-examine your relationship with money and debt, go read David Graeber.

[8] We need to think bigger as a society about this issue. People propose ideas like a universal basic income, but we could just consider something we've done before. In the 1950s we transitioned from a 6–day work week to a 5–day work week. We could do it again, a 4–day work week! — jobs for all and cheap energy *and* long weekends every week.

for America. It probably does cost about that much, but it is spread over 15–20 years, and it is mostly spending we were going to do anyway — everyone is going to buy a new car or two in that 20 years, and appliances, and home retrofits, and all of that spending that was going to happen anyway shouldn't be considered an extra "cost."

And in reality, we will save. If we followed something like the recipe this book outlines that lowers everybody's cost of electricity, and powers their homes and cars, it'll save every family $1500-2000 a year. These savings add up for our 120 million odd households to be a savings of $200–300 billion a year!

The other important point to make is that the government won't bear all of the cost. If the government uses a mechanism like loan guarantees for this infrastructure, the government doesn't outlay cash; rather, it uses its heft and reputation to give everyone the best interest rate possible. Similarly, the government doesn't have to pay the full cost of every item to make them cost–effective — just enough to tip the market in favor of decarbonized solutions with the right subsidies that are a fraction of the cost of the whole item.

For instance, the current renewable tax credit in the US is set at 26%. If, for argument's sake, we apply this as the government's share of all these costs, it would only amount to about $300bN a year project for the 15 years of the mobilization. This is only a third of our current military budget. Not only that but our household and business savings will pretty much cover it.

We need to change the unhealthy narrative that saving the earth is going to cost us money. It won't. If we do it right, we all stand to reap the benefits and save money — and have longer weekends!

Jobs Everywhere

Jobs are a very political topic. A veteran climate political operative[9] I spoke to while looking at all of these numbers said, "One million future jobs don't have nearly the political currency of the dozens of jobs of one small loud interest group or union."

[9] Appropriately jaded and cynical to prove it.

That's probably true. We won't be able to win every heart and mind.

But to reassure those hearts and minds, remember we won't be shuttering plants and closing all the fossil fuel components of the economy immediately. Those jobs will transition out at the replacement rate of the machines that are retiring. It'll mean a slow and steady transition into new clean energy economy jobs over the next 20 years.

One thing that really matters to people is where jobs are. The nice thing about the plan we outline in this book is that a huge portion of the solution is in your driveway, on your roof, in your basement. These are jobs that can't be off–shored, sent to China or Mexico, or even done by robots. These are jobs in every zip code in America, and many are biased suburban and rural. These are also neither boffin[10] jobs in lab coats, nor minimum wage jobs in restaurants. These are skilled blue and white collar jobs, the great majority in the trades — electrical, plumbing, construction — that will pay well and are rightfully the kind of satisfying jobs where people will go to work in (an electric) pickup truck, feel proud of their day's efforts and contributions to their community, and be part of the larger national project they are building towards. A better, rewired, America.

As I'm fond of saying — there will be so many jobs we'll need robots to do them. We need not fear the future if we decide to make it what we want.

The interested reader can look at a more in depth version of this jobs study at https://www.rewiringamerica.org/jobs-report

[10] An endearing Australian term for nerd.

11 Yes, and ...

We wanted people to be able to fly through the main body of this book without getting stuck in the details. Here we try to offer you dinner party–ready talking points for the main questions that people will inevitably throw at the main argument of the book. Each topic is worthy of a book in itself. If we dispose of a favorite technology of yours too quickly here, or you think we have it all ass–backwards, then we should grab a beer sometime.

Yes, and ... what about carbon sequestration?

Carbon sequestration would be great, if it were a good idea. It is attractive because it gives us the illusion we can just keep on burning fossil fuels if we can figure out how to suck the emissions back out of the air.

This idea derives from the natural processes that have kept our planet in balance for millions of years. Trees, plants and microbes evolved to turn atmospheric CO_2 into a useful product — biomass or wood. They do so using cascades of elegant chemical reactions and enzymes. Plants create a huge amount of surface area in their leaves and branches that allows them to do a great job of absorbing CO_2 from the atmosphere.

All of the planet's trees and grasses and other biological machines pull a grand total of about 2GT of carbon a year. To put that in context, our fossil burning is emitting 40GT a year. Imagining that we can build machines that work 20 times better than all of biology is a fantasy created by the fossil fuel industry in order to keep on burning.

When considering carbon sequestration, we should first remind you just how STAGGERING that 40 GT of CO_2 is. If you had a giant set of scales and put all the things humans make or move on one side, and all of the CO_2 we produce on the other, the CO_2 would weigh more. We show this material balance for the united states in Figure 11.1 — our 6000 Million Tons of CO_2 outweighs everything else we move.

The worst version of carbon sequestration is the most seductive one: capturing CO_2 from thin air. This is energetically difficult,[1] because you have to sort through a million molecules to find the 400 that are carbon, then convince those 400 to become something they don't naturally want to be: a liquid, or better yet, a solid. That sorting and conversion costs energy –– a lot of it. Even if we could make it work reasonably, we'd have to install zero–carbon energy to run it, which is like using zero–carbon energy to supply our energy needs anyway, except more complicated and expensive. We should fund the research, but reasonably and with skepticism, and understand that it's a miracle technology that we'd like to have, but don't technically need, and probably can't afford.

The challenge of air capture is illustrated in Figure 11.2. It's quite the treasure hunt looking for CO_2 needles in the atmospheric haystack. You have to look at 2500 molecules before you find 1 CO_2 molecule. For context, it is far easier to find Waldo, who in his various books appears at concentrations of around 1200 to 4500 PPM (or more accurately WPP, Waldos Per Persons)[2]

More seriously, the paper on the topic that I think is the most informative is that by House et al.[3] House and his colleagues analyze carbon capture from chemistry first principles and place a very high bar on anyone claiming to be able to cost–effectively sequester carbon dioxide from ambient air. They project it would likely cost $1000 per ton of CO_2 ; the most optimistic estimate is $300 per ton. Using the likely overly–optimistic number, that would be the equivalent to adding more than a dollar to the cost of a gallong of gasoline, 30¢/kWh to the cost of coal–fired electricity, or 15¢/kwh to the cost of natural gas. We should invest our time and money in things that are going to work instead.

[1] And by difficult we are talking juggling babies, bowling balls, electric chainsaws and flaming tiki torches.

[2] https://slate.com/culture/2017/03/where-s-waldo-didn-t-just-get-harder-to-find-he-got-80-percent-smaller.html

[3] https://doi.org/10.1073/pnas.1012253108

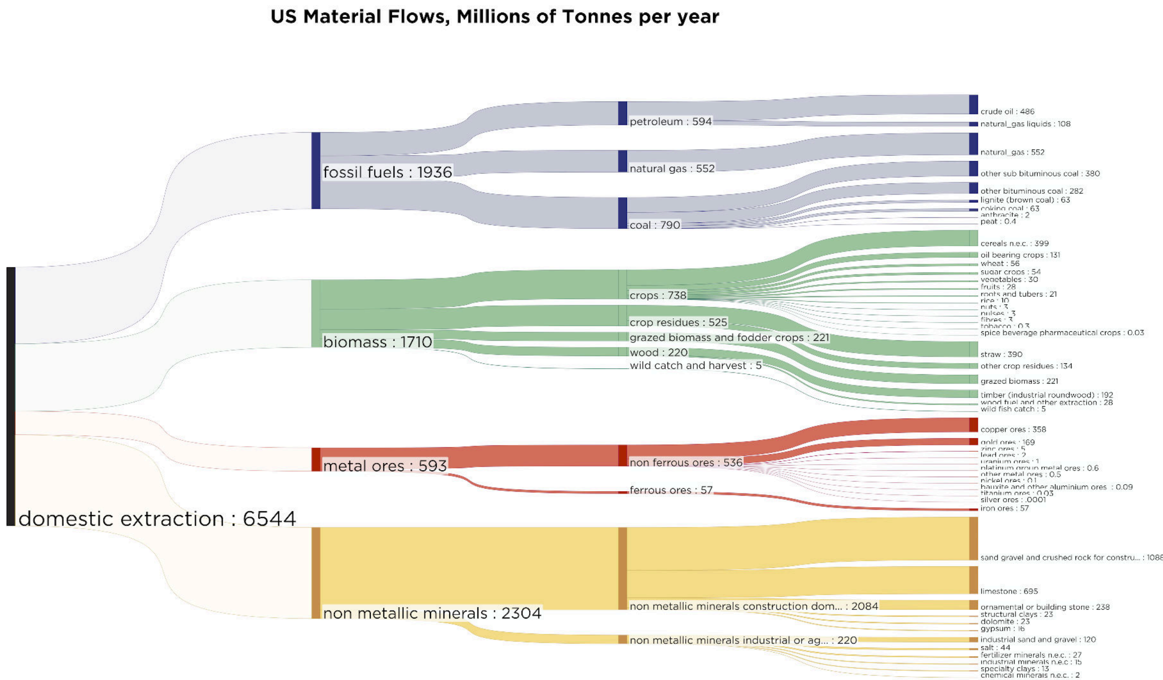

Figure 11.1: *Tons of all U.S. material flows in the U.S. economy.*

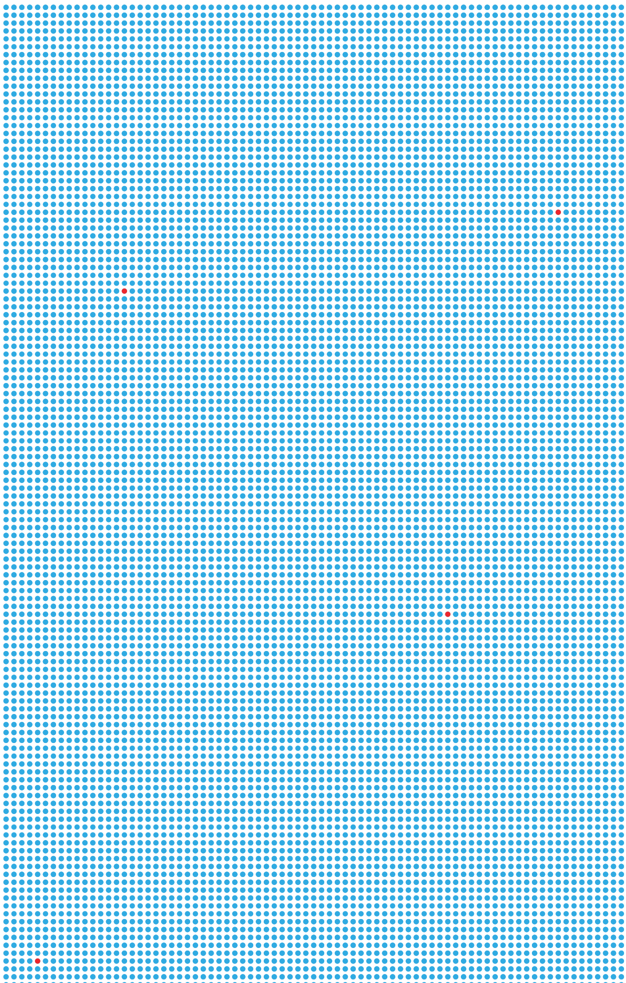

Figure 11.2: *Finding and removing four red dots among 10,000 is the same as the problem of finding the 400 parts per million of* CO_2 *in the atmosphere and turning them into a product that will keep them out of the atmosphere forever.*

A slightly better idea is capturing the highly–concentrated CO_2 gas in a smokestack and somehow burying it. It is a little bit easier than the troubled idea of atmospheric CO_2 separations, because for some fossil fuels you can start with a concentrated flow of CO_2 in the smokestack, instead of a dilute gas we have to filter from the atmosphere.

Sounds promising. But when we burn fossil fuels, we mix them with oxygen (that's what combustion is), and in so doing they become much larger (and also a gas which makes them larger still). The idea behind carbon sequestration of fossil fuels is basically to stuff the carbon back in the hole in the ground from whence it came. But even if you squeeze carbon back down into a liquid, which costs you yet more energy and money, the volume is much larger (around 5X) than the volume that came up. That's because when it came up it was mostly carbon, and when it goes back it is carbon with lots of oxygen. People propose we might put it in other underground reservoirs, or at the bottom of the sea where the pressure of the water could contain it. Spring a leak, and you lose all that hard work.

The economic argument against sequestration is that renewables are already competitive with coal and natural gas in most energy markets, and the added expense of carbon sequestration is not going to help fossil fuels compete. It is not unreasonable to say that the expense of carbon sequestration will be the death knell of fossil fuels.

Even though smokestack sequestration is a bad idea, the fossil fuel industry is happy for you to confuse that bad idea with the worse idea of capturing the more diffuse emissions from the tailpipes of cars, furnaces, or kitchen stoves. Those emissions are extremely distributed — they happen at the furnace and stove–top ends of the 4.4 million miles of the U.S. natural gas pipeline distribution network and our 260 million tailpipes. It is nearly unimaginably difficult to collect the CO_2 from those sources and render it into a form that doesn't end up in the atmosphere.

In addition to the obvious business–as–usual reasons for the fossil industry to champion fossil fuels with carbon sequestration, the self interest goes further. By injecting this CO_2 into the ground they can force more fossil fuels back up; in fact, most of the CO_2 that humans have sequestered so far has been used to help with "enhanced" oil and fossil fuel recovery — perpetuating our reliance on fossil fuel. These are expensive, multi–layered cakes of bad ideas with cynical frosting.

Frack 'em all.

Yes, and ... what about natural gas? (NO!)

Natural gas sounds benign, like the energy version of organic kale, but it's largely methane, mixed with ethane, propane, butanes, and pentanes. When natural gas burns, it emits carbon dioxide, carbon monoxide, and other carbon, nitrogen, and sulfurous compounds into the atmosphere — just like other fossil fuels, contributing to the global greenhouse gas effect and local air pollution. Don't be fooled by those who will profit from confusion, with ideas like natural gas as a bridge fuel. Coal gets more air–time as a dirtier fuel, but natural gas is just as filthy if you account for the fugitive emissions. It is an unsafe, collapsing bridge to nowhere. We burned that bridge... with natural gas.

Yes, and ... what about fracking? (NO!)

Fracking — or hydraulic fracturing — is the process of pumping pressurized liquid into well holes to fracture the surrounding rock, which enables gas and other hydrocarbons to be more readily extracted. This technology, and the accompanying revolution of horizontal drilling, gave us cheap natural gas at just the wrong moment in history.

Fracking spews methane directly from the mining sites, which offsets the nominal win from burning natural gas instead of coal. It also leaks from its network of distribution pipes. There are many other underlying problems with mining natural gas, such as water table pollution and the creation of seismic instabilities. It's a huge distraction from the things that we know to be zero carbon like solar, wind, nuclear, pumped hydro, electric vehicles, and heat pumps.

Yes, and ... what about geoengineering?

We are already geoengineering, we are just doing it badly and heating the earth up and cutting down our planetary lungs. Burning fossil fuels is geoengineering that gives us climate change. The question is, can we geoengineer for good instead?

Geoengineering is not a decarbonization strategy. It is a hope to control the temperature of the earth while giving up on CO_2 strategy. Many of the early arguments for studying geoengineering were that we should know how, just in case the world turns out to be apathetic about climate change. We now know multiple paths to geoengineering climate change: most of them amount to managing the incoming flux of energy from the sun. You have probably heard of these ideas — giant space mirrors, scattering reflective particles in the atmosphere, artificially–generated clouds. In an ecosystem as complex as that of earth, they will all have unintended effects.

Geoengineering would also make us dependent on always needing geoengineering in the future. It's a bit like using liposuction as the solution to obesity when you're just going to keep eating cheeseburgers. Even if it works, and we do it, we can't afford to take the pressure off the better, cleaner solutions proposed in the rest of this book.

The problems of trying to control the climate are many. Who sets the temperature? Low–lying islanders and people who love coral or northern Europeans who might benefit from a slightly warmer climate? We don't really know all of the unintended consequences — environmental, social, or political.

It is a good idea to study geoengineering schemes, and it does help us understand Earth systems better, but this is not a realistic permanent solution. It could draw large amounts of resources away from technologies we already know can solve the problem.

Yes, and ... what about hydrogen?

Many people believe hydrogen is the answer we need for decarbonization. But hydrogen is not a source of energy. You don't discover hydrogen; it is a battery in the form of a gaseous fuel.[4] Only a tiny amount of hydrogen exists naturally as a gas on Earth. To make hydrogen and store it we first have to create electricity to power a chemical process called electrolysis, which is not highly efficient. Then we'd have to capture the hydrogen gas and compress it, which consumes about 10-15% more energy. Then we'd have to decompress the gas and burn it or put it through a fuel cell. More losses.

As a battery, hydrogen is pretty ordinary; for the one unit of electricity you put in at the beginning, you probably only get 50% out at the other side. This is called "round–trip efficiency." To run the world off hydrogen, we'd have to produce twice the amount of electricity, already a monumental challenge. Remember, chemical batteries typically have 95% or so round–trip efficiency.

Germany and Japan[5] invested heavily in **hydrogen** because they don't have domestic natural gas. They want something with the energy density of gasoline.[6] In theory, hydrogen has about three times more energy per pound (lb)[7] than gasoline, but that is when it is a gas. You have to compress it and store it in a tank made of exotic materials.[8] The tank weighs much more than the hydrogen gas itself. If you include the tank in your calculations, hydrogen ends up being about a quarter of the energy density of gasoline and only a little bit higher energy density than batteries. Hydrogen can be the high–temperature gas for industrial processes such as steelmaking and can solve some niche transportation problems. Hydrogen will be useful, but it is not *THE* answer.

[4] The fossil fuel industry is happy to promote the hydrogen fiction as the majority of hydrogen sold today is actually a by–product of the natural gas industry.

[5] And to a lesser extent the US DOE.

[6] 123 MJ/kg as compared to 44

[7] I grew up metric, so it pains me to use all these imperial units, though having lived in the U.S. for 20 years now I have come to believe that they are more romantic

[8] I started a company called Volute that built better CNG and hydrogen tanks and the technology is now licensed into both of those industries, so even as someone who would profit greatly from a hydrogen economy, I'm pretty confident it will only end up being a niche player. We can argue about the size of the niche.

Yes, and ... what about a carbon tax?

A carbon tax isn't a solution. A carbon tax is a market fix meant to motivate all of the other solutions to compete. It's designed to slowly increase the price of carbon dioxide, and slowly make fossil fuels uncompetitive. The idea is that a high enough carbon tax would make all of the fossil fuels more expensive than at least some of the other solutions, and then a perfectly rational market would use those solutions.

Carbon taxes might have been sufficient if we'd started with them in the 1990s, but for the taxes to achieve the 100% adoption rates we need now they would have to ramp up very quickly. They would be difficult to implement, as well as regressive, hitting lower–income people hardest. It is probably just as effective to eliminate fossil fuel subsidies, which in many markets would tip the scales in favor of alternatives anyway. And by the time we have the political will to implement a carbon tax, renewables with batteries will be cheaper than fossil fuels.

A carbon tax is useful in decarbonizing the hard–to–reach end points of the material and industrial economy, but won't be rapid enough to transition home heating to furnaces to heat pumps, and vehicles from internal combustion engines (ICEs) to electric vehicles (EVs) at the rate required.

Yes, and ... what about technological miracles?

"Miracle" technologies include fusion, next–generation nuclear fission, direct solar rectification,[9] airborne wind energy, high–efficiency thermoelectric materials, ultra–high density batteries, and miracles we can't yet imagine. All of these miracle technologies would, in fact, help with various components of decarbonization, and we should invest in them as research topics. With good management, some of them might come to fruition.

[9] Direct solar rectification differs from conventional photovoltaic cells by taking advantage of the wave nature of light (recall from your quantum mechanics class that light can be considered *both* a wave and a particle). Much like the conversion of AC electrical power to DC, optical rectification converts the oscillating electromagnetic fields of light directly into a electrical current. Theoretical maximum efficiencies of this approach far exceed those possible with photovoltaics, but so far the technology has not been practically demonstrated.

However, it would be unwise to bet our future on miracles, as our timeline for climate change solutions is too short. Any ambitious technology like these would take decades to develop. We don't have decades.

The actual miracles are that solar and wind are now the cheapest energy sources, electric cars are better cars than those we already have, electric radiant heating is cozier than our existing heating systems, and the Internet was a practice run and blueprint for the electricity network of the future.

Yes, and ... what about the existing utilities?

There is no way we win this war without the utilities. We need them to deliver 3–4 times the amount of electricity they do today. They are perfectly poised to be a giant participant.

Utilities should be the natural leaders in this project as they already have five valuable characteristics[10]: 100% Market penetration; 100% billing efficacy; 100% knowledge of how we use electricity today (if they want to know it); access to low capital; and an incredible local workforce in every zip code.

Beware the utility that prioritizes its natural gas business over its electricity business. Get yourself on the board of your state's utility commission and steer it in the right direction.

Yes, and ... what about plastics?

We don't talk much in this book about the problem of ocean plastics, and of the larger plastic pollution nightmare. But it is an enormous concern. Perhaps not surprisingly, the fossil fuel industry expanded from the low–margin industry of energy supply into the higher–margin industry of plastics. They have had astounding success with the project, as evidenced by the plastics that pervade our marine environments. We need all combinations of behavior change and new technology here. I have hope for biologically–derived plastics that will biodegrade. This is a critically important problem to solve as the current pathway to making the plastics we use every day produces large

[10]Thanks to Hal Harvey for pointing this out.

quantities of nitrous oxides and other gases even more harmful to our atmosphere than CO_2 .[11]

Yes, and ... what about emissions that are not energy–related?

This book principally concerns itself with the ∼85% of greenhouse gas emissions related to our energy system.[12] They are the overwhelming majority of our emissions. The other emissions come from the agricultural sector, land use and forestry, and from industrial non–energy use emissions. If we undertook the mobilization to address climate change as suggested in this book it would also address much of the industrial non–energy emissions, and a little of the other two as well. Decarbonizing our energy supply is 85% of what we need to do. On the other 15%, people are successfully making and selling synthetic meats, we know pathways to cooling without terrible refrigerant emissions, we have pathways to steel with hydrogen and aluminum without CO_2 . I have to believe if we commit to the 85%, the smart and passionate people working on the other 15% will do their part too, and the temperament of society will have changed for 100% of the challenge.

Yes, and ... what about agriculture?

The moonshot to ignite the heartland's creativity is replacing a harmful monoculture system with an agriculture that sequesters carbon and heals our soils while also preventing the pesticide and fertilizer run-off that is polluting our rivers, estuaries and oceans.[13]

Yes, and ... what about meat?

There are a number of problems with meat, as any vegan will tell you. One is the amount of land required to grow the feed.

[11] *Plastic & Climate: The Hidden Costs of a Plastic Planet.* Center for International Environmental Law. May 2019.

[12] *World Greenhouse Gas Emissions: 2016*. World Resources Institute, 2020.

[13] Our world-class system of land-grant universities should be able to knock this out of the park.

Another is that ruminants (cows, sheep) belch methane, which is far worse as a greenhouse gas than CO_2 . Eating less meat remains one of the easiest consumer decisions to reduce climate impact, but alone it cannot solve our climate problem. On an infrastructure scale, better land management and new low-carbon farming alternatives will lower the impact of eating meat occasionally. My old friend David Mackay used to quip that the best way to harness solar energy in Scotland was to grow and eat sheep. Meat–eating doesn't have to all go away, but it does need to become more conscious.

Yes, and ... what about zero–energy buildings?

Building standards for extremely efficient homes that need no net energy input, such as "passivhaus,[14]" are a good idea. Exactly what constitutes "no net energy input" is up for debate because of the complexities of tracing material and energy flows. And these houses, no matter how they are built, will be rare birds. In the U.S. we only build new housing at the rate of about 1% per year. Remember also, only about 2% of houses are built with an architect; the majority are built from common plans by a contractor. I think of passivhaus and other similar architectural plans as a wonderful library of very good ideas for building efficient houses, and even some retrofits, and we all, especially architects and builders, should embrace the ideas and create even more.

An idea with perhaps more potential for impact are the culture shifts required to live in smaller, simpler houses. Mobile homes have gotten a bad cultural rap, but have a smaller carbon footprint than conventional houses, and could offer one of the fastest pathways for adopting modern decarbonized domestic infrastructure.

Yes, and ... what about the rest of the world?

America is only responsible for about 20% of current annual global emissions (though historically, it has produced a larger

[14] An idea of European origin of houses that are so efficient they require no external energy inputs.

share). People say this is why our efforts to decarbonize aren't worth bothering. China will emit more, or the Saudis, or India, or Africa. If we all adopt that attitude we are done. If America leads, however, it is likely that most will follow once they see the economic advantages. The early movers will own the lions' share of these critical 21st–century industries.

Yes, and ... what about rare earth metals?

Many renewable technologies rely on rare earth metals such as neodymium, scandium, and ytterbium for critical components. The rare earth metals used in high energy magnets and electronics are actually not as rare as their name implies. Their costs pose some challenges to critical components like electric motors and batteries, and so finding ways to decrease the amount needed can reduce the costs of these devices.

Developing robust and efficient recycling pathways for solar cells, batteries, motors, and carbon fiber will offer further opportunities to lower costs of critical components by lowering material costs.

Yes, and ...can we make enough batteries?

No two ways about it, we will need a lot of batteries. This is not impossible, though, given current levels of manufacturing capacity. To replace our 250 million personal gasoline–powered vehicles with EVs in the next 20 years, we will need over a trillion batteries, or around 60 billion 18650[15] batteries every year. That is similar to the 90 billion bullets[16] manufactured by the world today. We need lots of batteries, but it is possible. We need batteries, not bullets.

[15] (18650's are 18 mm in diameter, 65mm long — slightly larger than your flashlight's AA-size)

[16] If you need only one statistic to summarize what is wrong with humanity, it is that we only make about 19 billion LEGO bricks every year, yet we make 90 billion bullets — enough to shoot everyone on earth 11 times a year! Imagine the world where we made 90 billion LEGO's, and cut our bullet consumption back to just a few billion.

Yes, and ... what about steel, aluminum, and cement?

Over 10% of global emissions are attributable to the use of steel and cement, so reductions in their use represents an effective way to reduce emissions. Industrial efficiency can chip away at this problem by reducing the amount of raw materials (including aluminum, plastic, and paper) used to make the things we need. This includes lightweighting designs, reducing scrap rates, reclaiming materials, and extending lifetimes.

Making steel without carbon and designing concrete that sequesters carbon are moonshot projects with massive potential impacts. Industrial efficiency could take us further still. If you would like go down a delightfully wonky rabbit hole that will show we can do even better, I recommend the Department of Energy's bandwidth studies.[17] With dedication and innovation, we can make the chemicals, forestry products (such as paper and cardboard), iron and steel, and processed food — all with much less energy, and no net carbon. We can extract even more use out of these materials by using them to lock up sequestered carbon, which is a more reliable method than injecting it back underground.

The Romans and the Greeks figured out how to make concrete that got stronger over time and absorbed CO_2 . We just need to do that again.

Yes, and ... what about flying?

Flying is energy–intensive per minute but not per mile. Normalized per passenger–mile traveled, it is approximately the same as driving in a car with a passenger.[18] That said, reducing the number of flights taken is one of the most effective ways for individuals to reduce their energy footprints.

In the electrified future, short–haul flights (<500 miles) will be electric, enabled by increases in the power density of motors

[17] *Energy Analysis, Data and Reports.* U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy.

[18] See Chapter 5 in *Sustainable Energy Without the Hot Air*, David Mackay.

and batteries. Long–haul flights will use biofuels to get enough range. Passenger and freight flights in the U.S. require a total of 2 quads, and military aviation is another 0.5 quads. The U.S. can produce about 10 quads of biofuel energy, easily covering the tab for flying, in addition to other hard–to–electrify things like construction and mining equipment (another 1-2 quads).

I have several friends who have electric aircraft companies; they are very bullish on flying cars. I have another colleague who accurately states that at about 80mph it starts to take more energy to keep the car on the ground than just flying it — keeping the car's tires on the ground costs you a lot in energy! It is even possible to convince yourself that small electric aircraft will have energy efficiencies per passenger mile similar to electric cars. This is true if you fly naked, but not if you pack a lot of luggage. Also, if we could all fly everywhere quickly, we'd do it more, and lose the gains in extra miles traveled. This will remain the domain of billionaires.

Yes, and ... what about autonomous cars?

Like flying cars, autonomous cars have captured the public's imagination (not to mention the self–interested parties trying to profit from them). Supposedly, they will reduce traffic and lower emissions. This is almost certainly not true. When groups of people were given a chauffeur as a stand–in for autonomous vehicles, they drove many more trips, and would occasionally send the "autonomous" car across town to buy them their favorite sandwich.[19] Autonomous cars will almost certainly induce more miles traveled.

In the taxi industry, there is something known as "carriage–miles." This is the ratio of miles driven without a passenger to miles driven with one. For taxis this ratio is about 1.7, meaning the car has to drive 1.7 miles to move a passenger 1 mile. In disrupting the taxi industry, Uber and Lyft were able to get this number down to about 1.4. This is probably a good proxy for

[19] *Projecting travelers into a world of self-driving vehicles: estimating travel behavior implications via a naturalistic experiment.* Mustapha Harb, Yu Xiao, Giovanni Circella, Patricia L. Mokhtarian, Joan L. Walker. Transportation, Springer, vol. 45(6), pages 1671-1685, November 2018.

what will happen with wide deployment of autonomous vehicles. Even if we all are driven around to the same places, we'll increase miles driven by 40%. Honestly, this is yet more Silicon Valley snake–oil.

Yes, and ... what about the dangers of nuclear power?

America has led the world on nuclear power. The U.S. Navy operates the largest fleet of small reactors in the world with an impeccable safety record. Nuclear is electrification and fits squarely with the plan to fight global heating, not in opposition to it. Nuclear power currently delivers around 100GW of very reliable electricity to the grid. Keeping this or even increasing it ambitiously would no doubt make the climate solution easier. Today's best estimates have nuclear energy at approximately double the cost of wind and solar. Without doubt those costs could be trimmed enormously given the advances in engineering, since most of these plants were designed 50 years ago.

The health effects of nuclear power have been well studied.[20] It is established that they are not the danger that they loom in our minds. But like shark attacks, it's the prospect of a low–probability event that could release radiation that drives our fears. We can lower the probability further by building dedicated infrastructure like the facility at Yucca Mountain, but we haven't been able to sufficiently convince people of that for 40 years. Nuclear power will remain a very difficult political topic unless we have a breakthrough in waste management.

Yes, and ... what about growing trees?

Yes, we should. At least a trillion. Grab a shovel. As a teenager I helped my mother germinate about 50,000 Australian native trees. I personally planted about 20,000 on a golf course and in a nature reserve. Thirty years later it is enormously rewarding to return home and see 100–ft trees that I put in the ground. The

[20] FAQ-9

best time to plant a tree is 30 years ago. The second best time to plant a tree is today.

Go plant a tree for your grandkids to climb on.

12 What can you do to make a difference?

It's time to get to work. Everyone has a role. Ask not what your planet can do for you but what you can do for your planet.

Your first role is as citizen. Become a political agitator, work on things that make a difference, embrace 21st–century solutions to 21st–century challenges, and only be nostalgic for the things that truly matter. To fix climate change, we need unlikely coalitions. We need to bring everyone to the table — urban and rural, government and business, red and blue, Black, Brown, and White, union and independent, young and old.

If you are eligible to vote, it is time to vote for politicians who take climate seriously. If you do, and they enact a plan as ambitious as the one outlined in this book, there is a glorious future for us all. If you do not, the next hundred years are going to be pretty grim. As the COVID–19 pandemic reminded us, threats that seem remote and distant can erupt far more suddenly than we expect. Just as the prospect of a pandemic seemed like something that *could* happen, but somehow seemed unlikely despite the warnings of experts, a far larger storm is brewing, and it's past time to prepare.

An event like the pandemic may hurt the old economy, but it is a transformative opportunity for a new one. We can maintain this economy that lurches from one predicted but unplanned disaster to the next, only to find ourselves mid–century in an endless string of climate change induced disasters that frankly make COVID–19 look like a picnic. Or we can wake up now and get to work right away building a better future. This project has the capacity to be the base of a new economy that employs more people in better jobs than we have ever achieved before.

If you are not old enough to vote, you should vote with your feet and your protesting. The youth climate strike is a fabulous place to start. You might also consider various ways to file lawsuits against the adults and industries that are stealing your future. Get angry, get creative, but remember to have fun and forge great friendships along the way. Chain yourself to a fence. Fall in love with the passionate activist beside you.

If you are a consumer, don't focus so much on your small decisions. While it may be helpful to buy shampoo in a bar to eliminate the plastic, or buy all–natural clothes that can be composted, what matters most are your big purchasing decisions. Your next car must be electric. You need to do everything you can to make your house run on solar power. If you are about to buy a house, consider a smaller one or a mobile home. Whatever you invest in turning your house into a big battery that can give back to the grid will have the most impact on climate change.

If you are a farmer, this is an incredible opportunity to reimagine agriculture. Central to global climate success is the American farmer and their incredibly productive lands. Let's make them generative and let's make them absorb carbon in the soils, not release it.

If you are an engineer, there is a lot of work to do. Get to work hammering out the details of our electrified future. Design the new grid. Make things more reliable and robust. Eke the lowest costs out. Squeeze the last few percentage points of performance.

If you are a lawyer, you should either be filing a suit for the children, or against the fossil fuel interests, or you should be overturning local ordinances and building codes that are impediments to rolling out climate solutions as quickly and cheaply as possible.

If you are a small business owner, differentiate your product by making it cleaner and greener sooner. Make it the product we all want.

If you run a school or community college, we need shop class again, we need trainees in the practical arts. We need to know how to install things, make things, turn screws, tighten bolts, and build the future.

If you are a designer, make electric appliances so beautiful and intuitive that no one would ever buy anything else. Make electric vehicles that redefine transport. Make products that don't need packaging. Make products that want to be heirlooms.

If you are a union representative, don't let a fear of jobs lost stand in the way of the enormous number of jobs to come. Prepare yourself and your union by working with environmental lobbyists for guaranteed job placements, transfer of pay and benefit levels, and retraining programs. Without labor, there will be no transformation.

If you are a teacher or professor, you need to communicate clearly to your students the intergenerational burden that has been placed upon them. You need to teach them about science and justice and inspire them all to be activists. You need to most of all help your charges understand that no one is coming to save us; we must save ourselves.

If you are a poet or an artist, we desperately need love letters to planet Earth. Inspire us with beauty to appreciate the world and each other. Help us ask the right questions.

If you are an investor, invest in companies that are working toward a carbon–free future. Divest from fossil fuels. Be less greedy. Remember that profits mean nothing if the planet is ruined.

If you are an electrician, prepare to be the busiest you have ever been. Train your friends, teach your children.

If you are a roofer, learn to be a solar installer too and prepare for giant demand.

If you are an hourly worker, advocate for the renewable economy, because your wages will go up. Better jobs are coming if we get this right.

If you are in construction or renovation, encourage your clients to shift to building houses that don't pipe in natural gas, and that are solar–powered. Learn to install heat pumps and batteries that make the house run efficiently.

If you are an architect, this is a great time to work on propagating new architectural solutions that maximize a building's potential to be part of the solution. This means rooftops that are flatter and face towards the sun (south in the Northern Hemisphere). This means moving more towards high–efficiency houses, and lighter construction methods and given that buildings use so many materials, finding ways for the materials that comprise the buildings to be net absorbers of CO_2 not net emitters.

If you are an entrepreneur, start the billion dollar clean energy company that addresses 0.5% of our energy economy. We only need 200 of you to succeed.

If you are a doctor or health care professional, you need to speak loudly and clearly about the cost to the medical system of pollution and our fossil fuel lifestyles. Respiratory illness caused by fossil fuel burning kills millions globally. Asthma, bronchitis, and pneumonia are all exacerbated by the particulate matter created by burning dead dinosaurs. Cancers proliferate that were caused by hydrocarbons and dioxins and other chemicals born of the fossil fuel economy. Sedentary, car–based lifestyles lead to obesity and diabetes, heart disease, and other ailments. We have enormously better public health outcomes to be gained by a rapid transition to a clean energy world.

If you are a mechanic, start building electric hot-rods. It's the sheet metal that we fall in love with, not the engine.

If you are a biologist, help make biofuels and biomaterials to power long-distance flights and sectors of the economy that can't run on wind, solar, or nuclear energy.

If you are a tech worker, stop making social media and delivery apps and make software that helps people use less energy, balances the grid, automates the design of solar and wind plants, makes public transit work better, and other useful things to accelerate our transition to renewables.

If you are a social worker, you can be an advocate for helping lower-income people access homes and transportation using clean energy sources.

If you are a city planner, help make our cities and towns more amenable to a zero-carbon future.

If you are a coal miner, thank you for your service, and now you'll have jobs helping to mine materials for batteries and electric motors.

If you are a an oil industry worker, thank you, too, for your service. Now you'll have jobs helping us build the massive infrastructure that is required for zero carbon future.

If you are a politician, you need to listen to people in this order: scientists, children, engineers. Then you need to rise above the din and clear the regulatory paths and financial paths to getting this job done. Work with everyone. Redefine political boundaries, parties, and coalitions.

If you are a local representative, listen to your constituents and find out what their barriers are to buying electric vehicles, installing solar power, purchasing clean energy from their utilities, retrofitting their houses, getting loans to buy decarbonization technologies for their home. Remove all of the barriers by whatever means are necessary.

If you are a mayor, change the local building codes as necessary to promote the fastest, cheapest ways to decarbonize. Install clean energy on local buildings. Create electric vehicle infrastructure everywhere in your town.

If you are a state assemblyperson, it is useful to remember that the states are experiments. No one has the perfect answer to decarbonization and we all have things to learn from each other. Get bold, take risks, write the brilliant piece of legislation that speeds up the clean energy transition that can be cut and pasted into other state policies and even federal programs.

If you are a congressperson or senator, stand up to corrupting influences. Remember that you were elected by people, not corporations, and that you were elected to improve our lives for the long term.

If you are a president, lead. With vision. Try some FDR, a dollop of Churchill, a dash of JFK, a pinch of Reagan, a seasoning of Mandela, a splash of Merkel.

If you are a corporate CEO, you should be leading your company with an authentic vision of the future, prepared to fully decarbonize your operations in a decade. You will need to listen to your youngest employees, and the frustrated older ones who have been telling you so for years. Between those groups you probably already have the solutions within your organization. Stop worshipping and juicing the quarterly numbers and build your company for the future.

If you are a billionaire, you might consider buying out a fossil fuel lease or two. Own a piece of history in some remote place. Turn it into a nature reserve. Divest your portfolio of fossils. Invest in start–ups with ambitious solutions, but that can't offer fast, guaranteed returns. Sponsor some activist kids. Lose some money swinging for the fences as though you were 24 years old again. You have nothing to lose other than the planet.

If you are a vegan cyclist, thank you. Live long and prosper.

If you are a singer or songwriter, nothing is more powerful than music to move people. We need anthems for our movement. We need some Neil Young,[1] some Cat Stevens, some Joni Mitchell.

> *Don't it always seem to go*
> *That you don't know what you've got til its gone*
> *They paved paradise*
> *And put up a parking lot...* [2]

In building an abundant and verdant future, there is a job for everyone. Good luck. May the winds be with us.

[1]Neil Young had his vintage Lincoln Continental electrified as demonstration of his commitment to the future.

[2]My children heard me say more than one too many times "Alexa, play Joni Mitchell" as I worked to finish this manuscript.

13 Look for yourself

EIA, MER Monthly Energy Review
https://www.eia.gov/totalenergy/data/monthly/
EIA, by Sector Energy Use
https://www.eia.gov/totalenergy/data/annual/
EIA, MECS, Manufacturing Energy Consumption Survey
https://www.eia.gov/consumption/manufacturing/
EIA, RECS, Residential Energy Consumption Survey
https://www.eia.gov/consumption/residential/about.php
EIA, CBECS, Commercial Business Energy Consumption Survey
https://www.eia.gov/consumption/commercial/about.php
FEMP, Federal Energy Management Program
https://energy.gov/eere/femp/federal-energy-management-program
ORNL, TEDB, Transportation Energy Data Book
http://cta.ornl.gov/data/index.shtml
DOT, ORNL, NHTS, National Household Transit Survey
http://nhts.ornl.gov/
EPA GHG Inventory
https://cfpub.epa.gov/ghgdata/inventoryexplorer/
MATERIALS
http://www.materialflows.net/visualisation-centre/raw-material-profiles/
US HOUSEHOLD SPENDING
https://www.bls.gov/cex/
US UNEMPLOYMENT DATA
https://www.bls.gov/cps/tables.htm
US EMPLOYMENT DATA
https://www.bls.gov/ces/

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Ron Trauner
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