POWER TO THE PEOPLE

energy holons to provide abundance, resilience & flourishing

Auke Hoekstra

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This is a draft of Power to the People. The text will still change, and new versions will replace this one. Chapter 29, the conclusion, is in preparation.

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PART I

Abundance



Earth as a candle burning up. A picture from my childhood classroom illustrating humanity was doomed because we were running out of fossil fuels and heating the earth at the same time.

1

Ending a Million Years of Fire

I was eight years old when I was taught we were doomed because of our addiction to fossil fuels.

It was 1974, in the Netherlands, and the oil crisis had hit. The Arab nations had cut off oil exports to punish the West for supporting Israel, and suddenly people were scared. On Sundays, the highways stood empty and my parents took me walking in the middle of one.

At school, my teachers tried to explain what was happening. They showed us a poster that the government had distributed. I can still see it: the Earth depicted as a candle, burning from the top, its wax dripping away into space.

Verstandig met energie, it said. Be frugal with energy. Energy was finite. Once we burned it, it would be gone forever.

They also explained global warming. The ice caps would melt. The seas would rise.

What unsettled me most is that nobody had a cure. Our civilization was doomed once we burned up all fossil fuels, or before that, due to global warming. That was it. No hope at the end of the lesson.

Now that I am older I still see that same absence of hope in younger generations. I see it in the Extinction Rebellion activists who block traffic in Amsterdam. I see it in young people who have decided not to have children because the world is ending. The emotional toll of believing we are doomed is immense. It's a weight that bends people's lives.

I spent the last 20 years of my life discovering the truth. I became a researcher at a technical university. I started large

research programs and my own simulation company. I gave countless presentations, keynotes, and interviews. I gained a modest following on social media. And now I've finally written everything I've learned down in a coherent format.

I discovered civilization isn't ending. Instead we are turning over a new leaf. We are finally ending a million year long era of thoughtlessly burning nature for energy. Using solar and wind we will create an energy system that works best if we start with small local units called holons. Energy will be easier to produce and harder to hoard leading to a fairer system in which everyone can get the energy they need. What follows is a hopeful vision of the future built on rigorous scientific research and easy to explain logical thinking.

1.1 Fire: Humanity's First Technology

Control of fire is what made us human. This is not metaphor. Anthropologists estimate that our ancestors learned to use fire somewhere between one and two million years ago, and the consequences transformed our species.[1]

Fire gave us cooked food, which released more calories and allowed our brains to grow larger.[2]

Fire gave us warmth, which let us colonize colder climates. Fire gave us light, extending the useful hours of the day and enabling social bonding around the hearth. Fire gave us protection from predators, a wall of flame between us and the darkness. Fire gave us the ability to shape materials: to harden spear tips, to fire clay into pottery, eventually to smelt metals into tools.

No other species controls fire. Chimpanzees, our closest relatives, can understand fire's behavior and calmly navigate around wildfires, but they have never been observed using or maintaining fire in the wild.[3] Fire is uniquely ours. It is the first technology, the foundation of everything that followed.

The ancients understood this. In Greek mythology, fire was so precious that it belonged only to the gods. Prometheus stole it and gave it to humanity, and for this crime he was punished eternally, chained to a rock while

an eagle tore at his liver each day. The story appears across cultures in different forms: fire as gift from the divine, fire as transgression, fire as the beginning of human suffering alongside human progress.

Apart from fire being a sinful transgression, these myths also encode a second truth. Fire requires fuel which is scarce. And for 99 percent of human history, this meant that energy was a constant struggle. Every family needed wood or dung or peat to survive the winter. Every growing village meant forests pushed further back.[4] Every war could be partly measured in whose army ran out of fodder first.

Life, for most of our existence, has been a fight for scarce resources. First food, then fuel. Everything that grows can be burned, and someone else might take it before you do. This is not neurosis. This is evolutionary inheritance. The scarcity mindset is hardwired into human psychology because scarcity was real for thousands of human generations and for over a billion years before that.

Consider how deep this goes. Children fight over toys before they can speak. Nations accumulate more weapons than they could ever use. We hoard, we compete, we assume that if someone else gains, we must lose. Economists call this zero-sum thinking, and they treat it as a cognitive error to be corrected. But for most of human history, it was simply an accurate description of the world. There was only so much wood in the forest. If your neighbor took it, you went cold.

1.2 Civilizations That Burned Out

The scarcity story left marks in the historical record. Civilizations rose on abundant energy and declined when that energy ran out.

Rome's expansion tracked its access to forests. The Italian peninsula was once densely wooded; by the height of the Empire, it was largely stripped.[5] Roman ships and Roman buildings consumed timber at rates the land could not sustain. The Empire pushed its logging frontier outward: to Gaul, to North Africa, to the limits of the Mediterranean

world. When the trees grew scarce, so did the ships. When ships grew scarce, so did trade. The relationship is not simple, and I am not claiming that deforestation *caused* Rome's fall, but it definitely was an important part of the fall of Roman civilization.

Or take the island of Hispaniola in the Caribbean, which today holds two nations, Haiti and the Dominican Republic. They share the same island, the same climate, the same starting conditions. Yet from the air, the border is visible: the Dominican side is green with forest cover; the Haitian side is brown and bare.[6]

Haiti's deforestation is not ancient history. It happened largely in the twentieth century, driven by population pressure and the need for charcoal fuel.[7] Without trees, the soil washed away. Without soil, crops failed. Without crops, poverty deepened. I don't mean this as a morality tale about Haitian decisions; I see it as a case study in what happens when a growing population depends on biomass energy and has no alternative. Today, Haiti is one of the poorest nations in the Western hemisphere.[8] The Dominican Republic, which made different policy choices and retained its forests, is comparatively prosperous. Same island. Different outcomes. Energy scarcity, compounded over decades, reshaped a nation.

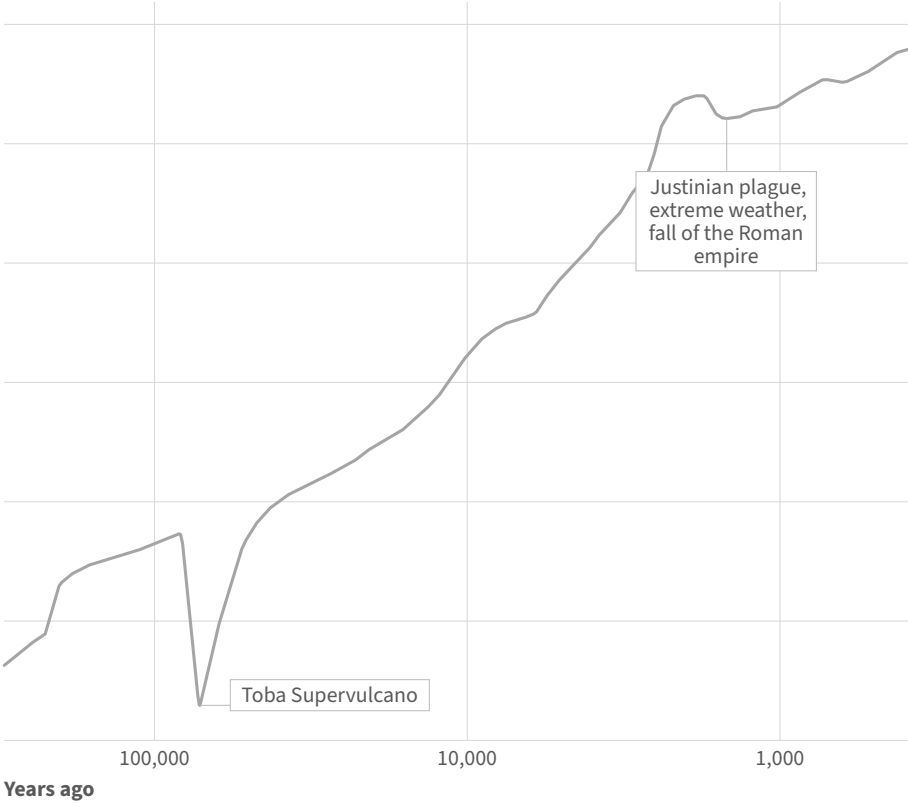
Or consider England. By the medieval period, England's woodland had already declined to around 15% of land area, with further losses in the sixteenth and seventeenth centuries for shipbuilding and charcoal production.[9] Domestic heating, shipbuilding for the navy, and iron smelting for industry had consumed the trees. England faced a choice: decline or adapt.

Adaptation came in black lumps dug from the ground. Coal was not a new fuel. It was well known but despised as a dirty fuel that smoked and stank. No one *wanted* to burn coal. But with the forests gone, there was no alternative.[10] The transition was driven by desperation, not choice.[11] We

learned to mine and burn fossil fuels because we had nothing else left.

Human energy use over time

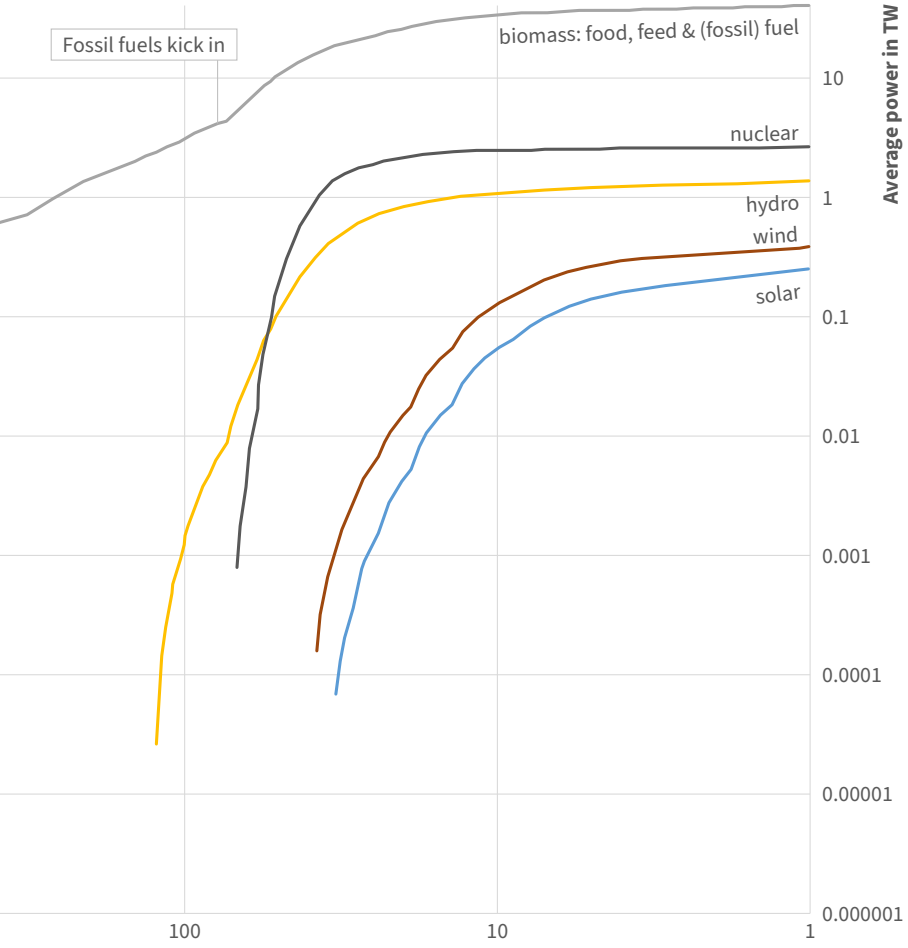
The axes are logarithmic. Energy use increased about a hundredfold from a hundred thousand to ten thousand years ago. Then it again increased a hundredfold from ten thousand to one thousand years ago. Finally it increased a hundredfold from a thousand years ago until now.



This graph tells the energy history of humanity in a single image. Both axes are logarithmic, compressing vast scales into something visible.

For most of human history, our energy came from burning biomass: wood, dung, and eventually the crops we grew. Energy use has increased exponentially throughout human history. A logarithmic plot shows roughly hundredfold increases across major eras: from the pre-agricultural period to early agriculture, from early agriculture to pre-industrial civilization, and from the pre-industrial period to today.

Notice the dip around 1,500 years ago: the Justinian plague and extreme weather that accompanied Rome's fall.[12] Energy use and civilization move together.



Then fossil fuels kicked in. We discovered grandmother's savings under the mattress and started spending.

Nuclear came next. It rises very quickly, but then flattens completely. It was a promise that didn't deliver and disillusioned my younger self. Hydro also flattened out, because there's only so much energy it can deliver.

But notice what happens at the far right: solar and wind are rising rapidly. They're still small compared to the grey biomass monster, diminutive even. But if you look at the logarithmic axis, you can see they are actually growing incredibly fast. And unlike everything else on this graph, they don't require burning anything. Could solar and wind really replace the biomass Leviathan? That monster that grew a *millionfold* in the blink of an eye?

1.3 Grandmother's Savings Under the Mattress

What we've been burning for the past two centuries is ancient biomass…

When we burn fossil fuels, we are burning hundreds of millions of years of accumulated sunlight.[13] We are spending our grandmother's savings, the energy she stored under the mattress across geological ages. And we have been spending it very, very fast.

The spending spree began roughly 250 years ago, with the Industrial Revolution.[14] In two and a half centuries, we have consumed a significant fraction of what took hundreds of millions of years to accumulate. At current consumption rates, oil reserves might last until the 2070s. Natural gas, perhaps a bit longer. Coal, which seemed inexhaustible to the Victorians, now has perhaps 100 to 150 years left at current consumption rates.[15]

These estimates are imprecise, of course. We may find new deposits. Technology may extract more from existing fields. Demand may rise or fall. But the fundamental mathematics is not in dispute: fossil fuels are finite, and we are currently drawing them down roughly a million times faster than any natural process could replace them.

The fear of running out is older than I am. The nineteenth-century whale oil industry experienced its own depletion crisis as whale populations collapsed from hunting, causing prices to rise dramatically before kerosene emerged as an alternative.[16] The transition to kerosene, derived from petroleum, solved that crisis, only to create the oil dependence that shaped the twentieth century. The 1970s brought "peak oil" theories that predicted imminent depletion. Those predictions proved premature, but they weren't wrong in principle. They were only wrong about timing.

And timing, as anyone who has lived through an oil crisis knows, matters enormously. The OPEC embargo of 1973 didn't happen because oil ran out. It happened because a cartel of producing nations chose to restrict supply. The result

was global economic shock, inflation, recession, and the car-free Sundays of my childhood.

When energy is scarce, those who control it wield enormous power. This is why the Gulf Wars were fought where they were. This is why petrostate dictators can fund wars and suppress their populations while the world looks away. We need what they have. That need shapes our foreign policy, our alliances, and our willingness to tolerate the intolerable.

I want to be clear about something here though: fossil fuels were miraculous. They lifted billions of people from poverty. They enabled the modern world, the food production that feeds eight billion humans, the medicine that extended our lives, the communication networks that connect us across continents. Anyone who lived through the twentieth century owes a debt to coal and oil and gas. We should be grateful.

But gratitude does not change the mathematics. We cannot burn what doesn't exist. And we haven't even counted the true cost of the damage they cause, the carbon loading the atmosphere, the methane leaking from wells and pipelines, the health toll of air pollution in every city on Earth. The price we pay at the pump or on our utility bills is not the full price. There is a bill we have been deferring to the poor and to our children, and it comes due whether we acknowledge it or not.

1.4 The Limits to Growth

In 1972, just two years before I sat in that Dutch classroom watching the Earth-candle melt, a team of researchers at MIT had used a new approach called system dynamics and a brand new technology called a *computer* to see where our civilization was going.[17] It's hard to imagine now, but a computer model was a bit of an awe inspiring novelty in those days. The computer model used stocks of resources: like the human population, soil for crops, fertilizer, oil reserves, pollution of the soil, et cetera. They traced the flows between them. They build their model, pressed "run" and watched

what happened when exponential growth met finite limits. They documented the result in a book called *The Limits to Growth*. It sold four million copies. It terrified a generation.

They concluded humans were unable to see things like exponential growth and feedback loops before it was too late. Which was why human civilization kept using up resources at an alarming rate. An explanation next to the central graph of the report states: "Food, industrial output, and population grow exponentially until the rapidly diminishing resource base forces a slowdown in industrial growth. Because of natural delays in the system, both population and pollution continue to increase for some time after the peak of industrialization. Population growth is finally halted by a rise in the death rate due to decreased food and medical services."[18]

A 1972 Time magazine story wrote: "The furnaces of Pittsburgh are cold; the assembly lines of Detroit are still. In Los Angeles, a few gaunt survivors of a plague desperately till freeway center strips . . . Fantastic? No, only grim inevitability if society continues its present dedication to growth and 'progress.'"[19]

The Limits to Growth model vividly demonstrates the power of exponential growth. Exponential growth is so fast that it takes our primate brains by surprise. And then we run out of food and the mass dying begins. Such predictions predate the use of computers. Malthus famously predicted famine would quickly hit this way in 1798. Tertullian went on about it almost two millennia ago.

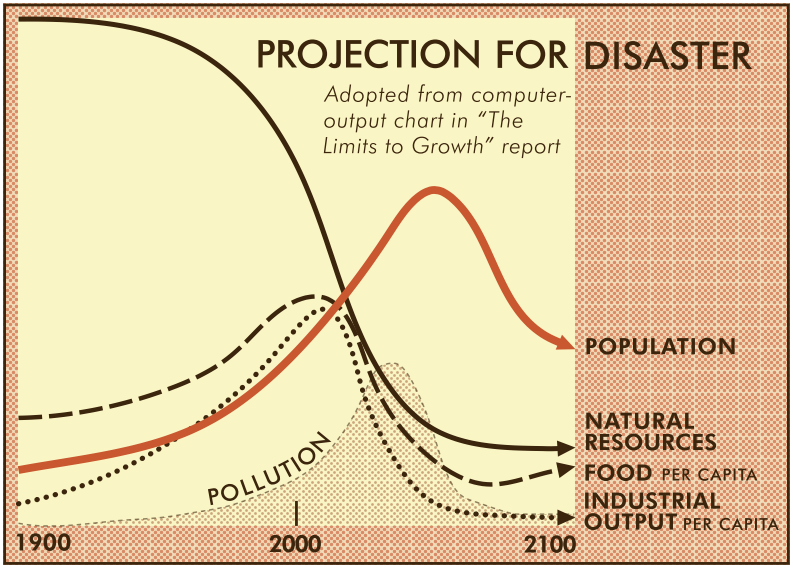
And while Malthus was wrong, famine and collapse due to resource scarcity is hardly a historical novelty. It's what happened to Rome's forests. Trees are a stock. They grow slowly: that's the inflow. Romans cut them for ships, buildings, fuel: that's the outflow. For centuries, outflow exceeded inflow. The stock depleted. By the height of the Empire, Italy was largely stripped bare and most Romans probably knew, deep down, that the end was nigh. The same pattern explains Haiti, the cedars of Lebanon, the whales of the nineteenth

century. Any time a civilization consumes a stock faster than it regenerates, the ending writes itself.

Still, most of the doom prophecies of the Limits to Growth report didn't come true yet. Why was that?

The first thing they underestimated, were feedback loops that pointed in the other direction. For example: once a stock gets scarce it becomes harder to find and less profitable. That slows down the exponential before it hits the wall. Scarcity also makes resources more expensive which makes it profitable to search for more resources and for substitutes. As economists like to say: the best cure for high prices, is high prices. Which is why we've managed to extend the deadlines from their business as usual scenario time and time again without hitting rock bottom yet.

The more fundamental thing they underestimated was that feedback loops could not only cause an exponential growth in problems, but also in solutions. I honestly think



An illustration based on the limits to growth study appearing in Time magazine in 1972. It shows how we will quickly run out of natural resources which will will lead to plummeting industrial output and food scarcity. Together this will cause the human population to plummet due to starvation.

that is how humanity can transcend its current and immature use of finite resources. In using computer models to come up with exponentially growing solutions. That's what my efforts have been about the past two decades and in essence that is what this book is about: finding the virtuous feedback loops that will get us out of this mess with the speed of exponential growth.

1.5 The Emotional Weight

This is also a story about grief, and this grief has names now: eco-anxiety. Climate grief. Solastalgia, the distress caused by environmental change in one's home environment.[20] Psychologists study it. Therapists specialize in it. A generation of young people has grown up with the assumption that the future will be worse than the present, that the arc of history bends not toward justice but toward catastrophe.

I know this weight. I carried it from that classroom in 1974: a kind of sombre soundtrack to any long term vision. In retrospect I think it was what plagued my teacher and I see it now in my students, bright young researchers who chose energy systems precisely because they want to help, and who struggle with despair when the numbers seem too large and the politics too broken.

I hear it when young people tell me they won't have children. Not because they don't want children, but because they believe it would be cruel to bring a child into a dying world. This is not a fringe position. Surveys show substantial minorities of young adults in wealthy countries expressing this view.[21] The fear has reached deep enough to reshape the most fundamental human decisions.

Part of this grief comes from the assumption that nature is zero-sum. If humans prosper, something else must suffer. If we grow, forests must shrink. If we consume, the world must diminish. This assumption runs so deep that it feels like physical law rather than a model that might be questioned.

And there is exhaustion too: the exhaustion of caring, year after year, while emissions keep rising and conferences

keep failing and politicians keep promising and breaking promises. At some point, the temptation of denial becomes overwhelming. If the problem is unsolvable, why keep suffering over it? Better to look away, to focus on what's in front of you, to leave the worrying to someone else.

I want to honor this. I understand where the despair comes from. The grief is earned. Anyone who tells you to simply cheer up has not understood the weight you're carrying. I can understand how genuinely believing that civilization is collapsing causes grief, denial, anxiety, and paralysis. The emotions follow from the beliefs.

But what if the beliefs are incomplete?

The Hunger Winter

In the winter of 1944-1945, the Nazis blockaded the western Netherlands in retaliation for a Dutch railway strike that had supported the Allied advance.[22] Food shipments stopped. Fuel shipments stopped. As temperatures dropped below freezing, more than four million Dutch civilians faced starvation.[23]

They called it the Hongerwinter, the Hunger Winter. People ate tulip bulbs and sugar beets.[24] They burned furniture for heat. They walked for miles to trade family heirlooms for a few potatoes. Approximately 20,000 people died, most of them in the cities of the west, before Allied forces liberated the country in May 1945.[25]

My parents were teenagers during the Hunger Winter. The experience shaped them and they shaped me.

What I inherited was not trauma but gratitude. Gratitude for warmth, for food, for the ordinary comforts that my parents' generation knew could vanish overnight. I also inherited a sense that security is not owed but earned, and that those who have it bear responsibility for those who don't.

I remember, around 1976, my mother packing our car for a family vacation to Hungary, then behind the Iron Curtain. But the car was not full of our vacation stuff. It was stuffed to the brink with clothing and supplies that our church had collected for Hungarian families. Through the church my parents had heard of people having less and for them it was just something you did. Mutual aid like that had kept people alive thirty years earlier.

This background shapes the voice you'll hear throughout this book. I believe prosperity is not a sign of virtue, and poverty is not a sign of vice. Comfort is something that brings with it responsibility: if you are warm, help others get warm. But also Dutch pragmatism: we built a country below sea level through collective action and long-term thinking and we are proud of that.

When I argue that abundant clean energy can lift billions from poverty, I feel that's both a moral imperative and the most pragmatic option.

1.6 What If We Were Wrong?

What if the scarcity story isn't the whole story?

I've spent the last two decades building models of energy systems. I've run the numbers on every scenario you can imagine. And I'm here to tell you something that I didn't believe myself until I saw it in the data: we are not running out of energy. We never were. We were only running out of the particular form of stored ancient sunlight that was never the final answer anyway. The sun itself continues to flood the Earth with more energy every hour than human civilization uses in a year.[26]

The question was never whether the energy existed. The question was whether we could capture it smartly. And in the past two decades, without most people noticing, the answer changed.

Two technologies now exist that break the pattern of the past million years. Solar panels convert sunlight directly into electricity. Wind turbines harvest the kinetic energy of moving air, itself driven by the sun's uneven heating of the atmosphere. Neither requires burning anything. Neither draws down a finite stock. Both tap into flows of energy that renew themselves every day, every hour, every moment the sun shines or the wind blows.

This is not wishful thinking. This is not idealism. The numbers are in, and they are astonishing. I will show them to you in the chapters ahead: how cheap solar and wind have become, how fast they are still falling in price, how the experts kept predicting they would fail and kept being wrong.

We thought we were running out. What if we were wrong?

2

The Stone Age Will Not End For Lack of Stones

In the previous chapter I compared fossil fuels to grandmother's savings hidden under the mattress: a one-time inheritance we've used for an increasingly lavish spending spree for the last two centuries.

The question that haunted my generation, the question planted by that burning-candle poster and watered by *The Limits to Growth*, was simple: when do the savings run out?

I spent years worrying about this, and I wasn't alone. The 1970s oil shocks seemed to confirm our fears. I think that's why *Limits to Growth* sold thirty million copies. A whole generation learned to see the future as a cliff edge, that we were headed toward like mindless lemmings running to their death.

But just like the award-winning Disney documentary showing lemmings running over a cliff turned out to be a cruel fabrication (the filmmakers threw them),[1] this narrative of humanity heading toward a cliff because of fossil fuels running out was also a fabrication, borne from our fears and the knowledge of journalists that doom scenarios sell.[2]

Ahmed Yamani turned out to be much closer to the truth. In the year 2000, Sheikh Ahmed Zaki Yamani, Saudi Arabia's oil minister for a quarter century, told an interviewer from The Telegraph: "The stone age did not end for lack of stones, and the oil age will not end for lack of oil."[3]

He was echoing a pattern as old as technology itself. The bronze age didn't end because we ran out of copper and tin. The age of whale oil didn't end because we hunted the last whale. The age of horses didn't end because we ran out of oats.

Each era ended because human ingenuity found something cheaper, more convenient, more powerful. And the incumbent industry, confident in its irreplaceability, rarely saw it coming.[4]

The fossil fuel era is ending the same way. Not with a dramatic depletion, but with a slow economic squeeze. The wells keep producing. For now. The tankers keep sailing. For now. But the financial statements keep deteriorating. We are watching a crash in slow motion.

I will show you the evidence. But first, let me remind you why this matters beyond economics.

2.1 Scarcity Brings Out the Worst in Us

Scarcity activates our tribal instincts. Psychologists have documented this even in infants: when resources are limited, babies as young as thirteen months expect in-group members to favor their own over others.[5] In classic experiments with older children, competition for scarce prizes rapidly generated intense intergroup hostility.[6] We define our in-group smaller and smaller. We treat out-groups with increasing suspicion, then hostility. We look for scapegoats.

This is not a moral failing. It is an adaptation. For most of human history, scarcity was the normal condition. When the harvest failed, there was not enough for everyone. The question was only who would go without and die. Evolution rewarded those who secured resources for their kin, even at others' expense.[7]

I think of the Dutch Hunger Winter of 1944-45 that my parents impressed upon me. Twenty thousand Dutch civilians died of starvation while German occupiers confiscated food. The Hunger Winter was brief and local. Impressive for

them and me but insignificant on a global scale. But this also happened elsewhere.

The Holodomor was systematic and vast. In 1932-33, Stalin's Soviet regime confiscated grain from Ukraine, sealing borders to prevent escape. Around four million Ukrainians starved to death.[8] This was not famine from crop failure. It was famine as policy, engineered by controlling a scarce resource. The grain existed. It was simply taken.

The pattern repeats throughout history. The siege of Leningrad. The Bengal famine of 1943, where multiple factors including wartime policies, Japanese occupation of Burma, and inter-provincial trade barriers led to mass starvation—a distribution problem, as Amartya Sen demonstrated, not an absolute shortage. Mao's Great Leap Forward, which killed tens of millions through centralized control of agricultural production.[9] In each case, the horror came not from absolute scarcity but from who controlled the distribution.

Concentrated resources create concentrated power. And concentrated power, history suggests, eventually gets abused.

2.2 Those Who Wield a Scarce Resource Wield Absolute Power

This dynamic translated directly to fossil fuels. When coal powered the Industrial Revolution, the coal barons became kingmakers. When oil replaced coal as the lifeblood of industrial civilization, the pattern intensified beyond anything that came before.

A single commodity, liquid and energy-dense, became the life blood of modern economies.[10] Whoever controlled the oil controlled the world. The 1973 oil embargo made it visceral. The Arab states turned off the tap, and suddenly the most powerful nations on Earth had to ration gasoline. That's what the control of concentrated energy flows can do.

There are many examples where we literally traded blood for oil.[11] In 1953, the CIA and British intelligence overthrew

Iran's democratically elected government because it had nationalized oil production. They installed the Shah, whose brutality created the conditions for the 1979 revolution, whose aftermath we are still living with.[12]

The House of Saud made a different bargain. In exchange for American protection, they kept the oil flowing and the prices stable.[13] They also funded the global spread of Wahhabism, the austere and intolerant strain of Islam that shaped the ideology of al-Qaeda.[14] Fifteen of the nineteen September 11 hijackers were Saudi citizens.[15]

In 2022, Vladimir Putin demonstrated the lesson again. Russian oil and gas had flowed to Europe for decades, a symbol of mutual dependence that was supposed to make war unthinkable. Germany's policy of *Wandel durch Handel* —"change through trade"—was meant to integrate Russia into the European order.[16] Instead, it made war fundable. The fossil fuel revenues filled Russia's war chest. When Europe objected to the invasion of Ukraine, Putin weaponized winter itself.[17]

Power corrupts, the saying goes, and absolute power corrupts absolutely. Fossil fuel wealth is not quite absolute power, but it is close. The "resource curse" is well documented: countries with oil wealth tend toward autocracy, corruption, and stagnation.[18] The oil does not cause the tyranny directly. But it makes tyranny sustainable. A dictator who controls the oil does not need his people's consent. He does not need their labor. He barely needs them at all.

I expected this power to grow as we headed for the cliff. The logic seemed inescapable: as fossil fuels depleted, whoever controlled the remaining reserves would wield ever greater leverage. The bullies would become more dangerous, not less.

Fortunately, I was wrong.

2.3 Fossil Fuel: From Bully to Bankrupt

I went looking for evidence of the squeeze, and I found it. But the squeeze was working in the opposite direction from what

I expected. The fossil fuel titans weren't getting richer. They were bleeding money. Not all of them, not every quarter, but the trend was unmistakable once you knew where to look. The industry that had controlled the world for a century was quietly becoming insolvent.

Not because the oil ran out. The proved reserves on the balance sheets looked as robust as ever. The tankers kept sailing. The pipelines kept flowing. Something changed in the economics. Something inevitable that is slowly driving the former bullies and kings of the earth toward bankruptcy.

2.4 Coal: Cathedrals Built to Be Abandoned

First I turned to coal. We theoretically have centuries' worth in the ground. It's technically the simplest to extract: no drilling, no fracking, no deepwater platforms. Just dig it up. Coal has generated more electricity than any other source for over fifty years.[19]

And coal is being massacred.

2.4.1 The Dutch Mistake

In 2015, three major European utilities, RWE, Uniper, and Engie, commissioned brand-new coal plants in the Netherlands. These were not aging relics limping toward retirement. They were the newest, most efficient coal plants in Europe, representing over €6 billion in investment. State-of-the-art technology. Decades of expected operation.

Within one year, the collective book value had fallen to €2.5 billion. RWE's Eemshaven plant alone cost €3 billion to build; RWE later wrote down its entire Dutch conventional fleet to €1.3 billion. Analysts at the Institute for Energy Economics and Financial Analysis estimated the plants might actually be worth closer to €400 million each.[20]

The utilities are now suing the Dutch government for compensation after a 2030 coal ban. RWE claims €1.4 billion; Uniper claims nearly €1 billion. The courts have been unsympathetic. They ruled that the government had a legitimate interest in meeting climate commitments.

Economics, even more than climate policy, is spelling doom for coal. The newest, most efficient coal plants in Europe were economically obsolete before the ribbon-cutting ceremony was over. The companies that built them, with all their expertise and due diligence, made multi-billion euro mistakes.

2.4.2 The Birthplace of Coal Shuts It Down Completely

On September 30, 2024, at midnight, the Ratcliffe-on-Soar power station in Nottinghamshire finished its final shift.[21] With that, 142 years of coal-powered electricity in Britain came to an end.

Britain invented coal-fired power generation. The first public power station, at Holborn Viaduct in London, opened in 1882. At its peak in 1920, more than one in twenty British workers labored in coal mines.[22] For more than a century, coal was synonymous with British industry, British power, British identity. As recently as 2012, coal generated 40% of British electricity.

Twelve years later: zero.

The plant manager, Peter O'Grady, told reporters: "When I started my career 36 years ago, none of us imagined a future without coal generation in our lifetimes."[23]

Britain became the first G7 nation to phase out coal power. UK coal demand in 2024 fell to its lowest level since 1666—the year of the Great Fire of London.[24] The country that started the Industrial Revolution walked away from the fuel that made it possible.

Coal was not replaced by gas. It was replaced by wind, which grew 315% over the period, along with solar and simple efficiency gains.[25] Power sector emissions fell 74% from their 2012 levels.[26]

2.4.3 Germany Pays Plants to Close

In December 2020, Germany held its first auction for coal plant closures. The government had set aside €165,000 per megawatt as compensation for operators who agreed to shut down early.

The auction was massively oversubscribed. Operators accepted an average of just €66,000 per megawatt, less than half the ceiling. Some bids came in as low as €6,047 per megawatt.[27]

Read that again. The government offered to pay companies to close their coal plants. The companies competed to close first. They fought for the privilege of exiting coal.

The fear that phase-out would be expensive proved backwards. Keeping coal running was the expensive option. The companies were eager to stop the bleeding.

Uniper's Datteln 4 plant opened in 2020 as "one of the most modern power plants of its kind in the world."[28] It was expected to operate until Germany's 2038 coal phase-out deadline. Five years later, Uniper sold it.[29] The company now aims to exit coal entirely by 2029.[30]

2.4.4 China: The Counterintuitive Case

"But what about China?" people ask. "They're still building coal plants."

They are. And that makes what's happening even more striking.

In 2000, coal generated about 80% of China's electricity.[31] By mid-2025, that share had fallen to 51%, a historic low.[32] The decline accelerated in 2024, when clean energy met 84% of new electricity demand.[33] In the first half of 2025, for the first time, growth in renewables didn't just supplement coal but actually drove a 2% decline in fossil generation.[34]

The numbers are staggering. In 2024, China installed 277 gigawatts of solar, more than twice the total solar capacity the United States has ever built.[35] China's 2030 target of 1,200 gigawatts of combined wind and solar was reached in 2024, six years early.[36]

Why does this matter? Because clean energy has become too economically important to abandon. It now contributes over 10% of China's GDP and accounts for more than a quarter of all economic growth.[37] The "new three" industries, electric vehicles, batteries, and solar, are what keeps China's

economy expanding. Without clean energy growth, China's 2024 GDP growth would not have been 5%, right on target, but just 3.5%.[38]

Yes, China continues to build coal plants, the legacy of a 2022-2023 permitting surge driven by energy security fears. But permits have since fallen 83%.[39] Many of these new plants will be like the Dutch coal cathedrals: built but barely used. Coal plant utilization is already falling. The question is not how many coal plants China is building. The question is how much coal they will actually burn.

The country building the most coal is also the country where coal's share is declining fastest. The economics are winning, also in China.

2.4.5 India: The Arithmetic Becomes Undeniable

India's Parliamentary Standing Committee on Energy identified 40 gigawatts of stranded coal projects.[40] Solar tariffs in India have fallen below the fuel cost alone of running existing coal plants. Not the total cost, the fuel cost. It is now cheaper to build new solar than to buy coal for the plants that are already built.[41]

NTPC, India's state-owned power giant and largest thermal generator, announced it would not pursue any new greenfield coal projects. The company is pivoting to 60 gigawatts of renewable capacity by 2032.[42] No new coal-fired power plants have been announced in India in the past twelve months.

A 2025 study in Nature Communications calculated that aggressive coal retirement in India could yield net economic gains of $171 billion in Chhattisgarh and $110 billion in Uttar Pradesh alone.[43] Early closure would reduce air pollution deaths and save costs that exceed the value of the stranded assets by a factor of four. (Nearly 1.7 million people die each year in India from air pollution, with fossil fuels responsible for more than 750,000 of these deaths.[44])

India doesn't have to choose between development and decarbonization. Once you understand what is happening,

you will see that maximum progress on both fronts is happily aligned.

2.4.6 The Global Pattern

These are not isolated anecdotes. Ember research shows coal power has halved across OECD countries since peaking in 2007.[45] According to Carbon Tracker, nearly 80% of coal plants in the European Union were losing money in 2019, before COVID, before the 2022 energy crisis.[46]

The pattern holds from Newcastle to New Delhi: coal isn't dying because we're running out. It's dying because something better came along.

2.5 Gas: The Transition Fuel That Wasn't

Natural gas was once hailed as the transition fuel. It emits about half as much carbon dioxide as coal when burned for electricity. Cleaner burning. Fewer particulates. The 'sensible compromise' between dirty coal and uncertain renewables. Then came fracking.

2.5.1 The Google of Oil and Gas

Chesapeake Energy pioneered hydraulic fracturing in the American shale formations. The company was once valued at $37 billion.[47] The press called it "the Google of oil and gas." Its CEO, Aubrey McClendon, graced the covers of business magazines. Chesapeake almost single-handedly made the United States the world's largest natural gas producer.

In June 2020, Chesapeake filed for bankruptcy with $9 billion in debt.[48]

The details are instructive. Between 2010 and 2012 alone, Chesapeake spent $30 billion more in drilling and leasing than it earned from operations.[49] The company produced gas at a phenomenal rate, but the production never covered the costs.

When auditors examined the books, they found curiosities. Some $110 million had been spent on two corporate parking garages. There was a wine collection hidden behind a broom closet.[50]

Chesapeake was an extreme case, but it was not an outlier. The entire U.S. shale gas industry followed a similar pattern: record production, capital destruction. The gas flowed. The money vanished.

Fracking also had another problem. Methane, the main component of natural gas, is a potent greenhouse gas, about 82 times more warming than CO2 over twenty years and about 30 times more over a century.[51] Studies found that methane leaking during drilling and transport could make fracked gas as damaging to the climate as coal.[52] So much for the transition fuel.

2.5.2 Gazprom's Artificial Resurrection

In Russia, the state-controlled gas giant Gazprom reported a remarkable turnaround in 2024: a profit of 1.2 trillion rubles, up from a loss of 629 billion rubles the year before.[53]

The numbers deserve scrutiny.

The 2024 "profit" included 500 billion rubles from Gazprom Neft, the company's oil subsidiary. The gas business itself made only 719 billion rubles. Meanwhile, the 2023 loss had included a 1.3 trillion ruble windfall tax to fund military spending and 1.15 trillion rubles in write-offs of European assets seized after sanctions.[54]

Strip away the one-time charges and the oil subsidiary's contribution, and what remains is a gas business barely breaking even.

More telling: Gazprom's net debt service costs quintupled between 2019 and 2024, from 171 billion rubles to 719 billion.[55] The company is using oil profits to subsidize gas operations while debt climbs toward dangerous levels. This is not recovery. It is financial triage.

2.6 Oil: The Last Man Standing Isn't Standing

I expected oil to be the last holdout. It is the most valuable fossil fuel, the most versatile, the hardest to replace. Liquid gold. The stuff that keeps armies moving. If any fossil fuel would survive the transition, surely it would be oil.

2.6.1 The $300 Billion Bonfire

From 2010 to 2019, the U.S. shale oil industry generated negative $300 billion in cumulative free cash flow.[56] Over 190 companies filed for bankruptcy.[57] More than $450 billion in invested capital was written off.[58]

This happened while oil averaged over $80 per barrel for much of the period. At that oil price they should have been printing money. Instead they burned it. According to Deloitte, 30% of shale operators were technically insolvent at $35 per barrel.[59]

The industry produced record volumes of oil but also destroyed record volumes of money.

2.6.2 The Supermajors' Quiet Hemorrhage

Shale drillers, you might argue, were always gamblers. Small operators, undercapitalized, chasing the next boom. Surely the supermajors would show how it's done. ExxonMobil. Shell. Chevron. BP. TotalEnergies. A century of experience. The deepest pockets in the business.

The Institute for Energy Economics and Financial Analysis examined their SEC filings and found a different story.[60]

From 2010 through 2019, the five supermajors collectively generated $340 billion in free cash flow. That sounds robust until you learn that over the same period, they paid $556 billion to shareholders in dividends and buybacks.

The gap: $216 billion. More than $200 billion that they paid out but didn't earn.[61]

Extend the analysis to 2005 through 2020, and the cumulative deficit reaches $325 billion. The supermajors funded this shortfall through a combination of new debt, adding over $210 billion in long-term borrowing, and asset sales.[62] BP and Shell each sold roughly $70 billion in assets over the decade.[63]

In only three of those fifteen years did the supermajors generate a cash surplus.

2.6.3 Prices Up, Profits Down

The IEEFA documented a striking comparison between the second quarter of 2023 and the third quarter of 2021—two periods with comparable oil prices that allowed them to isolate the effect of rising costs.[64] Oil prices had gone up but the supermajors' combined free cash flow was down more than 20%. The industry made less money while selling its product for more.

This is what rising extraction costs look like when translated into dollars. When costs rise faster than revenues, margins compress even as prices increase. The headline numbers look stable. The underlying economics are deteriorating.

2.6.4 The Confessions

In mid-2020, as the pandemic cratered demand, the supermajors finally started admitting what their balance sheets had been showing for years.

BP wrote down $17.5 billion in assets. Shell followed with up to $22 billion.[65] Both companies simultaneously lowered their long-term oil price assumptions to $55-60 per barrel, an acknowledgment that the future they had planned for was not coming.[66]

Wood Mackenzie, the energy consultancy, called it "a message about stranded assets."[67]

The world's largest, most experienced oil companies were admitting their own forecasts had been wrong.

Russia-related write-offs alone cost foreign oil and gas companies nearly $58 billion in 2022, with BP taking the largest hit at $25.5 billion.[68]

2.6.5 Europe's Refinery Extinction

The decline is visible in industrial infrastructure. Europe lost 400,000 barrels per day of refining capacity since early 2024: five refineries closed in two years, including three since March.[69] High taxes, climate rules, and smaller-scale sites are making European refineries less competitive than those in other regions.

Long-term naphtha and diesel demand forecasts have collapsed under the weight of electric vehicle adoption.[70]

These aren't marginal adjustments. They're structural amputations. European refineries must now reinvent themselves or close.

2.7 Sidebar: Why Costs Keep Rising (EROI)

The financial deterioration traces back to physics. Energy Return on Investment, or EROI, is the ratio of energy obtained to energy expended. Think of it as the profit margin of physics.

2.7.1 The Concept

In the early days of oil, EROI was spectacular. The oil at Spindletop in 1901 essentially pushed itself out of the ground. Drill a hole, stand back, let gravity and pressure do the work. For every barrel of oil equivalent invested in extraction, you might get back a hundred barrels. An EROI of 100:1.

Those days are gone. Conventional oil fields still producing today have EROIs around 18:1 to 20:1. Respectable, but far from the early gushers. New production increasingly comes from unconventional sources: deepwater drilling (EROI around 10:1), Canadian oil sands (around 5:1), tight oil from shale (5:1 to 10:1).[71]

The easy oil came first. This is not conspiracy or mismanagement. It is common sense. You don't start with the hardest rock when easier rock is available. But there is nothing we have looked for more tenaciously on earth than oil. So we already found most of the easy rock. What remains is deeper, dirtier, more energy-intensive to extract.

2.7.2 The Alberta Tar Sands Example

Take the Alberta oil sands. Industry sources often claim an EROI of about 5:1, meaning you get five barrels of energy for every barrel you invest. That sounds acceptable. But this figure is measured "at the mine mouth," and it hides enormous losses downstream.[72]

The extraction process uses vast quantities of natural gas for heating and for generating electricity to run pumps. Producing that natural gas has its own energy costs. Converting gas to electricity loses about half the energy. Transporting the heavy bitumen requires diluting it with lighter hydrocarbons (which themselves required energy to produce) or upgrading it on-site (more energy). Refining the resulting crude into gasoline burns more energy still. Trucking the gasoline to your local station: more losses.

By the time tar sands oil reaches your fuel tank, a reasonable accounting suggests the net energy gain may largely evaporate. As Charles Hall of SUNY has noted, the EROI for oil sands would fall closer to 1:1 if the full life cycle, including transportation, refinement, and end-use efficiency, is accounted for.[73]

2.7.3 The 4.6:1 Threshold

A 2024 study in Nature Energy examined this problem systematically. The researchers asked: what EROI at the extraction point is actually needed for fossil fuels to deliver net energy to society, accounting for all the losses in processing, refining, and distribution?[74]

Their answer: 4.6:1 at the mine mouth, at minimum.

Below this threshold, the energy source may be profitable in dollar terms (if energy inputs are cheap and outputs are expensive) while actually draining energy from the economy. Money can flow in circles even when net energy doesn't.

This explains an odd phenomenon: tar sands projects that receive billions in subsidies despite questionable energy returns. The gas used for extraction is cheap because it's abundant and undertaxed. The gasoline produced sells for more because it's in demand. On a spreadsheet, this looks profitable. In physical terms, society is putting in more energy than it gets back.

2.7.4 Why Renewables Are Different

For fossil fuels, the EROI at the mine mouth and the EROI at the point of use are drastically different, because combustion-based energy systems have large losses at every step.

For renewables, this gap largely disappears. A solar panel factory powered by solar panels doesn't lose 50% of its energy in conversion. An electric car charged by solar doesn't waste three-quarters of its energy as heat the way a gasoline engine does. The whole chain becomes more efficient.

This means a solar installation with an EROI of even 10:1 at the panel delivers far more useful energy to society than a fossil fuel source with the same nominal EROI. And current estimates put solar's EROI at 12:1 and rising, wind at 24:1 and rising.[75] As manufacturing scales and efficiency improves, these numbers continue to climb.

Practically speaking EROI has become a non issue for renewables but is increasingly becoming a show stopper for fossil fuels, especially unconventional fossil fuels.

2.7.5 The Dallas Fed Evidence

The falling EROI shows up directly in producer surveys. The Dallas Federal Reserve asks oil producers each quarter what price they need to profitably drill a new well.[76]

In 2019, the average breakeven price in the United States was $50 per barrel. By early 2025, it had risen to $65 per barrel. That's a 30% increase in six years, faster than general inflation.[77]

One survey respondent put it plainly: "The U.S. oil cost curve is in a different place than it was five years ago. $70 per barrel is the new $50."[78]

Enverus Intelligence Research projects breakeven prices could hit $95 per barrel by the mid-2030s as producers work through their remaining prime inventory.[79]

"Profitable" Isn't What You Think It Is

Understanding the slow squeeze requires distinguishing between two concepts that sound similar but measure different things.

Reported profit (or net income) equals revenue minus expenses as defined by accounting rules. These expenses include operating costs, depreciation, interest, and taxes. By this measure, the supermajors report profits most years.

Free cash flow equals actual cash generated from operations minus capital expenditures. It's the money left over after paying for everything needed to maintain the business, including drilling new wells to replace depleting ones.

This distinction matters because oil companies must continuously invest just to stay in place. A typical shale well loses 50-75% of its production in the first year alone.[80] Conventional fields decline more slowly but still decline. Without constant drilling, income falls.

This capital spending is enormous. For the supermajors, it typically runs $15-25 billion per year, each. Accounting rules spread this cost over many years through depreciation, which smooths reported profits. But the cash goes out the door immediately.

A company can report accounting profits while spending more cash than it generates. The income statement shows health. The cash flow statement shows hemorrhage. The balance sheet, over time, shows the truth: debt rising, assets falling, the company slowly consuming itself.

This is not theory but it showing up in reality. From 2010 to 2019, the five supermajors:

- Reported cumulative net income of roughly $400 billion
- Generated free cash flow of $340 billion

- Paid shareholders $556 billion[81]

The gap between cash generated and cash distributed was filled by borrowing and asset sales. This is sustainable for a while. It is not sustainable forever.

When an industry consistently pays out more than it earns, and funds the difference with debt and divestitures, it is not investing in its future. It is liquidating while keeping up appearances.

2.8 The Pyramid Scheme Dynamics

Across all three fossil fuels, the same pattern emerges. Costs rise faster than revenue. Dividend checks keep coming, but debt grows and assets shrink. The headline numbers look stable while the foundation rots. And it's not even the fault of the CEOs, because this is what they are paid to do.

CEOs are paid to deliver shareholder value. Shareholder value equals stock price plus dividends. Cutting dividends crashes stock prices. So their salary depends on keeping dividends going, even when cash flow doesn't support them. This will go on until the scheme collapses. Any CEO who doesn't want to play along will be replaced, and by the time the consequences arrive they will be retired anyway. What would you do?

I am not accusing any individual of fraud. As often it's the structure itself that produces the behavior. Every CEO's incentive is to maintain confidence until after they've collected their bonus. The industry runs a slow-motion liquidation disguised as stability.

But once the confidence falters, the downward spiral can lead to a crash. Oil fields that turn out to be economically unrecoverable stranded assets get written off. Credit ratings slip, so borrowing costs rise. Debt service becomes unsustainable, so dividends must be cut. Dividend cuts crash the stock. Stock crashes get executives fired. New executives inherit a gutted company.

This is not speculation about the future. It is simple extrapolation of what we are seeing in the financial report, and explained by the physics of rising EROI combined with cheaper alternatives for fossil fuels.

In 2020, Wood Mackenzie estimated that price crashes and demand destruction removed $1.6 trillion in value from the world's upstream oil and gas industry.[82] This was not called a crash. It was called "fundamental change hitting the entire oil and gas sector." The language of financial analysts pussyfoots around the problem because it's a problem too large to face head on.

2.9 The Stone Age Didn't End For Lack of Stones

I feel no sorrow for Putin as the funding for his war evaporates. For the House of Saud as the basis for their bargain with religious extremists disappears. For the oil majors that spread doubt about climate change for decades while their own scientists knew the truth. Humanity has profited immensely from fossil fuels these last two centuries, but we can say goodbye to the politics and scarcity surrounding them without remorse.

Sheikh Yamani's warning came true, though probably not the way he expected. The oil age is ending not because wells are running dry but because the economics are running dry. The reserves on the balance sheets are still there. Economically speaking, most of it is becoming stranded assets. Because something better than stones came along.

I went looking for doom and found, to my surprise, a kind of liberation. I started with the thought of a scarce resource creating a cliff we were running toward. A centrally controlled resource that created tyrants in the process. For decades I feared that fossil fuel depletion would trigger resource wars, authoritarian consolidation, civilizational collapse.

Instead, I find the power of and need for fossil fuels are waning. I underestimated human ingenuity. It almost seems like we are inventing our way out of the trap we invented our way into.

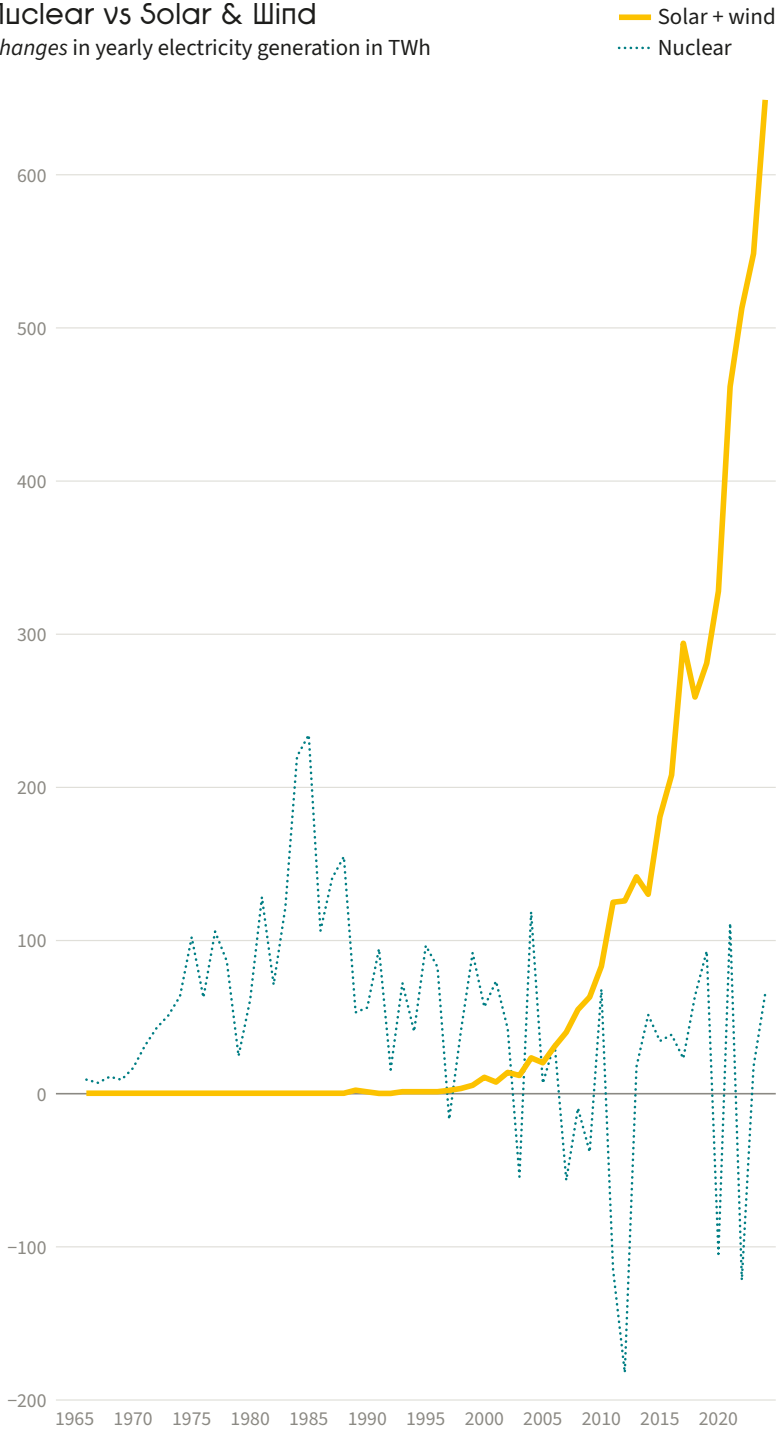
But if fossil fuels are dying, what replaces them?

For a long time, I thought I knew the answer. A technology that seemed to offer unlimited clean power. Energy too cheap to meter, drawn from the heart of the atom itself.

I wanted nuclear power to be the solution. The physics seemed so elegant, the energy density so remarkable. Then I looked at the actual numbers.

Nuclear vs Solar & Wind

changes in yearly electricity generation in TWh



3

The Nuclear Mirage

I really wanted nuclear to work.

Not just because it would be the answer to our civilization-ending lack of fossil fuels. There is something genuinely wonderful about harnessing the power of the atom. When I first learned about nuclear energy as a teenager, it seemed like the obvious solution. Vast quantities of low-carbon electricity from improbably small amounts of matter. If this book were written by my childhood self, this would be a jubilant chapter about building reactors everywhere.

The promise seemed so real. In 1954, Lewis Strauss, chairman of the U.S. Atomic Energy Commission, predicted that nuclear power would become "too cheap to meter."[1] Clean, dense, powerful, and seemingly limitless. I believed in that promise for a long time.

But I cannot, in good conscience, present nuclear as a solution in this book. Not because it isn't impressive. It is. Not because it isn't low-carbon. It is. Not because the waste problem is unsolvable. It is. And not because it isn't safer than fossil fuel. It's all these things.

But the growth of nuclear peaked in 1985 and in recent decades there has basically been no growth at all while solar and wind kept soaring higher and higher. All in all there are four problems that I call the four horsemen of my nuclear disillusionment. Taken together, they unfortunately disqualify it from the future we need to build.

3.1 How Nuclear Energy Works: Just Another Way to Boil Water

Before we examine those four horsemen, it helps to understand what nuclear power actually is. In essence it's a new way to boil water. That is not meant to be derogatory. Boiling water is how we currently produce most of our electricity. We boil water, which produces steam, which turns a turbine, which generates electricity.

In a fossil fuelled power plant the heat for boiling water comes from combining carbon atoms and oxygen atoms which produces CO2 and heat. We call this process a fire. It's a chemical reaction that produced our energy for almost a million years.

In a nuclear power plant the heat comes from nuclear fuel. It works by splitting atoms in a process we call nuclear fission. Usually the atoms we split are uranium atoms so let's stick to that in our short explanation.

As you might know from school, an atom consists of a core with electrons swarming around it. The core is responsible for the atom weight. The core is called the nucleus and consists of two types of particles. Protons that are positively charged, and neutrons that are just as heavy but are not charged.

Each atom is named for the amount of protons in its nucleus. Uranium is a super heavy atom with 92 protons in its nucleus. But you can find it in two flavours that have different amounts of neutrons. These flavours are called isotopes. Most uranium occurring in nature has 146 neutrons in its nucleus which, together with the mandatory 92 protons, gives it a total weight of 238. That's why we call this isotope U-238.

But we are mostly interested in the lighter isotope. It's more unstable and hot-headed cousin, U-235. U-235 plays hard to get and in nature it is always found in small quantities together with a lot of U-238 that it hides behind.

You might have heard about *enrichment*. Enrichment is a process that Iran might be using to prepare atom bombs. Enrichment is also the process we use for creating nuclear fuel. In essence it just means that we take naturally occurring uranium with very little U-235 and we spin it in a centrifuge until the heavier U-238 goes one way and the lighter U-235. The end result is some uranium that is richer in U-235.

Now the fun starts. When you hit U-235 with a neutron, it temporarily becomes U-236 but that's so unstable that it immediately splits into three loose neutrons plus other atoms like krypton and barium. That's why it's called nuclear fission. From the latin fissio meaning splitting and related to the word *fissure* meaning a crack or split.

This is a big deal because the result of this reaction is a tiny bit lighter than U-236. And maybe you've heard of Einstein and the formula *energy is mass times the speed of light squared?* It doesn't matter if you haven't. Bottom line is that even that tiny amount of mass that went missing, goes a long way to producing heat.

On top of that we also got three loose neutrons. And we had all these unstable U-235 types that fall apart as soon as you hit them by a neutron. See where this is going? A chain reaction.

In a bomb the chain reaction is unchecked. In a nuclear power plants there are movable rods with material that absorbs neutrons to control the reaction. And that's how it boils water.

3.2 Yearly Growth Is Trending Down Since 1985

Nuclear power had its moment in the 1980s but then its popularity waned and it never recovered. While experts debate nuclear in conferences and op-eds, the data tells a clear story. Nuclear market share started dropping in 1996, but if you look deeper you see that the growth per year actually peaked in 1985. After that the yearly growth became less and less. So nuclear lost its momentum long before solar and wind began their exponential rise.[2,3]

By 1996, fossil fuels had reclaimed market share, and nuclear began its long decline. Today, solar and wind are taking that share instead.

3.3 From "Too Cheap to Meter" to "Too Expensive to Matter"

If nuclear power were merely expensive, we could debate whether the premium was worth paying. But nuclear is three times the cost of alternatives. That's a price premium no investor can overlook.

Lazard's 2024 LCOE analysis shows new nuclear at $0.142 to $0.222 per kilowatt-hour.[4] More expensive than gas combined cycle. Around three times as expensive as both wind and utility-scale solar. Fraunhofer and CSIRO put nuclear's costs even higher.[5,6] Yes, you must include storage for when the sun doesn't shine and the wind doesn't blow. But in a well-designed system, that makes surprisingly little difference, as we'll see later.

Then there are the cost overruns. Nuclear projects consistently promise one price and deliver another, usually two to three times higher. This is not occasional misfortune but a persistent pattern that makes investors wary and they make sure the risk shifts to taxpayers before they agree to build.[7,8]

Nuclear has also achieved something remarkable: negative learning. Most technologies get cheaper as production increases. We call this a learning curve, and it is so important that the next chapter is devoted entirely to understanding it. Solar panels, wind turbines, batteries, power electronics: all follow learning curves. The IEA and NEA use a method called NOAK (nth of a kind) that confidently predicts this will happen to nuclear too. They have been confidently predicting this for decades now. Unfortunately, empirical data shows the opposite is true. Newer plants cost more, not less.[9,10] There are occasional exceptions, and in China everything is cheaper, including nuclear power plants, and South Korea has also achieved cost stability. Maybe someday nuclear will buck the trend elsewhere.[11,12] But so far, all the empirical

evidence—as opposed to the aspirational predictions—shows nuclear has been on a negative learning curve.

Finally, there are hidden costs. About 1.5% of nuclear reactors that are built have experienced core meltdowns. If their number doesn't grow this would statistically mean a major accident somewhere in the world roughly every 10–20 years.[13] Chernobyl and Fukushima together tally close to $1 trillion in direct financial damages, with estimates ballooning when ongoing and indirect costs are included.[14] Spread that over total historical nuclear generation and you get about one cent per kilowatt-hour and a lot of uncertainty. Add waste storage—uncertain, multigenerational, and expensive—and the economics become difficult to justify.

There is also the cost of being slow. Nuclear plants take a decade longer to build than renewables.[15] During that decade, fossil fuels continue emitting greenhouse gases and killing people through air pollution. If we are honest about cost-benefit analysis, those deaths and emissions belong on nuclear's ledger too.

3.4 More Nuclear Energy Means More Nuclear Weapons

That nuclear power plants enable nuclear weapons is the elephant tapdancing in the room that most polite society prefers to tiptoe around. Preferably while humming. The link between nuclear power and nuclear weapons remains debated, but empirical evidence suggests civilian nuclear cooperation increases proliferation risks.[16]

Today we have about 415 nuclear reactors in 31 countries.[17] In total, about 30 countries have sought nuclear weapons, and ten are known to have succeeded.[18] Of these 10, seven have a civilian nuclear program. If nuclear were to replace the energy from fossil fuels worldwide, not just for electricity but also for heating and transport, every nation would need them and we would need 20,000 nuclear reactors. That's six times more nuclear nations and fifty times more nuclear power plants.[19] The probability of prolif-

eration rises accordingly. More if you take reprocessing into account.

One path to bomb-making is reprocessing spent fuel from civilian power plants. Reprocessing extracts up to 70 times more energy from the original uranium.[20] It is clearly the way to go if we want to scale up nuclear. Unfortunately, reprocessed fuel is also ideal input for weapons. India got its atom bomb from a Canadian reactor design that had provided the material for the Manhattan bomb building program, combined with a US reprocessing plant. Both under the "Atoms for Peace" program.[21,22]

Then there is thorium. Thorium advocates often claim the technology is "proliferation proof," but this requires ignoring the well known protactinium loophole. I've looked at that loophole in some detail and I am comfortable claiming that it actually makes bomb-making with thorium *easier* than with uranium.[23,24] Five kilograms of bomb-grade U-233, enough for one Hiroshima,[25,26] can be made from just one tonne of lightly regulated thorium that fits in the back of any van. All you need on top of that is a small research reactor, some chemical separation equipment, and one month of patience.[27]

Without reprocessing, running the world on nuclear means running out of uranium within five years: a non-solution.[28] (There is discussion about this, but even if it was a bit longer, it would still not be a solution.) And even "regular" reactors that don't use reprocessing need enriched uranium. You enrich uranium using centrifuges, and as Iran has demonstrated, simply running them a bit longer produces weapons-grade fuel.

A Pakistani scientist known as A. Q. Khan ran a black market for nuclear technology that sold to Libya, Iran, and North Korea for decades before being discovered.[29] For some of the material we still don't know where it ended up. For terrorists with less contacts or funds there is the dirty bomb. Or you can create a crisis using an existing nuclear power plant as

Russia did at Zaporizhzhia. Or you could use explosives on a lightly defended spent-fuel pool.

Pretending that we can scale up nuclear without more actors acquiring nuclear weapons requires a faith in international institutions and human restraint that history does not support.

3.5 Nuclear Is a Bad Fit for a Decentralized Grid

Nuclear can scale up and down,[30] but in order to keep the already high cost within limits, nuclear plants must produce a high output all day, all year. But a future grid with millions of rooftop solar systems, neighbourhood wind turbines, batteries, electric vehicles, and local energy communities behaves differently: power appearing and disappearing in response to sunlight, wind, and local demand.

Solar and wind have zero marginal cost.[31] Once built, the electricity is essentially free whenever the sun shines or the wind blows. That means nuclear often sits idle while free electrons flow from renewables. And for nuclear, every hour of idleness means the enormous investment must be paid back over fewer kilowatt-hours produced. A huge battery could solve that problem, but would drive up the price further.

Our grid is evolving toward local systems that stabilize themselves at the house, neighbourhood, and region level to avoid congestion. I call them holons. Large centralized plants are a poor fit for this new system. They represent concentrated supply trying to serve distributed demand, with all the fragility and infrastructure costs that entails.

Nuclear is not a villain. But it was built for a world that is fading. In a centralized, no-renewables universe, I would be enthusiastically pro-nuclear. We do not live in that universe.

3.6 The Verdict

I want to be clear about what I am not saying. I am not saying nuclear is evil, or that we should be afraid of accidents, or that existing plants should be shut down prematurely, or

that the people who work in the nuclear industry are doing something wrong. I myself consider nuclear better than coal on almost all metrics, and many nuclear advocates are thoughtful people who have arrived at different conclusions through careful reasoning. This is a domain where reasonable people can disagree.

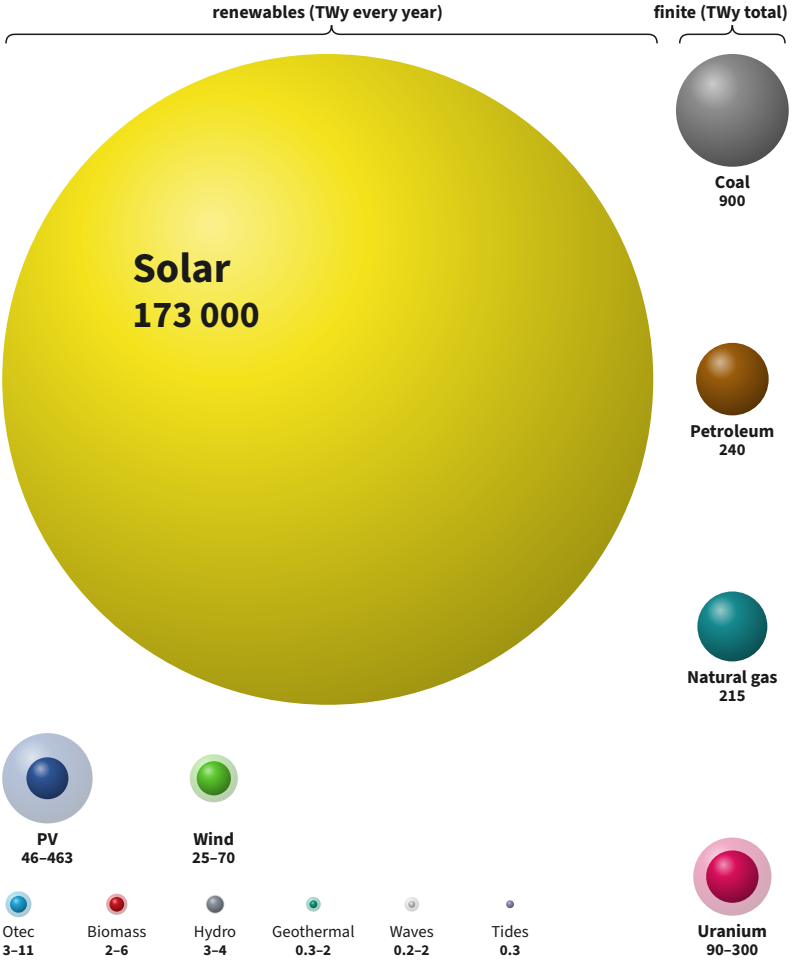
But when I look at the four problems together – losing market share, too expensive to matter, proliferation risks, poor fit for the emerging grid – I see a technology from the age of centralization, trying and failing to compete in the age of distributed energy. I see old thinking: ultimately just another way to produce heat, similar to burning biomass. And I see an opportunity cost, because every euro and every year spent on nuclear is a euro and a year not spent on the technologies that are actually winning.

The dream was beautiful. The reality did not match. And so I was forced to move on.

Energy on earth

Illustrating our abundant renewable energy flows

28 world energy consumption (2050, estimated) in TWy/year



The volume of each ball shows an amount of energy in terawatt-years: per year for the renewable sources and for world energy use, in total for the finite reserves. A solid ball inside a pale one shows a range, from its low to its high estimate. Numbers are from Perez et al.[1] except the solar energy intercepted by the earth and the 2050 energy consumption and the potential for PV production that I estimated. PV production was calculated assuming all roof surface or all built environment (see page 140) and future 40% efficient solar panels.

4

More Energy Than We'll Ever Need

Once you learn about energy flows in our solar system, the idea that the energy we currently require for human civilization is scarce becomes a bit absurd. You understand that the energy from the sun dwarfs our needs and our fossil fuel reserves.

Even the fraction we receive on earth, and the fraction of that we could easily harvest with solar panels and wind turbines, is much more than we'll conceivably need or than what fossil fuels could ever give us.

If the yearly solar energy reaching the earth was a basketball, all human energy use would be no more than a blueberry.

The sun gives us 173 thousand terawatt continuously[2] while we currently use 18 terawatt on average[3]. That means the sun gives us roughly ten thousand times more than what we need. (The solar energy that doesn't reach the earth is 2 billion times more than that.) Best-in-class panels can now convert more than a quarter of sunlight directly into electricity[4]. Lab records for tandem cells have exceeded 34%, and the theoretical limit for multi-junction designs reaches above 50%[5]. The efficiency of solar panels is still increasing. The potential of solar panels is orders of magnitude bigger than that of any other energy source.

Wind is also abundant. The sun heats the atmosphere unevenly, creating pressure differentials that drive air move-

ment. The resulting wind energy is a tiny fraction of the energy of solar radiation, but it carries roughly 100 times more energy than humanity needs. Even if we just harvested 20% available at good sites, it could still give us all we need[6].

Scientists have known this for over a century. They were not secret. But for most of that time, they were academic curiosities, because we had no practical way to capture diffuse sunlight at scale. The learning curves described in the previous chapters changed that.

The problem, it turns out, was never scarcity. The problem was that we were capturing energy in an extraordinarily roundabout way.

4.1 The Long Way Around the Sun

Consider what we have been doing for the past two centuries.

Hundreds of millions of years ago, plants captured sunlight through photosynthesis and stored it in their tissues. When those plants died, some were buried under sediment before they could decompose. Geological pressure transformed that ancient biomass, over tens of millions of years, into coal, oil, and natural gas.

Today we locate these deposits, often kilometres underground or beneath the ocean floor. We drill or dig. We extract the material, sometimes expending enormous energy just to bring it to the surface. We transport it across oceans in ships that themselves burn fossil fuels. We refine it. Finally, we burn it.

The burning releases heat. We use that heat to boil water. The steam spins a turbine. The turbine generates electricity. Along the way, we lose 60 to 70 percent of the energy as waste heat[7].

And all along, the sun kept shining. Every day. Every hour. Ten thousand times more energy than we needed, arriving without extraction, transportation, or combustion.

This was not stupidity. Burning was simply the only game in town. It's only recently that we've learned to capture sunlight directly and efficiently.

4.2 Photons to Electrons

Solar panels still seems like magic to me. One hundred and fifty million kilometres away, across an unimaginable vast nothingness, this giant fireball in the sky is fusing hydrogen atoms into helium, and sending out bright light in the process. The sun hurls that light, which according to Einstein consists of tiny particles called photons, towards us over that unimaginably large distance.

This shower of photons powers all life on earth. If it hits a solar panel the result is a process that is astoundingly simple to understand and use. Basically the solar panel turns the energy in the photons into electricity just by lying in the sun.

In a bit more detail: the photons strike a semiconductor, typically silicon. Each photon is like a small packet of energy. When that packet of energy hits an electron in the silicon, it can knock that electron loose. The loose electron flows through a circuit. That flow is electricity[8].

Sunlight in, electricity out. No combustion, no steam, no turbines. No intermediate steps involving ancient plants, geological transformation, extraction, or refinement. No transport all over the earth. Just photons hitting silicon anywhere on earth where there's sunshine.

Once the panel is manufactured and installed, the fuel is free. It will be free tomorrow. It will be free for the panel's thirty-year lifespan[9]. No one can embargo sunlight. No cartel can restrict supply. No war can threaten the shipping lanes.

There is no waste stream. A coal plant produces ash, sulfur dioxide, nitrogen oxides, particulate matter, mercury, and carbon dioxide[10]. A solar panel produces nothing. It just sits there converting photons to electrons, decade after decade.

There is almost no maintenance. No moving parts in the panel itself. Panels installed in the 1970s still generate electricity today, albeit with some degradation[11].

This simplicity is why solar rides such a steep learning curve. When something uses little material because it needs no fuel and can be produced and installed one small unit at a time, improvement compounds faster. The learning of solar

is closer to the learning we know from computing than the learning we know from nuclear and coal.

I've got a roof consisting entirely of solar panels and they deliver twice the energy I need year round (including the electricity for my heat pump and my electric vehicle). In the gloomy Netherlands! Put a little panel on a roof in Africa, attach a small battery and an LED light, and a child can do homework at night, without a kerosene lamp that is poisoning her lungs and that her parents constantly have to buy expensive fuel for. It is worth pausing on how extraordinary this is.

Wind turbines work differently, capturing kinetic energy from moving air rather than electromagnetic energy from photons. But they share the essential feature: once built, the fuel is free, and the wind blows everywhere without anybody able to block it.

4.3 From Stock to Flow

Fossil fuels are a stock with no meaningful inflow: grandmother's savings, draining fast. But sunlight is different. It's not a stock. It's a flow: 173,000 terawatts arriving continuously, whether we harvest it or not. The faucet is always open. It has been open for five billion years and will stay open for five billion more.

This fundamentally changes our relationship with energy. For most of human history, energy scarcity was not a mindset. It was an accurate description of reality. The inflow and stock were both very limited. There was only so much wood in the forest, only so much grain from each harvest. If your neighbor took more, you had less. Zero-sum thinking emerged because the world was, in fact, mostly zero-sum.

When we discovered fossil fuels, we made ourselves believe that we had found a hack out of that scarcity. The stored sunlight of millions of years allowed humanity to escape the immediate constraints of the land. But we drain down our bathtub full of fossil fuels at an alarming rate while the inflow is negligible. And some countries have lots of it while

others have very little. Deep down we always knew that we were spending savings, not earning income. That the bathtub would run dry. That we were living on borrowed time.

Solar and wind are flows that we cannot deplete. If your neighbor installs solar panels, it does not reduce the sunlight falling on your roof. Energy is no longer a competition over fixed resources. Both of you can harvest the sun.

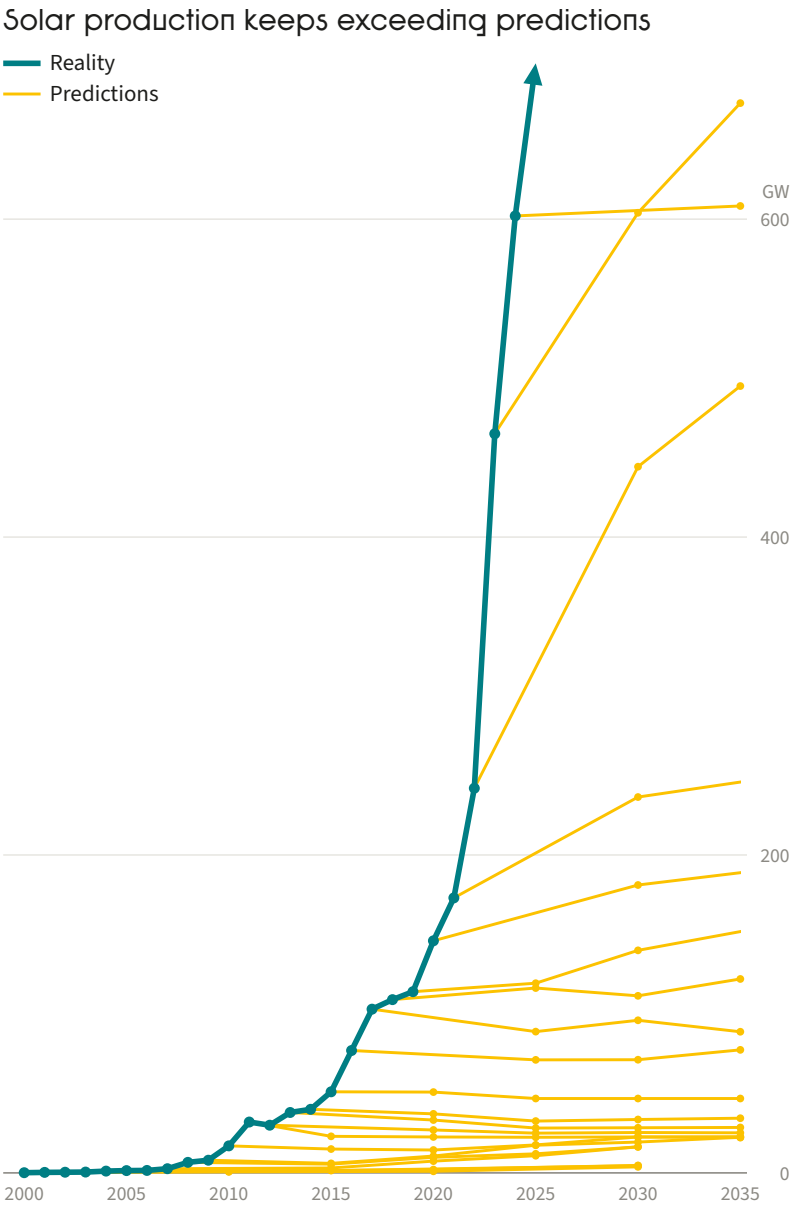
That doesn't mean it's a done deal that this will create human flourishing in harmony with nature. I wouldn't have written this book if I thought that. Building the infrastructure to capture solar energy requires materials, labor, and capital. Status quo interests will make the transition difficult and contested. New stakeholders will try to control us in new ways. Conflicts will not disappear simply because energy becomes abundant.

But the fundamental constraint has shifted. The resource itself, the energy, exists in quantities that dwarf any conceivable human demand. The sun does not need to be discovered, drilled, or transported. It is already there.

The teacher who showed us the burning candle in 1974 was not wrong about the danger. Fossil fuel depletion was real. Climate change was real. What he did not know was that another option was gestating in laboratories, too expensive to matter at the time, but riding a learning curve that would make it cheaper than coal within fifty years.

The scarcity that seemed inevitable has become optional. That is not an opinion. It's simply what the arithmetic shows and in the rest of this book I will explain it in detail.

We thought we were running out. Instead, we were just capturing energy in a very roundabout way. But are these solar panels for real? Most status quo experts still doubt that. So I made a visualisation to show how wrong they are.



I've been making this graph since 2008 and later it gave me my first followers on social media. First it shows reality in the form of solar panels produced each year. That's the rapidly rising thick line. Secondly it shows the predictions. These are the relatively horizontal lines. Both are from the IEA, the International Energy Agency: the biggest and most important thinktank in the energy world. I've taken the "Stated Policies" scenario because the "Current Policies" scenario is even lower. The predictions are from the WEO 2002 to 2025. It's clear reality keeps surprising the IEA.

The Rising Sun

Once I understood that solar panels were our biggest hope I wanted to understand how they developed. I had just taken a sabbatical after 15 years of Internet consultancy. I wanted something new and this seemed to fit the bill.

What I found was that solar was still small but had an incredibly predictable yearly exponential growth. For somebody with an Internet background that is a very recognizable phenomenon. So I started interviewing people who worked in the energy industry, and I started to doubt myself.

The Dutch fossil fuel company Shell was and is one of the leading energy companies in the world. I interviewed people there and they were not convinced at all. How could *they* miss this when I saw it so clearly? The International Energy Agency (IEA), an enormous organization doing nothing else than collecting energy data and interpreting it for governments, didn't seem that convinced either. They had one job. If anybody would know, it would be them I thought naively.

But they told me I was an idiot to believe in Internet 15 years earlier. And it turned out I was right regarding that. So I thought, can't hurt to look at this in more detail. So I took the numbers from their flagship *World Energy Outlook* reports, eager to learn how they thought the exponential revolution would play out. But it didn't. Solar didn't even produce a blip. How could that be?

I dug deeper and made an intuitive leap: "What if they treat solar panels like coal?" Something that is burned in the same year it is produced. Not something that produces energy for

30 years after you put it on your roof like a solar panel does.[1,2] Maybe their model simply can't handle this new dynamic. Their numbers were all in total cumulative solar power production but not in yearly solar panel production.

So I set out to find what these numbers implied about *how many solar panels are sold each year*. The growth of the solar industry if you wish. That information is not shared by the IEA and it took some reverse engineering and guestimating, but it lead to the first version of the graph that would later propel me to some energy system niche fame on twitter and would become the star of articles in PV Magazine[3] and The Economist.[4] It possibly put some pressure on the IEA.[5,6] What I'm most proud of is its inclusion in a TED talk by Al Gore arguing climate action is unstoppable and "climate realism" is a myth.[7] I'm talking of course, about the graph that opens this chapter.

The green line going up sharply is the yearly sales of solar panels. A very clear exponential growth. The almost perfectly horizontal yellow lines are the scenarios of the IEA. Year after year, the model of the IEA accepted that the solar industry had grown, but concluded that now this foolishness would end. Not once, but continuously over a period of twenty years, even though people inside the IEA told me my criticism was well known.[8,9]

But I didn't go public yet. I felt that first I had to find an explanation before making a fool of myself. And boy, did I find one. It's shown most clearly in the picture that kicks off the next chapter.

Calculating Exponential Growth

If you want to become an exponential growth detective yourself, to detect what orthodox experts get wrong, you have to know a little bit about exponential growth. If you like making calculations you might find this interesting. But if that's not your hobby, you might want to skip this sidebar.

So what is exponential growth exactly? Let's calculate something first to show how amazing it is. Let's take solar as the example. Over the last 20 years solar grew exponentially with 36% per year on average.[10] What does that mean?

In 2005, solar produced a mere 0.02% of global electricity.[11] But in 2006 it was 36% more. Still only 0.027% or so. But in 2007 again 36% more. And that gets big fast. To get a growth of 36% you multiply by 1.36. And you do that for every year. So after 20 years you have done that 20 times. If you multiply a number by itself 20 times, mathematicians say you raise that number to the power of twenty. When they program it in Excel or Python they use the "^" symbol to signify that. They use the "*" symbol for multiplication.

So how much does 0.02% become after it grows 20 years with 36%?
0.02 * 1.36 ^ 20 = 8.8%.

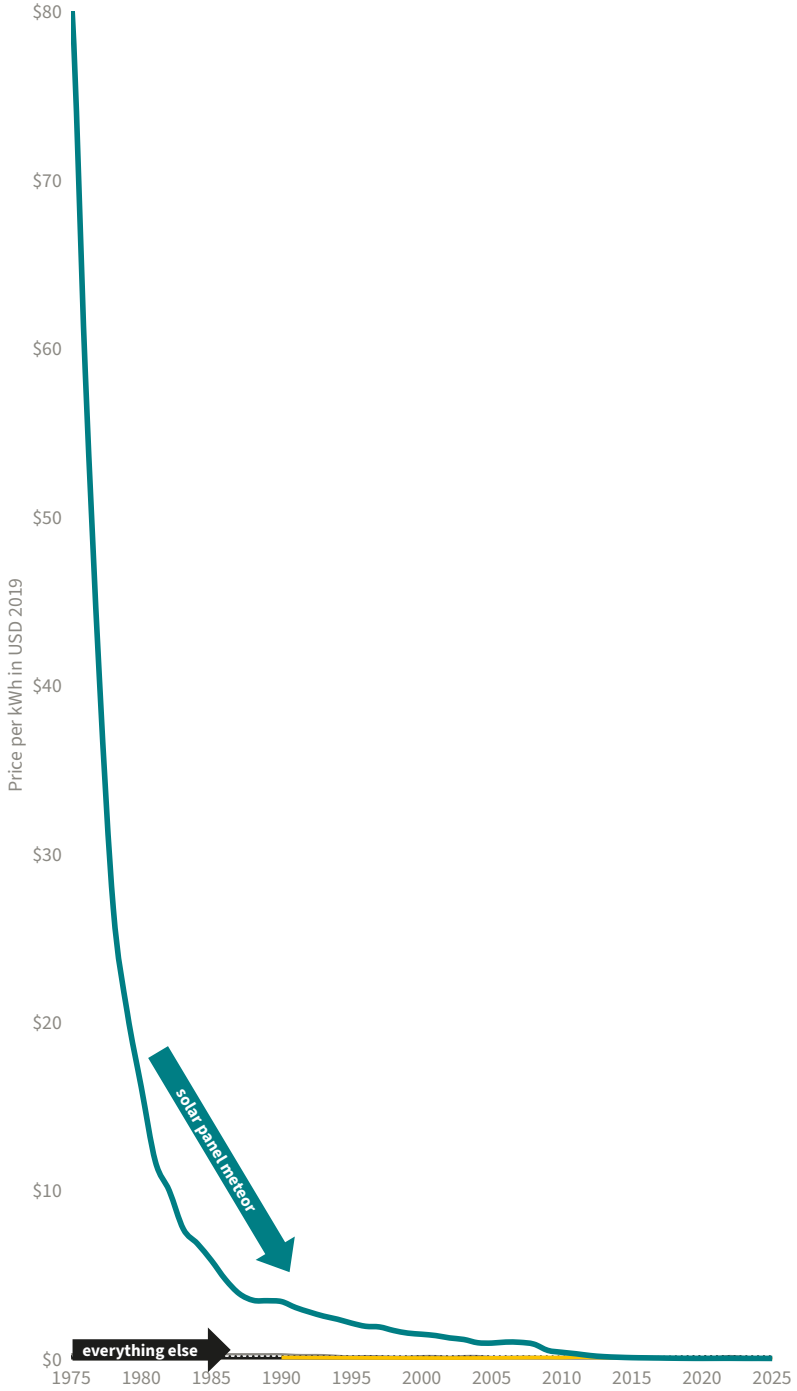
That's where we are today: solar produces nearly 9% of global electricity, a growth of over 400 times in 20 years! If it kept doing that for another 10 years it would be producing over 190% of our current electricity!

We often use the R squared calculation to determine how well our formula fits the data. R squared ranges from 0% for no fit at all to 100% of a perfect fit. Anything over 90% is very very good, and anything over 95% is truly excellent.

In a spreadsheet program you can put the calculated values next to the empirical values and simply use the RSQ function to compare the two ranges. If I do that and compare my empirical data for solar with my exponential function growing at 36% per year, I find the R squared is 97% which means the fit is exceptionally good.

Now that I know the R squared that expresses how well my exponential growth curve fits the data is 97% it is abundantly clear that solar is growing exponentially and that the growth over the past twenty years was around 36%.

The solar panel meteor crashing the fossil fuel party



The Learning Curve Crashing the Fossil Fuel Party

If there is only one thing you take from this book, let it be this: never make predictions about energy without using *learning curves*. Learning curves explain more about our energy future than all the experts and policy debates combined. It changed my life and it will change yours.

But I hadn't found the learning curve yet when I first made the graph from the previous chapter. I just had that graph and a severe bout of imposter syndrome. Who the hell was I to claim I saw something that all these real experts seemed to miss?

6.1 How Learning Curves Changed My Life

I read some papers by academics like Harmon and Nemet on how solar was going down in price 20% for every doubling of production[1,2]. I immediately thought: this is just like Moore's law regarding computer chips that dominated my previous career! Solar cells are even made of the same materials as computer chips!

But academics can sometimes be a bit removed from the real world and I still felt that it was impossible that so few people seemed to notice this. The scientist Richard Swanson had been presenting this insight at conferences since 2003[3], but this was long before *The Economist* coined it Swanson's law and popularized it in 2012. Long before Tony Seba wrote about Clean Disruption of Energy and Transportation[4].

I started to read everything I could find about learning curves for solar and wind until I finally found an industry paper on the topic. It was titled Experience Curves for Energy Technology Policy[5]. Best of all: it was published by the IEA itself. The report convincingly proved that solar was the future I thought, and yet I had this graph proving that the IEA was denying it. How was that possible?

I suddenly thought back of one of my first experiences at work. All of a sudden my imposter syndrome evaporated and was replaced by a stubbornness that propels me to this day.

I remembered a meeting at KPN, the biggest Telecom company in the Netherlands. It was 1994 or so. I was allowed to present my ideas about this new phenomenon called *The Internet* to a group of hotshots. I wanted to show them why The Internet would become very important and eventually replace analog telephony. After my talk I looked around nervously and saw the venerable experts looking at me with pity. "We will set aside 5% of future capacity for these pesky modems of yours, because they often stay connected for long periods" they said to me. An olive branch to this foolish but enthusiastic youngster and his sponsor. Then I was immediately shooed out of the room as the adults continued to discuss important things. Fifteen years later my last project at KPN was called *All IP:* We replaced the last bits of analog telephony with the Internet Protocol. The last bits of the stuff that these venerable experts thought was more important, swept up and put in the dumpster.

Now here was the IEA, exhibiting what felt to me like exactly the same kind of behaviour as those venerable telecom experts. I had seen this movie before! I wasn't going to let myself be shooed out of the room again. This time I would not go quietly into the night. I would not let the planet go to hell in a wastebasket. I would not allow other kids to have the same traumatic classroom experiences. Just because some experts were too stuck in the past, too arrogant and too self-important to admit they were wrong.

I got a paper published in the Dutch Financial Times in July 2007: "the promise of solar cells is that everyone will produce their own cheap energy", I said. The experts, Shell, the International Energy Agency, they all seem to be missing it, but if the trends hold solar electricity will cost 1 cent per kilowatthour in 2032. And now I'm writing this book. Twenty years after the thrill of being published in a newspaper. Fifty years after that unpleasant experience in the classroom. Hoping that *this time* people will listen.

What I've done in the past 20 years is study how we must use this historic chance to revamp the whole energy system to make optimal use of abundant solar energy. I've written Dutch books, started a large research program at the university and a small company that model how to do it cost effectively. A few years back I've realized that combining the learning in solar panels with the learning in batteries and power converters takes the solar revolution to the next level. That's why I needed to write this book. But I'm getting ahead of myself again.

First I want to show you how this learning curve works. I want to give you X-ray vision for the energy transition. By the end of this chapter, you will understand something that has eluded the world's foremost energy experts for decades. You will see why predictions keep failing, why solar and batteries keep winning, and why the future looks radically different from what most institutions expect.

6.2 Practice Makes Perfect (and Cheaper)

Imagine you are installing your first solar panel. The mounting brackets are unfamiliar. The wiring diagram might as well be hieroglyphics. You drop a connector, fumble with the tools, second-guess every step. Four hours later, you have installed a single panel.

Now imagine your tenth installation. You know which tools to grab first. Your hands remember the sequence. You have developed little tricks: this bracket goes easier if you

angle it slightly, that wire clips in faster from the left side. Four hours later the entire roof is done.

Your hundredth installation? You barely think about it. Ninety minutes, and you are already planning lunch.

This is obvious, of course. Practice makes perfect. But something else is happening too, something less visible. Your tools got better because the manufacturer learned what installers actually need. The panels got easier to install because designers heard feedback from the field. The supply chain learned to stock the right parts in the right places. The whole ecosystem learned alongside you.

This happens at every scale: individual workers get faster, companies develop better procedures, industries accumulate shared knowledge, supply chains optimize themselves. Learning compounds like interest.

The remarkable thing is that this learning follows a *predictable pattern*. When humanity does something twice as many times, we get measurably, reliably better at it. Not by random amounts. By consistent percentages.

Most people know this intuitively. What most people do not know, including most energy experts, is what this pattern means for the future of energy.

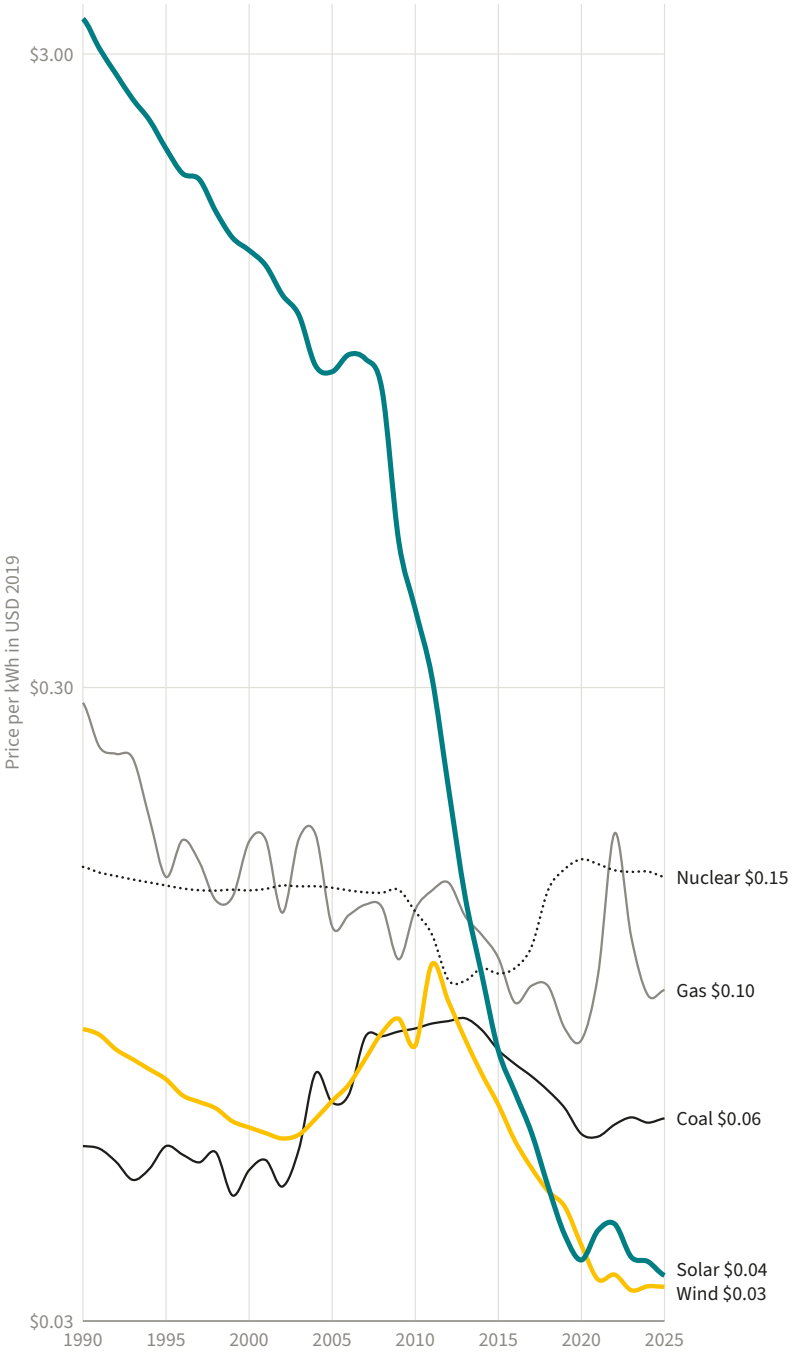
6.3 The Solar Meteor Crashing the Fossil Fuel Party

Now that I had convinced myself that I could extrapolate the exponential growth, I could combine the learning curve from Wrights law to predict the price development per year in the future. Below is a figure that shows what *actually happened*. I call it "The solar panel meteor crashing the fossil fuel party." It's almost exactly the same as what the simple extrapolation showed my energy newbie self in 2007.

First you see the non logarithmic version. I like to think of it of showing the meteor crash clearly but from a distance. It started with solar being eye wateringly expensive in 1975. Back then it cost $80 per single kilowatt hour of energy. On an average day my house and electric car need about 22 kilowatt

The solar panel meteor crashing the fossil fuel party

(logarithmic axis and from 1990)



hours. That means energy would cost me around $2000 *a day* using these 1975 solar panels.

What happened next is hard to see on a non-logarithmic axis. That's why I've repeated the figure on the right. This time using an exponential axis and starting in 1990. It's like you are zooming in. You can see how the cost of solar kept plummeting. It followed Wrights learning curve almost perfectly as production scaled up. The result is that energy from solar panels now costs around $0.04 per kilowatt hour[6]. Roughly $1 per day for my house and electric car. That's 2000 times cheaper in 50 years.

Pause on that number. Imagine any other product in your life becoming 2000 times cheaper. A car going from $50,000 in 1975 to $25 in 2025. A house going from $500,000 in 1975 to just $250 in 2025. It's insane, right? No wonder the experts could not believe this was happening to the energy system they had known all their lives. But it was not insane. It was not random. It was not luck. It was not unpredictable. It was simply Wrights Law playing out decade after decade.

Only wind can keep up with solar somewhat, but even wind is going to be severely undercut in terms of costs by solar.

As you can see from the graph, fossil fuel isn't really learning. It's not keeping up[7]. That's no fault of the fossil fuel industry. It's an inherent and unavoidable result of the fact that fossil fuels are fully mature, don't scale up anymore, and need to burn lots of ever scarcer raw material.

I want to stress that this graph leaves out a lot. For starters, it leave out societal costs as quantified by empirical economists. Societal costs mean we put a number on people dying from particulate matter from burning fossil fuel, on footing the bill of climate change to next generations. Et cetera. In an ideally rational world this would double or quadruple the cost of fossil fuel[8] as we will see in part 3 of the book.

This graph also leaves out the benefits of solar for implementation. Everybody can simply put solar panels on their roof, even in places where there is no grid. Solar is not

only the cheapest but also the simplest to implement, most distributed, most democratic, and hardest to control energy source in history.

In our capitalist society, many problems are attributable to capitalist benefits that do not match societal benefits. For solar, societal benefits and capitalist drive are aligned.

6.4 Wright's Law: The Pattern Behind Progress

In 1936, an engineer named Theodore Wright noticed something peculiar about airplane manufacturing[9]. Every time the cumulative number of aircraft produced doubled, the cost per plane dropped by roughly 15%. Not randomly. Not sometimes. Every time.

This was not a policy. No one had decreed that planes should get cheaper at this rate. It emerged from the activity itself: from workers learning, from processes improving, from designs evolving through experience.

Wright had discovered a law of industrial learning. Every doubling of cumulative production yields a fixed percentage reduction in cost.

The pattern turns out to be remarkably robust. It applies to ships and semiconductors, to chemicals and cars. And it applies, with particular force, to the technologies of the energy transition.

Solar panels have followed Wright's Law with startling consistency. Since 1975, every doubling of cumulative solar production has reduced costs by approximately 20%[10]. In 1975, a watt of solar capacity cost about $106. Today it costs around $0.20[11]. That is a 99.8% decline, tracking the learning curve almost exactly.

Wind turbines show a gentler but still powerful curve: roughly 12% cost reduction per doubling[12]. Wind started from a lower cost base than solar, so the absolute savings per doubling are smaller. But the pattern is the same. Modern wind turbines produce electricity at a fraction of what they cost two decades ago, and the learning continues. Offshore

wind, still early on its curve, is falling even faster as the industry masters the challenges of building in the ocean[13].

Batteries show an even steeper curve: roughly 28% cost reduction per doubling[14]. Lithium-ion batteries have fallen from over $1,000 per kilowatt-hour in 2010 to under $140 today[15]. This is the technology that makes intermittent renewables dispatchable, that enables electric vehicles, that will eventually let your home ride through blackouts on stored sunshine. And it is still learning fast.

Digital power converters are the unsung heroes of the energy transition. Every solar installation needs an inverter to convert the panel's direct current into the alternating current your appliances expect. Every battery needs a bidirectional inverter to charge and discharge. Every electric vehicle charger, every grid-scale storage system, every wind turbine depends on power electronics to manage the flow of electricity.

These devices have followed the semiconductor learning curve, benefiting from decades of progress in digital electronics[16]. The same manufacturing improvements that made your smartphone cheap and powerful have made solar inverters cheap and reliable. A residential solar inverter that cost thousands of dollars fifteen years ago now costs a few hundred, and does more.

The beauty of this quartet is that they learn together. More solar and battery deployment means more inverter production, which means cheaper inverters, which makes solar and battery installations cheaper, which drives more deployment. Cheaper batteries make solar more valuable by storing midday surplus for evening use, which drives more solar deployment, which drives more battery deployment. The learning curves reinforce each other.

These are not projections or hopes. They are measurements, extracted from decades of data.

Twenty percent per doubling might sound modest. It is not. Doublings *compound*. Ten doublings in solar production means cost fall to 10% of where they started.

Wright's Law does not tell you when doublings will happen. That depends on demand, investment, and deployment. But it tells you what happens when they do. If you can estimate future production, you can estimate future costs with surprising accuracy.

This is the closest thing to a crystal ball that the energy world has. And for decades, the most influential energy institutions refused to use it.

6.5 Why the Experts Missed It

Why could outsiders like me see the pattern, while the International Energy Agency, with hundreds of analysts and decades of data, could not. This is not about intelligence. The experts I've met are smart people, often brilliant. So what went wrong?

Part of the answer lies in what Thomas Kuhn called paradigm blindness.[17] Experts trained in one paradigm struggle to see another emerging. The energy analysts who built their careers on fossil fuels understood extraction: finite resources, geological constraints, depletion curves. Their mental models assumed scarcity.

Learning curves assume something different. They assume improvement through practice. They assume that doing more of something makes you better at it. This is a fundamentally different way of thinking about energy, and it was almost invisible to people steeped in the old paradigm.

I had an advantage they did not: I came from a world where learning curves were the whole story. In telecom and computing, everyone understood that costs would fall with scale, that performance would improve with each generation, that today's expensive novelty would become tomorrow's commodity. This was not a revelation; it was the water we swam in. When I looked at solar, I saw something familiar. They looked at solar and saw something foreign.

There is also the problem of exponential growth itself. Humans intuitively think linearly: we underestimate exponential growth and perceive it in linear terms[18,19,20]. If something

grew this much yesterday, our intuition expects it to grow about that much tomorrow. Exponential growth feels wrong, implausible, suspicious. Even people who understand exponentials intellectually struggle to feel them in their bones.

The IEA, again and again, assumed solar growth would slow down. Every year they bend down the exponential curve. This is what happens when human apply intuition to a domain where human intuition fails.

And then there is institutional inertia. Energy agencies advise governments. Governments plan infrastructure. Infrastructure takes decades. Admitting that your predictions were systematically wrong threatens your credibility. It is easier to adjust slightly than to admit the model is broken.

The cost of this collective blindness is difficult to calculate. By my count it's at least dozens of trillions in misallocated investment. Decades of delayed climate action. Countless decisions made on faulty projections. The world built gas plants and planned coal expansions when it should have been building solar farms and battery factories.

But recrimination is not the point. Understanding is. Now that you see what they could and maybe can not, you can evaluate energy forecasts for yourself. When someone tells you renewables are too expensive, or that growth will slow down, or that we will always need fossil fuels, you can ask: are they using learning curves? If not, why should you trust their numbers?

6.6 Why Solar Learns Faster: The Physics of Improvement

Wright's Law applies to many industries, but not all industries learn at the same rate. Solar's 20% learning rate is steep. Nuclear power, as we saw in the previous chapter, has a negative learning rate: newer plants cost more, not less[21]. What explains the difference?

The first answer lies in what engineers call material intensity: how much physical stuff you need per unit of useful output. Coal power requires enormous quantities of material. You have to mine the coal, transport it (often across

continents), combust it, and deal with the ash and emissions. A coal plant needs massive boilers, extensive pollution controls, and constant fuel delivery. Every megawatt-hour requires hundreds of kilograms of material to be moved, processed, and disposed of[22].

The second answer lies in unit size: if it's a product that is produced again and again so there's plenty of opportunities to learn, or if it's a megaproject. Nuclear power plants are megaprojects and every time there is learning about what could go wrong, it potentially makes the next megaproject more expensive. It also requires extraordinary precision engineering: containment vessels, cooling systems, radiation shielding, multiple redundant safety systems. The materials may be smaller in volume, but the complexity is immense, and that complexity grows with every safety upgrade.

Solar is different. A solar panel is essentially a thin layer of processed sand, arranged to catch photons. That's it. No fuel to mine or transport. No combustion. No cooling towers. No emissions to scrub. The entire system is solid-state: no moving parts in the panel itself.

The result is startling: solar uses over 100 times less material per unit of energy delivered than fossil fuels[23]. And that is before we start recycling, which is much harder to do with stuff you burn and blow into the atmosphere.

This matters because of where learning can happen. When raw materials dominate costs, learning is constrained. You can get better at mining coal, but digging is a pretty mature technology and with the amount of mass you need to move, coal is pretty close to its floor price. With megaprojects, most people will only do one project in their lifetime. There is very little potential for learning. But when material costs are low and research keeps bringing them down, when costs are dominated by fabrication and assembly that is repeated time and time again, learning is unleashed. Every step in the research and production process becomes a target for improvement.

Solar panels are, in this sense, closer to making microchips than to mining. They benefit from the same learning dynamics that gave us smartphones and laptops: the relentless refinement of semiconductor manufacturing[24]. Silicon, copper, aluminum, glass, and a bit of silver, combined with manufacturing techniques that improve year after year.

Digital power converters are very similar and resemble chip manufacturing even more closely. Recent breakthroughs in power transistors (like the tiny switches on your smartphone chip but larger and able to handle much more electricity) promise extremely powerful power converters with energy losses below 1%[25]. Low losses in turn means little heat which in turn means smaller devices using less material. Which in turn means they can become cheaper still.

This is why my telecom background let me see the pattern. I had watched semiconductor economics play out for a decade. Solar was the same story in a different costume.

Wind turbines sit somewhere in between. They have more mechanical complexity than solar panels: gearboxes, generators, blades that must withstand decades of stress. But they too benefit from manufacturing learning, from better materials, from designs refined through millions of operating hours. The 12% learning rate reflects this middle position: not as steep as solar, but still powerful over time.

Batteries surprised me. I had expected them to have lower learning curves because of the material costs. But it turns out this is the most vibrantly innovating field of all. Maybe because it's not about mechanical systems but about better chemistries and production processes where so much is still unknown. Expensive metals like cobalt and nickel are being replaced by iron and phosphate. The resulting batteries have material costs that are trending towards just $10 per kWh[26]. And sodium batteries that replace lithium metal with sea salt have the potential to bring the material costs much lower still[27].

This learning is not a policy outcome. Yes, governments investing in science stand at the basis of these breakthroughs. Yes, the German *energiewende* made it possible that solar panels scaled up when they were still expensive, and this drove their global price reduction[28]. But no government decreed that solar should learn faster than coal. It emerges from physics, from the fundamental nature of what these technologies are and how they are made.

And this is why my optimism is not based on hope or faith. It is in the physics of the technology itself. The learning curves will continue because the physics allows them to continue. The only question is how fast we move down the curves.

The Math Behind Wright's Law

For those who want to verify the pattern, here is the mathematics. Wright's Law is expressed as:

$C(n) = C(1) \times n^{-\alpha}$

where C(n) is the cost after n cumulative units of production, C(1) is the cost of the first unit, and α is the learning coefficient.

The learning rate is related to α by the formula: learning rate = $1 - 2^{-\alpha}$. For solar panels, α is approximately 0.32, yielding a learning rate of about 20%[29]. This means costs fall to 80% of their previous level with each doubling of production.

You can test this yourself. Plot the logarithm of cost against the logarithm of cumulative production. If Wright's Law holds, you will see a straight line. The slope of that line is −α. Researchers have done this for solar panels going back to 1975, and the line is remarkably straight[30].

The math does not tell you when doublings will happen, only what happens when they do. Forecasting deployment is harder than forecasting learning. But once you know the learning rate, and once you have a deployment scenario, the cost trajectory follows.

This sidebar is for those who want to check my homework. The main text has everything you need.

When Growth Slows Down

A reasonable objection: nothing grows exponentially forever. At some point, solar growth must slow. When?

Technologies typically follow an S-curve: slow initial growth, then rapid expansion, then saturation as the market fills up.[31] Refrigerators followed this pattern. So did televisions, mobile phones, and cars.

The question is not whether solar will saturate. It will, eventually, when most suitable surfaces have panels and most electricity comes from the sun. The question is where we are on the curve.

The answer, by almost any measure, is early. Solar provided less than 9% of global electricity in 2025[32], and as the transition progresses, more and more processes will be electrified. We can expect decades of growth before saturation.

The same applies to batteries and power converters. Three quarters of cars sold by the end of 2025 will still contain a combustion motor[33]. Stationary storage is just
beginning to scale. The learning has decades to run.

The experts kept predicting the slowdown would come next year. It kept not coming.

7

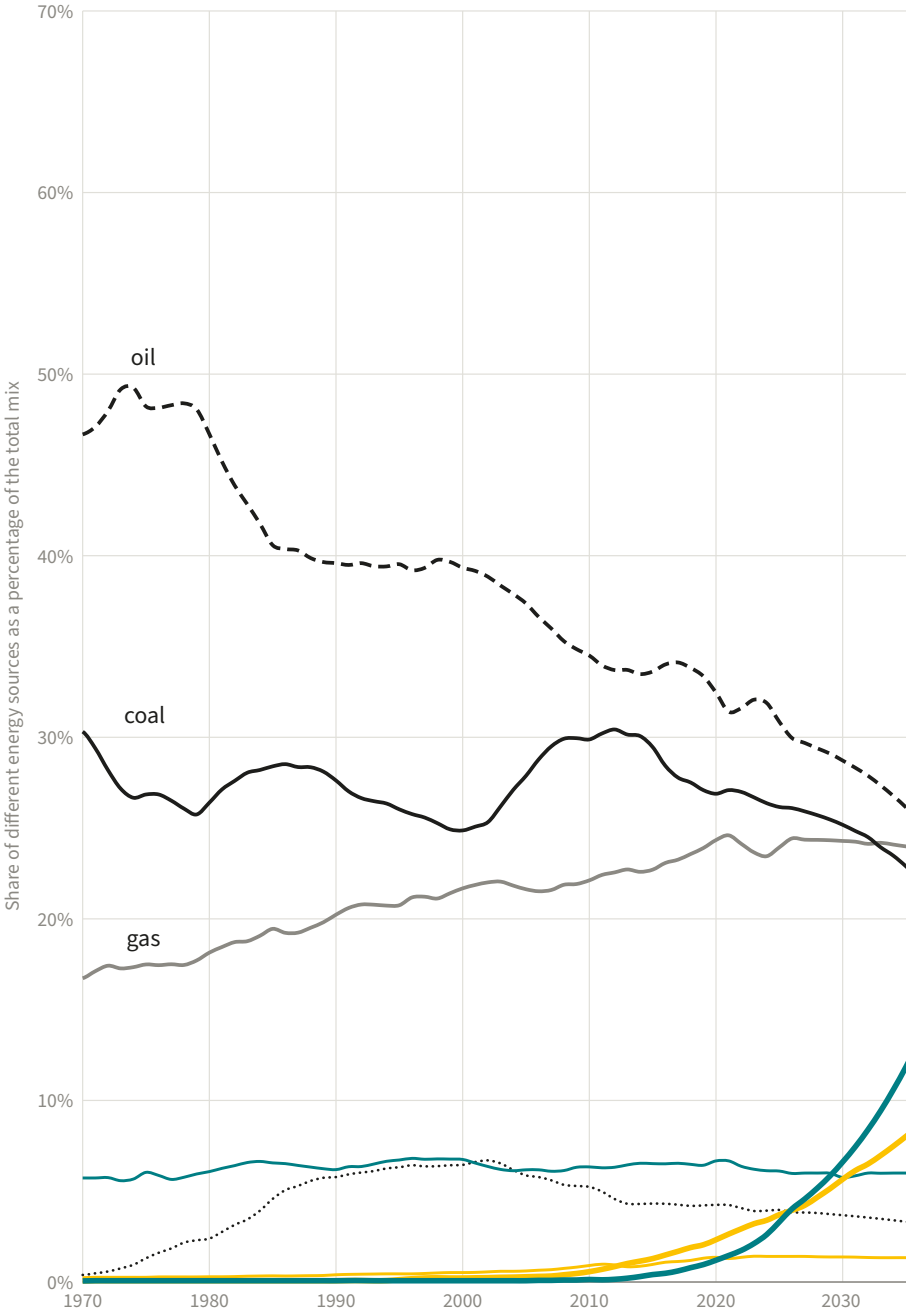
Our Sunny Future

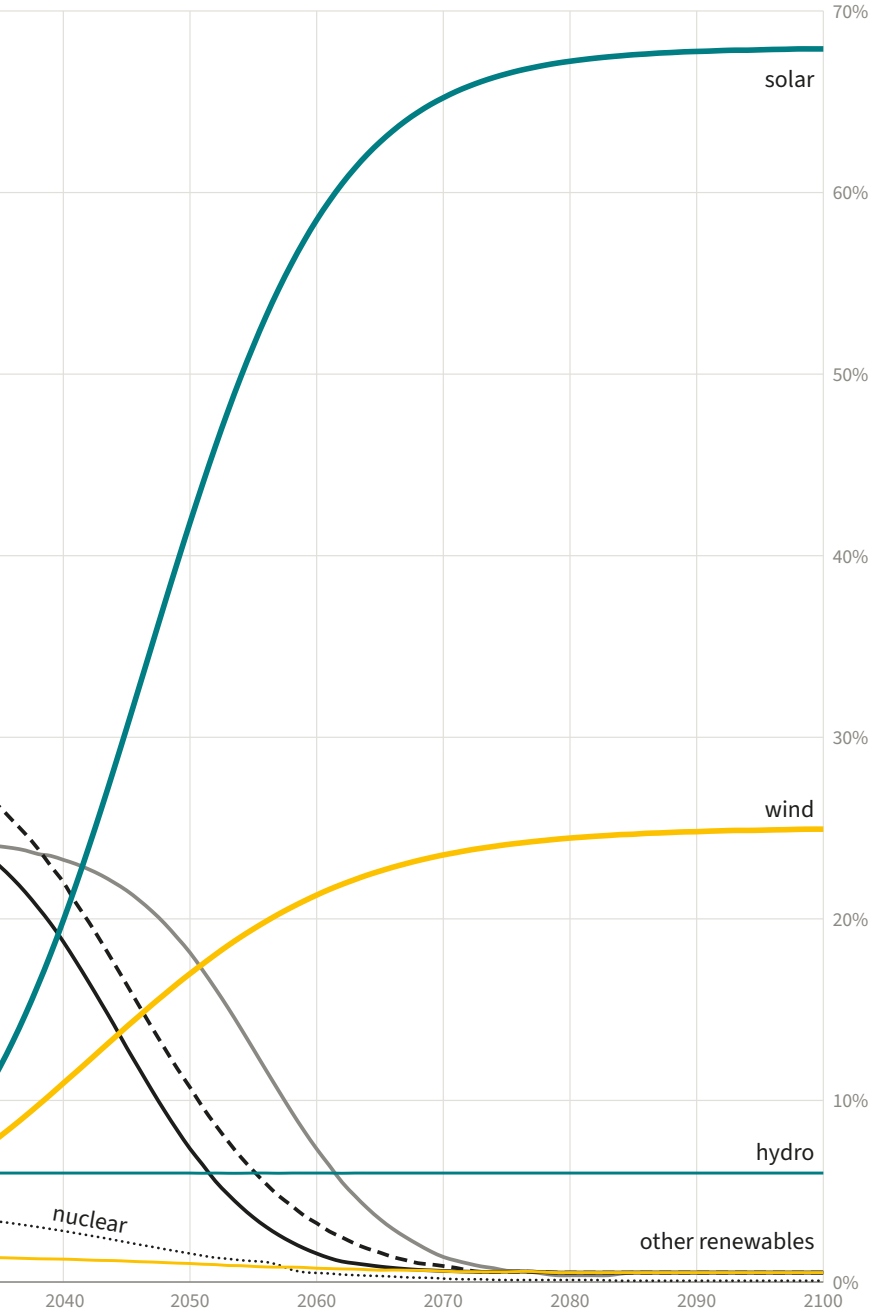
We have a virtuous cycle of growth driving cost reductions, driving growth, et cetera.[1] This flywheel will end the fossil fuel interlude that started a century ago.[2] Our civilization that adopted fossil fuels during the industrial revolution, will turn to cheap, clean and abundant electricity from solar panels and wind turbines. It will do so in the coming decades.

Can change really be so rapid? Can we really put a stop to one million years of burning stuff so quickly?[3] It seems almost impossible. Especially to the experts that know the status quo best. Still it seems to me, this is where the observed trends, commercial advantages, societal benefits, and logic all point to.

The graph shows what I see happening in the data, to the best of my abilities.

My prediction for the energy transition




70%
60%
50%
40%
30%
20%
10%
0%
solar
wind
hydro
other renewables
nuclear
2040
2050
2060
2070
2080
2090
2100

It's based on my attempts to extrapolate developments I think the data shows. However, I have not been able to quantify all developments deeply with the limited time and manpower I've been given. On top of that, predicting the future is notoriously hard. You can trust the directionality, but you should take the exact percentages with a grain of salt.

- Solar growth seems impossibly steep, even to me. But this trend is so rock solid statistically that I decided to put it first. If fit an S-curve to the data of the past 20 years and I was able to find a trend that fit the data with uncanny precision. (If it means anything to you: R2 99.8% and NRMSE 2.0%.) And every time during the 20 years that I denied the historic data a straightforward best-fit extrapolation, the extrapolation proved to be more correct than I was. Let alone when the data fits so extremely well. I can also explain and understand it. That's what most of this book is for. So here goes nothing. This is my prediction.
- Wind will continue to be the cheapest backup to solar in areas with lots of wind and little solar in winter like my country the Netherlands.[4]

The trend fits the data only marginally less extremely well than the solar growth data. (R2 99.7% NRMSE 2.8%) And again I can understand and explain it, so I've decided to run with it, even though is far outside the mainstream.

- Hydro will expand a little in absolute sense, but the places where it can be realized are limited,[5]

still apart from the impact this has on local ecosystems.[6] Therefore it will slowly shrink in overall market share as overall energy use grows.

- Fossil fuels will gradually become less and less commercially attractive. They will basically be pushed out of the market by wind and solar. There is simply no reason to use these more expensive and more polluting fossil fuels for electricity or for driving vehicles anymore. The so called "hard to abate sectors" like long distance flying and shipping will continue to use fossil fuel longest, especially oil.[7]

My expectation is that even there will come a switch to eFuels and direct electricity after 2050. This based on a combination of regulation (a feeling of "let's finish the job now that we have completed 90%") and market push. Oil will remain in use as a feedstock. Just not as an energy source (except for niche applications like old-timers). Gas benefits from the shale gas revolution that substantially lowered fuel costs, making gas-fired generation competitive with coal on a per-MWh basis in many regions,[8] while the investment cost of a gas fired power plant is much lower than that of a coal plant.[9] So as solar and wind become more prominent, gas peakers are better able to make a profit while not working most of the time.[10]

- Nuclear will profit from recent initiatives but will still start a slow decline in market share,[11]

based on a combination of commercial unattractiveness,[12] although nuclear can be technically used flexibly,[13] it is a bad economic fit with solar and wind,[14] unpopularity compared to solar,[15] and a desire to get rid of nuclear weapons.[16]

- Biomass from agriculture and forestry will be used as feedstock or food, but will be phased out as fuel. It has become clear in recent decades that substituting fossil fuel with biomass is not helpful for nature[17]

or human health.[18] But geothermal and some other niche renewables will make up for that.

I'm not religious anymore but it was almost like someone had put that data there and was trying to tell us something. Like reality was leaving trails of breadcrumbs for us to follow. Still, the Calvinist I am at heart couldn't believe it right away. The first and most obvious question seemed to be: did we have the materials for all these solar panels, wind turbines and batteries?

S-curves fitting

In the previous chapter, I showed you how to construct exponential growth curves, so you can see what linearly thinking experts miss. If you stop here, you are already ahead of the pack. That's what I did for years when I started out to be honest. But if you want to upgrade you skill to the advanced level, and you are not afraid of math, this explanation is for you.

Exponential growth never lasts forever. After it has reached about 50% of its maximum it starts to level off. For example, if solar kept growing from current levels at 35% per year for 20 years, 1500% of our electricity would come from solar. That's clearly nonsensical and it's why we need the S-curve. It's called an S-curve because it looks a bit like an S. The graph illustrating the end of the fossil fuel interlude shows S-curves for solar and wind.

If I extrapolate exponential growth with S-curves I use a six step process:

1. Gather all the empirical data you can and put it into a time series that is your historic reality.

2. Estimate your maximum value for the growth. For example, I estimate solar will eventually produce 68% of our energy because it will be by far our cheapest and most easy to implement form of energy generation. It can come out of your data partially, but it's essentially unknowable from your trend if you estimate further in the future. The data can tell you a lot about the steepness of the trend but less about when it will end. You have to defend your maximum using logic.

3. Choose your middle year. That's the year when growth is 50% of the maximum. You will play around with this number later. Just choose something. My initial guess for solar was 2045. I later modified it to June 2039.

4. Choose the steepness of your curve. Often 0.2 is a good start for a transition taking a couple of decades. This is the other value you will play around later. For solar 0.2 proved the optimum fit.

5. Create a second time series (next to your time series from step 1) based on the formula for an S curve and filling in the values from step 2, 3 and 4. Extend these calculated values as far into the future as you like. They will usually level off soon to become close to your maximum.

6. Play around with the middle year and the steepness of the curve to get the best fit for your historic data. I usually try to maximize the R squared value and the NRMSE at the same time.

In this case I could see, just by eye, that the fit for solar would be good, but I did not expect what I got. I optimise using a combination of NRMSE and R2 at the same time. I don't use a solver. I find it goes just as fast by hand and gives you a feel for the data.

Let's start with the NRMSE. That's the sanity check and it has priority for me. The NRMSE is less well know but growing in popularity and I consider it more important overall. It measures how close the data is to your values. An NRMSE of 2% (also written as 0.02) means that on average your trend is within 2% of the value of the data points. Try to get it as low as possible. The NRMSE of 2% for solar is not perfect but pretty darn good.

Then the R2. That one is a bit unreliable in the sense that it tells you a lot about how well the *shape* of your trend fits the data but not so much about how near the trend is to your data points. Many papers still use R2 exclusively and that was fine in the olden days when estimating linear trends was considered state of the art. But with exponential trends and S-curves, R2 by itself doesn't cut it anymore.

Still, once your NRMSE is within acceptable bounds, the R2 is a great way to know how well the shape of your curve matches the data. With an R2 value of 99.8% (sometimes written as 0.998) we say that the trend explains 99.8% of the data. For processes that we see in reality, any value over 90% is pretty good. A value of 99.8% is *ridiculously* good.

Same for wind. Here I found an S curve with a steepness of 0.13, middle year of 2036.9, and maximum of 24%. That gave me an NRMSE of 2.8% and an R2 of 99.7%. Also an almost incredible fit. I would challenge any expert to explain to me why they made a different fit to the data and to defend why that's more accurate.

If you want to calculate an S-curve in a programming language or spreadsheet, you have to use a function that raises the natural number e to an exponential. My advice: don't try to understand what I just said and simply use the EXP function and the rest of the standard formula. In that case calculating the S-curve in LibreOffice Calc, Microsoft Excel, or Python means simply filling in the formula below for every year you want to calculate:

value for a certain year = maximum / (1 + EXP(−steepness * (year − middle_year))

Doing More With Less

Abundant energy… feels fishy right? The sun delivering ten thousand times more energy than we need. Learning curves making clean alternatives super cheap. Fossil fuel simply displaced by something better. No running out of raw materials anymore. It all sounds too good to be true. It *feels* too good to be true. I know that feeling, believe you me.

I'm Dutch. We have a Calvinist tradition that runs deep, a conviction that nothing good comes without suffering. "By the sweat of your brow you shall eat bread," Genesis tells us. No easy guilt-free flourishing for us. No having your cake and eat it too. No such thing as a free lunch.

I try hard to be sustainable. I drive electric. I build a house from wood. It produces more energy than I use. I avoid flying. Eat no meat. I really try. But I still feel guilty. Because it's actually a very *nice* wooden house. A very *nice* electric car. And my wife's vegan cooking is *wonderful*. So it feels suspiciously easy. *Too* easy. Why would I have it so good when so many others have it so bad?

That's the kind of person I am. So take it from me: I take the objections to abundant energy very seriously. Both rationally and emotionally. I've spent most of my life wrestling with them, and I'm still wrestling. I can't help it. It's also what initially attracted me to the report *The Limits of Growth* as described in chapter 1.1 and later the degrowth movement. They put things I was taught to care about first: helping people in poor countries, staying within planetary boundaries,

not chasing after endless growth on a finite planet. That felt trustworthy. Morally serious.

Some readers will recognize this feeling. Others might think I'm strange. But at least I hope you all believe me when I say I take the objections to abundance very seriously. Nevertheless, I was wrong.

8.1 The Things We Really Need to Degrow

Degrowth appealed to my guilt. It told me that my suspicion of comfort was correct, that abundance itself was the problem, that the only ethical path was less. Consume less, produce less, want less. Share the shrinking pie more fairly. And degrowth is right that we are already exceeding planetary boundaries while far too many people live in abject poverty and we should do something about all that.

But the solution they offer doesn't survive contact with reality. Austerity combined with redistribution. Managed decline for the wealthy nations. These are political nonstarters. You are asking billions of people to vote for decline, and democracies don't vote for decline. Dictators don't choose it either, by the way. You might get a few percentage points of voluntary reduction, but you will never get the factor ten or more that we need. It's just magical thinking that feels good when you're on a guilt trip.

It also doesn't help the planet. Even if you somehow achieved this unprecedented redistribution, the planet wouldn't notice. You'd have the same total energy use, just distributed differently. The same carbon emissions. The same material extraction. The planet doesn't care who burns the coal. To really make an impact through reduction, we would have to use radically less energy globally, and in any realistic scenario that would cause suffering on a scale I find unacceptable. Simpler technology doesn't help either. I discovered that per person, hunter-gatherers needed an area of between 20 and a whopping 1,000 square kilometres.[1,2]

In the end, I decided that degrowth appealed to me because I was like a junkie and degrowth was the dealer

providing me with the guilt trip I felt I needed to feel. It was an unhealthy relationship. It didn't make me happy. It didn't offer workable solutions. And most importantly for the debunker I am at heart: it got its facts wrong.

So I put my feelings aside and started calculating and gathering facts. First I did a deep dive into planetary boundaries. I found the problem isn't wealth. The problem isn't energy. These abstractions don't transgress planetary boundaries or cause poverty. The real problems are far more specific.

Raw materials, geopolitical tensions, land use, and pollution. Those are the things we need to degrow. These are the real concerns. They deserve serious examination. They are what the coming chapters of the book are about. And when you examine them, they dissolve. Not because they're unimportant, but because the solutions are better than we thought.

Let's start with raw materials. What if I told you we could use give every human on earth abundant energy and *still* use a *thousand* times less raw material?

8.2 Coal Is Consumed, Sunlight Is Forever

Fossil fuels are consumed. Every kilowatt-hour requires new fuel to be mined, transported, and burned. The material passes through once and is gone forever, transformed into carbon dioxide and ash. You cannot recycle exhaust. The coal that powered last year's electricity is now dispersed in the atmosphere.

Solar panels work on sunlight that's produced fresh daily. Solar panels themselves aren't used up. They sit on your roof for thirty years, converting photons to electrons. When the panel eventually gets a lower efficiency, you can take it apart and recover the components.

That's the ideal, but we live in a less than ideal world. So here are the realistic numbers.

To produce one kilowatt-hour of electricity with coal, you have to burn approximately 500 grams of coal.[3] That coal is gone. It also produces carbon dioxide as it burns by combin-

ing the carbon atoms with oxygen atoms. Every 500 grams of coal produces roughly one and a half kilos of carbon dioxide that is dispersed through the atmosphere.[4]

To produce one kilowatt-hour with a complete solar system, panels plus batteries plus power converter, you need approximately 2 grams of material spread across the lifetime of the equipment. That's already 250 times less. Before any recycling. Before any future improvements. Right now. That's not a policy standpoint. It's a physical fact.

But we can do much better. Those 2 grams of material don't vanish when the panel reaches end of life. The emissions are also not as dispersed as tailpipes and chimneys. We could bring the solar panels to recycling addresses when they reach end of life after 35 years of so. With 95% recycling, already achievable for most components, you need only 0.1 grams of new material from mines per kilowatt-hour. 500 grams versus 0.1 grams. That's 5,000 times less raw material. Pause on that. Five thousand times. That's not an incremental improvement. That's not something you achieve by preaching and talking people into feeling guilty. Five thousand times less is an entirely different category of thing.

The bathtub metaphor helps me to understand this. From the perspective of consumers, coal isn't just a stock we're draining: it's flow we keep consuming continuously. Every kilowatt-hour requires new material through the system that is burned and gone at the end. But silicon, copper, aluminum? These are stocks we're building. The atoms don't vanish when used. They stay put, available for the next cycle. Coal flows through and disappears. Metals accumulate and persist.

With solar and proper recycling, we could produce three and a half times more energy than we use today while extracting a thousand times less material from the Earth. This is effective degrowth. Degrowth of something that matters. Not asking billions to sacrifice. Building systems so efficient that the question of sacrifice doesn't arise. It still *feels* too good to be true for me, but here's where the facts lead me.

The 500 Grams vs 0.1 Grams

How much raw material does it take to produce one kilowatt-hour of electricity?

Electricity from	Input (g/kWh)	Raw material cost (cents/kWh)	CO_2 output (g/kWh)
Coal	500	5	1,500
Natural gas	200	10	500
Diesel generator	220	17	1,270
Solar system	2	0.4	0
…with 95% recycling	0.1	0.2	0

Sources: Coal consumption and efficiency from[5]. Coal CO_2 lifecycle from[6]. Natural gas from[7] and[8]. Diesel from[9]. Coal price from[10].

For fossil fuels, I've counted only the fuel itself. Note the CO_2 column: burning one kilogram of coal produces roughly three kilograms of CO_2 because the carbon combines with oxygen from the air.

For solar, I've included everything needed for a standalone system: the panels themselves, the batteries for storage, and the power converter.

Without recycling, solar uses 250 times less material than coal.

With 95% recycling, solar uses 5,000 times less new material from mines.

This dematerialization explains why the learning curve that we already talked about can be so steep for solar. When raw materials dominate your costs, improvement is constrained. You can optimize mining, but digging is a mature technology. With coal, raw material costs are about 5 cents per kilowatt-hour. That's a floor you can't get under.

When materials are a tiny fraction of lifetime energy output, learning can compound indefinitely. Solar's raw material cost is heading toward 0.2 cents per kilowatt-hour, and it can go lower still. Dematerialization is the engine of the learning curve.

8.3 What's Actually Inside

Critics talk about "critical minerals" as if solar panels were made of rare and exotic substances. The reality is more mundane.

A solar panel is mostly glass. About two-thirds by weight. That's sand, essentially, processed into sheets.[11]

The frame is aluminum, about 13%.[12]

Aluminum is the third most abundant element in Earth's crust.

Then comes the plastic encapsulation of the cells and the backsheet, about 10%.[13] The silicon that actually converts light to electricity is only about 2.5% of the panel's weight. Glass and silicon are made from SiO_2, more commonly known as "sand."

Copper for wiring makes up about 1%. Silver appears in trace amounts that are being replaced by copper.

More than 90% of a solar panel, by weight, is made from sand, aluminum and plastic. Not exactly scarce resources.[14]

Materials in a 10 kWp Solar System

A 10 kWp (kilowatt-peak) solar system can power a typical European home, including heating and an electric vehicle.

Solar Panels (10 kWp)

Material	Weight (kg)	Cost ($)
Glass	280	85
Aluminum (frame)	53	139
Polymers (EVA + backsheet)	43	50
Silicon	11	28
Copper	5	52
Other	23	42
Total	~415	~396

Material weights based on[15] composition data for standard crystalline silicon modules.

LFP Battery (10 kWh)

Material	Weight (kg)	Cost ($)
Steel casing	15.0	9
Graphite anode	11.1	9
Iron	6.0	5
Phosphorus	4.0	4
Copper	2.0	32
Lithium	0.8	40
Other	26	15
Total	~63	~114

Battery composition from[16].

Glass and aluminum dominate by weight. The “critical minerals” everyone worries about are small fractions. The total raw material cost is around $765 for a system that will generate electricity for 30 years.

Batteries tell a similar story. The chemistry that's winning, LFP or lithium iron phosphate, uses iron and phosphorus as its main active materials. Not cobalt. Not nickel. Iron and phosphorus.

A 10 kilowatt-hour LFP battery contains about 6 kilograms of iron, 4 kilograms of phosphorus, 11 kilograms of graphite (carbon), and less than 1 kilogram of lithium.[17] The lithium that makes headlines is a little over 1% of the battery pack weight.[18]

Glass, silicon, aluminum, iron, phosphorus, carbon. These are not exotic substances. When people talk about resource scarcity in renewables, the most discussed materials are lithium, cobalt, rare earth metals, and copper.

8.4 Lithium: The "New Oil" That Isn't

Of all the materials critics worry about, lithium gets the most attention. "White gold," they call it. The new oil. The resource that will determine who wins the twenty-first century.

I understand why. Electric vehicles run on lithium batteries. So do grid storage systems. Demand is growing at about 30 percent per year.[19] If lithium was truly scarce, we might have a problem.

But lithium is not scarce. Not even close.

As of 2025, the world has identified about 115 million tonnes of lithium resources.[20] Current annual production is about 240,000 tonnes.[21] At this rate, identified resources would last almost 500 years. And "identified" is the key word. Every time production increases, exploration increases. New deposits are found in new places: Germany, Canada, Mexico, the United States, across Africa. The reserves grow alongside the demand. I did a deep dive recently and found a whopping 95% correlation between production and reserves. And this is before we start talking about getting it from sea water where it is truly abundant. So the idea that it is scarce is ludicrous.

On top of this there are alternatives. In April 2025, CATL, the world's largest battery maker, launched the first mass-

produced sodium-ion battery for electric vehicles.[22] Sodium sits right below lithium on the periodic table, behaves similarly in batteries, and is over a thousand times more abundant in Earth's crust.[23] It is literally the main ingredient in table salt. Sodium-ion batteries store a bit less energy per kilogram but CATL's newest sodium batteries already achieve 175 watt-hours per kilogram, approaching lithium iron phosphate territory.[24] For city cars, delivery vans, and stationary storage, this is more than enough.

None of this means lithium mining is unproblematic. In Chile's Atacama Desert, the world's second-largest lithium producer,[25] mining companies pump brine from beneath ancient salt flats and let it evaporate in enormous ponds. Now it's not that anything lives in the salt flats where this happens. But the dropping water tables lead to land subsiding around extraction wells. Indigenous communities have filed complaints and organized protests. The Chilean government has sued mining companies for exceeding water extraction limits.[26] For that reason, I'm glad that production has shifted to countries like Australia that now produces more lithium than any other country.[27] Hard rock mining generates tailings and requires significant energy, but this energy increasingly comes from solar panels, there is no water scarcity, and Australia has strong environmental regulations. Personally, I think the future is filtering brine from deep wells and sea water that I expect will become both easiest and most sustainable.

But the question is not whether lithium mining is perfect. Mining never is. The question is whether lithium scarcity will block the energy transition. And the answer is no. We already know where to find enough for centuries, there are large deposits on every continent, and sodium batteries could take over if lithium ever became a problem.

Lithium is not the new oil. Oil is geologically concentrated in a few places and must be burned continuously. Lithium is found nearly everywhere, is used in durable goods that last for decades, and can be recycled indefinitely. There will be

no lithium-OPEC. There cannot be. The physics and geology are fundamentally different.

8.5 Cobalt: The Problem We Routed Around

Cobalt presents a different kind of challenge. It is not about scarcity. It is about where cobalt comes from and how it is mined.

The Democratic Republic of the Congo produces about three-quarters of the world's cobalt.[28] Much of that comes from large industrial mines. But perhaps 15 to 30 percent comes from what are called artisanal mines: small operations where families dig by hand, sometimes in tunnels that collapse, sometimes with children doing the digging.[29] UNICEF estimates that 40,000 children work in Congolese cobalt mines, some as young as six.[30] The conditions are brutal: respiratory diseases from dust, spinal deformities from carrying heavy loads, the constant risk of being buried alive.

This is a genuine horror. Anyone who cares about human rights should care about what happens in these mines. Anyone buying an electric vehicle or a smartphone should at least be aware of where the materials might have come from.

But there is something worth noting. Cobalt has been used in petroleum refining for decades. Every oil refinery in the world uses cobalt-molybdenum catalysts to remove sulfur from diesel and gasoline. This has been standard practice since the 1950s.[31] Nobody objected. Nobody made documentaries. Nobody called for boycotts. Cobalt was invisible because it was embedded in the fossil fuel system that everyone took for granted.

Then cobalt appeared in electric vehicle batteries, and suddenly it became a reason to reject the energy transition altogether.

Here is what actually happened while critics were pointing fingers. The battery industry routed around the problem. Not through ethics alone, but through chemistry.

Lithium iron phosphate batteries, LFP for short, contain zero cobalt. They use iron and phosphorus instead: two of the

most abundant and inexpensive elements on Earth. In 2020, LFP batteries held about 10 percent of the global electric vehicle market.[32,33] By 2024, they held nearly 40 percent.[34] In China, where the transition is furthest along, LFP dominates with over three quarters of market share.[35] Tesla uses LFP in its standard-range vehicles.[36] BYD, the world's largest electric vehicle maker,[37] has built its empire on cobalt-free batteries.

The trend is accelerating. Industry analysts expect LFP to become the dominant battery chemistry by 2028,[38] not because companies have suddenly become ethical, but because iron and phosphorus are cheaper than cobalt and nickel, and because LFP batteries last longer and are safer. The market is solving the problem that critics said was unsolvable.

Even the lightweight lithium batteries that still use cobalt, so called NCM batteries for their use of Nickel, Cobalt and Manganese, are using less of it. A decade ago, cathodes were roughly one-third cobalt.[39] Today's high-nickel formulations have reduced that to under 10 percent, and new chemistries are pushing toward 5 percent.[40]

Does this mean we can ignore the conditions in Congolese mines? Of course not. The International Labour Organization, UNICEF, and various industry initiatives are working to formalize artisanal mining, get children into schools, and improve safety conditions. These efforts matter. But they exist alongside a technological shift that is making the problem smaller.

In absolute terms, cobalt is not scarce either. Global resources are estimated at 25 million tonnes,[41] enough for centuries of production at current rates. Indonesia has emerged as a major new producer, going from almost nothing in 2021 to 10 percent of global output in 2024.[42] Australia, Canada, Cuba, and the Philippines all have significant deposits. The concentration in the Congo is a result of history and economics, not geology.

8.6 Rare Earth Metals: Neither Rare Nor Earthy

Whoever named them should be fired from the naming committee. "Rare earth metals" sounds like something precious and scarce, hoarded in secret vaults. In reality, these elements are neither rare nor earths. They were called "rare" because they were first isolated from uncommon minerals, not because they are geologically scarce. Cerium, the most common rare earth element, is more abundant in Earth's crust than copper. (USGS, 2024) The "earth" part is an archaic term for metal oxides. The name stuck, and it has been causing confusion ever since.

Rare earth elements are used primarily in permanent magnets. These magnets appear in wind turbines, electric vehicle motors, and various electronic devices. And although they are not particularly scarce, they are often the most expensive raw material in an electric motor. For that reason, engineers are increasingly making them optional.

For example by using synchronous reluctance motors that use no permanent magnets at all and are becoming increasingly popular in industrial applications. These motors are a bit harder to control and design, but as you will see in the second part of this book our ability to control electricity is increasing at an impressive pace. Others choose to use permanent magnets that do away with the rare earths. Tesla announced in 2023 that its next-generation motors would eliminate rare earth elements entirely, using alternative magnet designs. (Tesla Investor Day, 2023) Other manufacturers are following. The transition from rare-earth-dependent to rare-earth-optional is already underway.

The pattern should be familiar by now. Critics identify a potential bottleneck. Engineers route around it. The bottleneck never materializes, but it stays a talking point for many years.

8.7 Copper: The Tightest Constraint

When I researched this with master students, copper was the one that gave us pause. This is a concern for many other ex-

perts too and that's easy to understand. Your house contains about 90 kilograms of copper wiring. (CDA, n.d.) An electric vehicle needs 80 to 90 kilograms, about three and a half times what a combustion car uses.[43] A 3-megawatt wind turbine contains up to 4.7 tonnes. (CDA, 2018) The grid that connects everything runs on copper. As we electrify transport, heating, and industry, demand is surging.

The numbers look daunting. Global demand reached 27 million tonnes in 2024 and is projected to hit 37 million tonnes by 2050. (IEA, 2025) The IEA forecasts a 30 percent supply shortfall by 2035. (IEA, 2025) Meanwhile, ore grades have declined roughly 40 percent since 1991. (IEA, 2025; Calvo et al., 2016) The world's largest copper mine, Escondida in Chile, started in 1990 processing ore at 2.5 percent copper. Today it's at 0.5 percent, digging five times as much earth for the same output. (Earth Resource Investments, 2025; BHP, 2024) Experts and headlines scream shortage. What I found was different.

The U.S. Geological Survey reports current reserves at about 1,000 million tonnes.[44] At 2024 production rates, that's roughly 40 years of supply. Sounds tight. But since 1960, there have always been about 40 years of reserves.[45] Every decade, people predict we'll run out in 40 years. Every decade, reserves grow alongside production. Between 2000 and 2022, the world mined 396 million tonnes of copper. Over the same period, reserves *increased* by 457 million tonnes.[46] We ended up with more than we started with.

Beyond reserves lie identified resources totaling 2.1 billion tonnes, plus another 3.5 billion tonnes that geological surveys predict exist based on where copper forms. (USGS, 2025; Johnson et al., 2014) At current consumption, identified resources alone would last over 200 years.

The real question is whether we can extract it fast enough. Mining projects take 15 to 20 years from discovery to production. (IEA, 2021) Investment has lagged. This is a legitimate concern for the 2030s.

But two forces are solving it: substitution and recycling.

Aluminum has already replaced copper in most power transmission lines worldwide. Those high-voltage cables strung between pylons? Almost entirely aluminum. It's only 60 percent as conductive as copper, but one-third the weight and one-third the price. (USGS, 2025) Engineers are pushing aluminum further: underground cables, wind turbine generators, vehicle wiring. Tesla's next-generation vehicles will use aluminum where possible and run at 48 volts instead of 12, cutting conductor needs by three-quarters. (Musk, 2023)

The pattern should be familiar. When a material gets tight, engineers route around it. Sodium instead of lithium. LFP instead of cobalt. Reluctance motors instead of rare earths. Aluminum instead of copper.

Then there's recycling. Copper may be the oldest recycled material in civilization. We've been melting it down for 10,000 years. The atoms in your wiring might once have been Bronze Age tools or Roman plumbing. An estimated 80 percent of all copper ever mined is still in use, locked in buildings and infrastructure.[47] It hasn't been consumed; it's been accumulated. As today's infrastructure ages out, it becomes a copper deposit for future generations.

The 2030s may see genuine supply crunches and price spikes. This is not a problem that solves itself without effort. But it solves itself *with* effort. Aluminum substitution is proven. Recycling infrastructure is growing. And the fundamental resource base is not scarce: it's a matter of extraction rates, not geology.

Most importantly, copper shares the characteristic that distinguishes all renewable materials from fossil fuels. It's a stock, not a flow. Once we've built the renewable energy system, the copper stays in place, generating electricity for decades, available for recycling when eventually replaced. We're not burning through it; we're building with it. Which brings us to recycling. Because isn't that a scam?

8.8 Recycling: This Time Is Different

You might be skeptical about recycling promises. You should be. We've heard them before. Plastic recycling turns out to be largely a fraud: less than 10% of plastic ever produced has actually been recycled.[48] The little triangle on your yogurt container is closer to greenwashing than reality. So when I tell you that solar panels and batteries can achieve 95% recycling rates, you're right to ask: why should I believe you?

I have an answer, and it's sitting under the hood of your car. Lead-acid batteries have achieved 99% recycling rates for decades.[49] Not a target. Not a promise. The measured reality, confirmed every year. We already know how to do this. We've been doing it for a century. Lead-acid batteries have higher recycling rates than aluminum cans, glass bottles, or newspapers.[50] A typical new lead-acid battery contains 80% recycled material.[51] The lead has been cycling through batteries for decades, perhaps longer.

This matters because the objection I hear most often about electric vehicles and grid storage is: "What happens to all those batteries?" The worry is lithium batteries piling up in landfills, toxic and wasted. But we already recycle batteries at industrial scale. We've been doing it for a century. The question isn't whether battery recycling is possible. The question is whether the conditions that made lead-acid recycling work also apply to lithium batteries and solar panels.

8.9 What Makes 99% Recycling Possible

Lead-acid batteries didn't reach their 99% recycling rate by accident. Four conditions had to align, and understanding them tells us what to expect for solar and lithium.

First, the materials must be valuable. Lead commands a decent price. When a battery reaches end of life, someone will pay to collect it because there's money in the lead. Collection happens because it's profitable. This is very different from plastic where new plastic is actually cheaper than recycled plastic and both cost very little. With plastic the business simply isn't there.

Second, the products are consistent. Every lead-acid car battery has roughly the same design: lead plates, sulfuric acid electrolyte, plastic casing. Recyclers know exactly what's coming in. They can build efficient processes optimized for materials they'll encounter every time. Compare this to plastic recycling, where a single collection bin might contain dozens of different polymers, often contaminated with food and other non-plastics, mixed in ways that make separation expensive and imperfect.

Third, the physics allows it. Lead is an element. You can melt it down and recast it indefinitely without degradation. The lead in your car battery might once have been in a Roman pipe. It might become part of a battery a century from now. Metals don't wear out the way polymers do. Plastic chains break down with each recycling cycle; after a few rounds, the material is only good for park benches. There are ways to get around this and upcycle plastic but they are uneconomical. Metals like lead on the other hand, never run out of cycles.

Fourth, the infrastructure exists. This took decades to build. A network of collection points, processing facilities, regulations requiring retailers to accept old batteries. The system works because someone designed it to work. And to be honest, this is why we shouldn't expect 99% recycling for solar panels and lithium batteries tomorrow. The collection networks don't exist yet. Not just because everything is so new, but also because there is little to recycle yet. Most of the solar panels and car batteries that were made will take over a decade before they are ready for recycling. Building the infrastructure takes time and volume.

But the first three conditions, value, consistency, and physics, are already in place, so we can be confident the infrastructure will be built.

8.10 Renewables are Great for Recycling

Solar panels contain roughly $10 to $15 worth of recoverable materials: silver, copper, high-purity silicon, aluminum,

glass.[52] That sounds modest until you realize there will be hundreds of millions of panels reaching end of life every year by 2050. Rystad Energy estimates the annual value of recyclable materials from solar panels could approach $80 billion by 2050.[53] Companies are racing to build recycling capacity because there's real money in it.

Lithium batteries offer even better economics. A single electric vehicle battery pack contains hundreds (with lithium iron phosphate batteries) or even thousands of dollars (with nickel cobalt manganese batteries) worth of recoverable metals.[54] Unlike plastic, which costs more to recycle than to replace, these materials command prices that make collection profitable.

The consistency is there too. Solar panels are manufactured products with standard formats. Every crystalline silicon panel has the same basic structure: glass on top, encapsulant layer, silicon cells, backsheet, aluminum frame. The composition is known and predictable. Recyclers can optimize each step because they know what's coming in. Lithium batteries are similarly consistent and especially the larger cells now becoming standards give recyclers nice hefty chunks of battery to work with.

And the physics is on our side. Aluminum is aluminum. Copper is copper. Silicon can be purified back to solar grade. You can melt these materials and reuse them indefinitely. We've been recycling copper for 5,000 years.[55] An estimated 80% of all copper ever mined in human history is still in use somewhere today, locked up in buildings, wires, and equipment.[56] It hasn't been consumed. It's been accumulated. You cannot destroy the atoms in metals. Recycling just means that you relocating atoms into new useful configurations. This is why the comparison between fossil fuel extraction and renewable mining is misleading. Fossil fuels are consumed. Renewables are a stock that we are building.

8.11 What's Already Happening

The infrastructure is being built faster than most people realize.

First Solar has been recycling its thin-film panels since 2005.[57] Twenty years of industrial-scale recycling, not a pilot project. They recover over 90% of semiconductor material and 90% of glass. Their facilities in the U.S., Germany, India, Malaysia, and Vietnam process 2.6 million modules per year. In 2023, their global material recovery rate averaged 95%. They've recycled nearly 400,000 metric tonnes of panels to date.[58]

For lithium batteries, Redwood Materials has become the largest recycler in North America.[59] Founded by Tesla's former chief technology officer,[60] they now receive over 20 gigawatt-hours of batteries annually.[61] They claim 95% recovery of lithium, cobalt, nickel, and copper.[62] In 2024 alone, they recycled enough material to supply batteries for 1.5 billion phones.[63]

The recovery rates for individual materials have improved dramatically in the past five years. Silicon extraction has improved dramatically, with recent processes achieving over 90% recovery rates.[64,65] Silver recovery, once considered too difficult, now reaches over 95% with the resulting silver being over 98% pure, with some methods completing extraction in under ten minutes.[66,67] Glass and aluminum that make up most of the material in a solar panel routinely hit 90 to 95%.[68]

These aren't laboratory demonstrations. They're operating facilities processing real waste streams at industrial scale.

8.12 What We Can Honestly Expect

I don't expect solar panels and lithium batteries to reach 99% recycling rates any time soon. Lead-acid had a century head start and the advantage of being concentrated in auto shops rather than scattered across millions of rooftops. Collecting

distributed equipment is harder. But 90% is achievable, even in the short term, because many facilities are already there.

With 90% recycling, the material extracted from mines drops by a factor of ten compared to no recycling. With 95% recycling, already achieved for some components, it drops by a factor of twenty. The 500 grams of coal burned per kilowatt-hour versus 0.1 grams of new material extracted with solar recycling: that comparison holds even if we never reach lead-acid's 99%.

The trajectory matters too. Recovery rates that seemed impossible five years ago are now routine. Processes that took hours now take minutes. The learning curve applies to recycling just as it applies to manufacturing. Every year, the processes get better and the economics improve.

Europe already requires solar panel manufacturers to finance collection and recycling under the WEEE directive.[69] California has solar-specific recycling regulations.[70] The pattern is spreading. These are the same policy tools that built the lead-acid recycling infrastructure over the past century, now being applied to renewable equipment.

By 2050, an estimated 78 million tonnes of solar panels will reach end of life globally.[71] That's an enormous waste stream if we get this wrong. It's also an enormous resource stream if we get it right: enough recovered material to manufacture tens of millions of new panels every year without new mining.

The lithium battery recycling market is expected to grow from approximately $5 billion in 2024 to over $24 billion by 2032.[72] Redwood Materials is building toward 500 gigawatt-hours of annual recycling capacity by 2030, enough to supply materials for 5 million electric vehicles.[73] These are investments being made now, facilities being built now.

We know how to do this. We've proven it with lead-acid for a century. The conditions that made lead-acid recycling work, value, consistency, physics, also apply to solar panels and lithium batteries. The infrastructure is being built. The

question isn't whether recycling will happen. It's how fast we build the systems to make it happen at scale.

8.13 Spending the Inheritance vs Guaranteed Income

From fossil fuels to renewables is a fundamental shift in the mental model. They aren't called renewables for nothing. Fossil fuels is like spending an inheritance. We discovered millions of years of stored sunlight, compressed into coal and oil and gas. We've been withdrawing from that bank account for three centuries. We draw it down a million times faster than it was created. The spending has been glorious, lifting billions from poverty, building modern civilization. But the account is finite. The balance is dropping. The end is coming into view quickly.

Renewables is like getting a regular income. The sun deposits energy into your account every day. You live on what arrives. And not just while you're employed, or until your pension runs out. For billions of years. The materials you use to capture that deposit last for decades and can be reused again and again.

Solar and wind are not something strange and new. In a way, it's going back to a past in which we lived on what the earth gave us. The sun showed up daily, growing crops, filling rivers, pushing sails. We spent what arrived. Burning wood was just a very inefficient way to collect sunlight, and now we're replacing it with something more efficient. Same source. Same principle. We're just finally getting good at it.

8.14 The Big Picture

Sometimes it helps to step back and see the big picture in all its glory.

Global fossil fuel extraction runs about 15 billion tonnes per year.[74] That's coal plus oil plus gas. This isn't a one-time cost during some transition period. This is every year for as long as fossil fuels last.

The total material needed to build a fully renewable global energy system, all the solar panels, all the wind turbines, all

the batteries, all the power converters, comes to roughly 6 to 7 billion tonnes cumulatively through 2050. And 90% of that is steel and aluminum.[75]

After that, recycling dominates. The system maintains itself with minimal new extraction.

So: fossil fuels require 15 billion tonnes extracted every year, forever. Renewables require 6 to 7 billion tonnes total over 25 years. The renewable system requires less material to build than the fossil system extracts in a single year. And then we start to recycle and no physical law says that we can't recycle everything in the distant future.

People miss this because we've normalized fossil extraction. Coal trains and oil tankers are invisible infrastructure. They've been running for so long that we don't see them anymore. Renewable construction is new and visible. A wind farm going up catches your eye. A coal mine operating for the hundredth year doesn't. The fish doesn't notice the water. Even when it's running out.

8.15 Dematerialization Continues

Everything I've described is based on today's technology. The trajectory points toward even less material per kilowatt-hour.

Silicon wafers in solar panels keep getting thinner. Each generation uses less silicon than the last. Newer panel designs are eliminating silver entirely, replacing it with copper or aluminum contacts.

Battery energy density keeps improving. The same kilowatt-hour of storage requires less material every year. Sodium-ion batteries are entering production, eliminating lithium from the equation entirely for stationary storage.

Power converters are approaching efficiencies of 100%. This means almost no waste heat, which in turn means incredibly compact and lightweight devices that uses very little energy.

Panel lifetimes keep extending. Some panels installed in the 1970s still generate electricity today, albeit with some

degradation.[76] Forty-year lifetimes are becoming plausible. Fifty years may follow.

On top of this recycling is developing fast. Recovery rates that seemed impossible five years ago are now routine. Processes that took hours now take minutes. Technologies that required toxic chemicals now use environmentally friendly alternatives. So if today we are at 0.1 grams per kilowatt-hour with recycling, this could be 0.05 grams or less by 2050. Dematerialization is not a one-time achievement. It's an ongoing process, driven by the same learning curves we discussed earlier.

Fossil fuel is the only truly scarce material in the energy transition. "Critical minerals" aren't scarce and can be recycled endlessly. Dematerialization is the most effective form of degrowth. I now feel less guilty about the luxury I live in because I know my flourishing doesn't require anyone's deprivation. But could minerals make us dependent on new masters? That's the next question.

9

No New Petrostates

My parents lived through the Dutch hunger winter. They didn't throw away food. They told me to clear my plate. "The children in the third world would be very happy with this food," they would say.

Years later, I found a demographic chart with two strange dips. Enormous gaps in population that I couldn't explain at first. The first was the Holodomor, Stalin's deliberate starvation of Ukraine in the 1930s.[1] When Ukrainian peasants resisted collectivization, Stalin sealed the borders, confiscated food, and waited. Approximately four million dead.[2] The second was Mao's Great Leap Forward. Thirty million dead.[3] I didn't sleep well that week.

Just like the Dutch hunger winter, these weren't famines, I realized. They were weapons. Centralized control of what people need to survive is the tyrant's oldest tool. Energy is now as essential as food. Without it, the lights go out. Communication stops. Transport stops. Buildings go cold. Hospitals fail. Within weeks, cities become uninhabitable.

And like Soviet grain production, fossil fuel infrastructure is easy to control. A few dozen refineries. A handful of pipelines. A few power plants per region. Every one is a chokepoint.

In 2022 Russia throttled gas pipelines to Europe.[4] Nord Stream 1 deliveries cut to 20%, then halted entirely.[5] European gas prices reached ten times their historical average.[6] Factories closed. Governments scrambled before winter. Putin thought he had Europeans on a leash.

Venezuela's corrupt regime first survived economic collapse because it controls oil revenue.[7,8]

Many suspect the coup by American president Trump against the illegitimate sitting president of Venezuela Maduro in 2025 is also about access to oil.[9,10] Saudi Arabia's absolute monarchy distributes energy wealth as patronage.[11] We have built our civilization on a tyrant's tool.

9.1 What Our Oil Money Bought

Fossil fuels concentrate wealth for whoever controls it, often to the detriment of regular people. The pattern is consistent enough to have a name: the resource curse. We are part of that pattern.

In 1953, Iran had a democratically elected prime minister. Mohammad Mossadegh wanted to nationalize Iranian oil, then controlled by the Anglo-Iranian Oil Company, now BP.[12] As historian Ervand Abrahamian put it: "If nationalization in Iran of oil was successful, this would set a terrible example to other countries where U.S. oil interests were present."[13] So the CIA and MI6 organized a coup. Operation Ajax. Operation Boot.[14] Mossadegh was arrested. The Shah took power. The Shah ruled for twenty-six years.[15] His secret police tortured dissidents. His corruption alienated the middle class. His Western backing alienated the religious establishment. In 1979, the revolution came.[16] We wanted cheap oil. We got Khomeini.

The House of Saud controls the world's second-largest oil reserves, after Venezuela, and more importantly the cheapest to pump up.[17] Western nations have armed and protected the regime for decades in exchange for reliable oil supplies.[18] The regime exported more than oil. It also exported Wahhabism: the most intolerant form of Islam.[19] Our money, used by the House of Saud, has built Wahhabi mosques and madrassas across the world. One of my closest friends from university is Dutch. He met his Indonesian wife during his master thesis research and married into a Christian family on Bali. For years, he says, Indonesia was

a model of tolerance. The culture was easygoing. His wife's family had Muslim neighbors they'd known for generations. The national motto was "Unity in Diversity." Last time we spoke, he was worried. Saudi-funded mosques have been going up across the archipelago. The Islam they teach is not the relaxed Indonesian tradition. It's imported. Rigid. His wife's family feels under siege. The mosques keep going up.

Fifteen of the nineteen 9/11 hijackers were Saudi nationals.[20] The ideology that motivated them was Saudi-funded. The madrassas where they learned were Saudi-built. None were from Afghanistan, where we launched a war. None were from Iraq, where we launched another.[21]

We kept buying their oil.

General Wesley Clark, former NATO Supreme Allied Commander, said in an interview: "The truth about the Middle East is, had there been no oil there, it would be like Africa. Nobody is threatening to intervene in Africa."[22] Alan Greenspan, Federal Reserve Chair for nearly two decades, wrote in his memoir: "I am saddened that it is politically inconvenient to acknowledge what everyone knows: the Iraq war is largely about oil."[23]

Senator John McCain called Russia "a gas station masquerading as a country."[24]

Russian oligarchy is built on fossil fuel wealth. That wealth funds the military that invaded Ukraine. Every cubic meter of Russian gas burned in German homes, every oil drum bought globally, helps pay for missiles falling on Ukrainian hospitals.

Then there are those who didn't ask for oil to be under their land. The Standing Rock Sioux, fighting a pipeline through their water supply. The Dakota Access Pipeline was originally routed near Bismarck, the state capital, but moved away due to concerns about contaminating the city's water.[25] The same threat was deemed acceptable for the Indigenous reservation downstream. Standing Rock Tribal Chairman Dave Archambault II told the UN Human Rights Council: "The oil companies and the government of the United States

have failed to respect our sovereign rights."[26] Communities in the Niger Delta live on land contaminated by 6,800 documented oil spills.[27] Life expectancy there has dropped to 41 years, twenty years below the national average.[28] Indigenous peoples of the Amazon watch their forest burned.

We built this system. We funded it. Then we looked away.

9.2 Solar Liberation

Are we trading one vulnerability for another? Will there be solar sheikhs? Fortunately not. Physics won't allow it. Fossil fuels are geologically concentrated. Some countries have oil; most don't. This is why petrostates exist. They exploit this wealth with a few oil wells and refineries. Seize those facilities, and you control the wealth.

Oil is like the spice of the Dune saga. "The spice must flow." Or civilization crumbles. Your car needs new fuel every week. The electricity system needs it constantly. Cut the flow, and everything stops within days. Countries try to stock up but the flows are so massive that they cannot outlast a siege of more than a few weeks, maybe months. That's why OPEC's embargo worked. That's why Russia's gas cutoff caused panic.

Sunlight is different. It falls on every country. Every rooftop. You cannot embargo sunlight. You cannot form a cartel of countries that have sun. Everyone has sun. A solar-powered nation has millions of rooftops, thousands of solar farms. There is no central facility to seize. No chokepoint. No lever.

Solar panels are a stock you build up. Once installed, they keep generating whether or not new panels arrive. Your roof keeps producing. Your battery keeps storing. If supply chains are disrupted, your existing capacity keeps working. You're not dependent on continuous flow. You're standing on accumulated capacity. Oil dependence is flow dependence: continuous vulnerability. Solar is stock dependence: accumulated resilience.

I'm not exactly a prepper. But my home could deliver all the energy I need if the grid went down. My wife isn't a prepper either. But she has ordered me to find a battery system that supports islanding, so the solar panels keep working when the grid fails. Solar isn't just for environmental idealists. It's for anyone who prefers not to be too dependent on systems they don't control.

OPEC has maintained pricing power for fifty years because oil has high margins. Extract it for ten dollars, sell it for seventy.[29] That margin funds kingdoms and wars. Solar panels are commodity products. Intense competition. Thin margins.[30] You cannot form OPEC for solar panels. The economics don't support it. There's no cartel premium to capture.

The petrostate model requires geographic concentration, centralized infrastructure, continuous flow dependence, and high margins. Solar breaks all four.

9.3 But What About China?

China dominates clean energy manufacturing. There's no use denying it. Solar panels: about 80% of global production.[31] Polysilicon, the purified silicon that goes into those panels: roughly 90%.[32] Solar wafers: 97%.[33] Battery cells: 77%.[34] Electric vehicles: over 70% of global production and rising.[35] These are not small advantages. This is dominance.

And honestly: what China built is an achievement. Not a conspiracy. Not a theft. No abuse of geological advantage. Chinese manufacturers earned their position through strategic investment and deployment at scale while Western countries talked. In 2000, the United States dominated solar manufacturing.[36] By 2008, Germany funded the global solar boom and paid for the global price reduction.[37] But it was China who invested, scaled, and rode the learning curve to dominance. And there is no resource curse in sight. No country in history has lifted more people out of poverty than China: 800 million people in forty years.[38]

That said... I like the kind of democracy we have in the Netherlands. I worry about Chinese dominance. About how they treat Uyghurs, Tibetans, and people in Hong Kong and Taiwan. So I understand the questions I hear at every conference and in every comment section. Are our good intentions supporting forced labor? Are we trading one dependence for another? Will oil sheikhs be replaced by solar panel mandarins? OPEC replaced by Beijing?

9.4.1 Forced labor

Polysilicon production has been concentrated in Xinjiang.[39] There are credible reports of coercive labor practices in the region, part of a broader pattern of repression that includes detention camps and forced cultural assimilation for Uyghurs.[40] But those who use Uyghur concerns to argue against the energy transition don't seem trustworthy to me. They sound as hollow as those starting to complain about children mining cobalt after we started to use it in electric vehicles instead of gasoline production. And I've noticed that some of the loudest voices on this issue show no interest in Uyghur welfare when the topic isn't solar panels.

It would also be easier to make this moral argument land if the West didn't have a colonialist past. If it hadn't spent a century ignoring labor conditions in its own supply chains. Cobalt mining in the DRC. Garment workers in Bangladesh. Farmworkers in the American South. But that doesn't make forced labor in China ok. So what does help?

Try to buy from supply chains that can prove they don't use forced labor. Buy from verified non-Xinjiang sources. Support traceability requirements. Accelerate manufacturing outside China. The United States has implemented the Uyghur Forced Labor Prevention Act, requiring companies to prove their products are not tainted.[41] The EU has adopted a regulation banning products made with forced labor from its market.[42] Major manufacturers have been moving production outside Xinjiang in response. The market is responding. Slowly, imperfectly, but responding. Non-Xinjiang

polysilicon capacity is expanding. Traceability systems are being implemented. The pressure is working.

But this is not a uniquely Chinese problem. Moreover, it is not a supply chain security risk that puts us at the mercy of China. Supply security asks whether civilization can function if supply is cut. Conflating them produces moral panic without analytical clarity.

9.4.2 Factories Move, Deposits Don't

Most commentary treats Chinese manufacturing dominance as if it were equivalent to Saudi oil reserves. It is not. The difference is fundamental.

Oil deposits are where plate tectonics and ancient biology put them. Saudi Arabia has 17% of global reserves.[43] No amount of policy or investment will change that. You cannot decide to have more oil. Geology is permanent.

Manufacturing is where humans put it. The United States dominated solar manufacturing in 2000. Germany dominated in 2008. China dominates in 2024. Each shift happened through investment decisions and industrial policy, not because silicon migrated across the Pacific. What moved twice can move again. And it is moving.

Remember what solar panels and batteries are actually made of. We covered this in the previous chapter. Silicon is made from sand. Sand exists on every continent. High-purity polysilicon requires processing, but processing is manufacturing, not geology. You cannot run out of sand. You can only fail to build processing facilities.

Aluminum is the third most abundant element in Earth's crust.[44] Bauxite deposits span Australia, Guinea, Brazil, Vietnam, Jamaica, India.[45] No country has a monopoly. No country can have a monopoly.

Lithium: Australia produces nearly half of global supply, with Chile, China, and Argentina contributing most of the remainder.[46] Massive deposits have been identified in Bolivia, Germany, the US, Mexico, and across Africa.[47] The lithium

could be mined everywhere. The question is who wants to do it.

LFP batteries, the chemistry that's winning, uses iron and phosphorus next to lithium. Iron is 5% of Earth's crust by weight.[48] Phosphorus has major deposits in Morocco, China, the US, Russia, Jordan.[49] These are not rare.

China dominates processing and manufacturing. That's undeniable. But China does not have a geological monopoly on any critical material. Manufacturing moves to where investment goes. That's why Chinese renewables dominance is our choice, while Saudi oil dominance is a given.

9.4.3 Not OPEC 2.0

The petrostate model requires five things: geographic concentration, flow dependence, chokepoint infrastructure, high margins, and non-substitutability. China's position has none of these.

No geographic concentration. Deposits are everywhere and factories can move.

No flow dependence. As we just saw: solar is a stock, not a flow. China could embargo panels tomorrow, and Europe's 338 gigawatts of installed solar keeps generating over 300 terawatt-hours per year.[50] Every deployed battery would keep storing. The embargo would affect future installations, not current operations.

No chokepoint infrastructure. Oil wealth concentrates in a few dozen major fields globally. Seize those facilities, and you control the oil wealth. Solar manufacturing is spread across multiple companies and regions, even within China. There is no solar valve to turn off.

No high margins. OPEC maintains pricing power because oil has high margins. Extract for ten dollars, sell for seventy. That margin funds kingdoms and wars. Solar panel gross margins run 10% to 15%.[51] Battery margins are still 20-25% for market leaders like CATL, but as batteries commoditize like solar cells, these margins will come down too.[52] Chinese companies compete ferociously with each other. You

cannot form OPEC for solar panels because there's no cartel premium to capture. Coordination requires something to coordinate over. With commodity margins, there's nothing.

Great substitutability. If Chinese panels become unavailable, Indian, Vietnamese, American panels exist. Production can restart or expand elsewhere. The knowledge is not secret. The technology is not proprietary. Try substituting Saudi oil with... what, exactly? Other oil from other places with the same dependencies?

9.4.4 Diversification Is Already Happening

China didn't have solar manufacturing dominance in 2005. They built it through investment and policy over fifteen to twenty years. The same path is available to others and could be sped up.

In the United States, the Inflation Reduction Act has triggered $369 billion in clean energy investment.[53] Solar manufacturing capacity announcements have jumped from roughly 5 gigawatts in 2022 to over 50 gigawatts expected by 2026.[54] Battery manufacturing announcements exceed 700 gigawatt-hours.[55] First Solar, Qcells, and others are building American facilities.[56] The IRA is industrial policy. It's what China did, arriving two decades later.

Europe moves more slowly, but the European Solar PV Industry Alliance has set targets. The European Battery Alliance is building manufacturing. Meyer Burger, Enel, and others are building European capacity. The EU Net Zero Industry Act passed in 2024.[57]

India is running the same playbook China ran. Production-linked incentives for solar manufacturing. Rapidly expanding domestic capacity. Tata, Adani, Reliance entering the market.

Vietnam, Malaysia, and Thailand are already significant manufacturers. Some facilities are Chinese-owned, but they're local, with local workers, diversifying the geography of supply.

Diversification takes two to three years for module assembly, and three to five years for significant upstream manufacturing capacity in cells and wafers.[58] Not instant, but not generational either. By 2030, non-Chinese capacity will be substantial. The question is not whether diversification is possible. It's whether we do it.

9.4.5 Chinese are (Primarily) Doing it for Themselves

Something often missing from Western analysis: China has its own reasons to want clean energy that have nothing to do with leverage over the West.

Clean energy is roughly 10% of Chinese GDP and growing.[59] Millions of jobs depend on these exports. An export ban would devastate Chinese manufacturers before it hurt Western deployment. China needs customers. An embargo hurts the embargoer.

China has a domestic air pollution crisis. More than a million premature deaths annually from particulate matter.[60] Clean air is a priority for both the government and the population.

China imports more oil than any other country.[61] Energy security is an obsession for Chinese planners. A healthy obsession, one we might want to copy. The Chinese government understands that solar and wind reduce that vulnerability.

China installed 216 gigawatts of solar in 2023 alone.[62] More than the rest of the world combined.[63] They added 37 gigawatts of battery storage in 2024 alone, more than doubling their capacity in a single year.[64] They are not just doing this for us but primarily for themselves.

When we see Chinese solar factories as a threat, we miss that they're primarily serving Chinese energy needs and Chinese employment. This is an export product. Not a resource we can't do without. Not a weapons arsenal.

9.4.6 The Improbable Lose-Lose Scenario

Imagine China invades Taiwan and announces a complete export ban on all clean energy equipment, effective immedi-

ately. Set aside the invasion itself, even though that would clearly be the bigger issue.

Day one through thirty: all existing solar panels keep generating. All existing batteries keep working. All existing wind turbines keep spinning. No immediate impact on current energy supply. Some panic in markets. Some prices spikes. 99% of people notice nothing personally. We still drive on Sunday. Nobody shows pictures of a world burning up.

Months one through twelve: new installations slow dramatically. Prices for available equipment spike two to five times. Non-Chinese manufacturers ramp production to meet backlog demand. Used equipment markets emerge. Some projects get delayed, some cancelled. Some people lose their jobs. But not enough to cause an economic crisis and everybody understands this is a temporary nuisance, not a threat to our way of life.

Years one through three: alternative supply chains expand rapidly. The investment case is now obvious. India, Southeast Asia, the US, and Europe accelerate capacity. Learning curves continue. Technology doesn't forget. Engineers don't forget. Prices normalize as new capacity comes online. People get rehired. The transition continues. Just slower and a bit more expensive.

Year three onward: non-Chinese supply chains mature. Possibly more diversified and resilient than before. Local suppliers flourish. The embargo accelerated what was happening anyway.

Meanwhile, in China: millions of manufacturing jobs lost. Export revenue collapses. Overcapacity. Political backlash domestically.

For us it would be inconvenient and expensive, but not civilization threatening and it would not stop the transition. China's economy would take the biggest hit. Both sides lose, but China would lose most. If it ever came to blows between China and those buying her renewable products, chances are

others would punish China with an embargo, not the other way round.

9.4 Power to the People

For a century, energy has meant dependence. On petrostates. On centralized infrastructure. On chokepoints that could be weaponized against us.

Solar and wind are structurally different. When you put solar on your roof, no embargo can touch you. No pipeline dispute can raise your heating bill. When your community has its own generation and storage, the weapon that Stalin used with grain doesn't work.

This book is called "Power to the People." I mean that literally. For the first time in history, the power that runs civilization can be generated everywhere, by everyone. Not concentrated in the hands of whoever won the geological lottery. Not vulnerable to the ambitions of dictators or the calculations of cartels.

There will be no solar-states. The physics won't allow it. We are not trading one master for another. We are stepping outside the master-servant relationship. In terms of energy, we become uncoercible.

So that's the good news about the raw materials we need and how much control that gives others over us. But what about pollution? This was the stuff that goes in. What about the stuff that comes out?

10

Everything Must Go Somewhere

I still remember her so vividly. “I’m so happy now that you are here again,” she would say, smiling, clasping my hand in hers and trying unsuccessfully so sit up in her hospital bed. “I am so blessed to have you and Iris. And your sister of course. Did you know that woman at the entrance has nobody at all? I really feel for her.”

And I would shake my head and smile at how she always put other people first. At how welcome she made me feel even though *she* was in the hospital. But then I would look at her, and my heart would break again, as I saw my mother lying there, fighting for air even though she had a tube with oxygen going up her nose. Overweight, high blood pressure, brittle bones. The increased infection risk that would do her in in the end. All from the prednisone they were forced to give her because of her failing lungs.

Did you know that 7 *million* people die, every year, and *hundreds of millions* suffer, from the particulate matter we put into the air by burning fuel?[1] Why is everybody talking about global warming, but so few people about the people who are suffering *right here, right now* from the same cause. I can’t determine to what extend my mother’s death and suffering was caused by burning fossil fuel. But emotionally, it affects me even stronger than the obligation that I feel to future generations.

I didn't plan to write that. But sometimes a number like 7 million only becomes real through one.

We have been talking about the raw materials we need as the inflow of the bathtub. We have been talking about the bathtub itself when we considered its land use. Now it's time to look at all the unwanted stuff that flows out of the bathtub as we produce the energy that our civilization depends upon.

10.1 Barry Commoner's Ecological Laws

The title of this chapter honours Barry Commoner, an American biologist who helped launch the modern environmental movement.[2] By all accounts he was as kind as he was brilliant and he inspired countless students, often to the point of giving him a standing ovation after a lecture. In 1971, he wrote a book called *The Closing Circle* in which he posits four "laws of ecology."[3] The first was: *everything is connected to everything else*. Commoner understood systems thinking. He saw the feedback loops, the stocks and flows, the way a change in one part of a system ripples through every other part. He would have approved of our bathtub metaphor.

His second law gives this chapter its title: *everything must go somewhere*. Matter doesn't vanish. When you burn coal, the carbon becomes CO_2 in the atmosphere. When you spread fertilizer, excess nitrogen runs off into rivers. When smoke rises from a chimney, it enters someone's lungs. There is no "away."

His third law, *nature knows best*, is often misunderstood. Commoner was not a primitivist rejecting all technology. He opposed the use of synthetic chemicals that ecosystems cannot break down: DDT accumulating in eagle eggs, PCBs persisting in rivers, plastics that nothing can digest. Materials that evolution never prepared nature to handle.

His fourth law, *there is no such thing as a free lunch*, warned against the fossil fuel economy specifically: the idea that we could draw down ancient stocks without consequence. Commoner saw the solution clearly. In 1976, he wrote *The Poverty of Power*, arguing for solar energy as the alternative to both

nuclear and fossil fuels.[4] He understood that sunlight is a flow, not a stock. That capturing it doesn't deplete anything. That a solar economy could honour all four of his laws. He was fifty years ahead of his time.

What Commoner couldn't foresee was the learning curve. He advocated for solar when solar panels cost five hundred times more than what they cost today.[5] He was right about the destination but had no way to predict how fast we would get there. Now we have arrived. The technology he championed is finally cheap enough to win. Reading an interview with him from 2007, five years before his death, I hope and think he would have been delighted with this book.[6]

The question in this chapter is whether we will be able to honour his second law: whether we will stop treating the atmosphere, the water, and the soil as bottomless sinks for our waste.

10.1.1 What We Breathe

Let me put some numbers around the seven million.

The World Health Organization and the Lancet have studied this for decades. Their conclusion: air pollution kills roughly seven to nine million people every year.[7] That makes it one of the leading causes of death globally, exceeding malaria, tuberculosis, and HIV/AIDS combined.[8] Ninety-nine percent of the world's population breathes air that exceeds WHO guideline limits.[9] Not people in particularly polluted cities. Nearly everyone, everywhere.

This is not a distant problem affecting faraway places. Air pollution shortens lives in Amsterdam and London and Los Angeles. It correlates with dementia, depression, and reduced cognitive development in children.[10] It is linked to heart disease, stroke, lung cancer, and of course the respiratory diseases that plagued my mother.[11]

Roughly half of these deaths, approximately 4.2 million, come from outdoor air pollution.[12]

The primary culprit is particulate matter, especially the tiny particles called PM2.5. These are particles less than 2.5

micrometers in diameter, small enough to pass through your lungs into your bloodstream.[13] You cannot see them. You cannot smell them. But they accumulate in your body and cause damage.

Where does PM2.5 come from? Mostly from burning things. Coal power plants. Diesel trucks and buses. Industrial furnaces. The combustion that powers modern civilization leaves a residue in the air, and that residue enters our lungs.

Coal is the worst offender. A single large coal plant can emit thousands of tonnes of particulates, sulfur dioxide, and nitrogen oxides per year.[14] The areas downwind have elevated rates of asthma, bronchitis, heart attacks, and premature death.[15] In China, the coal boom of the early 2000s created air so thick in some cities that people wore masks long before Covid made it fashionable. India faces similar struggles. Even in Europe and North America, where coal is declining, the legacy plants that remain still kill. And of course the exhaust from road traffic is also a big contributor.

The other half of air pollution deaths, roughly 3.2 million, come from indoor air pollution.[16] Over two billion people still cook with solid fuels: wood, charcoal, dung, coal.[17] The smoke fills their homes. Women and children are most exposed because they spend the most time near the cooking fire. Natural gas is much cleaner but make no mistake, it's a silent killer too. It is estimated that it kills around 19 thousand people who cook with it per year in the US[18], and around 40 thousand in Europe.[19] If we apply the same ratio to all people cooking with gas worldwide, that would mean at least hundreds of thousands of people killed every year. A simple solar panel with a battery and an electric cooktop could eliminate this exposure entirely. The technology exists. The cost is falling. The only question is how many people will suffer and die before we deploy it.

10.1.2 The Climate Bathtub

You have probably heard the climate argument a thousand times, so let's keep it short and make it a bit different. The

bathtub metaphor makes it simple. Carbon dioxide in the atmosphere is a stock. Emissions from burning fossil fuels contribute to the inflow. Natural processes, forests absorbing carbon, oceans dissolving it, are the outflow.

For roughly ten thousand years, inflow and outflow were balanced. The concentration of CO_2 in the atmosphere stayed around 280 parts per million.[20] The climate stayed relatively stable. Human civilization developed in that stable window.

Then we started burning coal, oil, and gas in ever-increasing quantities. The inflow vastly exceeds the outflow. The CO_2 stock in the atmosphere keeps rising. We've now crossed 420 parts per million (PPM), higher than at any point in at least 800,000 years.[21] We call the result "global warming."

But we are not done yet. If things go on as planned we will reach 540 PPM before we are done.[22] That level was last reached 15 million years ago[23] when the earth was three to four degrees hotter[24] and the sea level up to 40 meters higher.[25]

However, if we play our cards right, and we stop emitting CO2 soon, this short spike will be partly neutralized by natural processes absorbing the CO2 again. After that we could also build a kind of thermostat for the earth in the form of carbon capture devices that regulate the temperature by capturing excess CO2. But that will already be very expensive. Doing it while we keep emitting CO2 would be prohibitively expensive and unrealistic. So how do we stop emitting green house gasses?

Approximately 76 percent of greenhouse gas emissions come from energy use: electricity, transport, heating, industry.[26] This means that if you solve energy, you solve three-quarters of the climate problem. Not all of it. But most of it. The transition to solar and wind addresses this directly. Solar panels and wind turbines produce zero emissions while operating. There are emissions embedded in manufacturing, in mining the materials, in transporting and installing the equipment. But life-cycle analyses consistently show that solar produces 20 to 50 times less CO_2 per kilowatt-hour than

coal.[27] The emissions required to build a solar panel are paid back in one to two years of operation.[28] Then it runs clean for another 28 years or more.[29] Once we start producing solar and wind with solar and wind, the CO2 emissions become zero.

Build the system once. Run it clean for decades. Recycle the materials. Repeat.

That leaves the remaining 24 percent: agriculture, land use, and certain industrial processes.[30] Electrifying energy doesn't touch these directly. But they lead us somewhere unexpected.

10.1.3 The Invisible Flood

Fossil fuels dominate air pollution deaths and climate change. Once you have replaced fossil fuel with solar and wind, the largest remaining emitter (by a mile) will be agriculture. Partly from "land use change" (cutting down trees) and partly from belching ruminants. Yes. Really.

But there's another reason we must look at food. Commoner's laws remind us that *everything* must go somewhere. There are patterns of pollution that most people seldom think about, pollution that transgresses planetary boundaries even more severely than carbon dioxide. And the biggest driver of this pollution is not energy. It is food.

Consider nitrogen. Every living thing needs nitrogen to build proteins and DNA. The atmosphere is 78 percent nitrogen gas[31], but most organisms cannot use it in that form. For most of history, usable nitrogen was scarce. Farmers relied on manure, crop rotation, and the slow work of nitrogen-fixing bacteria in legume roots.

Then in 1909, Fritz Haber discovered how to pull nitrogen from the air and combine it with hydrogen to make ammonia. Carl Bosch scaled up the process industrially.[32] The Haber-Bosch process, as it came to be known, is one of the most consequential inventions in human history. It enabled the production of synthetic fertilizer at massive scale. Food production soared. The population explosion of the twenti-

eth century would not have been possible without it.[33] Some historians estimate that half of the nitrogen atoms in your body came through a Haber-Bosch plant.[34]

So far, so miraculous. The problem is what happens to the nitrogen we spread.

Less than half of applied nitrogen fertilizer actually ends up in crops.[35] The rest leaches into groundwater, runs off into rivers, and eventually reaches the ocean. There it triggers algal blooms: explosions of plant growth that consume all the oxygen in the water when they decompose. Marine life suffocates. The result is a "dead zone," an area where almost nothing can live.

The Gulf of Mexico has a dead zone the size of New Jersey that appears every summer, fed by nitrogen washing down the Mississippi from Midwestern farms.[36] The Baltic Sea has similar problems. So do estuaries and coastal waters around the world.

Some of the excess nitrogen also converts to nitrous oxide, a greenhouse gas roughly 300 times more potent than CO_2 per molecule.[37] Agriculture, primarily through nitrogen fertilizer, is the main source of nitrous oxide emissions.[38]

Phosphorus tells a parallel story. It is essential for life, with no substitute.[39] We mine it from ancient deposits and spread it on fields. Much of it washes into waterways, causing the same eutrophication problems as nitrogen. Unlike nitrogen, phosphorus cannot be synthesized from the air. We are drawing down a finite stock. Some analysts worry about "peak phosphorus" in the coming decades.[40]

Then there are the chemicals that Commoner warned about. Pesticides designed to kill insects don't stay on the fields where they're sprayed. They spread through ecosystems. Studies have documented dramatic declines in flying insect biomass in some regions, sometimes over 75 percent in a few decades.[41] The causes are complex, but pesticide exposure is one of them. Neonicotinoid insecticides have been linked to declining bee populations.[42] We are loading

ecosystems with synthetic molecules that evolution never prepared them to handle.

However, we have solutions. Using the bathtub metaphor again it's clear we want to reduce the outflow. But as with CO2 the outflow is highly diluted and hard to capture. So we have to reduce the inflow.

There are roughly two ways to reduce the application of fertilizer. Together they can theoretically reduce our application by a factor of about ten. The first is using meat replacements instead of animals. To illustrate using phosphorus: in order to get 1 kg of phosphorus from our food we have to feed plants about 1.4 kg. If we feed plants to animals and eat the meat we need about 5.6 kg.[43] Yes, you can use animal manure as fertilizer, but it is a pretty leaky bucket compared to not using animals at all. The second is precision application of fertilizer in just the right amount and at the right time, so less will be washed away instead of used by crops. Research shows that improvements in agricultural practices can reduce nitrogen losses from 52% to 22%, meaning less than half as much pollutes the environment.[44] This without compromising yields. Reduction to 10% losses seems possible before the soil is mined for nitrogen.[45] This type of precision farming is still considered too expensive but I think that will change.

Pesticides come in two categories. Insecticides that kill insects and herbicides that kill weeds. Instead of insecticides you can use nature by exposing the insects you don't want to their natural predators. The trick here is to use small lanes or plots with the right mix of crops. If you use really small plots it's called "pixel cropping" and the fields look completely different, both visually and in terms of biodiversity. Instead of herbicides you can use a weed killing robot. You can already buy them, although they are still expensive.[46]

Personally I think that, apart from meat replacements, the answer will come from small autonomous agricultural robots. That may sound like a pie-in-the-sky fantasy, but allow me to quickly make the case. The potential impact

is huge and once you look at it through a learning curves lens, it becomes very plausible. Computer intelligence and data communication are learning faster than anything else. It's only logical that in the coming decades little computers costing a few dollars will have more agricultural knowledge than a PhD. Paired with sensors, communication, and self-driving capabilities, I can't see how they would be unable to do the jobs described above. Weeding robots and their cousins are still expensive now, but costs are falling quickly. At the same time, the costs are rising for land, food, fertilizer, and the externalities we're finally recognizing. Falling and rising costs are bound to cross some time in the future. That conclusion, as a certain detective might say, is elementary.

The Chemical Load We're Only Beginning to Understand

In 2022, scientists at the Stockholm Resilience Centre published an update to the planetary boundaries framework. They added a new boundary: "novel entities."[47] This category includes synthetic chemicals, plastics, and other materials that don't occur naturally.

Their conclusion: we have already crossed this boundary.[48] The sheer quantity and variety of synthetic chemicals in the environment has reached levels that may cause irreversible harm to ecosystems and human health.

We produce roughly 350,000 synthetic chemicals.[49] Most have never been tested for environmental effects.[50] Many accumulate in food chains. Some disrupt hormones at very low concentrations. Microplastics now appear in human blood[51], breast milk[52], and rain falling on remote mountaintops.[53]

This is not an energy problem. Most of these chemicals come from agriculture (pesticides, herbicides), industry (manufacturing, mining), and consumer products (plastics, textiles). Electrifying the energy system helps only indirectly, by reducing the fossil fuel feedstocks used to make some of these chemicals.

If you want to reduce humanity's chemical footprint, solar panels are not where to look.

Why am I writing about food in a book about energy? Two reasons. First of all because I'm a system thinker. For me both food and fossil fuel are both energy sources. One for our bodies. One for our machines. In both cases the problem is that getting them is unbalancing the natural world we depend upon. Separating them feels lazy and artificial. Secondly because critics of solar and wind sometimes worry about pollution from their manufacturing and waste. They point to the chemicals used in making semiconductors, the energy required to purify silicon, the waste products from battery production. These concerns are not baseless and I take my critics seriously. I know they mean well. But for that reason I want to help them to have a positive impact instead of causing harm.

The reality is that solar and wind don't exist in a vacuum. So you have to take the systems thinking approach and see how to reduce the damage of the system as a whole. You have to learn to *compare* interventions and see their impact on each others. With fossil fuels it's pretty clear cut. Since fossil fuels emit orders of magnitude more than solar and wind, slow-walking the expansion of solar and wind by asking "critical questions" leads us to use fossil fuels longer, and thus exacerbates the problems you are trying to reduce.

The impacts from food in terms of pollution are even worse than those of fossil fuel. If you really care about protecting the environment and your time and money are limited, you should focus on changing the food system, not squabbling over the impacts of solar panels. The nitrogen we spread on farm fields every year dwarfs the materials that go into solar panels. The pesticides we spray dwarf the chemicals in solar manufacturing. The habitat destruction from agriculture far exceeds any land use from solar farms.

This is not whataboutism. This is prioritizing. If you want to reduce humanity's pollution footprint, electrify energy and reform food. But of those two, food is the harder problem. We know how to generate clean electricity. We are still working out how to feed 8 billion people without drowning the world in fertilizer.

10.1.4 Comparing the Kilowatt-Hours

Not all energy sources are created equal. Every kilowatt-hour has a cost in human lives and environmental damage. The question is how big.

Researchers have calculated the deaths attributable to each energy source, including air pollution, accidents, and supply chain effects.[54] They have also calculated the lifecycle greenhouse gas emissions per unit of electricity generated.[55] The numbers are striking.

The Deadliest Energy Sources and Biggest Emitters

Deaths per gigawatt-hour of electricity generated:[56]

Source	Deaths per TWh
Coal	24.6
Oil	18.4
Biomass	4.6
Natural gas	2.8
Hydropower	1.3
Nuclear	0.05–0.5
Wind	0.04
Solar	0.02

A note on nuclear: The range reflects a large uncertainty. The lower estimate counts only direct deaths and uses conservative figures for long-term cancer mortality from accidents like Chernobyl. Higher estimates include best estimates for the excess deaths from radiation exposure over subsequent decades. What is not in dispute: nuclear's death toll is far lower than fossil fuels, even using the highest estimates.

Greenhouse gas emissions (grams CO_2-equivalent per kWh):[57]

Source	g CO_2/kWh
Coal	740-1100
Natural gas	410-860
Biomass	430-660
Solar	41
Nuclear	12
Wind	11

A note on coal, natural gas and biomass: For coal the range reflects plant efficiency, and inclusion of life cycle analysis. For natural gas the range mostly depends on whether you use newer and higher aerial measurements for methane leakage or lower official estimates. For biomass indirect land use change is included.

Coal kills hundreds of times more people per unit of energy than solar, wind, or nuclear. It emits 20 to 75 times more greenhouse gases over the full lifecycle.

Natural gas is cleaner than coal but still far dirtier than renewables. Biomass, often marketed as “green,” has significant emissions and health impacts from combustion.

Solar and wind occupy a different category entirely. Their health impacts come almost entirely from manufacturing and installation. Once operating, they produce nothing that enters anyone’s lungs. Nothing that warms the climate. Nothing that runs off into rivers.

The comparison is not close. Every coal plant we shut down and replace with solar panels saves lives immediately. Not in 2050. Not when the climate stabilizes. Now, this year, in the lungs of people who would otherwise be breathing particulates.

When Chapter 6 argued that solar uses thousands of times less material than coal, it was talking about the inflow to our bathtub. When this chapter shows that solar produces hundreds of times fewer deaths, it is talking about the outflow.

With closed-loop recycling, the manufacturing emissions become a one-time cost, not a continuous burden. Build the panels. Run them clean for thirty years. Recycle the materials. Build new panels from the recovered silicon and aluminum. Each generation produces a smaller environmental footprint than the last.

10.1.5 We Already Proved We Can Do This

We have solved this kind of problem before. In 1985, scientists discovered a hole in the ozone layer over Antarctica.[58] The cause was traced to chlorofluorocarbons (CFCs), synthetic chemicals used in refrigeration and aerosols.

Two years later, 46 countries signed the Montreal Protocol, committing to phase out CFCs.[59] Today, 197 countries have ratified it, making it the first treaty with universal participation.[60]

Results:

- CFC concentrations in the atmosphere peaked in the late 1990s and have declined since[61]
- The Antarctic ozone hole stopped growing
- Full recovery is expected by approximately 2066[62]

The Montreal Protocol prevented an estimated 2 million skin cancer cases per year by 2030.[63]

It also had climate benefits: CFCs are potent greenhouse gases.[64]

This is not a story about environmental doom. It is a story about a problem identified, addressed, and solved. The same trajectory is possible for air pollution and climate change, if we choose it.

But in 1987, the world signed the Montreal Protocol, agreeing to phase out CFCs. It worked. CFC production dropped. The ozone layer stopped thinning. It is now slowly recovering. Scientists expect it to heal fully by the middle of this century.

The Montreal Protocol is the most successful environmental treaty in history. It demonstrates that humanity can identify a planetary boundary, agree to stop transgressing it, and actually follow through. We are capable of collective action on global environmental problems. We have done it before. We can do it again.

So we can limit raw mineral use until it's not a significant problem. We can get rid of the fossil fueled tyrants. And we can get rid of almost all pollution that kills countless people each year and causes climate change. But that brings us to

our last and ultimate scarce resource: the surface of this beautiful planet. Will we have enough land?

11

Land: The Ultimate Scarce Resource

Did you ever pause to think how strange it is that a person from the Netherlands wrote this book about how solar panels will become our main source of energy?

Did you know that 95% of the people in the world get more sun than we Dutchies do?

The further away from the equator, the less sun year round, especially in winter. The Netherlands is *very* far from the equator. On top of this we are also one of the most densely populated countries in the world with a lot of energy intensive industry: greenhouses, data centers, chemical plants. In short we are uniquely *unsuited* for solar energy. For this reason, the most cost effective solution for the Netherlands is one in which wind energy takes the lead. I expect that we will get about 70% of our energy from wind turbines, dotted over about 10% of our part of the North Sea. The turbines themselves, including their foundations, occupy about 0.01 percent of that sea area. The rest is open water. Fishing boats can still fish. Ships can still sail. The small artificial reefs around the turbine foundations actually increase biodiversity compared to the sandy bottom that was there before. Ecologists have documented more fish, more crabs, more seabirds in the wind farm zones. I utterly fail to see the land-use problem of wind.

For most of the world, the situation is very different. They live in places with more sun than we have. I estimate that for

90 percent of the global population, solar panels on rooftops with modest battery storage is the most cost-effective solution. How much space would that take?

11.1 The Surprising Arithmetic of Solar Land Use

Consider a future in which every person on Earth uses as much energy as the average American. Not the average European, who gets by with half. Not the average Indian, who uses far less still. The average American, who uses a luxurious four times more than the average world citizen.

Americans are not exactly famous for frugality. They drive large cars, air-condition large houses, and run more appliances than anyone. On top of that you have industry, flying, building... We are going to replace all of that with solar panels. The whole shebang needed to power the country. Can everybody on earth have that much energy?

If we produced all that using solar panels, it would be about 75 kilowatt-hours per person per day.

Three-quarters of the world's population lives in places that receive about 4 kilowatt-hours of solar energy per square meter per day, averaged over the year. Current solar panels today convert 20% to 25% of that into electricity. Their efficiency is still increasing constantly, but let's conservatively take 25% efficiency. Then each square meter of solar panel produces about 1 kilowatt-hour per day.

That is a nice number to remember: most solar panels will produce about 1 kilowatt-hour per square meter per day.

That means that for 75 kilowatt-hours per person per day, you need 75 square meters of solar panels.

That might sound like a lot until you start comparing.

In developed countries, the roof space per person alone is 75 square meters. The built environment, including roads, parking lots, driveways, commercial buildings, and industrial facilities, is about 750 square meters per person. So we're talking about solar panels covering 10 percent of the built environment. Or, if you prefer a more intuitive measure: roughly one and a half parking spaces per person.

At the global scale, 75 square meters per person across 10 billion people would be about 0.4 percent of Earth's land surface. Less than half a percent. The world already has more than that in paved roads and parking lots. I think we'll manage.

The objection that solar takes up too much space becomes even more absurd when you compare solar to what we already have. Open pit coal mines leave scars visible from space. Mountaintop removal in Appalachia has leveled hundreds of peaks and buried thousands of miles of streams. The tar sands of Alberta have stripped boreal forest from an area larger than some European countries. Oil extraction requires drilling pads, access roads, pipelines, refineries, storage tanks, and tanker ports. Natural gas needs much of the same. The fossil fuel system already has a sizable land footprint too. We just stopped noticing it.

We Have Room

Land use of solar vs. built environment

What	Area
Solar panels needed per person (US-level consumption)	~75 m^2
Existing roof space per person (developed countries)	~75 m^2
Total built environment per person	~750 m^2
Solar as fraction of built environment	10%
Solar as fraction of all land	0.4%

Solar panels fit on existing roofs. We have ten times more built environment than we need for solar. We don't have to take anything away from nature or agriculture.

Land use of solar vs agriculture

What	Fraction of habitable land
Agriculture	60% (needs fertile soil)
Nature	37% (needs fertile soil)
Built environment	3% (1% 'impermeable infrastructure')
Solar needed for all energy	0.4% (doesn't need fertile soil)

11.2 The Myth That Won't Die

Once you know these numbers, you might wonder why so many people keep insisting that solar and wind cannot work. The claim is usually that their "energy density" is too low.

The argument goes something like this: fossil fuels and nuclear pack enormous energy into small spaces, while solar and wind are diffuse, spread thin across the landscape. Furthermore, the argument continues, history has always moved toward denser energy sources, and solar and wind represent a step backward.

Vaclav Smil, whom I consider a great energy historian, has made versions of this argument for decades. He believes there is a kind of natural law pushing civilization toward higher energy density. This implies nuclear power must follow fossil fuels because nuclear produces more energy per square meter than anything else.

There's just one problem. History has already falsified his prediction. We have been choosing solar and wind over nuclear for four decades now. Not because politicians or environmentalists forced it, but because markets did. Solar and wind rode their learning curves downward while nuclear rode it upward. Whatever "law" Smil thought he discovered, the world decided to ignore it. He is a great energy historian, but a great energy futurist he is not.

The energy density argument persists anyway, pushed by three groups who have accidentally formed an unholy trinity.

First, we have the fossil fuel lobbyists. This will surprise exactly nobody. Armed with deep pockets and a playbook borrowed from the tobacco industry they spread fear, uncertainty, and doubt (FUD). They will not hesitate to make solar seem impractical on any dimension, whether it's true or not.

Second, nuclear proponents. I interact with them constantly, and many are smart, sincere, and genuinely worried about climate change. They believe that land use is the killer argument against solar, the one that will finally convince people that nuclear is the only serious option. And they have

a point, narrowly speaking: nuclear does produce about 100 times more electricity per square meter than solar.

But 100 times more than a tiny number is still a small number. If solar requires 75 square meters per person and we have 750 square meters of built environment per person, then solar "uses" 10 percent of a an area that can't be used for nature or food anyway. And you can't build a nuclear plant on your roof.

Third, farmers and conservationists. This is the group that puzzles me most, because they have it exactly backwards. They worry that solar farms will pave over agricultural land and nature reserves. They think they're defending the Earth, but they are attacking it. And they are worried about the wrong thing entirely.

11.3 The Real Land Hog

About 60% of all habitable land on Earth is used for agriculture. Nature comes in as a distant second with 37%. The total build environment is about 3% of which 1% is actually paved over.

Within that agricultural land, about three quarters is devoted to livestock: pastures for grazing, and cropland for growing animal feed. The other quarter grows food that humans eat directly. That quarter produces 80% of calories and 60% of protein.

A single beef burger, containing perhaps 25 grams of protein, requires about 40 square meters of land to produce. Two burgers per year require more land than solar panels to cover all your energy needs. Not just your electricity needs. Not just your home energy needs. *All* your civilizational energy needs. Two burgers.

If you're worried about humanity's land footprint, the solar panel on your roof is the last thing you should worry about.

The Real Land Hog

Meat's Land Footprint

Food	Land use per 100g protein
Beef	164 m^2
Lamb	185 m^2
Pork	11 m^2
Poultry	7 m^2
Eggs	6 m^2
Tofu	2.2 m^2
Pulses	1.5 m^2
Microfermentation	0.3 m^2
Future Food	0.03 m^2

Beef requires over a 100 times more land than pulses for the same amount of protein. Two burgers per year requires about 80 m^2 of land. That's a bigger area than the solar panels that care of *all* your energy use. And you can't put a cow on the roof.

Microfermentation can take sugar from sugarcane and let micro-organisms convert it to protein. You need about 250g of sugar for 100g of protein and you can produce that in a year with 3m2. You also need about 0.1 kWh per 100g protein to power the bioreactor but the amount of solar panel for that relatively insignificant.

For Future Food (which is still in the laboratory) I've taken the example of Solafood who produce protein by feeding micro-organisms hydrogen and CO2 that they produce with energy from solar panels. You need 50g of hydrogen produced with 2.5 kWh of electricity. You also need 500g of CO2 captured with (in the future) 5 kWh of electricity. Bioreactor operation, water treatment, etc. takes another 2 kWh. About 10 kWh per 100g protein in total. That means about 0.03 m^2 of solar panels on your roof. Cool right?

Solar vs agriculture: energy per square meter	
Solar panels	1 kWh per m^2 per day
Average cropland (food calories)	0.005 kWh per m^2 per day

Solar produces roughly 200 times more energy per square meter than agriculture.

Why? Plants are beautiful but inefficient. Crops convert roughly 0.5% of solar energy into biomass. And most of that is inedible: roots, stems, leaves. What ends up on your plate (or in your tank as ethanol or biodiesel) is less than 0.1%. Solar panels convert 20-25% percent of sunlight into electricity and their efficiency is still increasing.

It becomes even worse if you feed that plant to an animal. By the time a calorie of sunlight becomes a calorie of beef, 99.99% has been lost along the way.

11.4 What We Could Give Back

Solar panels use sunlight over 200-times more efficient than crops. Over 10 thousand-times more efficient than beef.

These are not just interesting facts. This is what a rational energy land use discussion should be about.

Precision fermentation can produce proteins from microbes growing in tanks. Cultivated meat grows real animal muscle without the animal. Plant-based alternatives are improving so fast that for an increasing amount of products (like burgers) most taste testers can't tell the difference.

These technologies are still young and expensive but they are riding down the learning curve. Which means costs will fall, quality will rise, adoption will accelerate, which will make costs fall further... a virtuous cycle.

There is no physical reason that prevents us from producing protein that is healthier and tastier than beef. No reason that prevents us from doing that with a thousand times less land. (See sidebar.)

Then we can really start giving back to nature. Currently 60% of habitable land is being claimed by agriculture. If we replace animal protein production by something smarter we not only reduce animal suffering but we could also give back two thirds of agricultural land back to nature. If you care about nature, that's a lot more interesting than 0.4% of land that is already paved over.

Rewilding Success Stories

Oostvaardersplassen, Netherlands
What was once farmland became a 56-square-kilometer nature reserve in the 1970s. Wild horses, red deer, and Heck cattle now roam grasslands and wetlands. Rare bird species returned. Ecologists debate management methods, but the land transformation is undeniable.

Iberá Wetlands, Argentina
Once drained for cattle, now South America's largest rewilding project. Jaguars, giant anteaters, and pampas deer have been reintroduced. Ecotourism now generates more income than the ranching it replaced.

Scotland's Cairngorms
Scots pine forest is returning to the Highlands after centuries of sheep grazing. Native species are recovering. Red squirrels, capercaillie, and pine martens are spreading.

Yellowstone, USA
Wolf reintroduction in 1995 triggered ecosystem-wide changes. Elk behavior shifted, allowing riverbank vegetation to recover. Stream channels stabilized. Songbird populations increased. One species returned, and the land transformed.

European Bison
Nearly extinct in the wild by 1927, European bison now number over 7,000 across Poland, Belarus, Romania, and elsewhere. Rewilding projects are creating new herds and restoring grazing ecosystems.

When we stop using land, nature often comes back faster than we expect.

11.5 The Final Frontier

"Space, the final frontier." If you are a Star Trek fan like me you can hear these words in your head. The crew of the Starship Enterprise would go and discover new worlds everywhere in the universe. But for the foreseeable future, all life in the known universe is here on earth.

If I see a picture of earth from space, if I look at that blue marble, I feel wonder, awe, gratitude, responsibility.

Most life on earth lives in a band going from just a few meters below the ground to a couple of dozen meters above the ground. Scaled to a globe with a diameter of 30 cm, that's just a few micrometres. This incredibly thin layer, this surface tension, fed by the energy from the sun, is the ultimate scarce resource. The final frontier. And yet we are turning it into monocultural agricultural deserts. Overfeed it with fertilizer. Spray it with poison to kill all life we don't want. I understand we need to eat. Over 2 billion people in the world often don't have enough to eat. But let's try to feed ourselves efficiently and in harmony with nature.

If you are worried about land use, look at your plate, not your roof. So that concludes our deep dive in all the problems that could keep us from abundant energy. Time to wrap up using the framework called planetary boundaries.

12

A Mote of Dust Suspended in a Sunbeam

When I think about my father I think about books. Plural. Every time we moved, which was often, we had to make room and brought more books to the second hand bookstore than most people collect in a lifetime. He couldn't for the life of him hammer in a nail, but in his eagerness to read books, he became my Wikipedia and LLM rolled into one, long before either existed.

There is one single item that makes me think of him above all else. It's not a book but the globe I inherited from him. It went everywhere he went, and now it goes everywhere I go. For him, as for me, it signifies that we are, above all, inhabitants of planet earth. And every time I look at that globe, every time my fingers wander over the thin layer of transparent lacquer protecting the paper, I think how utterly astonishing it is that we exist. How everything that ever lived, loved and died in the known universe, did so in a layer thinner than that lacquer. And I think about that first photograph of Earth from Space. Of Carl Sagan describing it as "a mote of dust suspended in a sunbeam"[1]. Of how we seem mere surface tension between rock and vacuum. Isn't life miraculous? Isn't it worth protecting above all else?

In the life that led up to writing this book I've come to realize that we don't live on a candle we are burning up. Instead we inhabit a mote of dust suspended in a sunbeam.

12.1 Sunlight is Abundant but Earth Has Her Limits

The sunlight that falls upon us is abundant, but mother Earth's resources are not. Her soil is finite. Her atmosphere can only absorb so much. How close are we to the limits of mother Earth? How do we know when we've crossed them?

Jay Forrester, a professor at MIT[2], thought he had an approach that could give the answer. He became convinced that the human mind was excellent at identifying the components of a system (fossil fuels, people, pollution) but terrible at predicting how they interact over time through non-linear feedback loops. He argued that "mental models" were insufficient and that we needed computer simulations. Starting in the mid-1950s, he developed a field called system dynamics that models the world as a system of stocks that interact through flows, publishing his first book *Industrial Dynamics* in 1961[3]. I introduced system dynamics in chapter 1 and likened these stocks to bathtubs with an inflow (faucet) and outflow (drain). I jokingly called it *The Bathtub That Explains Everything*. He also build a simple world model.

System dynamics finally allowed us to model formally how abusive we had been treating mother earth. The first high impact system dynamics report was called *Limits to Growth*. It was written by Dennis and Donella Meadows, along with Jørgen Randers and William Behrens III, a team of young researchers assembled by Jay Forrester who extended his world model[4]. It came out in 1972 and was an immediate blockbuster with 30 million copies sold[5]. It helped that the first oil crisis began in October 1973, shortly after the book's publication[6], and that it was actively pushed to world leaders and the media by a group consisting primarily of European industrialists and scientists known as The Club of Rome[7]. But I think it's success was mostly because it proved mathematically what most of us had felt intuitively.

12.2 Doughnut Economics: the Floor and the Ceiling

This book makes a claim that might seem contradictory: we can have abundance *and* stay within planetary limits. Most

frameworks force you to choose. Environmentalists warn the limits force us to choose austerity. Economists promise endless growth. Each camp suspects the other of dangerous naivety. But I hope this book shows the math points somewhere neither camp expected.

The economist Kate Raworth became weary of both camps and came up with a synthesis. She captured the two requirements brilliantly with her image of the doughnut[8]. Do you see a doughnut in your mind? Now imagine that the outer edge denotes earths ecological ceiling: the planetary boundaries we cannot transgress without destabilizing Earth's systems. Further imagine the inner edge is the social foundation: the minimum level of human welfare below which dignity fails. Food, water, shelter, health, energy, education, political voice. Kate Raworth based the inner edge on twelve dimensions of human wellbeing derived from the United Nations Sustainable Development Goals[9]. Right now, there are billions of people for whom the minimum level of dignity is not met[10].

The doughnut itself, the ring of actual pastry, is the safe and just space for humanity. The sweet spot.

Most discussions of the doughnut treat it as aspirational, a distant goal we might approach if the rich sacrifice enough. Raworth herself tends toward caution about growth. She would probably raise an eyebrow at my optimism about providing abundance for everyone within planetary boundaries. But I think she might also be pleasantly surprised by where the numbers actually lead.

In the first chapter of the book I explained how the learning curve changes everything. When solar electricity costs are a tenth of what they were a decade ago and continue falling, when batteries follow the same trajectory, when the material intensity of energy production drops by orders of magnitude, the doughnut becomes more than aspirational. Abundance becomes achievable *without* transgressing boundaries, precisely because we're replacing high-impact systems with low-impact ones. The trade-off that

haunted twentieth-century environmentalism, prosperity versus planetary health, dissolves.

I don't say this lightly. In chapter 1.6 I confessed my Calvinist roots and my affinity to degrowth as a way to explain to my guilty conscience why I have it so good when so many haven't. But the numbers don't lie. If we deploy solar, wind, and batteries at the rates the learning curves enable, we can provide abundant energy to every human on Earth while staying within all nine planetary boundaries. Not by restricting demand. Not by immiserating the poor. By choosing technologies that are simply better on both dimensions.

12.3 Abundance Within Planetary Boundaries

This brings us to the framework we have been circling around in recent chapters without naming it. Chapter 1.6 examined what we take from the Earth: the raw materials, the mining, the extraction, the inflow to our planetary bathtub. Chapter 8 examined the bathtub itself: the land, the finite surface, the competing uses. Chapter 1.9 examined what we put back: the pollution, the emissions, the seven million deaths, the outflow. Inflow, bathtub, outflow: system dynamics applied to the planet.

In 2009, Johan Rockström and his colleagues gave the ceiling of Raworth's doughnut precise coordinates[11]. They identified nine processes that regulate Earth's stability and measured how close we are to destabilizing each one. Updated by Katherine Richardson in 2023[12], the framework is essentially a dashboard for Spaceship Earth. Where Raworth shows us *why* boundaries matter (human flourishing requires both a floor and a ceiling), Rockström shows us *where* those boundaries lie and how far we've transgressed them.

The standard approach to planetary boundaries is to present all nine, show we've crossed most, and leave the reader either paralyzed or numbly indifferent. A bit like the teacher who told me we were burning up the Earth like a candle and then offered no solution. I refuse to do that to you. Instead, let me use the bathtub metaphor to show that we can solve these

problems with an energy system that provides abundant energy to everyone while staying within the outer boundary of the doughnut.

Let's define the earth's ecosystem as the bathtub. By the earth's ecosystem I mean that thin layer around the globe consisting of fertile soil, breathable atmosphere, and the living beings that inhabit them. If you look at the planetary boundaries framework you will see that most boundaries are about what we are dumping into that bathtub. Climate change. Ocean acidification. Ozone depletion. Aerosol loading. Biogeochemical flows of nitrogen and phosphorus. Novel entities. Commoner's law returns: everything must go somewhere. The planetary boundaries are largely a catalogue of where we've been putting things we shouldn't. Now let's see how we solve it.

SIDEBAR: The Nine Planetary Boundaries (2023 Status)

Boundary	Status	Category	Primary Solutions
Stratospheric ozone	Healing	Inflow	Already solved (Montreal Protocol)
Climate change	Transgressed	Inflow	Solar + wind + food reform
Ocean acidification	Approaching	Inflow	Solar + wind + food reform
Atmospheric aerosol loading	Regional issues	Inflow	Solar + wind + food reform
Biogeochemical flows (N, P)	High risk	Inflow	Precision agriculture + meat replacements
Novel entities	Transgressed	Inflow	Pesticide reduction + plastics regulation
Land-system change	Transgressed	Bathtub	Meat replacements (free up land)
Freshwater change	Transgressed	Bathtub	Meat replacements + precision irrigation
Biosphere integrity	High risk	Bathtub	Meat replacements (free up land)

Key: Within safe operating space | Transgressed (increasing risk) | Highly transgressed (high risk)

Source:[13]

The sidebar categorizes each boundary as "inflow" or "bathtub". The same distinction we've been using since

Chapter 1.1. The pattern holds all the way up to the planetary scale.

Solar and Wind Solve a Lot

Three inflow boundaries share a common pattern: they are mainly, for about 75%, caused by burning things[14]. I'm talking about climate change, ocean acidification, and aerosol loading.

Coal, oil, and gas release carbon dioxide that warms the climate and acidifies the oceans when absorbed. Combustion also releases particulate matter that kills seven million people every year[15].

The solution is obvious. Stop burning biomass and produce the bountiful energy provided by father sun directly with solar panels and wind turbines. They don't emit anything into the atmosphere.

Fix Agriculture and All the Inflow Boundaries are Solved

Once we stop burning biomass, the rest of the inflow for these three boundaries (climate change, ocean acidification, and aerosol loading) comes from agriculture[16]. Through land use change (burning or cutting down forests) and burping cows and sheep.

On top of that agriculture causes the transgression of the nitrogen and phosphorus cycles. They do that by using more fertilizer than crops can absorb so that the rest runs off and wreaks havoc with ecosystems.[17] Agriculture is also a significant contributor to the planetary boundary called novel entities[18]. This is mainly about pesticides that kill far more insects, insect eaters (like birds), and plants than is sustainable.

The solution is two fold. Meat replacements would reduce all agricultural problems by about two thirds, because animals are a very inefficient way to produce food[19] (see chapter 1.8). We are talking about plant-based replacement, precision fermentation, or cultivated meat. We would still have the same amount of food and protein, but the use of

land, fertilizer and pesticide would be drastically reduced. Chapter 1.8 contains more details.

The second solution is precision agriculture: apply fertilizer more precisely (so runoff can be up to five times less)[20,21] and replace pesticides with weeding robots and crops that are strategically combined to support natural predators of insects that harm crops.

So we already solved one inflow boundary: ozone. Transitioning to solar, wind and smarter agriculture can almost completely solve the other five. What's left?

Agriculture Can Also Fix The Bathtub Itself

What's left is the three boundaries that are about the bathtub itself: land-system change, freshwater change, and biosphere integrity. These have little to do with energy for our machines. Unless you're foolish enough to pursue bioenergy at scale. What affects them is, again, how we produce energy for our bodies.

We already discussed the enormous land use of agriculture (especially for meat) in paragraph 11.3.

Freshwater change tracks our disruption of the water cycle. Agriculture accounts for roughly 70 percent of global freshwater withdrawals[22]. Aquifers drain faster than they recharge[23].

Biosphere integrity is perhaps the gravest planetary boundary we've crossed. Extinction rates run 10 to 100 times the natural background[24]. We are living through the sixth mass extinction[25]. The main cause is the land use by agriculture, followed by pesticide use and fertilizer runoff by agriculture[26]. Since meat is responsible for about 80 percent of agricultural land use[27] and indirectly for most pesticide and fertilizer use, meat replacements are the biggest lever we have to stop the 6th mass extinction.

Fortunately, I think that meat replacements will show a steep learning curve. They simply need fewer materials and cause fewer problems (still aside from the animal welfare issue). I'm convinced they will become a no-brainer once they

slid down the learning curve enough to become cheaper, healthier and tastier.

Then we still need to stem the inflow of plastics, that portion of novel entities that isn't pesticides. We still need to improve some industrial processes like cement, and steel. We need a way to run long distance aviation and shipping on electrically produced fuels. But abundant energy within planetary boundaries is not the problem.

12.4 Silver Bullets

There is a phrase that makes me want to throw things: 'There are no silver bullets.' I've noticed it gets deployed whenever someone proposes a solution that actually works. It sounds wise but it counsels paralysis. 'Find me some goddamn bullets' would be more useful.

Solar panels. Wind turbines. Batteries. Digital power converters. And for the hard cases, hydrogen or synthetic fuels made from electricity. That's basically all we need to stop burning nature to feed our machines. Five technologies, all riding learning curves, all getting cheaper every year, all already deployed at scale somewhere in the world.

For agriculture, which drives most of the rest of the ways we transgress boundaries, you need meat replacements and precision farming, both of which are riding learning curves.

I used to look at that globe and feel wonder tinged with guilt over what we were doing to it. By pictures of the earth burning up. No longer. These days I enjoy the sight and feel wholeheartedly. Because now I understand we can all flourish while protecting this mote of dust suspended in a sunbeam. Isn't it marvellous?

PART II

Resilience

13

The Prize

Amsterdam, 2050.

My hands rest on the iron railing of a bridge over the Keizersgracht – the Emperor's Canal. It was dug in 1615 to serve merchants who wanted their packages delivered by boat to their front door. The façades lean forward, so the furniture or merchandise being hoisted up on beams sticking out from the top of the façade wouldn't scrape the brickwork. It's late afternoon and light catches the tall windows of one particularly picturesque house across the water and turns them briefly, outrageously, gold.

I ache in the places that I used to play, and at eighty-five that covers a lot of territory. But I'm happy. A tour boat glides through water so clear I can see fish darting along the canal bed. I can even check that there are no drowned bicycles down there — which, for Amsterdam, is quite astonishing.

Two teenage girls are giggling hysterically at something they're sharing through their VR glasses. A couple of Americans at the terrace below me along the water are delivering a full-volume verdict on the *bitterballen*. "It's like a croquette but *angry*," one of them announces, and I smile, because that's exactly right, and because some things apparently never change no matter how much technology you throw at them.

I breathe in deeply. I let the clean air go all the way down in my lungs while I'm trying to get a scent for what's happening down there in the canal. Hanging there over the railing of this bridge I'll probably look like a golden retriever hanging

out of a car window. But decorum left me somewhere around my sixtieth birthday. I don't miss it much.

And it is so quiet. I can hear the water against the canal wall. I can hear the Americans. I can hear blackbirds in the lindens, singing as if the entire city were built as an amphitheatre for their personal recital. The tour boat passes close now, making a soft hum that could be a large cat with a clear conscience.

Small vehicles weave past me on the bridge — three-wheeled, roofed, barely wider than a bicycle. They thread between pedestrians at walking speed. One swerves patiently around a child who has stopped dead to stare at a dog with an expression suggesting she has just discovered dogs exist. The vehicles cope without problems. They don't honk. They silently flow around obstacles with the grace of water going around a rock.

I watch them for a while, this silent choreography in a clean city, and I feel something in my chest that might be joy, satisfaction, or even pride. Pride of a stubborn old man who spent decades arguing that this was possible and then — against what felt for a long time like the combined resistance of every energy company, grid operator, government official and tenured professor on the continent — lived long enough to stand here leaning on this bridge and watch it happen.

* * *

Yesterday, or was it last week? Things are a little bit foggy these days. I had a virtual reality call with my friend Amara, my contact on the ground in Kenya. The VR is so good now that I could almost smell the red earth around her home. She walked me around her two hectares while small robots scurried between the rows of maize — squat, rugged machines about the size of a Jack Russell, weeding with surgical precision. She talked to them the way you'd talk to a slightly dim but willing dog. "Kidogo, you missed one." Kidogo obediently reversed course and got the weed.

One of the robots was off fetching veterinary supplies from the village depot, twenty kilometres away. It would be back within the hour, Amara said, and shrugged as if dispatching an autonomous robot on a forty-kilometre round trip were as unremarkable as sending your kid to the corner shop.

Her roof had solar panels — maybe eight square metres. More than enough, she said, for the small robots, the fridge, the induction stove in the kitchen, and the LED lights in every room. The amenities of modern civilization in the middle of nowhere. Her kids were doing homework at the table with the focused irritation of teenagers everywhere who would rather be anywhere else. The house was cool and clean and quiet, and Amara was showing me her new grain dryer, which ran on a heat pump, and which she described as the best thing after weed robots.

My thoughts turned to my parents. I was now older than they had ever been. They had missed this new reality — this Amsterdam and this Amara — by decades. But they would have been so happy. My father, who taught me that it was the job of a man to avoid suffering for those less able to stand up for themselves. My mother, always so gentle but fierce when it came to people in need, because she knew what not having enough looked like. They both knew that you measure any system by how it treats the people at the bottom. Not the top. Not the average. The bottom.

My father would have asked Amara questions and would have beamed with joy at her improved standard of living. My mother would have cried a little, pulled herself to me, and would have told me: this was how it should be.

My thoughts wander again, turning to the conference I had attended only yesterday. A conference at – what was it again – ah yes Lappeenranta. The city where LUT University[1] sits on the shore of Lake Saimaa — the fourth largest lake in Europe with birch forests in every direction. I had been at the annual energy transition conference. Halls full of young PhD students figuring out what to do with their lives, milling

around poster sessions, drinking terrible conference coffee, looking faintly terrified about their upcoming presentations. Some things never change.

Tucked into the Wednesday afternoon programme was a session that Michael Liebreich[2] had christened "Old Geezers Doing a Victory Lap." Our little reunion.

For over four decades, we had insisted, with varying degrees of diplomacy, data, and recklessness, that the energy transition would go faster and further than the mainstream believed, and especially faster and further than the mainstream *experts* believed. The mainstream had spent the last four decades catching up with us at the speed bureaucracy discovering email. But we had been there first, and this was our victory lap, and God help anyone who tried to take it from us.

* * *

The session opened with climate. Glen Peters[3] of CICERO, Zeke Hausfather of Berkeley Earth, and Justin Ritchie[4], who back in the 2020s had done the meticulous, thankless, occasionally career-limiting work of demonstrating that the most extreme climate scenarios were built on an implausible assumption of a global return to coal[5]. For years, the worst-case scenario — RCP8.5, which projected a six-fold increase in global coal consumption per capita by 2100 — had been treated as "business as usual" by most researchers, hundreds of newspaper headlines, and approximately every climate anxiety article ever posted on social media. Justin first, Glen and Zeke later, had pointed out that this was simply wrong. Michael and I had been piling on. Michael even invented a hashtag for it: #RCP85isBollocks[6]. A lot of people told me that is how they learned what *bollocks* meant. And it was bollocks, because coal was already declining when the scenario was written. The whole edifice of the worst climate horror scenarios was built on a six-fold expansion of something everybody could already see was shrinking.

They and we had not been popular for saying this out loud. Climate sceptics had seized on the work to argue that climate change wasn't a problem. Climate activists had accused us of downplaying the threat. We had, in fact, been doing neither. We had been doing science, which is the radical act of checking whether your assumptions match the data and reporting the answer even when it is not what you would like it to be and even if both sides of the political divide would rather you hadn't asked.

Their presentation in Lappeenranta was a shared exhale. Emissions had peaked in the late 2020s. The trajectory now pointed to about 1.3 degrees of warming by 2100. Not zero damage — that ship had sailed long ago — but a planet very different from the catastrophe that once seemed inevitable. Glen, who had spent his career parsing emissions data with the affect of a man auditing a particularly hostile spreadsheet, allowed himself a smile. It was like watching a glacier do something unexpected.

* * *

After them came Jenny Chase[7] of Bloomberg New Energy Finance (BNEF), who had been tracking solar since the industry's entire global capacity could have fitted on a large car park. Jenny's talk was simple. When we started, solar was an ambition; now it had completely taken over the world. Not as a supplement. Not as one option among many. As *the* dominant energy source on the planet. I had discovered that almost half a century ago — around 2006 but it was still a surprise to some people. She showed a chart of cumulative installed capacity that started as a timid pencil line in the early 2000s and ended as something you'd need to stand well back from to see the top of. I caught her eye and mouthed *told you so*. She rolled her eyes with the precision of a woman who has been rolling her eyes at overconfident men in the energy sector for thirty years and has got rather good at it. Her analysts were the best in the business but she not-so-

secretly agreed with me that they often "chickened out" (her words) when predicting rapid adoption.

Then our host – and my friend of five decades – Christian Breyer[8] took the stage. Christian had spent his entire career at LUT modelling 100% renewable energy systems[9], even when the phrase alone was enough to get you disinvited from serious policy discussions. He had published study after study showing it was feasible, viable, and necessary. He had been ignored, disputed, patronised, reluctantly cited, and finally vindicated — the full academic stations of the cross, in the correct order. Now retired but showing no signs of stopping — the sort of man who will give a presentation about solar energy at his own funeral, and will still make the audience stay for the Q&A — Christian explained with undimmed enthusiasm that solar was *still* finding new niches. Even wind power, he noted, smiling in a way that made the wind energy people in the audience shift in their seats, was now losing market share to solar.

And then his main focus: direct air carbon capture, powered by surplus solar, pulling CO_2 back out of the atmosphere. Slowly. Less expensively by the year. More steadily and forcefully by the year. That was what had made 1.3 degrees by 2100 — and falling — possible. Christian said this as if reporting a minor correction to a spreadsheet.

* * *

Then Michael Liebreich[10]. Now eighty-seven. No less opinionated in his talk than at thirty-seven, which is saying something if you know Michael. Here was the man who had founded New Energy Finance before it became Bloomberg New Energy Finance, and before renewable energy had been treated seriously. The man who had created the hydrogen ladder[11] — the simple graphic that had done more to deflate the hydrogen hype than a thousand white papers. He was doing what he had been doing for four decades: explaining that he had been right about everything all along, and doing

it so entertainingly that you didn't mind. Or at least that you didn't interrupt.

The hydrogen ladder had been heresy when he first published it around 2020. Hydrogen enthusiasts — and there had been many, most of them holding freshly printed government strategy documents — had wanted hydrogen everywhere. Heating homes. Propelling cars and busses. Anything that would justify the massive infrastructure investments their employers were lobbying for. Michael had pointed out that for most of these applications, you were better off just using electricity directly. Converting electricity to hydrogen and then back again was a costly way to throw away half of the electricity. Hydrogen made sense for seasonal storage, for some industrial feedstocks, for a few niche applications. For everything else it was, as Michael had loved to say, a hydrogen soufflé[12]: a lot of hot air, destined to collapse the moment you looked at it properly.

Of course he had been right. Actually many people in this room had been right, although they hadn't produced this easy-to-understand ladder. By 2050, hydrogen occupied exactly the niches most of us centenarians in the reunion had predicted, and approximately none of the ones its loudest champions had promised. Michael covered this in about five minutes, which for him was an act of restraint bordering on the heroic.

Then he turned to what everyone in 2025 had called the "hard-to-abate" sectors — and which he had written about years ago on his Substack[13] under the heading that these sectors were not, on closer inspection, all that hard to abate. Cement, which once accounted for roughly 8% of global CO_2 emissions[14]. Steel. The poster children of the "some things just can't be electrified" argument — an argument that had aged about as well as "heavier-than-air flight is impossible." Now we had green hydrogen for the direct reduction of iron ore and electric arc furnaces, running on solar electricity, had replaced their coal-fired ancestors at lower cost. Not overnight — these were slow-moving industries run by cau-

tious people who considered a thirty-year planning horizon adventurous — but decisively. Michael dispatched all of this with the brisk efficiency of a man who had been saying "I told you so" professionally for fifty years and had optimised the process.

* * *

The session turned to transport. Colin McKerracher[15] of BNEF was now taking the stage. He was the youngest person in our session, which in this company meant about seventy-five. We called him "the teenager." Like me, he had been tracking electric vehicles since before most car companies took them seriously. I should note, and I will note, because nobody else is going to and this is my book, that my friend Maarten Steinbuch[16] and I had been making the case for electric cars and even electric trucks since 2009. Five years before Colin started working on them, I had already written a (Dutch) book on electric cars. Maarten had sat in the frunk of his Tesla and was telling anyone who'd listen – and the others too – that his great-great-great-grandfather had helped found the automotive school at TU Eindhoven[17] for combustion vehicles, and that he, Maarten, had created an automotive master striving to make combustion obsolete. We were early. We were weird. We were right.

Colin's presentation was almost anticlimactic: electric cars had fully displaced combustion in new sales. Trucks too. These were not predictions. They were history. What interested Colin now — the reason he'd dragged himself to Finland, although we kept pointing out that he'd only recently retired and should really stop complaining about his joints — were the last holdouts: long-haul shipping and long-haul aviation.

Shipping had gone through two acts. First, batteries conquered everything under about 1,500 kilometres. Weight doesn't matter much when your vehicle already displaces ten thousand tonnes of water, and both iron-air and sodium batteries had become obscenely cheap. For longer voyages,

ships had at first switched from diesel to ammonia and methanol synthesised from renewable electricity. But then — and in hindsight this was obvious, which is the most annoying kind of obvious — enterprising women and men started building offshore wind farms that functioned as a kind of car charger on sea, but larger. Same principle as the solar carport in your driveway with its car charger, now scaled up by a factor of about a million. Once you could top up mid-ocean, batteries started winning the long routes too. The ammonia and methanol producers were just as unhappy as the diesel producers had been fifty years earlier. And everybody at the conference felt about as sorry for them as they had felt for the diesel producers in that bygone era.

Maarten took the stage after Colin. Short-haul flights had gone battery-electric in the 2030s. Longer distances had initially switched to synthetic kerosene — electro-fuels. But battery energy density kept climbing, and since electric motors are roughly three times more efficient than jet engines, there came a point where even batteries that weighed twice as much as kerosene were winning on energy delivered to the propeller. Even long-haul was going electric. Maarten explained this with the satisfaction of a man who had been fantasising about this for most of his career and had now been able to board his once fantasy at Schiphol on his flight to the conference.

* * *

After lunch the mood shifted as George Monbiot[18] took the stage. Eighty-seven years old, still writing, still angry about large corporations dominating the little man, still angry about animal abuse, and most of all still angry about people demolishing wildlife in England. Still capable of making a room full of energy specialists feel like they'd been staring at the problem through a keyhole. He'd spent the morning inspecting the birch forest around the university and had returned in high spirits, which for George means newly furious.

He shamed us. That is the only word for what he did — and most of the room was already on his side, which somehow made it worse. He reminded us that in 2025 humanity had been running what amounted to the largest system of deliberate torture ever devised, and had euphemistically been calling it *factory farming*. He cited a study from Heilongjiang Bayi Agricultural University[19] where researchers had tried to find the most effective way to induce clinical depression in pigs — for medical research, not cruelty, although George left a pause there that did a lot of work. The answer? Confine the pig so tightly it can't turn around, and isolate it from other pigs. In other words: standard factory farming practice. The exact conditions in which billions of animals — creatures more intelligent and more social than the dogs we'd go to prison for treating the same way — had spent their entire lives. We had known this. We had known it and we had eaten our lunch and we had not thought about it very hard.

Then George pivoted from animals to land. The staggering share of the Earth's surface that had been devoted to growing feed for the livestock we tortured and consumed. The forests razed. The biodiversity annihilated. He'd been writing about this on and off since *Regenesis*[20] came out in 2022, and by 2050 the data was vindicating him with an almost embarrassing thoroughness. But George wasn't here to take a bow. George was here to make sure we remembered how bad it had been, because George does not believe in letting people off the hook when there is still work to be done, and there is always still work to be done.

Jonathan Foley[21] went next and was a shade more analytical, which after George was like stepping from a cold shower into a heated towel. Jonathan had run Project Drawdown[22] for years — the most comprehensive effort to rank and quantify climate solutions. He piled on the data about how terrible the food system had been, but then he turned the corner: reduced food waste, plant-based diets, precision agriculture, cultivated meat — together, they had freed up vast amounts of land. And that land was rewilding. Forests regrowing.

Grasslands recovering. Species coming back from edges they should never have been pushed to. Jonathan showed maps of rewilded territory spreading across the continents and I found myself blinking hard, which at eighty-five I will blame on dry air and not on anything as undignified as the urge to cry.

Elliot Swartz[23] from the Good Food Institute[24] presented on cultivated meat — real animal protein grown from cells, no animal required. By 2050, cultivated and plant-based proteins had taken most of the global market. Only about ten percent of meat was still from animals. Eating it was becoming, as I like to put it, like wearing fur. Not illegal. Just not something you bring up at dinner parties.

* * *

The last speaker before me was Kingsmill Bond of the Rocky Mountain Institute[25], who had spent decades mapping what happens when the fossil fuel economy unravels. His concept of the electrostate — the geopolitical order that emerges when energy is domestic sunshine instead of imported oil — had gone from a provocation to a fact of life. Nations that had once been petrostates now had the geopolitical leverage of a country whose chief export has gone out of fashion. You cannot embargo the sun. You cannot put sanctions on the wind. Energy politics had shifted from extraction to manufacturing, from scarcity to abundance, from a few nations sitting on fossil reserves to every nation sitting under the same sky.

And then it was my turn.

Of course, I said, looking out at the audience — half PhD students who were wondering why these old people kept congratulating each other, half government officials who were getting slightly annoyed about exactly that — of course everybody in this room thinks holons are obvious. Of course the grid is organised as nested systems, because it is like any other complex adaptive system. Of course every home is an energy node. Of course your neighbourhood balances its

own supply and demand before bothering the wider grid. Of course, of course, of course.

But it's good to take a moment, I said, to realise how much has changed in the last decades. Because forty years ago this was still a very strange idea. The grid was centralised, and power flowed one way — from big plants to dumb consumers. The notion that your home, your street, your city could each function as a semi-autonomous energy cell was loved but uncomprehended by social scientists, and struck most grid engineers as naive, most economists as irrelevant, and most policymakers as pie-in-the-sky thinking.

I'd been one of the first to insist that this was the missing piece. The organisational architecture without which solar panels and batteries and smart inverters would remain clever gadgets rather than the foundations of a new energy civilisation. And I'd been one of the early voices — not the only one, but one of the early ones — shouting into the void that experts were massively underestimating the growth of solar, electric cars, electric trucks, vehicle-to-grid, stationary batteries. I had the receipts.

For most people in that room, the changes to flying, shipping and food were much more tangible, and seemed much more important, than anything I was about to say. And as I was standing there I secretly thought that my most important contribution might be none of those things. It might be the quiet, stubborn, slightly obsessive insistence that the energy system should be structured the way nature structures everything: as nested, semi-autonomous cells. Each one whole in itself and part of a larger whole. Holons. Borrowed from Arthur Koestler, applied to the electricity grid, dismissed for years, vindicated by events.

That was arrogant. I knew it was arrogant. I thought it anyway. You get to be arrogant at eighty-five. It's one of the few perks.

* * *

Amsterdam, 2026.

I blink.

The fish are gone. The water is opaque, the colour of overstewed tea, and I'm sure there are many bicycles down there in the canal. The houses are leaning forward and still beautiful but coated in a familiar thin film of grime. The air is not clean but has the faint, metallic, taste of exhaust. The signature of a civilisation still running on controlled explosions. I know breathing this air will statistically shave two years of my life and probably killed my mother and millions of other people[26] far more quickly than that. But that's just how it is.

And the noise. God, the noise. A scooter tears past with the whine of a two-stroke engine designed by someone who hates ears. A delivery van shakes the bridge. The tour boat churns through the canal trailing diesel behind it like a bad reputation. The Americans might still be at the terrace but I can't make out their argument any more. The blackbird might still be singing, but I'll never know.

It was a daydream. All of it. The conference, the electric plane, Amara and her robots, the clear canal, the clean air, the quiet.

It is 2026 again. My parents have passed away, but the future they told me to build — one measured not by the comfort of the comfortable, but by what it does for people like Amara — is not there yet.

Right now, today, 770 million people[27] have no access to electricity. Over two billion people[28] still cook over wood, charcoal, dung, or coal — fires that fill their homes with smoke that kills roughly 3.2 million people a year[29], mostly women and children, and we have known this for decades. Children study by kerosene lamps that cost more per lumen than solar-powered LEDs already cost today[30], and those fumes are among the most concentrated carcinogens you can expose a child to.

The air outside is not much kinder. Another 4.2 million people a year die from outdoor air pollution. Ninety-nine percent of the world's population[31] breathes air dirtier than the WHO says is safe. Not people in particularly polluted

cities. Nearly everyone, everywhere. In rich countries we still burn fossil gas in our kitchens — an arrangement that kills nineteen thousand Americans a year[32] and around forty thousand Europeans[33], though most of them will never know what did it. India loses 1.7 million people a year to air pollution with fossil fuels responsible for more than 750,000 of those. Meanwhile we keep building gas pipelines that we will have to close early, and nuclear plants that take a decade longer to build than the renewables that would have done the job — a decade during which the existing fossil plants keep running, and keep killing people, which is a line item nobody seems to want to put on nuclear's ledger.

Land tells the same story. Roughly half of the planet's habitable land is given over to farming, and around 80% of that farmland feeds livestock[34] rather than people. Extinction rates are running ten to a hundred times the natural background[35]. The Amazon is still being cleared for soy to feed pigs in Europe and cows in China. Pigs we still torture using "factory farming". Petrostate dictators are still funding wars while the world looks away, because we still need what they have. The grid is still centralised, fragile, increasingly expensive and overdue for reinvention.

I'm standing on this bridge and I'm furious. This is not happening on my shift.

Getting from here to that daydream — from murky water to clear, from kerosene to solar, from a grid designed for the fossil fuelled century we left behind to one fit to support the energy transition in this one — is what the rest of this book is about.

14

Storing solar and wind

Fossil fuels were the "starter package" that nature "gifted" us to bootstrap our machine civilization. It's a quite extraordinary gift when you think about it. Four hundred million years before humans walked the earth, plants diligently started to convert solar energy into huge forests and swamps. Geological processes then buried them and turned them into coal deposits and gas fields. In the sea plankton cells did their part by turning solar energy into biomass and over similarly unimaginably long time scales they were converted into oil basins.

By the time humans wanted to kick off the industrial revolution, nature had everything ready for us: enormous reservoirs of compressed sunshine, conveniently stored, ready to be burned in our machines. Every year we are burning the equivalent of what nature captured for us in over a million years.

Now we are switching to a more permanent solution: directly harvesting sunshine using solar and wind. The good news is that solar and wind are cheap, abundant and last essentially forever. But the sun doesn't always shine and the wind doesn't always blow. So the bad news is that we need to create ways to store them.

Learning to leave fuel behind

After burning biomass for a million years, and creating a machine civilization build on burning fossil fuel, humans apparently have trouble letting go of the idea of burning

fuel. That was almost tangible when I started to research this twenty years ago. Often it persisted in places where it clearly made no sense anymore when you argued from first principles.

It's the best explanation I have for the biofuels craze. Biofuels need roughly five hundred times more land than solar panels to drive a car one kilometre forward. That large area of land also needs to be fertile and directly competes with nature and food. From a system perspective it's obviously an incredibly bad idea. Worse than fossil fuels and much much worse than electric vehicles. Yet most policy makers and energy experts lacked that simple insight when I wrote my (Dutch) book on electric cars in 2009.

I think it's also the main reason people cling to nuclear and fossil fuel. Deep down they feel that energy supply that doesn't include storage simply cannot be relied upon, no matter how many fancy simulations with batteries and other forms of electric energy storage you show them. For me nothing else can explain the vehement attacks on prof. Mark Z Jacobson: in 2009 he was one of the first to propose an energy system without nuclear, fossil fuels or biofuels could work and ten years later many scientists could still not forgive him for this "heresy".

But it's becoming harder and harder to deny that solar, wind, batteries and e-fuels are becoming by far our cheapest option and keep developing like crazy. Meanwhile, the competition – fossil fuels, biofuels and nuclear fission – is stuck. That means the playing field will continue to tilt towards renewables.

But how do we deal with periods without sunshine and wind?

Batteries to replace super-grids and space-based solar

A few decades ago, I didn't think batteries were the answer. I thought geometry was.

The sun, I thought, always shines somewhere on Earth. If you could just connect the place where the sun was shining to the place where the sun was needed, you would always have solar energy. Simple, right? When the sun set over Spain, it would be rising in the Caucasus. Same for wind. When the wind dropped over the Netherlands, it would be blowing over Morocco. With a sufficiently large and sufficiently low-loss super-grid, you would not need to store anything. When I started to research it in 2008, this seemed to be what everybody was thinking. I remember devouring every paper on superconducting cables I could find because that might become the holy grail of long distance electricity cables.

The continental-scale attempt was DesertTec[1], an industrial consortium launched in Munich in October 2009 by Munich Re, Siemens, E.ON, ABB, Deutsche Bank and others. The proposed budget was 400 billion euros and the aim was 15% of European electricity by 2050[2], delivered north through new high-voltage direct-current cables under the Mediterranean. By 2013 the founding foundation had walked out of its own consortium[3]. The official autopsy named the Arab Spring, water scarcity in the Sahara, and inter-partner squabbles. In retrospect the real reason was probably that technology was moving towards distributed energy systems.

Another dead end I poured many many hours into was space based solar. A photovoltaic panel in geostationary orbit gets sunlight more or less constantly: no night, no clouds, no atmosphere in the way. It's not fringe science and far from impossible. Peter Glaser at Arthur D. Little proposed it in 1968[4]. The US Department of Energy funded a major programme through the late 1970s[5]. Japan's space agency ran an active research effort for decades. As recently as 2023, a team at Caltech put a demonstrator into orbit[6] to test microwave power transmission from space. And with the cratering costs of space travel due to reusable rockets it is becoming cheaper every year. But it will be crazy expensive to start with, and

you either need giant receivers on earth that are comparable in size to a land based solar array, or you have to content with concentrated death rays that could easily cook all humans in a city if something went wrong.

Now the solution is obvious of course. Batteries can easily overcome the day-night cycle and with a little e-fuel for seasonal storage we need neither worldwide super-grids, nor space-based solar. But back then, storage felt so intractable that beaming gigawatts of microwaves from a geostationary satellite felt like a more solvable problem than putting cheap batteries on the floor. We really have come a long way the last twenty years.

Understanding energy storage options

This chapter will talk mainly about battery storage, because they have the biggest and most underestimated impact. But it's important that you understand what other storage options there are. Because batteries are not the optimal storage option in all situations. To understand why I created the table below.

Storage option	% losses	$/ kW	$/ kWh	kg/ kWh	l/ kWh	Typical duration
Diesel + motor	65	500	0.5	0.1	0.1	months–years
Corn ethanol + motor	70	600	1	0.15	0.2	months–years
Methanol from electricity	75	3,000	0.5	0.2	0.25	months–years
Ammonia from electricity	80	3,500	3	0.2	0.3	months–years
Hydrogen, 700 bar tank	65	2,500	20	0.6	1.2	days–months
Hydrogen, salt cavern	65	2,500	1	0.03	3	weeks–months
Pumped hydro (large existing)	22	2,000	15	700	700	hours–days
Thermal (molten salt)	60	700	30	45	25	hours–days
CAES (diabatic)	50	1,200	50	60	8	hours–days
Gravity storage (deep shaft)	18	1,200	300	370	50	hours
Flow battery (vanadium redox)	30	600	400	30	80	4–12 h
LFP battery pack	**10**	**100**	**200**	**6**	**5**	**2–6 h**
Flywheel	15	500	8,000	120	30	seconds–minutes
Supercapacitor	5	75	10,000	150	150	seconds

I've ordered them by the typical storage duration they are used for. Let's try to understand why a typical lithium iron phosphate (LFP) battery isn't always the best solution.

First, imagine you want to fly around the world. Your most important metric would be called "gravimetric energy density". Basically you want as few kilograms per kWh of energy as possible. Diesel has the same gravimetric energy density as jet fuel: 0.1 kg/kWh. LFP batteries weight 6 kg/kWh. That 60x more! It's clear that you cannot make a long distance plane with LFP batteries.

For short distance flying, batteries are fine, as you might have guessed from all the battery electric drones buzzing around these days. And batteries can become much lighter than current LFP. The best commercial batteries today are around 3.5 kg/kWh, lithium metal and solid state are ex-

pected to reach 2 kg/kWh within a decade, and with lithium sulfur (Li-S) 1 kg/kWh might be achievable. Take into account that electric engines are more efficient and battery powered flights of 2000 km would become attractive. Still, for transatlantic flights it's clear why most experts are betting on fuels, even in the medium to long term. A similar logic applies to long haul shipping, although off-shore wind farms equipped with fast chargers could plausibly solve that problem.

Seasonal storage is the other place where batteries find it hard to compete. Here the energy is only needed once or twice a year. The cost per kWh of storage becomes dominant in that scenario. In that scenario it's cheaper to use electricity to produce hydrogen and put it in salt caverns, or to produce methanol. The cost per kWh of storage is simply much lower.

However, you would never do this for energy you want to store and retrieve every day or week. Why not? Look at the efficiency! If you convert electricity to hydrogen and then back to electricity again, you lose 65% of energy in the process. For LFP batteries you only lose 10%. In the long term, I expect sodium-ion battery packs to fall below $20/kWh and cover durations up to two weeks.

Bottom-line: fuels produced with solar and wind, often called e-fuels, can take care of long duration storage and anything else fossil fuels can do. Their energy will be more expensive than the energy from batteries, but since only a tiny fraction of electricity will be turned into e-fuels, it does not have a big impact on overall system costs.

Supercapacitors are interesting at the other side of the spectrum. With graphene you could realistically go from 150 kg/kWh now to 5 kg/kWh in the long term. That's hardly heavier than lithium batteries now. But supercapacitors could do for robots and cars, what ATP does for human muscles: provide short bursts of power. And the burst of power supercapacitors could give a car or robot are mind boggling. Just one kWh of supercapacitor could theoretically deliver energy bursts of over 10 thousand kW.

So batteries will do the bulk of the work, but there are better alternatives for storing electricity over very long periods of time and over very short periods of time. If you are familiar with computers, a good analogy is data storage. Supercapacitors are comparable to fast DRAM memory, batteries to SSD hard drives and e-fuels to slow but large hard drives, glass or DNA storage.

Now let's get back to the main story: how to get from fossil fuels to solar and wind and how batteries help.

Demystifying batteries

In essence, a battery is just a place where positively charge atoms called ions can hang out. If you charge your battery, the ions leisurely swim towards the side of the battery that has the minus sign painted on it. We call this side the anode. This is the ions home where they chill before going to work. Their home is often made from a lattice of carbon atoms.

When you want the battery to do work for you, essentially what happens is that the ions swim to the other side of the battery with the plus on it that we call the cathode. Here they have their office. For a lithium iron phosphate battery the ions doing the work are lithium ions, and their office is made from iron-phosphate. For a sodium battery the workers are sodium ions and there are many different offices in development. From example offices from Prussian blue (iron, carbon and nitrogen) or from other abundant elements.

Building better batteries means learning how to build cheap but durable homes and offices for the ions and making sure they can get from home to work easily each day. There are also so called solid state batteries. Here the ions don't swim but walk to work because the electrolyte swimming pool between home and work has been replaced with a solid road.

As the ion workers swim or walk to their office, they are balanced out by electrons (negatively charged particles) flowing through the electricity wire of the equipment you want to power.

For over a hundred years, we used heavy batteries made from lead and acid. Somehow we never bothered to improve them. Then, which the rise of laptops and cell phones, we finally woke up and started to search for lighter ions. And there's still endless possibilities. Superlight batteries using lithium-sulphur or lithium-air. Super cheap batteries using sodium-sulphur or iron-air. Better electrolytes. Solid lithium/sodium/aluminium anodes. If you follow this space closely, you know that we have barely scratched the surface of what's possible.

Not a material problem

Many people are worried about the raw materials needed to make batteries. They shouldn't be. Just as the two or three hundred kilogram battery in an electric vehicle replaces more oil than the biggest oil truck can carry – before the battery is recycled instead of burned – stationary batteries are a spectacularly good addition to our energy system.

In part 1 chapter 10 we already saw that a solar system replaces 250 times it's weight in coal, before it can be recycled twenty times or more. But what you might have missed is how little battery was needed in such a solar system. The glass of the solar panels alone weighted over four times more than the battery. And especially for stationary batteries the materials are unproblematic.

The materials are also potentially very cheap. Keiner and colleagues[7] at LUT University, in February 2026, took a complete utility-scale lithium iron phosphate or sodium-ion system — cells, packs, racks, balance of plant, the lot — down to the raw materials and added the costs back up. Their medium scenario for 2050 produces a complete system at 29 to 52 dollars per kilowatt-hour. Their optimistic scenario lands between 11 and 14 dollars.

Learning to overtake even solar panels

In 2010, a kilowatt-hour of lithium-ion battery cost on average about 1,474 US dollars in 2025 money[8], while by 2025 it

was 108 dollars[9]: a 93% drop in fifteen years. This learning has been severely underestimated[10] and I wrote a paper with Floor Alkemade arguing recent data indicates roughly 28% learning per doubling[11]. I think we can expect about 7 more doublings which would take the pack price to below 25 dollars per kWh by 2050. And if there's one thing I've learned over the past 20 years, it's not to bet against the learning curve.

Solar panels have been the poster child for fast learning in energy, but batteries are overtaking them. That's because manufacturing battery cells is an even purer example of producing small units and learning to improve that with each new product.

The installation of batteries is also relatively straightforward. Batteries need very little space and you don't need to bolt them onto your roof. Instead you can put them basically everywhere. They are already much safer and healthier than e.g. a gas stove while they get safer all the time so placing them indoors is increasingly unproblematic.

Batteries are also much easier to place than power lines or transformers. Power lines must (by definition) go from a defined point A to a defined point B and there's bound to be some areas that need to be crossed where there's natural challenges or people who are opposed. Transformers must (by definition) be at the crossroads between multiple power lines which constrains their position. Batteries must basically be somewhere in the neighbourhood of a power line. That's it. Placement is much less of a challenge and in the future they will provide resilience and decoupling everywhere. I think new houses and businesses without batteries will become exceptional within ten years.

Batteries to replace the local grid

That batteries help solar and wind is widely understood by now, but what few people understand yet is how they will transform the electricity grid. Especially the grid operators

and their captured regulators seem incapable of seeing the obvious.

Grid operators mostly view batteries as a nuisance that can cause peaks on the grid when many batteries charge or discharge at the same time, not as a way to reduce peaks on the grids if you ask them nicely.

And yet, if the trend is clear anywhere its here: over the past 15 years the price of transformers has roughly quadrupled while over that same time, stationary batteries have become 15 times cheaper and 4 times longer lasting. So compared to transformers, battery cells have become almost a thousand times cheaper over the past 15 years. A thousand times. And yet the grid operators are acting as if nothing has happened and their old models don't need an update.

The cost of a grid connection depends on the size of the cable, the application, and where you need it. First size. Big cables are cheaper per kWh they transport. So if you have a lot of cheap energy in one place, and a lot of demand in the other, electricity cables will probably always be a good idea. Then application. If peaks and troughs in production are long lasting, batteries get more expensive the longer they last. That is why batteries are a much better complement for solar (with its day-night cycle) than wind (where fluctuations can last many weeks). Finally where you need it. If buildings are close together, connecting all of them with using an electricity grid is much more cost effective than when they are far apart.

So... for a dense city with little space for solar and a lot of wind nearby, going off-grid will probably remain unattractive. But for a rural area with a lot of solar, grids are already not attractive anymore. And as batteries get cheaper and local production with solar increases, batteries will keep chipping away at the need for a grid connection.

Even in cities that need a grid, batteries can optimise the local use of energy while reducing the peaks that determine the size of the cable and transformer you need. With my company I just researched this in a study for the Dutch gov-

ernment and we found that smart charging electric vehicles and using small batteries of 5 kWh per house could roughly halve the collective peak houses cause on a neighbourhood transformer. For the Netherlands where grid congestion is costing society over 15 billion dollar per year this could save billions per year. Worldwide we are talking about an upside of hundreds of billions every year.

And cost is only the beginning. A grid built around distributed storage, with batteries scattered through cars and homes and substations can be more resilient. Each part can keep functioning when other parts have failed. Each part has a degree of autonomy in deciding when to charge and discharge that no centralised generator could match. Each part is small enough that any individual failure is local. Such a system is far better able to gracefully deal with really big shocks – hurricanes, cyber-attacks, wars and a closed street of Hormuz – than the centralised grid that came before it.

But, I'm getting ahead of myself. Before we talk more about our resilient future with batteries, the next chapters will introduce you to two battery companions. They are revolutionary on their own, but together with solar the four of them are completely unstoppable.

15

Grid-Forming Inverters

On April 28, 2025, just past noon, Spain was doing exactly what energy optimists had been promising it would do. Solar panels were producing over half of the country's electricity. The sun was shining. The future was working.

And then it stopped. First, a solar farm in the south tripped offline. The voltage on the transmission network began to oscillate. Two large conventional generators that had been contracted to provide spinning reserve – the safety net the grid depends on when things go wrong – were not running. Nobody noticed in time. Within a minute, hundreds of solar plants disconnected in rapid succession, their inverters doing precisely what regulations required them to do: shutting down the moment voltage swung outside the permitted band. Within ninety seconds, Spain and Portugal went dark. Fifty million people without power. Trains stopped in tunnels. Traffic lights died. Hospitals switched to backup generators. The largest blackout in Western European history[1].

In the aftermath, commentators lined up to blame solar energy. The sun, they said, was unreliable. Renewables had made the grid fragile. Some called for a return to coal and nuclear baseload. The ENTSO-E final report[2] told a different story. The blackout was not caused by solar power. It was caused by generators that should have been running but weren't[3] and by regulations that forced solar inverters to disconnect rather than help. My own additional conclusion was that the cause was an electrical system still designed around the assumption that stability comes from the top – from big,

spinning machines – rather than from the millions of devices at the edges that could help to keep the system stable, and that can make sure most of the grid simply keeps running if one node trips. I thought of holons, but more about that later.

First let's talk about these new devices at the edges that can make the system distributed and stable.

Solar panels produce direct current. The grid runs on alternating current. The inverter is the translator between these two worlds, the connective tissue between every solar panel and the grid it feeds. In Spain, that translator had been shackled to rules written for an era of coal and steam. The inverters were grid-*following*: designed to ride a wave that someone else was making. When the wave broke, they had no choice but to let go. Solar had been made to follow a system that was never designed for it, instead of leading us into a future designed around what solar actually is: abundant, distributed, electronic. And it was all because we used the translator wrong.

This chapter is the story of that translator. Together with the battery from the previous chapter it can work miracles. It can stabilise voltage, set frequency, and respond to disturbances in milliseconds. Anyone with a solar system, a battery and an electric car can run a microgrid with no instructions from above. The inverter might be the most consequential, least celebrated machine in the whole energy transition.

But to understand why inverters are such a huge step forward, we need to start with the machine that has ruled the grid for a century and a half, and why, at the edges, its reign is ending.

One ring to rule them all

In 1831, Michael Faraday wrapped two coils of wire around opposite sides of an iron ring and discovered that a changing current in one coil induced a current in the other. He had built the world's first transformer, though it would take

another half-century before anyone figured out what to do with it.

Once they found out, it enabled them to use Faraday's ring to win the War of the Currents – the bitter, occasionally deranged 1880s battle between Thomas Edison's direct current and Nikola Tesla and George Westinghouse's alternating current.

The transformer is in essence two sets of copper coils wound around a shared iron core. No moving parts. No fuel. No software. Just copper and iron enthusiastically obeying the laws of electromagnetism as if they had a choice in the matter. Feed alternating current into one coil and the oscillating magnetic field it creates in the iron core induces a current in the other coil. So far it seems rather useless, but here it comes: if you give the input side more or less windings than the output side, a transformer can change the voltage on the output side. More turns on the output side, voltage goes up. Fewer turns, voltage goes down. The mathematics is a first-year physics problem. The execution, at scale, is art.

The efficiency is astonishing. A large power transformer – the kind that sits in a high-voltage substation, humming quietly behind a chain-link fence – converts 99.5 to 99.7 per cent[4] of the energy fed into it. Distribution transformers, the smaller ones on power poles and in street cabinets, manage 98.9 to 99.5 per cent[5]. That kind of performance is brutally hard to achieve with active electronics and flatly impossible for any machine that burns fuel.

Edison's DC had no device that could perform the trick of changing the voltage. Everything worked at the same relatively low and safe voltage. This had the disadvantage that electricity could not travel more than a couple of kilometres before most energy was lost due to resistance in the wires. Thicker wires helped but the required thickness quickly became impractical and prohibitively expensive.

Now voltage comes in. Due to laws that describe the behavior of electricity flows, resistance in a wire is proportional to

the current that flows through it, but independent of voltage. Bottom-line: if you increase the voltage, you increase the amount of energy you transport without needing thicker wires.

So alternating current can use a transformer to create very high voltages, make the electricity travel far with low losses through a relatively thin wire, then use another transformer to bring the voltage down again, et voilla your dishwasher is working.

During the trip this high voltage was of course dangerous, and Edison, in a last act of desperation, publicly electrocuted animals to prove this, including, in 1903, a circus elephant named Topsy.

But Edison's cruel theatrics couldn't change the physics and Tesla's AC won. The transformer electrified the world. And for the next 130 years, Faraday's rings sat at the heart of every grid on earth. Millions of them, connected by wires, stepping voltage up and down at every level of the system. One ring at the power station. Another at the substation. Another on the pole outside your house. The greatest machine ever built is, fundamentally, a mesh of Faraday's rings.

But there is a problem. Transformers are heavy. A 10 MVA substation transformer – the kind that serves a few thousand homes – weighs as much as a fully loaded shipping container. It arrives on a flatbed truck with a police escort. It gets bolted to a concrete pad and stays there for forty to sixty years. This is not a technology poised for disruption. This is a technology that has found its resting place.

The reason is physics. Specifically, 50 Hz physics. A transformer's iron core has to be large enough to carry the magnetic flux produced by the alternating current passing through it. At 50 cycles per second – 60 in the always exceptional United States – that requires a lot of iron. The magnetic flux density of grain-oriented electrical steel maxes out at about 1.5 to 1.8 tesla. You cannot cheat this. You can use better steel, you can optimise the geometry, but the fundamen-

tal relationship between frequency, flux, and core volume has not changed since Faraday did his first experiment.

Worse, the heaviness gets disproportionately worse as the device shrinks. A 10 MW transformer comes in at about 1.5 kilograms per kilowatt and is 99.5 per cent efficient. A 10-watt transformer, the kind that used to live in your laptop charger, comes in at about 30 kilograms per kilowatt and is around 65 per cent efficient. Your laptop charger used to be a warm brick because 50 Hz physics demanded that much iron and copper[6].

Then there is the second problem, which finishes the transformer's case. A transformer can only adjust voltage if it receives alternating current, and solar panels, batteries, computers, EVs and frankly most modern electrical devices run on direct current. Before transistors, if you actually had to convert DC to AC – say, to connect a battery bank to an AC grid – you used a motor-generator set[7]: an electric motor physically spinning a dynamo. A motor. Driving a generator. To convert one form of electricity into another. These contraptions were common in industrial settings and submarine power systems[8] well into the 1960s. They vibrated, they wore out, they leaked oil, and they added five to ten per cent losses on top of whatever you were already losing. Connecting a bona fide electric motor to your solar panel just to create the AC a transformer needs is, when you think about it, not a winning solution.

And the limitations do not end there. A transformer cannot adjust frequency either. It cannot manage power factor. It cannot respond to grid conditions. It cannot be updated. The capabilities it has are the capabilities it was wound with, engraved on its nameplate the day it left the factory, unchanging until the day it is scrapped. For a century, this did not matter. The grid ran on alternating current from large spinning generators, and the one trick the transformer was capable of was the only trick anyone needed.

But we are leaving that grid behind. Solar panels produce DC. Batteries store DC. Electric vehicles run on DC.

Computers run on DC. Heat pumps and modern appliances internally rectify to DC. The world is going direct, the transformer can only speak alternating, and we need far more tricks than just voltage conversion. Faraday gave us a ring, and we wound a civilisation around it. But at the edges of the grid, where DC rules and the future is being assembled one rooftop at a time, a contender has shown up. One that does the transformer's job at a fraction of the weight, with a whole arsenal of other tricks up its sleeve.

The transistor that learned to sing

You might have heard about the transistor. It's the device that brought you computers, smartphones and the internet. It's basically a tiny switch that can be flicked on and off using tiny power flows. That's how it encodes zeros and ones.

What you might not know is that transistors are also used in power electronics where they switch large power flows. I became interested in such power transistors when I was designing high-quality class-D amplifiers for my self-built active loudspeakers. I am what they call an audiophile, which means I pay way too much attention to how music is reproduced. Class-D amplifiers were, at the time, the new up and coming new generation amplifiers and I was amazed at how well you can make a transistor sing. Literally. It was only later, when I started reading about grid-forming inverters, that I realised they use exactly the same mechanism as a class-D amplifier.

To convert DC to AC with a transistor, you take a steady DC voltage – say, 50 volts from a string of solar panels – and you flick it on and off thousands of times per second, generating pulses in a carefully shaped pattern. That pattern of pulses can then generate an AC sine wave. Wider pulses push the voltage up higher, narrower pulses bring the voltage down. A small inductor and capacitor smooth the wave further and you end up with clean, grid-quality AC. This technique is called pulse-width modulation.

Unlike a transformer, which must be physically rewound to change its voltage ratio, the inverter can change voltage, frequency and waveform in microseconds. All by adjusting the timing of those on-off pulses. All in firmware. And the device that does the actual switching is tiny compared to a traditional transformer. A single power transistor module[9] – small enough to hold in one hand, weighing less than a kilogram – can switch over a megawatt. A transformer handling the same power? Over a hundred kilograms of copper wound around a half-tonne of iron core. A ratio of roughly two thousand to one. Imagine replacing a grand piano with a harmonica that sounds grander.

And the even bigger advantage is the repertoire. A transformer does one thing: voltage adjustment, at a ratio engraved on its nameplate. An inverter does all of the following, simultaneously, in milliseconds:

- *Voltage adjustment* – not a fixed ratio but a continuously adjustable range, changed on the fly.
- *DC to AC conversion* – the fundamental trick solar panels and batteries need, the one that used to require a spinning motor-generator set.
- *Frequency setting* – the inverter does not passively inherit the grid's 50 Hz. It can actively *set* it, pushing back against disturbances.
- *Power factor correction* – nudging the timing between voltage and current into alignment, reducing waste.
- *Waveform shaping* – producing whatever waveform the grid needs at that moment, not just a textbook sine.

When you have a solar system, all of this happens in a device the size of a shoebox bolted to your wall. None of that was possible in the era of the transformer. And because the inverter's behaviour is determined by software, it has something the transformer never will: a brain. A brain that can be upgraded over the internet. A software update can teach an old inverter new tricks. Which brings us to the trick that matters most for the holarchic bottom-up grid that this part of the book is about.

Grid-following vs grid-forming

There are two ways an inverter can connect to the grid. One is called grid-following. The other is called grid-forming.

A grid-following inverter listens. It measures the grid's voltage and frequency and synchronises to it. It's operating in lock step with the big boys that are allowed to think for themselves. Traditionally the coal plants, a gas turbines and big hydro generators. If the wave wobbles, the grid-following inverter wobbles too. If the wave breaks – if voltage swings outside the permitted band, or frequency strays too far from 50 Hz – the inverter does what its firmware and the grid code require. It disconnects. By design.

This was a perfectly sensible thing to require in 1990, when there were maybe a few hundred grid-connected inverters in the country and the grid's stability was guaranteed by a few dozen large rotating machines spinning in synchrony. The inverter was a guest. If something went wrong, the polite thing to do was leave the room.

By April 2025, Spain had tens of millions of grid-connected inverters. Solar covered more than half of national electricity production at noon on the day the grid went down. The polite guests were now the household. And their politeness – following the regulatory requirement to disconnect at the first sign of trouble – was the mechanism that turned a local oscillation into a continental blackout. Two large generators that should have been running for spinning reserve weren't. A voltage oscillation began. Hundreds of solar plants, each obeying the rules written for an earlier grid, dropped offline in succession. Each disconnection made the imbalance worse. The cascade took 90 seconds and then Spain went black.

A grid-forming inverter does not just listen to grid, it has a conversation with it. So there is listening involved – to the grid frequency mainly – but also talking. A grid forming inverters generates and maintains its own voltage and frequency using its internal clock and internal computer. If the bigger grid wobbles, a grid-forming inverter doesn't discon-

nect but gently the larger grid towards balance again. If the grid around a grid-forming inverter falls and nothing can be done anymore, a grid-forming inverter disconnects from the bigger grid and keeps its own microgrid up and running. As long as the local power supply and batteries are enough, everything inside the microgrid is protected. Then, as soon as the sensors at its edges see that the grid has recuperated from its fall, the grid-forming inverter clasps hands with the larger grid again.

Now imagine every home and every neighbourhood being managed by such an inverter. Each contributing stabilization of voltage, frequency, reactive power and harmonic filtering to the wires it shares with its neighbours. Disturbances get absorbed locally, in milliseconds, by the nearest device. With such a system, the Iberian blackout would not just have been avoided, it would have been impossible. When something fails in such a grid, the failure does not cascade. It inconveniences whoever is directly connected to the failing node and not under the protection of a local microgrid, but nobody else is impacted.

So a grid-forming inverter provides the following capabilities:

- *Local voltage and frequency stabilisation* – the grid's most precious commodity, previously generated only by spinning iron in distant power stations, now available everywhere there is solar plus battery.
- *Black-start* – restarting a collapsed grid currently requires hours of manually sequenced re-energisation and is one of the most precarious operations in engineering. With grid-forming inverters, it becomes automatic. Each island energises itself from its own DC sources and automatically synchronises when it reconnects once the grid is up again.
- *Islanding* – when something upstream fails, the local section continues operating on its own power. Hospitals, neighbourhoods and homes become electrically resilient by default rather than by emergency procedure.

- *Reactive power and harmonic filtering* – the housekeeping functions that determine whether AC arrives clean. In a microgrid your expensive appliances can reliably get high quality electricity.

You might wonder how this dialogue between the grid-forming inverter and the larger grid works. How can this be done without a central conductor?

The answer is that they use the same mechanism the grid has always used to synchronise its large generators. Which incidentally is the same mechanism Christiaan Huygens observed from his sickbed in 1665 when he noticed that two pendulum clocks hung from the same wooden beam would, after a few hours, swing in lockstep. It's called coupled oscillation. The internet is full of great video demonstrations.

Oscilators that are coupled because they share a medium pull each other into step. On today's grid, the medium is the alternating-current waveform itself, and the synchronisation mechanism is called droop control: as a generator gets loaded, it slows a fraction; as it gets unloaded, it speeds up a fraction; over hundreds of large generators connected to the same grid, the speeds converge. Grid-forming inverters do the same thing in firmware. What works for hundreds of large generators works equally well for millions of small inverters, because the physics does not care how big the oscillator is, only that it shares the wave. The grid does not become more complicated. It just acquires more nodes. Coupled-oscillator synchronisation has been confirmed in dozens of follow-up experiments since Huygens[10]; the question is not whether it works but how to make operators certify it.

Unfortunately, almost every solar inverter operating in the world today is grid-following. The hardware of grid-following inverters is largely identical to grid-forming ones. The difference is firmware and certification. IEA-PVPS Task 13[11] documented that the same power-electronics hardware that runs a grid-following algorithm can, in many cases, be upgraded to run a grid-forming one. New inverters can could

ship with grid-forming capability at negligible additional hardware cost once certification became routine. The premium, estimated at 25 to 50 per cent in 2022[12], is converging toward zero[13].

Grid codes have been slow to acknowledge this new reality, and in my humble opinion that is what caused the Iberian blackout. And even now, most jurisdictions still require inverters to disconnect during disturbances – the exact behaviour that turned a local oscillation into a continental cascade. Fortunately, after the blackout of April 2025, this has begun to change. Grid codes in Australia, the UK, and Germany[14] are moving toward requiring grid-forming capability for new installations.

Bottom-line: reason we don't use more grid-forming inverters today is institutional. The technology to prevent a repeat of Iberia exists, is commercially available, and is converging on free once grid operators accept and certify the new reality.

The incredibly shrinking inverter

Working on the energy transition is marvellous partly because you get to watch almost magical technological progress from so many directions. It might be too complex to easily explain to your uncle at birthday parties but it's highly motivating.

One recurring theme in this book has been how much less raw materials we need once we turn our back on fossil fuels. Solar panels and wind turbines were the first example. Batteries the second. But the inverter beats them hands down in that department.

My roof has eighty solar panels and a 30-kilowatt inverter that weighs about the same as one or two of those panels. In 2000, a transformer-based inverter at that power level would have weighed roughly 150 kilograms. Today's residential workhorses come in around 20 kilograms. The trajectory is clear. I've put it in a table, along with efficiency.

Year	Product	kg/kW	Efficiency
2006	SMA Sunny Boy 5000TL[15]	6.2	95.5%
2011	SMA Sunny Boy 5000TL-20[16]	5.0	97.0%
2020	SMA Sunny Boy 5.0[17]	3.5	97.0%
2024	Huawei SUN2000-5KTL-L1[18]	2.4	98.4%

If I fit a curve to these developments, it becomes clear that residential inverters halve their weight roughly every fourteen years. Two reasons drive it. The first is the wide-bandgap semiconductor revolution[19] – replacing the silicon in the power transistor with silicon carbide (SiC) and gallium nitride (GaN). These materials let the transistor switch faster and waste less energy doing it. Good old silicon switches at 5 to 20 kilohertz[20]. SiC manages 50 to 150 kilohertz[21]. GaN pushes that to 100 kilohertz to over a megahertz[22]: a hundred times faster than the silicon it replaces, with 70 per cent less energy lost per switch[23].

Why does switching speed matter? Because it determines the size of the biggest electrical components. The transistor itself is tiny. The inductor and capacitor next to the transistor are much heavier. Their duty is to smooth the pulses that come out of the transistor. As frequency goes up you need smaller inductors and capacitors to do that. A hundredfold increase in switching frequency yields, after some real-world friction with core losses, roughly a fifty to eightyfold reduction in passive component weight[24].

If I – as a speaker designer – want to understand it, the analogy of enormous bass woofers versus tiny tweeters is irresistible. You might know that the size of a speaker is determined by how much low notes it can produce. There are some tricks but roughly speaking, if a loudspeaker is smaller, it will also produce less deep bass notes. With power transistors that switch at a higher frequency, you are replacing woofers with tweeters.

But it's not just switching at higher frequency that makes the inverter shrink. It's also the increasing efficiency. An efficiency increase from 99% to 99.5% sounds dull, untill you realize this halves the cooling you need, which in turn

halves the heatsink and possibly eliminates the fan. Most of what makes an inverter heavy, even more than the filters, is the aluminum heatsink that gets rid of the waste heat from those components. Less waste heat, less aluminium, less enclosure, less weight and size.

Efficiency	Loss at 5 kW (watts)	Heatsink mass (kg)
95%	250	~3.4
98%	100	~1.35
99%	50	~0.68
99.5%	25	~0.34

When you go from 95 per cent to 99.5 per cent efficiency, the heatsink shrinks by a factor of ten. That is the difference between a component you bolt to a wall and a component you include on a circuit board. Inverter efficiency has been moving at a sober but relentless pace: from 88 per cent in 1988[25] to 95 per cent by 2000. In the laboratory, inverters achieved 99 per cent efficiency by 2017[26] and that is now also available for best in class commercial inverters for your home. There is no Carnot-style hard physical limit to how high efficiency could become and there 99.9% (with a heatsink mass of 70 grams) is possible.

The US Department of Energy targets[27] 0.07 kilograms per kilowatt for entire automotive inverters and BMW and Honda[28] are already approaching it in production vehicles.

An inverter you might know well is your laptop charger. Your laptop charger from 2010 – a warm rectangular slab the weight of a textbook, full of iron and copper at 50 Hz physics – has been replaced over the last decade by USB-C chargers with a tenth of the weight and twice the power. And it's happening for larger inverters too. My 30 kW 20kg inverter could well be replaced by an alternative weighting just 4 kg in 2050.

In essence the inverter is becoming ubiquitous. Every device will be able to stabilise its own frequency and voltage. And inverters will become so small that we will not even notice we have replaced Faraday's rings with a device that is infinitely more capable.

The incredibly shrinking cost

A solar inverter today costs around $42 per kilowatt at the wholesale level. The raw materials in it cost about $4.60. The other 89 per cent is manufacturing, testing, certification, firmware development, warranty reserves, distribution, and margin, and since these need no material at all they continue to fall in price quickly too as volumes increase.

If the curve continues at the rate of the last fifteen years, the projection is suspicious, even for someone who knows learning curves:

Year	$/kW
2025	$42
2030	$19
2035	$9
2040	$4.30
2050	$1.00

At a dollar per kilowatt, my 30 kW inverter would cost just $30 in 2050 and the cost of certification and warranty would dominate the bill. The contribution to my electricity bill would be less than a hundredth of a cent per kWh. The cost of converting DC to AC, of providing grid stability, of enabling solar panels and batteries to participate in the grid, is converging on zero.

What we are watching is the semiconductor revolution arriving to electric power flows. The most-manufactured object in human history – the transistor – having spent the better part of a century learning to carry information, has now learned to carry power. Wind taught the industry that learning curves apply to energy as well as to electronics. Solar steepened that curve. Batteries, in the previous chapter, steepened it again. The inverter steepens it once more. It's a cascade of increasingly fast moving improvements taking over the old grid by storm.

The sky is the limit

The conventional wisdom among grid experts is that inverters are fine for low voltage applications but do not work

at higher voltages because transistors cannot handle high voltages.

However, do you know what sector is also switching to inverters? Ultra high voltage direct current (HVDC). That's the technology that is used for the huge cables that connect enormous wind parks to shore. Cables that can span a continent. These cables use the highest voltages in the entire power system. Sometimes up to 1 million volts. And they use inverters.

The solution is a clever architecture called modular multilevel converters (MMCs) that was introduced by Siemens circa 2010. It basically consists of hierarchical stacks of relatively small inverter modules. Some MMCs already contain tens of thousands of low voltage inverter modules. More modules in parallel increase the total power. More levels of the stack increase the voltage. In a way it's a giant distributed computer for power flows.

We'll come back to this nested modular architecture very often in this part 2 of the book, often under the name of holarchy. For now it's simply interesting to note that many small modules make it possible for MMCs to profit from the learning curve in the much bigger market of consumer inverters. The learning curve makes conventional wisdom outdated once again.

What is also interesting, is that this became possible through a technology called photonics. You already use photonics because fibre optic cables transport most of the data on the Internet these days and it's also a major enabler for hyperscale datacentres. Photonics is essentially computing that uses light particles instead of electrons. Photonics is vital for MMCs because how else do you talk to an inverter module that is working at one million volts? With photonics it becomes easy because light provides near-perfect galvanic isolation.

That said, the standard mid voltage grid transformer isn't going anywhere soon. It's very hard to beat it's combination of ruggedness and galvanic isolation.

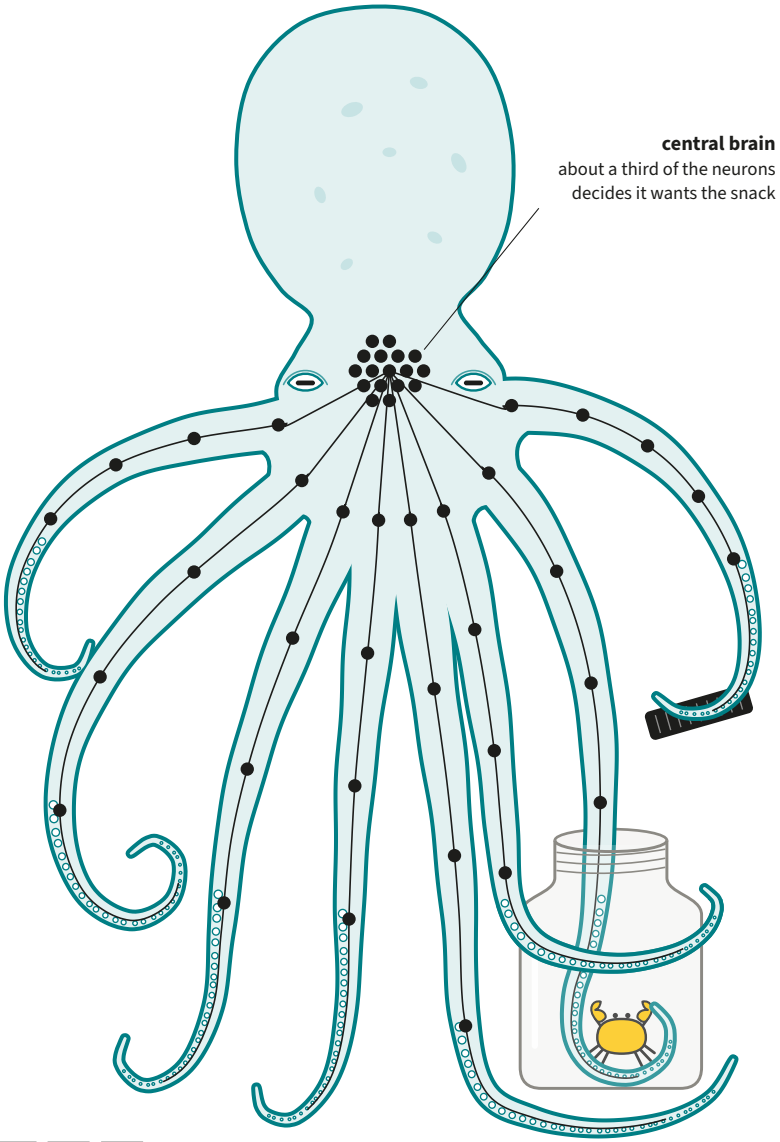
But apart from that basic plumbing in the middle of the grid, inverters are the future. They are the automatic choice when you connect the DC of batteries, solar panels and electric vehicles. As inverters keep getting cheaper and more powerful while transformers become more expensive, they will displace more and more transformers. And once we allow them to be grid-forming, they will make the grid distributed and inherently stable.

That's especially true once the last member of our team joins in the next chapter.

An octopus thinks with its arms

Two-thirds of its roughly 500 million neurons sit outside its head.

● = 10 million neurons



330

million neurons in the eight arms
work out how to get it, each on its own

Numbers from chapter 16, note 1. The 17 dots in the head are 500 less 330 million.

16

Computers: The Grid's Distributed Brain

An octopus has roughly five hundred million neurons. That alone makes it a respectable thinker, somewhere between a domestic cat and a grey parrot. But what's even more remarkable is where this brain lives. Two-thirds of an octopus's brain is not inside the octopus's head. It's distributed along its eight arms – about three hundred and thirty million little processors[1] in suckers and skin and connective tissue. When an octopus opens a jar -- and they do open jars, in laboratory tanks all over the world – the central brain decides it would like the snack inside. It does not micromanage the rest. Each arm reaches independently. It's gripping, tasting, twisting, and autonomously problem-solving[2]. With an octopus this surprises us because it's distributed the actual brain cells that we associate with intelligence, but your own intelligence is also less concentrated in your brain than you might think.

Your intestines take care of the highly complex food processing with no instructions from your brain whatsoever, and your brain wouldn't be able to replace them, not even with a PhD in food chemistry. Your heart has an autonomous build in pacemaker. Your spinal chord does not just transmit signals but also helps you to keep your balance. The cells in your body are highly autonomous advanced micro-factories that do their thing without coordination from your brain and with only minimal communication with the outside world.

You have a microbiome consisting of trillions of guests with their own opinions. These bacteria influence your immune reactions, hunger, anxiety and even your risk taking behaviour. So your perceive yourself as one integrated personality, but you are a federation of countless semi-autonomous parts.

I say all this, because the grid will also get such a distributed brain. Just like you or the octopus. So far we've been wrongly trying to pretend the grid is a monolith that should be guided from the top down, but that is entirely the wrong way to go about it. Instead every appliance will use a little computer to become a highly competent energy planner, and together they will make the grid amazingly resilient and cost-effective at the same time.

Moore's law

I hope you are not yet sick and tired of learning curves dear reader, because it's impossible to talk about computers without discovering their learning curve is the craziest of all. I'm betting it's even the first learning curve you heard about: Moore's law.

It was named after Gordon Moore[3], the Intel co-founder who in 1965 made a casual observation in a trade magazine and ended up describing the central economic fact of the late twentieth century. Moore noticed that the number of transistors you could fit onto a chip was doubling roughly every two years. He projected the trend forward for ten years. If we translate is more broadly in computing per dollar, it has held, along many announcements of its impending death, for sixty years. It even turns out this predictable increase in compute per dollar has been going on for 200 years[4].

As the transistor count per chip increased, the price per computation continued to fall. For sixty years, computing power has become thirty to forty percent cheaper every year[5]. Every year, decade after decade. The cost of a single arithmetic operation has fallen by something like twelve orders of magnitude[6]. That's a *trillion* times more computing

per dollar, with GPU's going faster still[7]. Solar panels getting over a thousand times less expensive is already quite extraordinary but this is something else altogether. The chip in a 2026 smartphone has more raw arithmetic capacity than the biggest room sized supercomputer of the 1980s[8].

On top of this, storage gets cheaper at twenty-five to forty percent per year[9]. The first commercial hard drive shipped by IBM in September 1956[10] stored five megabytes, weighed over a ton, was moved by forklift, and rented about thirty thousand dollars a month in modern money. A microSD card the size of a fingernail now stores a terabyte for 200 euros. Per dollar, that is roughly 30 million times more storage, plus the fact that you don't need a separate room and several engineers to use it. This fingernail-sized chip holds a thousand feature films, ten thousand books, the entire recorded output of Bach, or all your family photos from the day you were born to the day you die. We now treat this as a normal property of small plastic objects.

Bandwidth – the speed at which one computer can talk to another – follows the same shape, only steeper: thirty to fifty percent a year[11]. The dial-up modem on which I send my first emails ran at fourteen kilobits per second: you could practically hear it spell out the letters. A single low-resolution photograph took several minutes, an album of music several hours. Today we stream high-definition video to the back seat of a moving car and we don't even marvel about it anymore. The ethernet in my study runs about a hundred thousand times faster than my first dial-up modem.

On top of that comes the AI. The cost of training and running a large neural network is falling faster than Moore's Law alone could explain, because chip improvements are compounding with algorithmic improvements and software improvements.

Fast forward ten years in the future and you will have a $10 credit card sized Raspberry Pi computer – holding it's own with current smartphones – attached to every inverter, battery and solar array. Each appliance will be able to plan

and coordinate it's energy use in extremely sophisticated ways, and it will be able to do so basically for free, especially when compared to the cost of the grid, energy supply, and batteries.

We need to turn grid-planning on its head

Currently, fossil fuel and nuclear are still dominant in the way we organize the electricity grid. The fossil fuel lobbyist still have the best access to politicians and regulators. And the grid operators still spend almost all our money on more cables and transformers.

Solar and wind are increasingly taken seriously, but batteries are still seen as a nuisance, grid-forming inverters are hardly on the radar, and when you talk about smart semi-autonomous appliances you might as well save your breath.

Some of this is just generational nostalgia. The European policy frameworks that shape today's conversation were largely written between 1995 and 2015, when wind was the most visible new technology, solar still needed subsidising because it was expensive, batteries were boutique items, and the kind of distributed intelligence we are now talking about was science fiction. The policy frameworks made sense at the time, especially when you don't use learning curves to anticipate how things will change. But the people who wrote them seem unwilling or unable to say clearly that they have not aged well, to put it mildly.

The actual hierarchy of learning rates should invert this whole discussion. Using EVs, batteries and all other flexible devices in the smartest way possible should be the *first* priority. Policy makers or regulators that do not understand that should move out of the way. Making sure every building is run by a grid-forming inverter that is rewarded for keeping the grid stable should be the second priority. Scaling up batteries and enabling V2G should be the third. Scaling up solar and wind the fourth. And only *after* all that is done to the max should we spend money on grid reinforcements and fossil fuel stop-gaps.

The Future is Now

None of this is science fiction. Many home energy management systems are already skilled at optimising self use of solar panels and buying energy optimally, taking into account the weather forecast. They would love to trade with the grid operator too. EV charge controllers do similar arithmetic. Modern domestic solar inverters often are pretty smart. Heat pumps from manufacturers like Vaillant and Daikin learn the household's heating patterns, and modulate accordingly. The hardware is on the wall already. What is missing is not the silicon. What is missing is a system that asks it to do anything interesting.

Other industries are years ahead. A modern car contains more lines of code than a fighter jet[12] and runs models that decide, every few milliseconds, whether the wheel is about to slip on ice. A modern factory floor has sensors on every motor, talking to a local controller that talks to a central one and decides things in microseconds. Even your washing machine can detect, by listening to its own bearings, when it is about to break. The energy system is not going to acquire distributed intelligence as a luxury, or as the result of a heroic government programme. It is going to acquire distributed intelligence because that is what every adjacent industry has been doing for the last two decades.

The problem is systemic inertia

We have technology to use computers, grid-forming inverters and batteries to make the grid incredibly resilient and to use its hardware far more optimally. What's missing is the willingness of increasingly out of touch players like grid operators and their regulators to *use* any of it.

They insist on using the same price everywhere and fixing that price years on advance. We will learn that the scientific literature has agreed decades ago that that's a recipe for problems: you should always try to use prices that reflect reality or there will be no end of waste and gaming the system.

They invest tens of billions per year in the Netherlands alone but somehow can't find the money and motivation to monitor the use of that grid infrastructure over time, let alone disclose the data. The amount of resistance to spending money on intelligence and to sharing data is truly remarkable. Compared to the Internet, the intelligence of the "smart grid" is easily a million times less.

This gap is, as far as I can tell, the most under-appreciated fact in the energy debate. Using a bit more intelligence would easily earn back the investment hundredfold, but what's missing is the willingness to accept that using that intelligence might change things.

I telecom I experienced first hand how the telecom operators didn't want to use Internet technology because it made their customers more powerful and the central grid less powerful. Only when threatened with extinction by cable companies did they change their ways. Grid operators are publicly owned monopolies to they will not face the threat of extinction, but there are a couple of levers we can use to initiate change nevertheless.

But first we have to understand why the grid we inherited is no longer up to the task.

17

The Grid We Inherited

2.5.1. On the bridge of the Titanic

It is Sunday evening, late March 2026 when I decide things are so wrong that I have to take a stand and say it clearly: we must break up the electricity grid.

To almost any grid expert I know this sounds like herecy, but if we don't it will ruin us financially, keep us chained to fossi fuels, and make us increasinly vulnerable.

I am at home finishing a report for the Dutch government that I've been working on – on and off – for over a year that answers the question: to what extent could local autonomy solve the huge grid congestion problems the Netherlands is facing?

I take a break and open Bluesky to see what is going on. Someone alerts me to the fact that the Dutch grid operators have just published their new joint cost estimate for the onshore electricity grid through 2040: FIEN26[1]. It is the fourth in a series.

As I start reading the cost estimate I can hardly believe my eyes. Since the previous estimate[2], just 15 months ago, the estimated cost of reinforcing the grid has risen by roughly **€5,000 per household**. This on top of the roughly **€35,000 per household** that were already estimated. Not for solar panels. Not for a heat pump. Not for insulation. Just for *extra* wires that connect our sources to our users of electricity. And on top of that the Netherlands loses economic growth worth at

least **€1,000 per household *per year*** because of businesses and households that cannot be connected to the grid[3].

My first emotion, honestly, is despair. How are poor households going to afford this? Will this block the transition away from fossil fuel?

I talk to my colleagues at Zenmo. We quickly agree that our models indicate this is a spectacularly expensive way to do it. A different architecture — local coordination, flexible demand, smart use of batteries — could deliver the same transition at roughly half the cost, with no waiting list and no yearly economic damage. My colleagues are resigned. We are small. Grid operators are large. It will go their way. "That's just the way it is." But in my head I hear I hear Bruce Hornsby singing the next line: "Ah, but don't you believe them."

Then I call the people I know who work at municipalities, provinces, and consultancies. They are uniformly outraged. Roosmarijn Sweers[4], who handles energy planning in the Drechtsteden[5] region south of Rotterdam, and Bastiaan de Jonge at the province of Utrecht[6]. Both sketch the same picture: if this is really how it is going to go, the consequences for municipalities and provinces will be devastating. Five to ten years of effective lockdown, during which plans for siting new businesses and building new houses will be largely grounded. For them, this is a nightmare scenario. And my friend Maya van Steenhoven[7] has of course already read it and caculated the costs per households. *"How are ordinary households supposed to pay this kind of bill?"* she furiously exclaims with the righteous anger of someone who gives a damn.

The next day I happen to attend a workshop with the people who actually wrote FIEN26. Their reaction is not outrage. It is not panic. They are *proud*. They have improved their methodology. Yes, the number is higher, but the estimate is more precise — that is progress. This is the best cost estimate they have ever produced.

They are on the bridge of this ship, and on the bridge nobody is talking about a course correction as the Titanic is

about to run into the iceberg. Instead they ask themselves *how do we reinforce the hull enough to crush this iceberg*. The Titanic is being redesigned into an icebreaker — a technically possible project, but at monumental cost. A course correction is simply not on the menu. To understand how the hell that is possible, we have to take a step back.

2.5.2. The greatest invention of the twentieth century

In 1745, a Dutch professor named Pieter van Musschenbroek[8] discovered that you could store electricity in a glass jar. He called named the device – after the city he lived in – a Leyden jar[9]. His first attempt to charge it knocked him across the room. He wrote to a French friend that he would not repeat the experiment "for the whole of France." That friend, Abbé Jean-Antoine Nollet[10], of course replicated it immediately and within a year was standing before King Louis XV at Versailles with 180 Royal Guards in a circle holding hands[11]. As he sent a charge from a Leyden jar through the whole line, all soldiers leapt into the air in unison. The king requested a repeat. In Paris, Nollet did it again with a line of Carthusian monks, over a kilometre long.

For the next century and a half, electricity lived mostly in jars and in bodies, and in the imaginations of a handful of people who sensed that something new was happening. In 1831, Michael Faraday built the first generator in his basement at the Royal Institution — a copper disc spun between the poles of a horseshoe magnet — and produced, for the first time in human history, a continuous electric current on demand. In the 1860s, James Clerk Maxwell wrote down the four equations that describe every electromagnetic phenomenon in the universe on a single sheet of paper, which is one of those events that retrospectively seems much too large to have happened even in a single decade. But electricity, for almost everyone alive in the 1870s, remained a curiosity. You read about it in the papers. You had never seen it.

And then, rather suddenly, you had. At three o'clock in the afternoon of 4 September 1882, in a four-storey brownstone

at 255–257 Pearl Street in lower Manhattan[12], Thomas Edison turned on the first electricity grid. Steam engines started to turn six 27-ton dynamos and four hundred electric lamps over a square mile of lower Manhattan turned on. Edison's main investor Morgan and his colleagues were there. They had, until that afternoon, lived their entire working lives by candle, gaslight, and the occasional, brutal glare[13] of an arc lamp on a boulevard. The *New York Times*, also experienced the miracle and the next day described the miracle as *soft, mellow, and graceful to the eye … without a particle of flicker to make the head ache.*

Within a year, Edison had a dozen stations in operation. Within a decade, every major city in the United States and Europe had central stations of its own. Electric streetlights replaced gas lamps along the grand boulevards of Paris and Berlin and Budapest, and people who had spent their lives moving indoors at sunset discovered that they could now walk outside at ten at night as easily as at ten in the morning. And it was not just lamps. Factories installed electric motors and doubled their output without adding a single worker. Trams ran on overhead lines and displaced entire generations of horses — a huge, unnoticed, and enormously consequential environmental improvement, since a city of a million people had previously also been a city of a hundred thousand horses, with all the manure that implies. Electric elevators made twenty-storey buildings feasible and, in doing so, invented the skyline.

Edison's first grid ran on direct current, which turned out to be a technological dead end. Direct current could not be transformed — it could not be stepped up to the high voltages required to move electricity across long distances without losing most of it as heat in the wire. Alternating current could. And so, over the course of the 1890s, alternating current — championed by Nikola Tesla[14] and George Westinghouse[15] — won the War of Currents[16]. And the AC grid then spread, within a single century, across North America, Europe, Japan, the Soviet Union, and beyond.

Today, the grid holds tens of thousands of generators in synchrony across entire continents. A nuclear reactor in Finland, a hydroelectric dam in the Spanish Pyrenees, a lignite plant in Poland, a gas turbine in the Netherlands, a wind farm in the North Sea — every one of them is spinning at exactly the same rate, because every one of them is connected to the same continental-scale alternating-current machine. Supply and demand are balanced every second of every day. The elctricity grid keeps billions of people warm, fed, entertained, and alive in a way unconceivable two centuries earlier.

The National Academy of Engineering[17] named the electric grid the greatest engineering achievement of the twentieth century — ahead of the automobile, the aeroplane, the computer, and the internet. I worked at a grid operator for a number of years and I think most of us agreed with that. The grid truly is the greatest machine humanity ever built. The people on the bridge want to preserve this marvel.

2.5.3. The grid is the perfect answer to a question that is no longer being asked

There is a reason the grid is the way it is. When it was build, a few things were clear to anybody designing it.

Fuel was costly. Coal had to be mined, transported, and burned. Bigger coal fired power plants did that more efficiently and so economies of scale[18] dictated that bigger was better. As technology improved and size increased, thermal efficiency climbed from somewhere around 10% in 1900 to about 45% in the best modern plants[19]. Bigger meant cheaper per kilowatt-hour. Big centralised plants also meant fewer people were needed to manage them, which brought the cost down further. On top of all that, burning coal was dirty, so you did not want the plant near where people – especially rich people – lived. All this meant that power from the plants had to travel long distances. Long distance cables meant high voltages — the only way to move serious amounts of electricity without wasting most of it as heat in the wire.

High voltages, in the pre-semiconductor era, meant alternating current.

Storage was impractical. Batteries existed, but they were far too expensive to store electricity at any useful scale. This meant that supply had to chase demand, every second of the day. The continent needed a universal language of balance, and it found one: frequency. If generation keeps up with demand, the grid runs at 50 Hz. If demand suddenly outpaces generation, the spinning turbines slow a little and the frequency drops. If generation outpaces demand, frequency rises. Every generator on the continent listens to frequency and adjusts. The inertia of all those spinning masses acts as a buffer: during a sudden disturbance, the rotating metal buys the operators a few seconds to respond before the system drifts. This is how grid operators keep the grid stable.

Computers were not available. For the first decades of the grid there were no computers at all, and for the decades after that they were rare and expensive. So you could not put intelligence at every node. You ran the grid, instead, from a control room, with human planners, organised hierarchically. Wholesale markets were laid on top — day-ahead, intraday, balancing — to allocate generation between competing plants (EPEX Spot[20] became the reference for Europe). Each participant had to declare in advance what they would produce or consume; a system of "balance responsible parties" with fines for deviation kept the whole thing tractable. The lack of computers meant strict centralized planning.

Consumers had nothing to contribute. In the era that built the grid, the ideal of industrial efficiency was the assembly line. Cheap workers adapted to expensive machines, not the other way round. Consumers were treated the same way: predictable, passive, aggregate-able. Your kettle boils, your fridge hums, your light comes on. You just do what you always do, which makes you predictable, especially in large numbers. That way planners could treat demand as a static statistical pattern. Your inability to adjust was not a bug but a feature. The grid depended on it.

The grid was a copper plate. From all of this came the crowning promise: wherever you are and whenever you want electricity: you just throw a switch and you will have it. Everyone understand the allure of that simple promise.

A few simple truths that made the grid the way it is. And yet, quietly and without ceremony, technological progress has turned all of these unalienable truths into untruths.

2.5.4. A New Era is Dawning for the Grid

These are the new truths that we should build the new grid on:

Solar and wind are abundant, but arrive whenever they feel like it. Sunlight and wind are already cheaper than coal overall, but unlike coal, they do not take orders. You cannot call up the sun and ask it to work harder on Tuesday. From the point of view of the old paradigm, this is a catastrophe — the planning apparatus built around predictable fossil dispatch is in complete disarray. The fossil industry has responded, reasonably from its own point of view, by rebranding itself as "firm" and "dispatchable" — coded language for *reliable, unlike solar and wind*. But from the point of view of those who understand how the new grid can actually work, they are simply denying themselves abundance.

Storage is not just possible — it is getting cheap. Battery costs have fallen on a learning curve steeper than solar's. Stationary batteries plus the batteries sitting under electric cars will, within the decade, represent roughly ten times the balancing power[21] that thermal generation ever had — and unlike a coal plant, a battery can respond in milliseconds. And yet the grid operator today does not use them for balancing. The concept of a self-balancing grid is still too alien.

Computation is becoming essentially free. In 2025, a microprocessor with the capabilities of a 2005 supercomputer costs less than a sandwich. And yet the grid, at its coordination layer, is still run broadly the way it was run in the 1970s, with the addition of some SCADA screens and a great deal of PowerPoint.

Consumers are active. Remember the assembly-line deal from the previous section — the one where the consumer's job was to be predictable? That deal is over. Every rooftop with solar, every EV on the driveway, every heat pump in the utility cupboard, every home battery in the garage: these are not predictable loads. They are active participants. People want control of their own equipment. Tell them when they can charge their car, and they will politely tell you where to put that idea. But ask them nicely to actively solve grid problems in return for lower grid costs and they are eager to help.

The grid is no longer a copper plate. The promise that location and time did not matter cannot be sustained in a world where generation is distributed, demand is flexible, and the direction of flow changes with the weather. The result of trying to pretend the copper plate still exists in the Netherlands is that congestion is everywhere and connection queues are measured in years. And yet the Dutch grid has on average 80% of physical capacity left[22].

The way we are trying to solve congestion problems — by throwing ever more copper at it — is not working[23]. I've come to the conclusion that the real scarcity is not the amount of copper that is available, but the imagination by which it is utilized.

Allow me to summarize what is happening in the table below.

The first column is the grid we built. The second column is where we are now: grid operators pretending the first column still applies while the world has moved on. The third column is we are going.

Four years ago, the third column was little more than a premonition for me. An intuition if you like. I hadn't yet discovered the visionaries that had already described it. I didn't know yet that that it was business as usual in other domains. But right now, after years of simulation, fieldwork, and just reading the ruinously expensive new cost estimate of the grid operators, I'm willing to die on this hill: we need

to reorganise the grid using decentralized semi-autonomous microgrids. They will make the grid cheaper and more efficient while solving congestion.

But there is another – arguably even more important reason – to break up the grid into these decentralized semi-autonomous microgrids, and that is to make it less fragile.

2.5.5. The Current Grid is Fragile by Design

To explain why the grid should be split up instead of being one big monolythic system, it is instructive to look at potatoes in Ireland.

To explain why the grid should not be one big monolithic system but a loosely coupled ecosystems of microgrids, it is instructive to start with the story of the potato in Ireland. The potato reaches Ireland in the seventeenth century and spreads as food for the rural poor over the following hundred years. It yields more calories per acre than any grain and grows in soil that would barely sustain oats. By 1800 it is the staple of about half the population; by 1840, the near-exclusive staple of the poorest third. Irish population rises from two million in 1700 to eight million in 1840, essentially on the back of this one crop. Within potatoes, a cultivar called the Lumper emerges as the highest-yielding variety. By the 1840s, in much of Ireland, this is the variety that gives everyone food on the table.

In September 1845, *Phytophthora infestans*, an pathogen that has jumped the Atlantic on a ship, reaches Belgium, then Flanders, then Ireland. It immediately starts attacking local European potato's. My country the Netherlands is hit hard and over 50 thousand people die. But because there is a large variety of potato species in the Netherlands, because poor people also eat bread from wheat and rye, because many families do more than work on the land, and because the government intervenes, the size of the famine is limited. In Ireland the effects are far more severe. Because the Lumber is very susceptible to the pathogen and because it's the only type of potato grown in Ireland, counties watch their

entire harvest turn black. In 1846 the pathogen attacks again, and in 1848 again. Because it's the only staple poor people survive on, the end result is one million dead of starvation and disease. One million emigrated, mostly to the United States. Ireland's population drops by a quarter in seven years and still has not recovered to its 1845 level in 2026. Genealogically, it is the largest single event in Irish history. The British government's response — insistence on free-market doctrine, continued grain exports out of Ireland during the famine — makes the outcome worse. But the catastrophe was built in before any politician opened their mouth. It was rooted in a focus on efficiency over resilience.

Another example of how vulnerable homogeneous systems are can still be tasted when you drink European wine. Every wine grape in Europe is the same species, *Vitis vinifera*. When an American botanist imported experimental vines to Languedoc in the late 1850s; he also imported a tiny aphid on its roots. These aphids were harmless to the American vines with their hardened roots but European vines have no defence. By 1889, French wine production has halved, 40% of vineyards are dead, and thousands of vintners have emigrated. The eventual fix was to graft every European vine onto American rootstock that developed natural resistance to this pathogen.

Or take the American dust bowl. First World War wheat prices, tractors, and combines combine to tear up the prairy of the Great Plains. The deep-rooted native grasses that had held soil together for ten thousand years are replaced by wheat with roots twenty centimetres deep. When drought arrives in 1931, there is nothing holding the topsoil in place. On black Sunday, 14 April 1935: a thousand-mile dust storm turns afternoon to midnight. By 1938, 75% of topsoil is gone from half a million square kilometres (fifteen times the size of the Netherlands) and 3.5 million people are displaced. Another human system optimised for short term profit suffers because it's not resilient.

Modern mega-wildfires vividly illustrate the same phenomenon at work. A century of fire suppression has converted forests that have burned in small patches every decade for ten thousand years into even-aged, uniform, heavy-fuel landscapes that burn all at once when suppression inevitably fails, especially in the age of global warming. In California in 2018, the town of Paradise is destroyed in a morning. In 2019-2020 Australia faces it's Black Summer: 100 thousand square kilometres burned, and an estimated three billion vertebrate animals killed or displaced.

Fragility of human designed systems is not just about natural system. Other examples include the 2008 financial crisis, the Boeing 737 MAX crashes or the many examples in software. Some of you might remember CrowdStrike that crashed every Windows machine receiving it's software update, leaving many hospitals, airports, banks, stock exchanges and newsrooms in disarray but I think M.E.Doc is even more instructive. M.E.Doc is used by almost every business in Ukraine for tax compliance. In 2017 Russian state hackers manage to plant a backdoor in an automatic update and installed NotPetya: wiper software disguised as ransomware. It caused worldwide destruction. Maersk, the world's largest shipping company, had M.E.Doc installed on one machine in its Odessa office. Within hours, 45,000 PCs, 4,000 servers, and 2,500 applications across 600 offices and 76 ports were dead. The global supply chain ships 20% of its containers on Maersk vessels; there is now no IT. The company recovers only because of a single backup in Ghana that happened to be offline during a local power cut on the day of the attack — the one thing that survived was the one thing not fully integrated.

Let's finish this tour of destruction caused by fragile human designs with a grid blackout: the Iberian blackout, 28 April 2025. After one solar plant goes offline, voltage oscillations generate a cascade with many other solar systems going offline when voltages exceed limits at which they are permitted to function. It leaves 55 million people without

power across Spain and Portugal. Trains stop in tunnels. Traffic lights die. Hospitals go generators (that thankfully all work). On social media, the first response is to blame solar and the lack of fossil (or nuclear) inertia. Later ENTSO-E's final report[24] paints a very different picture, blaming mainly the regulatory framework that forced solar systems to turn off at the same time. As we will see, a far more robust defence would have been to allow solar systems to stabilize the voltage independently, instead of ordering them to shut off once the big fossil plants cannot manage anymore. And if we add smartly controlled batteries to the mix, blackouts like these become virtually impossible.

All these examples show how we invite disaster if we allow tightly coupled homogeneous systems without buffers or internal boundaries. The grid is a prime example of a system inviting disaster this way. Nature shows us there is a better way.

2.5.6. We Should Learn from Nature

Life on Earth has survived worse than anything humanity has experienced. The Permian-Triassic extinction[25] 252 million years ago killed about ninety-six per cent of marine species and seventy per cent of terrestrial vertebrates — the closest life has ever come to packing it in. The Cretaceous-Paleogene asteroid[26] 66 million years ago took out three-quarters of all species, including every non-avian dinosaur. Snowball Earth[27] froze the planet to the equator for something like ten million years, possibly twice. Any single one of these events would have ended human civilisation as we currently have it arranged. For the biosphere, none of them did. Something about the way life is put together allowed it to take hits on a scale that would turn human civilization to dust. What is it?

One thing life does, which our engineered systems almost never do, is nest smaller semi-autonomous systems inside larger ones while keeping the smaller ones alive. One of the most extreme examples is happening inside your cells

right now. Roughly two billion years ago[28], a single-celled organism swallowed another single-celled organism and, for whatever reason, did not digest it. The swallowed bacterium could use oxygen to generate energy. The host could not. They got on. Over generations they became a partnership: the host kept the bacterium fed and protected; the bacterium kept the host powered.

That swallowed bacterium is the mitochondrion. Every one of the roughly thirty trillion cells in your body[29] contains hundreds to thousands of its descendants. They still divide on their own schedule, on their own timing, and they still carry their own circular bacterial DNA, separate from the nuclear DNA you inherited from your parents. A similar event later, separately[30] produced chloroplasts which allows leafs to turn sunlight into energy: because of a merger, two billion years old, between a larger cell and a smaller one that was already good at turning light into sugar. You, the reader, are a collaboration of absorbed bacteria, all the way down and so is the spinach in your fridge.

When something goes wrong inside a mitochondrion, the cell it sits in usually carries on. When something goes wrong with one cell, the tissue it sits in carries on. When something goes wrong with one tissue, the organism carries on. Damage at one level does not cause catastrophic cascades up or down the chain. The whole reason you can survive a cut, a fever, a minor infection — the reason any complex organism survives anything — is that life has for billions of years run on nested, semi-autonomous systems with their own energy, their own repair mechanisms, and their own ability to keep going when a neighbour fails.

Life has even learned to *profit* from disaster. In the summer of 1988, Yellowstone caught fire. A drought, dry lightning, and gale-force winds combined, and by the end of the season about thirty-six per cent of the park had burned[31] — a quarter of a million hectares. It seemed a long term disaster but within a decade the forest was denser than before, because the dominant tree — the lodgepole pine, *Pinus contorta* —

produces cones sealed with resin that open only above about fifty degrees Celsius. When the fire kills the parent tree, the cones crack and drop tens of thousands of seeds onto freshly fertilised soil with no competition. The fire does not destroy the pine's reproductive architecture. It activates it.[32]

2.5.7. The course correction won't come from the bridge

The current crew and captain are feverishly turning the Titanic into an icebreaker. They are trying to create a grid for the future based on outdated thinking. And if given an unlimited budget they will probably succeed eventually. But why? If you look under the hood, the grid with all it's separate transformers is already a system of potential microgrids. A flotilla masquerading as big ship. Why not allow each ship the freedom to steer around icebergs on its own? Why not when this is what gets us to a future of clean abundant energy? Why not when this flotilla of independent ships gives us more safety and speed at lower costs?

This section I honestly found hard to write. As someone who has worked at the grid operator for a number of years I want to be fair to my former colleagues.

I went to Alliander, the largest DSO in the Netherlands, because I thought improving the electricity grid was the most important thing I could work on. If you want to decarbonise the economy, you have to electrify almost everything, and if you have to electrify almost everything, the grid is where the project succeeds or fails, I thought. I wanted to understand and fix the problem from the inside. That was the way I envisioned having the most impact.

Dutch grid operators are government-owned[33]. Their objectives should be aligned with those of society at large. There are no shareholders extracting value in ways that might be at odds with societal goals. And the resulting grid is one of the most reliable in the world. If change from within was going to work anywhere, Alliander was the grid operator where it should have worked.

I left Alliander because I became convinced that change from within was simply not an option. The engineers inside Alliander had plenty of ideas. Many of them had better ideas and deeper knowledge than I had. But the system they worked inside could only accommodate so much change. The big course corrections that were needed were simply not on the menu.

And to the extend course corrections were on the menu inside the grid operator, they were prevented because of the gridlock that existed in a system that also contains the regulator (ACM[34]), and the ministry (KGG[35]). Any change each of them makes has repercussions for the others in an elaborate system that rewards continuity and punishes deviation. The literature on regulatory capture and on institutional path dependency and inertia[36] in energy infrastructure describes this pattern with alarming accuracy.

This in turn is part of a larger pattern on monopolies and innovation[37] that is documented at length in the scientific literature and that shows that it's exceptional for market leaders to disrupt themselves, even if their survival depends on it. For monopolies, disruption is almost impossible.

So that is why this book is written for a broad audience. Ten years ago I would have written it for grid operators since they are the experts on the subject, but now I understand that they are captured inside a system that cannot disrupt itself. It is up to you, dear reader, to provide the disruption. It's up to you to gain entrance to the bridge and demand a course correction, even if the crew tries to deny you access and even if the captain is unwilling to comply.

18

Holons: The Universal Building Blocks of Life

1. The Parable of the Two Watchmakers

Allow me to introduce Tempus and Hora. Two watchmakers making identical watches of a thousand pieces. Tempus builds his watches in one go, and he does so very efficiently. But when he is interrupted – for example by a phone call from a customer – his entire assembly falls apart on the bench and he has to start all over again.

Hora has a different strategy. He first assembles sub-assemblies of ten pieces. Then he assembles those into larger sub-assemblies of a hundred pieces. And finally he assembles ten of those into a watch. Making these sub-assemblies takes a little bit longer per watch. But when the phone rings he only loses whatever module he happens to be working on. Everything already assembled holds its shape.

As it turns out, you can prove mathematically that in almost all complex systems, following the method of Hora – using sub-assemblies – makes you both more efficient and more resilient. It can be applied to almost anything, and we are going to apply it to the electricity grid.

The current grid, the grid we inherited, is like Tempus. When a substation on the Iberian Peninsula lost sync in April 2025 and all the lights went out from Lisbon to Marseille, it was like Tempus dropping a watch. It was an example of how fragile monolithic systems can be. Such systems become

much more resilient by nesting them – by giving them sub-assemblies inside sub-assemblies.

In this chapter we dive into the theory. And we give it a name: *holons*.

2. Herbert Simon and Near-Decomposability

The man who came up with the parable of the two watchmakers was Herbert Simon[1].

Simon is the kind of all-round genius who would make Leonardo Da Vinci jealous. He won the Nobel Prize in Economics[2] in 1978 and, three years earlier, the Turing Award[3] for artificial intelligence – the only person in history to have won both. He helped found Carnegie Mellon's business school and its computer science department. He was an amateur pianist, painter and mountain climber, and his professional career ran through economics, political science, cognitive psychology, and he became the father of artificial intelligence. In the year before he won the Nobel he was, for reasons of personal interest, teaching an undergraduate course on the French Revolution.

By the end of his life he could read professional papers in roughly twenty languages and literature for pleasure in half a dozen. He taught himself Dutch specifically in order to read Adriaan de Groot's 1946 doctoral thesis on how chess masters think.

In January 1956, walking into a graduate class at Carnegie Tech, he announced: *"Over Christmas, Al Newell and I invented a thinking machine."* The piece of software they wrote is now seen as one of the foundations of artificial intelligence. And yet he was, by all accounts, a personable, warm man. His student Fernand Gobet wrote that Simon's informal style made you sometimes forget you were talking to one of the greatest scholars of the twentieth century.

In 1962 Simon published *The Architecture of Complexity*[4], and, like this chapter, it opens with the parable of Tempus and Hora. Simon's central claim was that all sufficiently complex systems have to function like Hora to survive.

Life. Evolution. Cities. Companies. Any system complicated enough that you would consider calling it complex. He had a name for the property such systems share – the property of being built from semi-autonomous, independent sub-assemblies of the kind Hora uses on his bench. He called it *near-decomposability*.

Near-decomposable means this. Inside a module, interactions are strong and fast. Between modules, interactions are weak and slow. Parts within a sub-assembly bond tightly; sub-assemblies connect loosely. The asymmetry – strong-inside, weak-between – is what lets each level run its own business without being swamped by the others. Such a system is not *completely* decomposable. That would mean your cells have nothing to do with you. It is *near*-decomposable. Your cells communicate a lot more with the mitochondria inside of them than with you, but fortunately they listen enough to make you function as a human being.

The cell is just one example. A microchip is also near-decomposable: what happens inside the chip package is millions of times faster than what crosses the circuit board. A city neighbourhood is near-decomposable: you interact with your block several times a day, with the rest of the city occasionally, with the country a few times a year.

The Architecture of Complexity was the literary way to describe what Simon had shown one year earlier, with Albert Ando, mathematically. In this 1961 paper, Ando and Simon proved that in a near-decomposable system, fast local equilibria reach steady state inside their modules before the slow cross-module dynamics can interfere. The combinatorial nightmare in which every component is coupled to every other collapses into something a designer, or evolution, or a control engineer can actually reason about. Anything you can solve locally you should solve locally, partly because that is very fast. Anything you cannot solve locally you hand up a level – but this does tend to slow things down and create additional overhead.

So the parable of the two watchmakers is not merely intuition or story. It is something Simon had actually proved mathematically a year earlier.

The grid we currently run is the opposite. Every device, in principle, connects to every other. Every fault, every imbalance, every price signal propagates instantly through the whole thing. That is precisely the combinatorial nightmare that Simon and Ando warned about. They proved sixty years ago already that the current architecture of the grid is both more complicated and more vulnerable than it needs to be.

3. Koestler Who Coined the Term Holons

Although Simon described the mechanism, the word for it that we remember comes from Arthur Koestler[5]. Koestler was certainly not a saint[6]. When I think of him, I think of him first and foremost as a survivor of tyrannical monolithic systems – personally, at close range, under sentence of death more than once.

At the beginning of the Second World War, in Spain, he was arrested as a Comintern agent while reporting on the civil war, and condemned to death. The people in the cell next to him were shot. He only survived because one of Franco's ace pilots arranged a prisoner exchange for his wife. In 1939 he was interned as an undesirable alien in the concentration camp at Le Vernet[7]. In September 1940 he was so certain that he would die, horribly, at the hands of the Gestapo, that together with his friend Walter Benjamin[8] he arranged for suicide tablets – which killed his friend, but somehow he survived. During that time he wrote *Darkness at Noon*[9], about a victim broken by totalitarian Stalinist thought. And although you have probably never heard of it, it later led George Orwell to write *Animal Farm* and *Nineteen Eighty-Four*. So this is a man who knew what oppressive totalitarian systems looked like. And I can't help but read *The Ghost in the Machine*[10] through this lens. He wrote it much later, in 1967, and it is not a political manifesto at all, unless you know this background. It is also a way to extend the mechanism that

Herbert Simon had so brilliantly discovered, and to embed it in the social sciences. It is in this book that he coins the word *holon*, from the Greek *holos*, whole, with the suffix *-on* that physics already uses for particles like proton, neutron and photon.

A holon is simultaneously a whole in itself and a part of something larger. A cell is a holon inside a kidney, which is a holon inside a body, which is a holon inside an ecosystem. A home is a holon inside a street, inside a neighbourhood, inside a grid.

For me, Koestler was not merely renaming what Simon had described. He was seeing Simon through the eyes of a man who had tried to take his own life because of what monolithic systems tried to do to him. For him this was not just theory. It was lived experience. He did not only want systems that were more efficient and more resilient. He wanted systems that made us free.

4. Evolution Uses Holons

By now you might have noticed that the entire previous chapter was basically about giving you examples of how monolithic systems fail and how holons survive. The mitochondrion is a holon inside a cell. The cell is a holon inside the tissue. The tissue is a holon inside the organ. The organ lives inside a human being. Human beings form organisations, countries and in the end humanity. Holons make sure failure isn't catastrophic. An infected kidney does not infect the liver. A person dying doesn't end civilization. And life doesn't stop at making architecture robust. Life uses it to improve – as, for example, with the lodgepole pines that use fire to get the upper hand.

In 1996 the evolutionary biologists Günter Wagner and Lee Altenberg[11] formulated further support for Simon's claim – that evolution needs holonic systems to increase the complexity of life.

If your organism is modular, a useful mutation in one trait – a slightly better-placed eye, a slightly more efficient

enzyme, a wing feather that catches the air a little more cleanly – does not automatically scramble everything else. You can evolve the eye without breaking the kidney. If your organism is a monolith, with everything coupled to everything else, every small adjustment has a fair chance of being catastrophic. Evolution cannot get a foothold. The lineage does not persist.

Which, when you think about it, is a rather striking claim. Evolution itself – the single mechanism responsible for every living thing you have ever met, including yourself – does not work on monolithic systems. It *requires* holons. Three and a half billion years of the most ruthless optimisation process in the known universe, running continuously, on every species, in every niche, on every continent, in oceans, in deserts, in hot springs and ice cores and your own gut, and the verdict is unanimous: monoliths die, holons persist.

When we build a grid out of holons, we are not inventing a new architecture. We are adopting the one life on this planet has been stress-testing since before there was oxygen in the air.

5. The Internet Uses Holons

In 1984, three colleagues at MIT – Jerome Saltzer, David Reed and David Clark[12] – published a paper called *End-to-End Arguments in System Design*. Compressed into a sentence, its argument was: keep the network itself simple and stupid. Put the intelligence at the edges, close to the users. That is exactly what we are talking about when we are talking about home energy management systems, as you will meet in later chapters.

The network does not need to know what is flowing through it, let alone coordinate it all. This generic architecture made it possible to implement email, video, peer-to-peer, streaming and every application nobody had yet thought of. It could all be deployed without rebuilding the network underneath. If we apply this to the grid we can intro-

duce local flexibility and energy communities everywhere, and we don't need any central organisation to keep them in check.

Of the three authors, the one who became the public face of the philosophy is David Clark[13]. From 1981 to 1989 he served as Chief Protocol Architect of the Internet – a title nobody has held since, and one that sounds, in retrospect, slightly fantastical. In July 1992[14], in a plenary talk at the 24th Internet Engineering Task Force meeting, he compressed the entire design philosophy of the internet into fourteen words:

We reject kings, presidents, and voting. We believe in rough consensus and running code.

That sentence is one of the most quoted in the history of computing. It is also one of the most political things an engineer has ever said out loud, and it says a great deal about who the internet was built by and who it was built for. It was built by people who distrusted monolithic authority and had chosen a profession where that distrust could be encoded into architecture.

The reason to hold up the internet specifically, rather than some older system, is that the internet was designed for the world the grid now lives in. When the grid was designed, the five "inalienable truths" I listed in the last chapter – *expensive planned supply, no storage, centralised planning, passive consumers,* and *the grid as a copper plate* – were actually true. But that was over a hundred years ago. When the internet was designed, not one of them still held. Supply of bits was cheap and anyone could generate them. Storage was cheap. Computation was becoming essentially free, so planning could be distributed. Users sat at PCs and were anything but passive. And packet-switching had replaced the copper-plate ideal with a network that routed around any bottleneck. That made intelligence at the edges feasible.

The internet is what the grid would look like if it were built today, under modern constraints instead of constraints more than a century out of date.

6. Good Governance Uses Holons

In law and political science, the name for holons is *subsidiarity*.

Subsidiarity means that a decision should be made at the scale that matches the scale of its effects, and larger scales should step in only where the problem genuinely spills over. That is not because small is virtuous. It is first and foremost because people like to be free to make decisions themselves. That in turn is partly because they know their own situation and their own desires best, and partly for a host of psychological reasons that we will come back to in Part Three. Apart from that, it reduces overhead, reduces the chance of cascading failures, speeds up decision-making, and thus leads to an overall more efficient and resilient system.

Holons – or subsidiarity – has been a part of Catholic social teaching for quite a while. The principle was articulated implicitly in Leo XIII's *Rerum Novarum*[15] in 1891 and received its canonical formulation forty years later in Pius XI's *Quadragesimo Anno*[16], the key paragraphs drafted by the Jesuit Oswald von Nell-Breuning[17]. The word reached EU treaty law at Maastricht in 1992 and sits today in Article 5(3) of the Treaty on European Union[18]. The Union acts only where the objectives of the proposed action cannot be sufficiently achieved at national, regional, or local level. That is the test. It is a good test, but from casual observation of Brussels, not always the one that gets applied.

Everybody who knows Dutch history also knows the principle very well. In 1848, while thrones fell across Europe like decorations off an over-decorated Christmas tree, King William II, proclaimed he converted from conservative to liberal in a single night[19]. He then summoned Johan Rudolph Thorbecke[20] to write him a constitution. Thorbecke had written the most thorough commentary on the existing constitution anyone had ever produced, and this had made him rather unpopular. But now he was the perfect man for the job. He also wrote two further statutes – the *Provinciewet*[21] of 1850 and the *Gemeentewet*[22] of 1851. These explicitly distributed

competences across three layers of government: national, provincial and municipal. Each layer had its own mandate, each was answerable to its own electorate, and none could absorb the functions of the others. In Dutch this is called *het Huis van Thorbecke* – the home of Thorbecke – and it has stood for over 175 years.

E. F. Schumacher's *Small Is Beautiful*[23] (1973), written by the former Chief Economic Advisor to the UK National Coal Board, was explicitly framed in terms of Catholic subsidiarity. American federalism. Community-scale economics. Food sovereignty. Cooperative movements. Different accents, same architectural claim. Power works better when it is nested and autonomy is respected at every level: power works better when it uses holons.

To social scientists, political theorists, governance researchers and practitioners who have defended subsidiarity, federalism, polycentric commons or community-scale economics against the centralising default of modern policy I say: the holon framework is what you have been advocating for all along. This book is an argument that the energy system should finally catch up with your field.

When I look at all the citizen energy communities – village wind cooperatives, neighbourhood solar collectives, community batteries, *energiegemeenschappen*[24] in Dutch law, *Bürgerenergie*[25] in Germany, or simply people smart-charging their car or using solar with batteries – I see holons.

7. Holons to Escape the Tragedy of the Commons

One of the most inspiring characters in the holonic tradition – even though she prefers the word *polycentric governance* – is Elinor Ostrom[26] and we will introduce her in more detail in the next chapter.

Her evidence was field data, not theory. Irrigation channels in the Spanish *huertas*. Alpine pastures in the Swiss village of Törbel[27], continuously governed by a written agreement signed in 1224. Village forests in Japan. Inshore fisheries in Maine and Turkey. Groundwater basins under

Los Angeles. Over decades and dozens of cases, polycentric governance of shared resources, matched to the scale of the resource and run by the users themselves, outperformed both state monopoly and private ownership.

Ostrom was a political scientist, not an economist; all three of her degrees, including her 1965 UCLA doctorate, were in political science. She built her career over 47 years at Indiana University Bloomington, where in 1973 she and her husband Vincent founded a research centre they insisted on calling a *Workshop*, run without a hierarchy. In 2009 she received the Nobel Prize in Economics[28]. She is the only woman to have been awarded one.

Her work has quietly demolished one of the oldest assumptions in her adopted field – that common resources have to be either privatised or regulated from above to survive. They do not. Real communities in real places had been governing real shared resources for, in the Swiss case, 800 years, without either an emperor or an invisible hand, and doing it, measurably, better than either would have.

A grid is a shared physical resource. The case for organising it polycentrically is, at this point, not a hypothesis. It is an overdetermined conclusion.

8. The Grid Uses Holons, Well, Almost

Look at any electricity grid. Every low-voltage transformer serves its own customers, who interact with the rest of the world only through the medium-voltage layer above them. Medium-voltage substations interact with the rest of the world through high-voltage transmission. The physical topology of every grid on Earth is a perfect holarchy. The copper is already nested.

What is missing is buffers that can decouple different holons, grid-forming inverters that can steer power flows, computers that can automate the decision-making process, and the will to share power with end users and let them take their own decisions.

So let's define energy holons. An *energy holon* is a semi-autonomous microgrid that can maintain its own balance locally and presents a simple interface to the level above. That level above is then provided with all the flexibility the holon has to offer, without actually having anything to say about how the demands and flexibility are internally coordinated. An energy holon can stay stable for a limited amount of time on its own, but tries to contribute to the larger system whenever it can.

In the engineering literature, such a holon – such a microgrid – is usually small, like a house, a facility or a small cluster. The holon concept generalises it to any scale – from a single home, to a street, a neighbourhood, a city, a province, a country, or even a continent.

The architecture is not theoretical. The US National Renewable Energy Laboratory has been operating microgrid testbeds[29] since 2001. At the other end of the income distribution, the one-house holon is already lived reality for tens of millions of households. The 2024 *Off-Grid Solar Market Trends Report*[30], a joint publication of the World Bank, ESMAP and GOGLA, projects that 398 million people will have first-time electricity access through off-grid solar by 2030 under baseline scenarios. That is the population of the United States plus another hundred million – every one of them a working one-house holon, by necessity, because the grid never arrived.

The idea that the grid should be built using holons is not new. Yoichi Kaya[31] proposed a *"holonic path in the energy system"* in 1987. Nishikawa and colleagues[32] worked out the first engineering version in 1992. Wu, Kotak and Fleetwood[33] extended it in 2004 and 2005. Negeri, Baken and Popov[34] consolidated it between 2012 and 2013. In the Netherlands, Mart van Bracht[35], then at Topsector Energie, brought the word into national energy-policy discourse in October 2020.

This book merely gathers the different lineages under one roof and presents them in an integrated way, using prose that does not require an engineering degree to read.

So now we know that holons win across every domain humans have cared enough to test – biology, the internet, governance, commons management. And we have a grid whose physical topology is already well suited. The remaining question is how you organise the grid into such a system of holons – such a system of semi-autonomous units – without a commander to give the orders. How can cooperation arise without a central plan. And that is what the next chapter is all about.

19

The Grid Doesn't Need a Commander

I. The same fight, twice

I.1 1993

My working life began inside the Dutch telephone company KPN Telecom. It has just been unbundled from the post office in 1989 but it still ran the way it had run for decades. The architecture had a name engineers used without irony – the *intelligent network* – and inside that name there lived a complete worldview. Intelligence sat in the central exchanges. The instrument on your desk was, by deliberate design, as dumb as a brick: a microphone, a speaker, a dial pulse, nothing more. The job of the network was to set up a circuit between two endpoints, hold it open for the duration of the call, and tear it down at the end. Quality, billing, features, security, lawful intercept – all delivered from the centre.

It is easy, thirty years later, to be patronising about this. Don't. The intelligent network was not a relic. It was a deliberate, sophisticated solution to a deliberate, sophisticated problem: *how do you guarantee that any phone in the country can reach any other, in seconds, with reliable voice quality, while billing for the privilege?* The solution was elegant: make the network able to take charge of every call while making the device at each end as simple as possible. Centralise everything that needs to be centralised, and centralise quite a lot more besides.

The engineers who built that network were not fools. There was a coherent technical caste behind it, known in the trade as the *Bellheads* after AT&T's Bell Labs[1], and KPN had its own equivalent. Bellheads possessed a coherent worldview backed by a coherent technology backed by a coherent business model. The worldview was that telephony was hard, the technology was the intelligent network, and the business model was billing for minutes. These three things had been mutually reinforcing for almost a century, which is the kind of streak that tends to make an industry – whether it's Telecom or the electricity grid – feel that the next century will look more or less the same.

I.2 The fight nobody at the top wanted to have

For me, fresh out of my student days, the Bellheads and their architecture seemed decidedly odd. I was friends with a guy whose startup company later coined the term WiFi. His friend, started the first Dutch internet service provider, XS4ALL[2] (Access for All). I worked a student job at the computing centre of the Technical University of Twente[3] where I got to chat with people all over the world using this newfangled thing called the Internet. We all thought the future belonged to TCP/IP: the internet protocol. In telecom, such people were later called Netheads.

With TCP/IP you created a network built on packet switching instead of circuit switching. The network provided no setup, no teardown, no guaranteed circuit – each packet found its own way through whatever routers happened to be available. It was the inverse of the telephone network. Dumb in the middle, smart at the edges. Devices at the edges decided what to send and how fast. The network's job was simply to forward whatever it got, and to warn when it couldn't.

When I started working in telecom, TCP/IP was fringe and most managers and engineers fantasized about a future which held a more sophisticated version of the present. The favoured candidate was ATM[4] – *Asynchronous Transfer Mode*

– a connection-oriented packet protocol with quality-of-service guarantees and per-flow accounting. ATM was the Bellhead vision of how packet switching could be done *properly*: keep the network in charge, give it knobs to turn, preserve the operator's role as the responsible adult. The standards body for ATM was the ITU[5], the formal United Nations agency in which national operators had voting power. The standards body for IP was the IETF and it selected its protocols by what it cheerfully called rough consensus and running code[6]. One body wore suits. The other body wore T-shirts. Both bodies thought the future depended on the other one going away.

In 1997 a research engineer at AT&T named David Isenberg published an essay called The Rise of the Stupid Network[7]. The argument was as simple as it was rude to the Bellheads: the intelligent network was being eaten by a stupid one, because intelligence at the edge scales and intelligence in the centre does not. Isenberg used the word *stupid* on purpose, as a way of throwing it back at the people who had been using it to dismiss IP. AT&T did not enjoy the essay. Isenberg left soon after[8]. Tom Evslin[9], an AT&T executive at the time, later recalled that reading it was like getting a glass of cold water in the face (which he – in retrospect – meant as a compliment).

I.3 How it actually ended

KPN did not become an internet company because they read Isenberg and relished the cold water in the face, nor because a few people like me evangelised TCP/IP. KPN became an internet company because, starting in the late 1990s, cable TV operators[10] began offering all the services KPN was offering. They achieved this by running TCP/IP over the coaxial cable that had previously only provided television. Their all-in-one offering was much cheaper, and customers started to desert KPN in droves.

The architectural lesson is unromantic: *the incumbents did not reform by themselves.* The disruption arrived from outside the regulatory envelope built around the incumbents – cable

was a different industry under a different regulator – and the customers walked. The Bellheads were structurally incapable of initiating this move towards the internet architecture. Their institutional logic, their technical training, their billing systems, their relationships with national regulators were all organised around the worldview that the new architecture made obsolete. They were not bad people. They were the wrong people.

1.4 The same shape, in electricity

After all that – and after leading part of a project that switched everything within KPN onto the Internet Protocol – I felt I had reached an end. I had gone from one of the few lonely idiots promoting TCP/IP to nobody disagreeing any more. I decided I needed a sabbatical. During that sabbatical I discovered fossil fuels where losing due to the ongoing technological revolutions in solar, wind, batteries and electric vehicles, and it felt vaguely similar and at least as important. I decided this was my chance to start a brand new career. Now it's 2026, but in many ways it feels like 1993 all over again.

The grid now, it seems to me, is in roughly the position telecom was in around 1993. It has gone through one architectural reform – the unbundling that began with the EU's First Electricity Directive in 1996[11] and was implemented in the Netherlands as the Elektriciteitswet of 1998[12] – and that reform forced the invention of wholesale markets coordinating energy supply. Now it's possible for anybody to provide energy, just like the internet made it possible for anybody to start a blog and provide content.

But in terms of energy transport, this is still a network that ignores the intelligence at the edges and likes consumer equipment that is a dumb as a rock. And even though the electricity grid is a lot dumber in terms of routing and monitoring than the Internet, the intelligence that remains is in the centre.

The grid operators organise everything centrally, even though there are now massive amounts of intelligence and flexibility at the edges. All this intelligence and storage is largely unused, because it does not fit the centralised paradigm. There is a market for content, but not for transportation.

An alternative is possible. The grid could use all the intelligence and storage at the edges to use the grid far more optimally. It could use that same intelligence and storage to keep power flows and voltage stable. It could use simple protocols, similar to the internet protocol, to route energy in such a way that grid nodes that are in danger of being overloaded get bypassed using other nodes that are not. For somebody with an internet background, it all seems so logical, so efficient, so safe, so scalable, so resilient. And it has been proven in countless small pilots. We know it works. Yet it does not progress any further than that, because of the Bellheads of the grid.

The Bellheads of the grid are not bad people. They built a system that has kept the lights on in our cities for over a century. In many parts of the world it's so reliably that almost nobody under fifty has had to think about how it works. The institutional logic is built around protecting that. When the Bellheads of the grid look at distributed price coordination – markets at the substation, markets in the street, markets in the wall box – what they see is a million failure points where today there is one reliable operator. They are wrong about that, but they are not wrong for cynical reasons. They are wrong because their training, their tools, and their working lives have been organised around an architecture that is reaching the end of its useful life.

The Netheads of the grid exist. The DLMP[13] theorists, the PowerMatcher[14] builders, the Olympic Peninsula[15] and DSO+T[16] operators, the auction designers we shall meet in this chapter. For two decades they have been building, demonstrating, and being told to come back later.

As in 1993, the disruption that will end this fight is unlikely to come from inside. But as in 1993, it is already arriving from outside. Rooftop solar is profitable regardless of whether the regulator wants it. As household batteries become cheaper, they become profitable whether the grid operator wants it or not. Electric cars and electric trucks turn out to be the largest source of flexibility ever invented, and can either become the electricity grid's biggest nightmare or its biggest boon. There are countless companies packaging these new technologies in ways similar to the cable companies in the telecom revolution. They will keep forcing the grid operator's hand until it learns to embrace localized markets.

II. Why markets beat commanders

II.1 The knowledge problem

The solution we are proposing did not arrive with the internet protocol. It is far more generic and far older. Nature has been using this approach for billions of years, but let me skip to 1945 and to Friedrich Hayek[17]. He was arguing against the Bellheads of his day, who believed a sufficiently clever planner could allocate everything from the centre. In *The Road to Serfdom*, Hayek had argued that it was an easy slide from a centrally planned economy to an authoritarian one. Now he turned from ideology to practicality. He argued that a central planner would never be as optimal as a decentralized market, for a simple and generic reason: the relevant knowledge required to make optimal decisions is always dispersed. *You* know when you feel like getting up in the morning. *You* know when your partner would like a cup of tea. *You* know when you have to take your daughter to piano lessons. It is impossible for a central planner to know all that in as timely and detailed a manner as you.

II.2 The zero-duality gap

But even in the theoretical situation that a central planner would know everything a local market would know, there would still be no advantage to central planning over decen-

tralised planning. This is something many people intuitively do not expect. Many of us come from a tradition in which we expect a king, president, hero, or enlightened despot would theoretically be able to take the best decisions. It can, however, be mathematically proven that this is not the case. To return to the electricity grid: it turns out, under conditions Boyd and Vandenberghe set out clearly in their standard textbook[18], that exactly the same solution as reached by a central planner can be reached by a multi-level market of bidders adjusting prices and quantities under transparent constraints. This mathematical proof is often referred to as the *zero-duality gap*. In simple language: even in the unrealistic situation where a central planner has perfect knowledge, they still cannot improve on a well-structured multi-level market.

On top of this, multi-level markets break up the optimisation problem into smaller parts, and this has two advantages. First, if some local market fails, the markets above, below, or next to it do not. The failure is localised. When a central planner fails, that failure takes the whole system down. Multi-level markets are therefore more resilient. Secondly, finding the optimal solution for a small market is much easier, and therefore small markets can adjust prices faster. This in turn means they can counter shocks faster – which adds to their already superior resiliency. Add to this Hayek's argument that local markets have more knowledge, and it is clear that well designed local markets are superior to centralised top-down planning.

All of this is, of course, also in line with Simon's *near-decomposability* and the term *holons* we chose for it (following Koestler) that we presented in the previous chapter. Koestler, Simon, Boyd and Vandenberghe, Hayek – they are all saying the same thing. In the field of governance, giants like Ostrom[19] pile on. And in biology, ecology, trade and organisational science, holons are by now usually the standard, even though the terms used differ from domain to domain.

III. Why the current grid market is incomplete

For most of the twentieth century the grid was not a system that needed coordination between actors, because there was, in any given region, one actor. A vertically integrated utility owned the generators, the transmission lines, the distribution wires and the meter on the wall. Generation followed forecast demand by direct command from a control room. Costs were aggregated and recovered through a regulated tariff. Electricity was sold by the kilowatt-hour at a price that bore no detectable relation to the marginal cost of supplying it at any given moment. There was no market and no marginal price. There was a balance sheet and a regulator.

That changed with unbundling. The EU First Electricity Directive in 1996[20] required member states to separate generation from transmission ownership; the Dutch Elektriciteitswet of 1998[21] implemented the directive at home. Similar unbundling had already begun in the United States with PJM's wholesale market in 1997[22] and in the Nordics with Nord Pool going Nordic in 1996[23]. After unbundling, the same generators that had previously been dispatched by a control-room operator were now owned by separate companies. They could no longer be told what to do. They had to be paid. The wholesale market was invented to do that paying, in real time, for the marginal cost of meeting demand minute by minute.

The result is what people now call the wholesale stack. It is a frankly Byzantine set of markets, but let us pick out the four most important ones. *Day-ahead*: every producer and large consumer submits bids by noon for each hour of tomorrow. The exchange clears. Generators are dispatched. *Intraday*: as the day approaches and forecasts sharpen, market participants buy and sell residuals. *Balancing*: in the operating hour itself, the transmission system operator procures upward and downward reserves to match instantaneous supply with instantaneous demand. *Frequency control*: faster still, automatic, primary and secondary reserve, operating on physics rather than markets. Each is a centralised market over the

entire bidding zone, with prices that result from auctions. Auctions are cleared by one commander for the entire bidding zone, which is often a country.

The current grid uses the wholesale stack of markets to coordinate supply and demand over time. It's not a perfect system by any stretch of the imagination. It's too complicated, opaque, disintegrated and slow for that. But it's something.

What's entirely missing is the spatial and temporal coordination of grid capacity. Every home and every business sees the same transport cost, irrespective of where and when grid congestion occurs. As a result the grid is used far less efficiency than energy supply. This is what is causing the ballooning grid costs in the Netherlands and what caused the recent blackout in Spain.

IV. What the missing market looks like

IV.1 PowerMatcher (2005)

The alternative is not a hypothetical. In 2005 Koen Kok at TNO, with collaborators in Eindhoven and Alliander, published a paper[24] describing how to implement the missing market under the name PowerMatcher. All flexible devices bid directly. Local prices are cleared by an auctioneer. This can be done multiple times per second, if need be. Each device takes one constraint into account: the transformer's capacity limit. A heat pump knows what indoor temperature its owner is willing to tolerate, and moves its energy demand in time so the energy is cheapest and the transformer is not overloaded. An EV acts similarly, taking into account when it has to leave fully charged. A battery knows what its arbitrage opportunity is. Each translates that private knowledge into a bid curve. The auctioneer adds the curves up. The price falls out.

Kok later described the architecture, in his doctoral thesis[25] and again in a 2016 IEEE Power & Energy Magazine paper with Steven Widergren[26], as a *Society of Devices*: heat pumps, EV chargers, batteries and white goods as economic agents with bid curves, negotiating continuously. The grid

operator is no longer the conductor. It is the referee. It announces the constraint. The market works out who pays what to use the available capacity.

Sidebar A. A worked auction. Imagine a substation transformer with 100 kW of spare capacity for the next fifteen minutes. Behind it sit five EVs, each willing to pay something to charge, but each with a different urgency. EV 1 has to leave at seven and is empty: it bids 30 cents per kWh up to 11 kW. EV 2 is parked all night and will accept anything below 8 cents up to 11 kW. EVs 3, 4 and 5 sit in between with various combinations. The auctioneer stacks the bid curves from highest to lowest and walks down them until the cumulative demand hits the 100 kW transformer limit. Wherever that crossing happens, the price clears. EVs above the line pay the clearing price and charge; EVs below the line wait. Nobody negotiated anything. Nobody told a charger what to do. The transformer was respected. The most urgent EV charged first because its owner was willing to pay for it. Repeat in fifteen minutes with the new bidders, the new state of charge, the new transformer capacity. The grid operator, who built the substation, now collects a congestion rent from the difference between the clearing price and what the system above is paying – money that pays to upgrade the substation faster than a flat tariff ever would. No commander. One number. Cleared.

IV.2 Layered Decentralised Optimisation & DLMP (2016–2018)

Over the next decade the academic literature put new names on what Kok had built. Kristov, De Martini and Taft, in 2016[27], called it *Layered Decentralised Optimisation*: each layer of the grid – building, street, substation, bidding zone, inter-zone – clears its own market, presents its residual to the layer above, and accepts the layer above's price as its boundary condition. Below the layer, opaque. Above, opaque. Between layers, one number. Bai and colleagues, in 2018[28], worked

out the formal mathematics under the name *Distribution Locational Marginal Pricing*: every bus in a distribution network gets its own price, decomposed cleanly into five components – energy, losses, congestion, voltage, stability. In effect, every building gets its own bidding zone.

Muto and colleagues, also in 2018[29], answered the deployability question. The auction converges robustly even with devices joining and leaving mid-clearing – the *plug-and-play* property the grid actually needs, because of course not every appliance will participate, and of course participation will rise and fall through the day. The auction simply clears with whoever happens to be there.

V. Practical Examples

V.1 Olympic Peninsula (2007)

Hammerstrom and colleagues[30], at the Pacific Northwest National Laboratory, ran the first serious field trial. 112 households on the Olympic Peninsula[31] of Washington State, each equipped with smart thermostats, water heaters and dryers; an auction clearing every five minutes; a transformer-capacity constraint the auction was tasked with respecting. The Result: peak load down by something close to 15%, no loss of comfort that the participants reported, and the auction never failed to clear.

V.2 GridWise and USEF (2010s)

PNNL ran a sequence of GridWise testbeds across the 2010s, the American Energy Innovation Council compiled the lessons in 2019[32], and European replication ran through the USEF programme[33] and Universal Smart Energy Framework pilots[34] in Belgium, the Netherlands, and Germany.

V.3 DSO+T (2022)

In 2022 Reeve and colleagues at PNNL[35] ran DSO+T, the largest co-simulation of transactive energy to date. They coupled wholesale and retail markets through transactive prices and ran the result across the full ERCOT footprint. The verdict: substantial savings, no instability, no comfort loss. What-

ever the grid engineers were worried about, the simulation did not find it.

VI. So Why Isn't the Grid Holarchic

VI.1 Fairness – the strong but wrong objection

Locational and temporal pricing for transport could make people pay more or less, depending on where they live or what their consumption pattern is. Some areas and poor people who cannot buy flexibility might suffer. Cahana, Fabra and Wang on the Spanish case[36] and Galeano-Suarez document the concern and it was also *the* concern the minister in the Netherlands mentioned when rejecting the idea recently. It is the strongest counter-argument the Bellheads of the grid can make.

There are also multiple counter-arguments and solutions. First of all: when this makes grid costs balloon, everyone has to pay more, including those supposedly helped by foregoing locational marginal prices. Secondly: the objection assumes prices are *transferred directly* to consumers' bills without compensation. But that's not a given at all. A holon is the natural unit of solidarity. Inside a holon – a building, a street, a neighbourhood – members can choose to pool. Outside the holon, between holons and between regions, the price is a signal, not a tax. The signal between the neighbourhood and the substation is sharp. The settlement within the neighbourhood is human. This is the Kaplow and Shavell[37] result on efficiency-equity separation: distort prices to deliver efficiency, redistribute through tax-and-transfer to deliver fairness, do not blunt the prices in the name of fairness because that costs you both. Cramton and Stoft[38] spell out how to do it for electricity: split the bill into a fixed component and a variable component. If anybody's variable bill goes up unfairly, lower their fixed component until the total feels right. Setting the two knobs is politically fiddly. It is not, however, harder than rebuilding the grid in the absence of price signals – and that, increasingly, is the alternative.

VI.2 The institutional refusal

So now that we know the fairness argument has an answer, we can conclude the real obstical is probably different. I think it's institutional.

Directive (EU) 2024/1711[39] – the European market design reform that came out of the 2022 energy crisis – explicitly required member states to allow for differentiated network tariffs that reflect locational scarcity. Compliance has been uneven. The Commission's February 2025 infringement package[40] names the Netherlands among the laggards.

The Netherlands has been here before. Motie Kroger of February 2024[41] asked the minister to investigate whether locational tariffs could ease the country's now-famous grid congestion. The minister's reply in November 2024[42] was, in essence: we have looked at it and we will not do it. The reply rested in part on a 2019 report by Ecorys and D-Cision, commissioned by the regulator ACM[43] that concluded locational tariffs were not necessary in the Netherlands. The report was written, as it happens, in 2019, before the congestion the Netherlands has since acquired and which has now closed parts of the country to new industrial connections.

The Netherlands more or less invented modern decentralised governance, through the Thorbecke reforms we already met. That it's now so strongly resisting nested pricing is ironic.

The Bellheads of the grid are not always wrong. Quality of service, security, settlement integrity – the things the intelligent network did well – are real concerns, and they are *more* real for the grid than for the telephone network. A misbehaving Netflix stream cannot crash the internet. A misbehaving battery, badly programmed, can crash a feeder. But you should treat such concerns as engineering with answers like certified inverter EMS software and well-defined fallback behaviour. It's not ok morph it into a refusal to adopt better architecture.

But I'm afraid the institutional pattern is what it is. The grid will not reform from inside. I hope nobody takes that

verdict personally. I know from personal experience that neither the Bellheads of telecoms, nor the Bellheads of the grid are bad people. But their training, their tools, and their working lives have been organised around an architecture they cannot themselves replace. They are the wrong people for the job that comes next.

VII. The cable companies of the energy transition

As in 1993, the disruption that will end this fight is not coming from inside. As in 1993, it is already arriving from outside.

Rooftop solar is profitable regardless of whether the regulator wants it to be. Household batteries[44] are profitable whether the grid operator wants it or not, and getting cheaper every year. Electric cars and electric trucks turn out to be the largest source of flexibility ever invented, and can either become the grid's biggest nightmare or its biggest boon depending on whether the grid learns to bid for that flexibility or refuses to. Grid-forming inverters – the subject of the chapter after next – will hold a feeder's voltage and frequency up locally, without asking permission, in places the central grid is too slow or too saturated to reach.

Each of these is a coax cable. Infrastructure outside the regulatory envelope built around the incumbent architecture. They do not require permission. They are getting cheaper. And there are countless companies packaging them into services – aggregators, virtual power plant operators, smart-charging providers, energy communities – in roughly the way the cable companies packaged TCP/IP over coax in the late 1990s. They will keep arriving. The grid will eventually bid for what they offer, or be bypassed by them.

VIII. The grid doesn't need a commander

The architecture is settled. The mathematics is settled. The pilots are settled. The chapter title is therefore a flat statement of fact rather than an aspiration.

KPN did not become an internet company because its engineers changed their minds. It became an internet company because cable companies came in over coax that was outside its regulatory envelope, customers walked, and Skype turned voice into a free feature of the new architecture. The Bellheads were structurally incapable of building the network that beat them. They were displaced by infrastructure their regulator did not control. The grid is now where telecoms was around 1993. The question is how we create something that puts as much pressure on the grid operators as the cable companies did on the telecom operators.

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Your Home Is a Holon Waiting to be Kissed Awake

Once upon a time, there was a kingdom that fell asleep because it was put under a spell. There was no jealous queen, no enchanted apple, no spindle that pricked a careless finger. The spell that put the electricity system to sleep for well over a century, was cast by a few hundred earnest engineers working around turn of the 19th century. They were ordinary men and women working in ordinary offices in Berlin and Pittsburgh and Manchester. If you had visited them, the only thing that would have caught your eye is that their offices were remarkably well lit for the time. They didn't consider themselves wizards. They were just implementing electricity grids based on what was an entirely reasonable design choice at the time. The electricity system of the day had only one knob to turn – how much fuel was burned centrally – so they built a system that turned that one knob extremely well.

That system with that one knob worked beautifully for over a century. It worked for their children, their grandchildren and even the grandchildren of their grandchildren. And as the grid kept working – essentially unchanged – everyone forgot that other knobs existed that could be turned. These other knobs have become extremely relevant now that we are replacing fossil fuels with solar, wind, batteries and grid-forming inverters. Some people in the kingdom are waking up to that new reality. Unfortunately

the king (the fossil energy producer) and queen (the grid operator) are still deeply asleep.

In regular fairy tales a handsome prince arrives, kisses a beautiful princess, and the spell breaks. But, quite apart from the gender issues, this is, as you may have already suspected, not how it is going to work for the electricity system. The king and queen seem intent on sleeping a few decades longer. Instead the kingdom will have to be kissed awake one building at a time. Kissing a building awake is done by attaching batteries, grid-forming inverters and optionally solar panels and electric vehicles to the building. Thus activated the building becomes a little semi-autonomous kingdom of its own. A kingdom that can now provide its inhabitants with resilient, affordable and clean energy. The little kingdom becomes a safe energy refuge for its inhabitants, even when the kingdoms around it fail.

This is the chapter where we stop talking and start kissing.

Home Holons are Waking Up All Over the World

Amara's home

Remember Amara? She lives in rural Africa and cooks on wood and dried dung that she gathers during the day the way her mother taught her. It's labour intensive, the smoke is poisoning her lungs, it's harder and harder to find wood and dung, but it's the only fuel she can afford. In the evening her children do their homework while breathing in the poisonous fumes of tiny kerosene lights.

Amara is not alone. This is a reality for a billion people worldwide. Billions more are living in extreme energy poverty, at least compared to the majority of the people reading this book.

Amara's prince happens to be a woman and she doesn't arrive to a gala on a white horse but on a cheap electric bicycle on a hot and dusty Monday morning. Behind her bike is a small dinged up trailer containing her tools and a few solar panels, a battery, a cheap induction stove, a few LED lights, a phone charger and a satellite receptor. The woman screws

the solar panels and satellite receptor onto the corrugated iron sheets on Amara's roof. Then she shows Amara how all this works and how Amara can pay back the small loan for the system with micropayments by phone.

No grid was extended. No central plan was approved. No minister cut a ribbon. No bank did an audit of Amara's credit rating. But this is possibly the largest moral upgrade per dollar available to our species.

The system is harsh: when Amara stops paying, the electricity stops. But the system is also simple and with very little overhead that could be corrupted and that Amara wouldn't be able to afford. Technological progress has given us the ability to offer Amara energy in a cheap and simple to use product that can be delivered using competitive markets. Amara now has access to dependable energy and information. Once she has paid off her loan, that energy will be free. The unassuming princess on her bike has awakened Amara's home and now it is providing her with not just shade and protection but also energy and information. It helps to provide Amara income, dignity, autonomy and human flourishing.

The customers nobody saw

At the turn of the millennium, a Chinese woman called Susan Li was visiting the slums and rural areas in India. She had just had children of her own, and when she saw all those Indian children suffering in extreme energy poverty she thought: not on my shift. In 2004 she founded Shenzhen Power Solutions, making products specifically aimed at what she calls *bottom of pyramid customers*. The phrase was coined a few years earlier by the Indian-born scholar C.K. Prahalad[1], who had noticed that about four billion people worldwide hardly appear in corporate spreadsheets or government policies because they are simply too poor and therefore too unimportant to matter. Aggregate the four billion, however, and you get the largest unserved market on Earth[2] – plus

customers for whom every kilowatt-hour does life-altering work.

One of the products Susan Li sells is the most basic version of the magic that Amara received in the previous section. It consists of four tiny solar cells, connected to a what looks like a yellow lunch box. The lunch box contains a small battery and inverter. Plugged into the lunch box with thin long wires are five LED lights. The LED lights are tiny compared to what I'm used to, but still much brighter than the kerosene lamp Amara uses. And the lunch box can also charge a mobile phone.

To me Susan Li[3] is a bona fide heroine and it pains me that I live in a world where homes remain dark and children die from kerosene fumes because families don't have access to such a thirty dollar package.

Home holons are waking up everywhere

Fortunately it's not just Susan Li. Companies providing off grid electricity are popping up everywhere. 13 M-KOPA, founded in Nairobi in 2011, has installed more than five million pay-as-you-go solar systems across Kenya, Uganda, Nigeria, Ghana and South Africa and sixty-two per cent of its customers[4] report the system generates income for them because it buys them light to work by, a charged phone to take orders on, a fridge to keep food from spoiling, and so on. It's a bridge from subsistence to enterprise achieved because of entrepreneurs willing to see those bottom of pyramid customers and because renewable energy technology is now able to deliver.

In Pakistan, the grid is both expensive and unreliable. Pakistani households have responded in the way most households would when they see a way out: they imported a whopping seventeen gigawatts of solar panels in 2024, and outdid that feat the next year by importing a truly mind boggling fifty gigawatts in 2025. Not because they didn't have a grid connection, but because they were sick and tired of the cost and unreliability of the one they had. [Pakistan 17

GW 2024 / 50 GW 2025 import figures against most recent customs / IEA / BloombergNEF data]

In South Africa the situation is similar. The grid operator there has been turning off entire neighbourhoods for hours at a stretch because there is not enough power to go around, so by now every homeowner who can afford it has put solar panels on their roof and batteries inside their homes and is no longer impacted by the outages[5].

Compared to most grids, the Dutch grid is almost embarrassingly reliable. On average you will experience less than 1 day worth of outages in fifty years. Yet batteries also make sense for homes like mine. First of all because batteries allow me to make optimal use of my solar panels. That not just feels nice but it's also financially interesting because energy I sell back to the grid is worth just a fraction of what I have to pay when I buy electricity. (This mainly due to taxes.) With batteries I can run off my solar panels 90% of the time. On top of this my wife and I like the idea that in our home the light stay on when the unthinkable happens.

So you may not have noticed yet, but there is a revolution going on, with homes becoming reliable energy providers – holons – all over the world. And they don't require the blessing of big corporations or nation states. Just cheap renewable energy technology and people who see the opportunity and maybe give a damn.

Big Buildings Have Big Incentives

Most of what's true for small buildings like a home, is also true for bigger buildings. And the stakes increase if such a home cannot get enough grid capacity. This problem is especially pronounced in the Netherlands where more and more companies have to wait many years for a (bigger) grid connection.

For such buildings in need of more energy from the grid, step one is to buy batteries so they can max out the grid connection they were able to get. Peak shaving can often double the energy they are able to get within their existing

contract. This also gives them cheaper electricity because they can buy when the energy is cheap and optimise the use of their solar panels. Finally they now have an uninterrupted power supply so the power stays on for a while when the grid goes down. As batteries and grid forming inverters continue to become cheaper – see the chapters on learning curves – buildings will increasingly be equipped this way.

If the grid still can't provide energy, a diesel- or gas generator is needed. Where that is legal the business case for becoming a holon becomes even better because diesel generators produce very expensive electricity and you want to use as little of that as possible.

That's lot of larger buildings, also ready to wake up.

If I take a step back I feel that the ascend of building holons is already locked in. It's a survival kit for customers who cannot get a grid connection at all. It's a way to lower electricity costs for most other customers. It's increasingly a no-brainer for companies that cannot get enough electricity from the grid. And the costs keep plummeting. So the question is not whether building holons will ascend but how to use their abilities wisely, instead of denying they exist because of a spell that is now over a century old.

Your Friendly Neighbourhood Holon

But why stop at one building? Why not turn an entire neighbourhood into a holon? The local low-voltage transformer in a Dutch street serves around 50 to 250 households. Interestingly this is also a number sociologists will give you when you ask them how many neighbours you can feel close to without making an effort. A neighbourhood holon, as it happens, is a unit at which engineering and social science have independently arrived.

The hardware to wake up the neighbourhood up, not entirely unsurprisingly, the same as for a home but somewhat scaled up. A neighbourhood might decide to share a 20 foot battery container. Such a container can contain about 5 MWh of batteries and currently costs around 400 thousand euro's

in Europe, including financing. Over 20 years and 200 households that works out to 10 euro's a month: less than one tenth of the reinforcement costs per household planned in the Netherlands. And it would give each household a whopping 25 kWh battery.

For a project developer constrained by a grid connection, the ability to build two or three times as many houses at a cost of 2000 euro per house would be a no-brainer. Furthermore the battery would already earn itself back by it's ability to buy the neighbourhood energy from outside when prices are low. If we extend the learning curve the same 20 foot container will cost less than 1000 euro per household in 2040 and my prediction is that every prudent and frugal neighbourhood will get one.

On top of this, grid operators should pay neighbourhoods for avoiding peaks on the grid because this substantially lowers grid reinforcement costs. A simulation we ran for the Dutch government at our company Zenmo quantified this. We modelled three control regimes for an ordinary Dutch street. First the scenario in which demand does not respond to supply at all. This leads to bad peaks, especially from electric vehicles. Secondly the scenario where electric vehicles, heat pumps, solar panels and batteries react to existing markets for electricity production. This lowered the highest peak of the year by 15%. Finally a scenario where avoiding the worst peaks was explicitly rewarded. It turned out surgically rewarding neighbourhoods for avoiding the worst peaks lowered the highest peak of the year by over 50%. And best of all: because these peaks only occur very seldom (e.g. 3% of the time) it doesn't take a lot of compensation to seduce end users.

We are not there yet. People working at the grid operators are still inventing legal and operational barriers. And that's the ones that are willing to talk about this at all. But once that hurdle has been taken, it makes sense that neighbourhoods become little federated kingdoms that manage most of their energy problems themselves. I think we have a chance

because that way we would save a boatload of money and my fellow Dutchmen are very susceptible to that argument.

This is not just theoretical. Let me give some working examples, roughly in the order in which they came on line.

Olympic Peninsula – USA (2007 to 2014)

One of the earliest field trials of neighbourhood-scale price coordination ran on a peninsula in Washington State. This was before the advent of solar panels, batteries, and electric vehicles. A hundred and twelve households used smart thermostats and water heaters and dryers, a five-minute double-auction market, and a strict constraint: a transformer that was not allowed to overload. Although flexibility was very limited compared to modern pilots, peak loads came down by 15 per cent[6] while the participants reported no comfort loss.

PowerMatching City – Hoogkerk, the Netherlands (2009 to 2015)

In a Groningen suburb called Hoogkerk, twenty-five Dutch households[7] were wired up with PV, heat pumps, smart appliances and electric vehicles, all coordinated through a market that cleared every five minutes. The pilot grew to sixty households over five years. Peak load at the local transformer came down 30 to 35 per cent. The UN gave the project a sustainability award in 2012. The algorithm that ran it – PowerMatcher -- had been published four years earlier by Koen Kok[8] who is now a professor I often work with at my Eindhoven University of Technology.

The solution has been staring us in the face for over 20 years but somehow the spell prevents us from recognizing it's value.

SOLshare – Bangladesh

SOLshare is a fast-growing peer-to-peer trading platform for solar home systems. It connects 120 nanogrids serving more than 80 000 people, including a Rohingya refugee camp. Households consume at different times of the day and – due to solar panel orientation – also generate at different

times during the day. Trading between neighbours[9] unlocks roughly thirty per cent of solar capacity[10] that would otherwise be lost[11].

Husk Power – India and Nigeria

Husk is an initiative that's also growing fast. They claim to provide a "minigrid-in-a-box" solution that can be deployed within one day. In 2024 Husk doubled the number of minigrids[12] it served from 200 to 400 and it now serves over 2 million people and 30 thousand businesses.

OMC Power – India

OMC power has a unique and very clever holon solution that fixes the problem that rural cell towers for phone services often cannot get a grid connection. Without OMC, Telecom operators where running them on diesel generators. But refuelling was a pain and diesel was expensive, smelly and got stolen. Telecom operators hated paying for it since it could be up to 40% of their network operating cost[13]. OMC's offer is simple: we'll build a solar plus battery plant and provide you all the electricity you need so you can stop buying diesel. Once OMC has an agreement with a Telecom operator, they can go to a bank to loan the money to build the plant and once they have that plant they can make it a little bit bigger and sell the excess electricity[14] to houses near the cell tower. Is that clever or what?

It's actually very similar to how the electricity grid got started in Western counties roughly 120 years ago. Factories owners were often the launching customers and the electrification of households in the vicinity of the factory followed.

Sabang – Palawan, the Philippines (operational since August 2019)

In the Philippines, there is a village called Sabang that sits at the entrance of one of the longest underground rivers in the world. It's a UNESCO heritage site that draws hundreds of thousands of visitors per year interested in the river or in diving. (Or in picking up young girls for money, but let's

not spoil the mood.) And yet, until August 2019, each resort had to run its own diesel generator and households had no electricity at all. Now Sabang largely runs on renewable energy[15] and households have electricity. What took so long was not the technology or the business case but cooperation of the local grid operator. That grid operator had an exclusive claim on Sabang but could not profitably connect it to the bigger grid. It took many years before it was willing to give up its claim. This is a story we see everywhere: incumbents unable to deliver but unwilling to give up claims are often the biggest hurdle for establishing local holons.

Schoonschip – Amsterdam (operational since 2021)

In a former harbour in Amsterdam, forty-seven houseboats[16] have been quietly running their own grid for over 5 years now. About 500 solar panels divided across the roofs and thirty water-source heat pumps drawing low-grade warmth from the canal provide them with most of the energy they need. With shared batteries and blockchain-mediated peer-to-peer energy trading they have reduced their grid connection tenfold. Their community started as a pilot that was condoned but will now become in violation of Dutch regulation. It's one of the clearest examples of how backward Dutch regulation is compared to European regulation with regard to holons. Tragically enough there is no defensible upside. Just sluggishness from the incumbents that are comfortably sleeping under the spell.

This is really happening

I could go on. About Rwanda using local energy cooperatives that are perfect examples of neighbourhood holons as the vehicle for rolling out home holons[17]. Or about Indonesia, that string of pearls, that archipelago of more than 17 thousand islands, where island after island is exchanging diesel generators for microgrids[18] running on solar panels, batteries and grid-forming inverters. The pattern is the same everywhere, no matter what country or continent. Holons running on

renewable energy work and make neighbourhoods quieter and cleaner, while energy becomes reliable and affordable.

Holons all the way up

Do you remember Tempus and Hora? The two watchmakers? Tempus build his watch in one go, which was efficient, but easy to disrupt. Hora build his watch using subassemblies which was a bit more work but hardly suffered when disruptions happened. Herbert Simon created the parable to show why complex systems that survive consist of near-decomposable parts we call holons.

The important thing to understand about holons, is that it applies to a specific design pattern, not a specific size. We can create holons on the level of a house, or a neighbourhood, or a city, or a province, or a country, or a continent, or a planet. The essence of the design pattern we call an energy holon is that it's a unit that organises it's internal energy flows optimally, with minimal data and energy exchange with the environment, while possibly containing smaller holons inside of it and being part of larger holons. The reason to create such a nested system of holons is not just to create a more resilient energy system, but also that it needs less electricity grid.

So your home energy management system (HEMS) is the energy brain of your house, choosing when to charge the electric car, use the heat pump, discharge the battery, curtail the solar panels, et cetera. It takes into account all the appliances, preferences etc. that are important in your home. When your neighbourhood holon gives your HEMS a few simple signals that indicates how the neighbourhood is doing, your HEMS can help to optimise the neighbourhood holon. For your neighbourhood holon this simplifies things because it doesn't need to know what's happening in your house in detail: your HEMS takes care of that. For you it's nice that you stay in control of your house and that it keeps working when the neighbourhood fails.

But we can repeat this pattern endlessly. For example: a group of neighbourhood holons could make up a district, a group of districts could make up a municipality, and a group of municipalities could make up a country. Each holon would handle 99% of energy decisions and most energy flows internally, while supporting the smaller holons inside it and the larger holon it was a part of.

On a country level, every country in the world could strive to become fully energy independent! Imagine that: no more problems or expenses getting fossil fuels from other countries! Trading some energy with other countries would still be mutually helpful, but it would be an option, not a necessity.

For me, primed by the first oil crisis and now irritated by our dependence on oil and gas from Russia, Saudi Arabia and the US, that seemed an extremely worthwhile goal. But is it achievable? Can the Netherlands really rid itself of its dependence on foreign oil and gas?

Making the Netherlands energy independent

The Netherlands uses a *lot* of energy. The table below shows how much.

Dutch energy use per sector in kWh per household per day	2023	Electrified future
Home electricity	5	6
Home heating	34	8
Inland mobility	50	15
Chemicals & pharmaceuticals	64	55
Oil refineries	14	3
Steel	10	2
Food industry	10	5
Building materials and other industry	9	8
Services and public buildings	29	15
Data centres	2	8
Greenhouses and other agricultural excl. mobility	13	5
Seasonal storage overhead	0	11
Subtotal without bunker fuels	**240**	**139**
International shipping	48	54
International aviation	16	37
Subtotal bunker fuels	**64**	**91**
Total	**304**	**231**

As you can see, in the current situation household electricity is relatively tiny while mobility and industry together make up three quarters of energy use. That's mostly because the Netherlands has a huge harbour (Rotterdam) that services a large part of Europe, a huge industry in chemicals, pharmaceuticals and refineries, and a large international airport. So most of our energy use is actually for international services. (Most of our land use is agriculture which is also mainly for export by the way. The Dutch are very much into export.)

Let's assume that we electrify absolutely everything. The result of that is visible in the last column of the table. What jumps out is how much more efficient heating and inland mobility have become. I've assumed that melting ore to produce raw iron will be done in places where electricity is cheapest and few people live. You can also see that we invest 11 kWh per household every day in seasonal storage. This makes sure that we have enough energy to survive the long cold sun poor Dutch winters. All in all our energy use goes *down* from 240 to 139 kWh per household per day.

Now I've made one big crucial assumption here. I've assumed we will keep importing the fuel we need for international shipping and aviation. From a resilience standpoint that seems defensible to me. Firstly because something that interrupts fuel shipments will probably also interrupt other shipments and it's no use to produce fuel if the ships that need it are not arriving. Secondly, in a truly worst case situation, not getting fuel for international shipping and aviation would not cause distress inside the Netherlands and as such is more a question of international trade than national resilience. If you disagree you could allocate more land and/or sea to producing that fuel. It could very well be done but it's probably not economical.

So now we know what we need. But how much can we produce?

Solar and wind in the Netherlands

The Netherlands is a fairly densely populated country with a little over 500 people per km2, comparable to India, South Korea and Taiwan. The average household size is just above 2 people.

If we look at household holons, we end up with about 4000m2 land per household. Furthermore these households can lay claim to around 1000m2 of inland lakes and waterways and 7000m2 of sea per household. Is that enough to become energy independent?

Let's cover **roof surfaces and parking spaces** with solar panels first. Research indicates that around 50% of roof surface, 30% of facades and 63% of parking could be used for solar panels. Together that's 171m2 of solar panels per Dutch household. Notice this is a minute part of total land area of 4000m2 and only surface that has no other useful function. Taking into account shading and positioning and long term 30% efficient panels, this could produce around 120 kWh per household per day.

Furthermore, we could place wind turbines, spread out over **10% of the North Sea**. The little artificial islands per

wind turbine, spaced about 1.5 km apart, would only cover about 0.01% of the North Sea and actually *increase* biodiversity. The resulting wind would bring in 60 kWh per household per day, which is especially welcome in dark nights and Dutch winters that have relatively little sun. The total of these two measures lands at **180 kWh per household per day**.

That is actually *more* than what we need! We could electrify the Netherlands 100% with solar panels on unproductive surfaces and wind turbines spaced over 10% of the North Sea!

Where do we go from here?

We've now seen the holon stack from the bottom up. A house in rural Africa with four solar panels and a yellow lunch box that can evolve to a farmer completely escaping energy poverty. A street in Hoogkerk where appliances have been negotiating prices with each other every five minutes for over twenty years. A houseboat community in Amsterdam that has cut its grid connection by an order of magnitude. A village in Palawan where dive resorts and households share a microgrid as soon as the local incumbent stepped out of the way. A country – the Netherlands -- that could meet its full electrified energy demand from rooftops and a few percent of the North Sea, with energy to spare.

All of this is based on proven technology. All of this will become increasingly logical as learning curves make renewable technology better.

So why are holons still the exception to the rule?

Because the rule is the problem. What's missing is permission. The regulatory ecosystem is still enforcing the grid design that those engineers in Berlin and Pittsburgh and Manchester came up with over a century ago. We are still under their spell. There are new solutions that could give us a cheaper and more resilient grid if we would only let them. Instead we are mowing them down before they can flower. That needs to change.

PART III

Flourishing

21

Human flourishing

I've spent the last 20 years of my life researching and accelerating the transition from fossil fuel to renewable energy, but for me that's just a means to an end. The end, my goal in life, is to contribute to human flourishing in harmony with nature. So now that we've talked about abundant and resilient energy, we have to talk about how we design an energy system that is fair and contributes to human flourishing.

What gives me hope beyond anything else is that most humans share this goal of contributing to human flourishing on some level. But what is human flourishing? Who are we? What do we want? What makes us flourish? Science shows that we are fundamentally kind, even though we are drawn to stories about violence and evil that obscure this hopeful fact.

One of the best illustrations I've read comes from Rutger Bregman's book *Humankind*. It describes the story of six Tongan schoolboys, aged thirteen to eighteen, living in 1965. They were bored witless by their boarding school and on a fateful day, they foolishly decided to borrow a boat from a fisherman they disliked and to sail away to another island.

The adventure became a nightmare almost at once. A storm tore the boat apart. The boys spent eight days without food and with almost no water before they washed up on an uninhabited island. They were marooned there for fifteen months before a passing Australian sea captain found them.[1,2,3]

It is almost exactly the premise of *Lord of the Flies*. William Golding's novel has sold tens of millions of copies, was made into a film and inspired survival television like *Survivor*. And I, like many a good schoolchild, was made to read the book as a lesson in what becomes of children once the adults are gone. In the novel the boys turn feral within weeks. They invent a murderous cult, and three boys die horribly. It was one of the first books that taught me people are bad underneath and need a firm hand to stay civil.

But the non-fiction version went very differently. The conditions for the real Tongan schoolboys were hard enough. The boys drank the blood of seabirds when the rain failed. They shared a single knife, and at one point one of them slipped and broke his leg. And yet what the captain found was not a horror show. In his memoir Peter Warner describes "a small commune with food garden, hollowed-out tree trunks to store rainwater, a gymnasium with curious weights, a badminton court, chicken pens and a permanent fire, all from handiwork, an old knife blade and much determination." The boys had splinted the broken leg of their comrade themselves, and it had set clean. Six bored teenagers, one knife, fifteen months. What they produced was not a crazed cult but neat infrastructure.

I start here because those boys are the first witness in a case this whole book has to make. The standard objection to letting ordinary people run their own energy goes like this. A neighbourhood cannot be trusted to balance its own solar panels, batteries and demand. Its people don't understand it and are not to be trusted. Without a central operator in authority the thing will collapse into free-riding and chaos. This is the *Lord of the Flies* theory of the grid, and it's a myth.

If we are building an energy system meant to produce human flourishing, we should build it for humans as they actually are. We are cooperative and fairness-obsessed, and a good deal more capable of running our own affairs than the cynics allow. And we should trust ourselves enough to insist on staying in charge of it. I have come at this from every

angle I can find, and I keep arriving at the same conclusion. Only an energy system with the users in charge can reliably deliver human flourishing over the long term. I can't entirely prove it yet, but I think it's important enough to put on the cover.

Corporations, governments and experts will all try to wrest this power away from us. Not because they are part of a conspiracy concocted by a cabal of baby eating Satanists. Nothing so complicated. They simply overestimate their own infallibility and importance, and just like you and me, they would like a raise. Unfortunately the *effect* is the same as if it *were* a conspiracy.

Hand the power over and you end up with a system that treats you and the living world as deposits to be mined rather than masters to be served. Most of us would still get our energy abundance, but it would arrive expensive, unevenly shared, and quite possibly on a wrecked planet. I call this extraction: value taken by someone who did not create it. Chapter 24 is about how that happens and how to stop it. This chapter is about the humans worth stopping it for.

Humankind

If one island feels like a fluke, consider the laboratory. For half a century we ran experiments that seemed to prove we were barbarians under our veneer of civilization. They were taught to students as settled fact. The Stanford Prison Experiment of 1971 is the famous one. Assign students to be guards and prisoners, and the guards supposedly slide into sadism all by themselves. Except they did not, all by themselves. When Thibault Le Texier went back into the archive decades later, he found the cruelty had been stage-managed. Zimbardo's team coached the guards to "create a sense of frustration, a sense of powerlessness". Eleven of the seventeen "spontaneous" guard rules came from a research assistant hired for his self-described talent as a "master sadist". The prisoner whose filmed breakdown made the legend later

admitted he had faked it to get released. And two-thirds of the guards refused to be cruel even under that pressure.[4]

In 2002 the BBC let two psychologists run a properly controlled version on television. The guards proposed sharing the canteen with the prisoners, and the group voted to set up a commune.[5,6]

The same goes for Robbers Cave, a summer-camp study from the 1950s. It supposedly showed boys splitting into tribes and turning on each other at the first opportunity. The archives show the experimenters worked hard to engineer every conflict and quietly rigged the contests. And an earlier, un-rigged run of the same study produced boys who stubbornly made friends across the line. They refused to be provoked into hating anyone.[7,8] Notice the pattern? Getting humans to behave badly to one another takes effort, stage directions, and often a rigged scoreboard.

I think the same cynical assumption runs underneath every warning that a peer-to-peer energy system will be gamed. Open a market in which households trade flexibility with their neighbours, and someone will surely cheat. Let a community run its own microgrid, and someone will surely free-ride. Safer to lock it all down and police it from the centre. Maybe, and then we can manage it with technology, but I don't think we need too much of that. Cynical predictions rest on the same model of human nature the Stanford guards were meant to confirm. And that model keeps failing its own experiments. People cheat least under conditions close to the ones a local energy community creates and a faceless national market removes. We will come back to that with Elinor Ostrom later in this chapter.

One more, because it is the story I encountered most often in my life. In 1964 a young woman named Kitty Genovese was stabbed to death outside her building in Queens. *The New York Times* reported that thirty-eight respectable New Yorkers had watched from their windows and done nothing. I read it, as millions did, as proof that a crowd is where help goes to die. And I wondered uneasily what I would have done.

The police file tells another story. Most of the "witnesses" heard something muffled in the dark and took it for a row between drunks. Several did call the police. And Kitty did not die alone on the pavement. She died in the arms of her neighbour Sophia Farrar. Another neighbour, a gay man frightened of the police, climbed across the balconies to raise the alarm. Sophia ran downstairs without hesitating. The *Times* left Sophia and the phone calls out of the story because, in the writer's words, "they would have ruined the story".[9]

The research has since caught up. A 2011 review of 105 bystander studies found that in genuine, dangerous emergencies, where the onlookers can see one another, more bystanders mean *more* help, not less.[10] Marie Lindegaard's CCTV database from Copenhagen, Cape Town, London and Amsterdam shows someone stepping in to help the victim in nine public conflicts out of ten.[11,12] I have lived for twenty years in what the newspapers like to call one of the worst neighbourhoods in the Netherlands, and I can report two things with confidence. The stories of crimes in my street are a lurid exaggeration. And when something happens, people come out and help.

The bystander myth has an energy twin, and it quietly shapes policy. We take the job of finding the cold, energy-poor households that one nameless bureaucracy cut off, and we hand it to another nameless bureaucracy, because at bottom we assume nobody closer will care. That a local energy community would let the family three doors down sit in an unheated house and look away. The evidence says otherwise. Most energy communities are proud when they manage to send their surplus solar to a household like that. Most have a Sophia Farrar, who knocks on the door and asks, "How about I round up some people and we get you some insulation?" Most of us *like* helping others.

That the people helping others are actually pretty smart was shown by Martin Seligman, who founded the field of positive psychology. He once handed his students a two-part assignment. Do one thing purely for pleasure: eat a Magnum

ice cream, watch the trashy show you would never admit to. Then do one thing purely for someone else: clear the snow from an elderly neighbour's path, help the kid next door with her homework. Afterwards, compare how you feel. The pleasure wore off by bedtime. The kindness was still there in the morning. Helping people, it turns out, gave a deeper and longer-lasting lift than treating yourself ever did.[13]

Many of these stories come from Bregman's book. If you ever need an empirical antidote to cynicism about your own species, that book is hard to beat.

There is a reason the cheerful version is the one that surprises us. We are hypervigilant for threat. By almost any measure we have never been safer.[14] But a story about menace lurking next door grabs the attention in a way a story about quiet cooperation never will. And the companies that run our news feeds know precisely which one we click. The institutions that gain authority whenever we lose confidence in one another are content to keep our danger light blinking. So instead of enjoying our safety we let ourselves be triggered by threats constantly. The result is a species that systematically underrates its own talent for getting along, and that has too many stress related diseases.[15,16,17,18,19]

That underrating carries a price in the energy system. The first price is direct. Bureaucracies are usually more expensive than friendly neighbours. That drives up the price of energy in the neighbourhood. The second price is power. A population convinced its neighbours cannot be trusted is a population happy to hand its data, its choices and its power to a middleman who promises to take the worry away. Distrust is the most effective sales pitch a would-be toll-keeper owns. By a toll-keeper I mean someone who puts a toll booth on something everyone needs and collects a toll from everyone who has to pass. And we tend to hand over the keys with relief. That is why the question of who we really are is not a soft humanistic warm-up before the real engineering. It's a starting point that underpins the entire design of a better energy system.

So who are we, underneath the caricature? The cooperation we have seen so far could still be a fair-weather trait, the kind that evaporates the moment things turn genuinely hard. So let's look at the hardest cases on record, where every theory of the thin veneer predicts we should come apart at the seams. They tend to involve bombs.

We pull together when it counts

The bleak view of our deeper nature is old, distinguished and outdated. Many social scientists know the mottos Thomas Hobbes gave it. Life in the state of nature, he wrote, is "solitary, poor, nasty, brutish, and short", and "man is a wolf to man". Frans de Waal, the famous Dutch scientist who studied apes, gave the doctrine a name: veneer theory. It is the idea that civilisation is a thin coat of paint, and that underneath it we are the wolves Hobbes feared.[20] I am not about to argue that we can do without the rule of law. It takes only a few unchallenged bullies or free-riders to wreck things for everyone. I am as unpersuaded by anarchy as most people. But veneer theory, as a description of how humans behave when the paint cracks, is falsified. And the evidence is clearest exactly where the theory was most confident: in war.

Take the Blitz. German bombing killed more than forty thousand British civilians, and the planners expected the survivors to crack. Psychiatrists forecast a wave of trauma so large they built emergency psychiatric hospitals to absorb it. The hospitals sat empty. Suicide fell. Drunkenness fell. A morale survey in Hull found that morale had, if anything, risen. The government found that result so unhelpful that it was quietly shelved. Then the Allies reversed the experiment and bombed German cities ten times harder. German morale held too. When the bombs later fell on Vietnam, the result was the same again.[21] Bombing civilians only pulls them together, and all the killing and posturing achieves little besides killing and posturing.

We also see this in energy systems. When a storm takes the grid down and a street goes dark, the predicted looting and

panic almost never show up.[22] Instead you get neighbours with a generator. The café gives away the contents of its freezer before it spoils. The group chat works out whose fridge can hold someone else's insulin.[23] A resilient energy system is not only redundant cables and islanded microgrids. It runs on the same instinct that kept the Blitz hospitals empty. And that instinct is far steadier than we are told. To design as if a blackout will turn neighbours into looters is to design for a species we do not belong to.

Brian Hare and Vanessa Woods argue that across roughly two hundred thousand years the friendlier and more cooperative humans out-reproduced the rest.[24,25] Some think the evidence is written on our bodies. Our brains became about a tenth smaller since the last Ice Age.[26] Our faces softened, our brow ridges shrank, and our features turned more expressive.[27] We grew the visible whites around our irises that broadcast where we are looking to anyone who cares to watch.[28] And we grew the involuntary blush that advertises our embarrassment at precisely the moment we would most like to conceal it.[29] These are not the features of a poker-faced loner. They are cooperation hardware, evolved for a creature that lives or dies by how well the group can read each other's faces.

Selection for trust is, in a real sense, what made us us. It's only fitting that we build a bottom-up energy system that empowers us to help each other when trouble hits.

Learned selfishness

You've probably heard about learned helplessness, but what about learned selfishness? If we are wired for cooperation, why does the cynical picture survive? Partly because teaching it makes it truer. George Gerbner found that heavy news consumers suffer from what he called mean-world syndrome. They are measurably more frightened and more misanthropic than the statistics justify.[30]

Clayton Critcher and David Dunning showed that people primed to expect selfishness reinterpret plain kindness as a

hidden angle. That makes the cynical view conveniently unfalsifiable: any generous act can be waved away as secretly strategic.[31]

And Robert Frank, Thomas Gilovich and Dennis Regan looked at economics students. They are drilled year after year in the premise that humans are self-interested, and the researchers found that they *become* more self-interested as they go. They defect more in cooperation games, give less to charity, and rate selfishness more acceptable than their classmates do.[32]

We become what we are told we are.

Cynicism, then, is not a neutral read on the evidence. It is a self-fulfilling prophecy with running costs. The hopeful version is just as self-fulfilling, and you can watch it pay out. The Dutch home-care provider Buurtzorg threw out its management hierarchy. It reorganised into hundreds of self-directing teams of about a dozen nurses each. It became the best employer in the country. It delivered better outcomes for patients, and it cost less per patient than its conventionally managed competitors.[33]

When Jean-François Zobrist took over the French foundry FAVI, he bricked up the manager's spy-window, scrapped the time clocks and the bonuses, and trusted his workers. Its market share in transmission forks rose to half. The subtitle of the memoir he wrote about it is "the company that believes people are good." The examples in management are too many to mention. The simple conclusion is: you mostly get what you ask for.

Build the energy system around the assumption that people are lazy, dishonest and incapable, and you get a system that needs constant policing. It has to treat every user as a suspect and hand control to central institutions. Build it around the assumption that people will mostly cooperate when they can see each other and trust the split, and you get something closer to how the internet was actually built. Think of the protocols carrying this sentence to your screen. The encyclopaedia both you and your AI reach for first. The

operating system running almost every server on Earth. All were assembled, in large part, by people contributing to a commons. Their reasons make no sense to homo economicus, the selfish calculator of the economics textbooks, whom the next chapter takes apart.

Chapter 27 is devoted to open source. For now the point is narrower. Large-scale, unpoliced cooperation in our energy system is not a utopian hope. It's what made the internet, and it is what could make a better energy system.

Wired for fairness

We want to take an engineering approach to making an energy system fit for humans as they really are. For that we need to know how fairness-oriented we actually are. Fortunately, the experimental record on human fairness is now more than thirty years deep, and getting pretty sharp.

One famous result comes from the ultimatum game. An experimenter hands one player a sum of money. That player must make a take-it-or-leave-it offer to a second player. If the second player refuses the offer, both walk away with nothing. The self-interested prediction is that the second player pockets any crumb, since a crumb beats zero. Not so. The second player reliably rejects offers below a third or a quarter, at real personal cost. That happens even in anonymous one-shot games with no reputation at stake. We don't like it when our sense of fairness is violated.[34]

Another famous game is the dictator game. Here the first player can simply do with the money as they please. They don't have to hand over any money to the second player. And yet they do. Joseph Henrich ran the experiment across fifteen small-scale societies on five continents. The only reliably self-interested participants were chimpanzees.[35]

We are wired for fairness, and the instinct shows up before we can talk. Babies of twenty-one months expect an equal split for equal work.[36] Six-month-olds reach for the puppet that helped over the one that hindered.[37] And toddlers help spontaneously, then help less once you start paying them.[38]

In Bergen (Norway) a handful of economists have spent fifteen years taking fairness apart on a laboratory bench. In one clever experiment, two strangers each do a handful of small tasks on a computer. One ends up with six one dollar bills, the other with nothing. A third stranger is then handed the six one dollar bills and asked to redivide them or leave the division as is.

If the third stranger was told the division was due to effort, they often left it alone. But if they were told it was due to a coin, they often redistributed more evenly. On top of this, three distinct preferences were found. Some people are strict egalitarians who tend to redistribute as evenly as possible. Some are strict libertarians who tend to abhor any redistribution, even when the cause is pure chance. And some are meritocrats who prefer to divide based on effort.[39]

Run the same experiment with 65 thousand people in 60 countries and you'll find 35% libertarians, 34% meritocrats and 26% egalitarians. Meritocrats dominate in countries like Canada (66%), Australia (66%), and Japan (61%). In Scandinavia and the Netherlands it's the combo of meritocratic and egalitarian: only 15% is libertarian. Egalitarians dominate in Bangladesh (46%), Sri Lanka (42%) and Tanzania (42%). What astounded me most was that 65% of respondents in China and 56% in India were libertarians. I never would have guessed that this movement that I associate with the US actually has most proponents in Communist China![40]

For our energy system that means three things. First, most people don't mind some inequality as long as it's earned. So if someone buys a battery for the energy community, we won't mind if that someone keeps most of the money they earn providing flexibility services to the community. But if the profit was due to chance, we would probably feel a more even split with the energy community was warranted. Second, it would be best to stop inequality that is based mainly on luck from materializing in the first place. So don't pay first and claw back the money with taxes later, because this would alienate the libertarians. Third, the algorithm that divides

profits should be calibrated very differently from country to country and energy community to energy community.

What we want the distribution to look like

A central issue in our energy system is how energy will be distributed. So let's take one step back. How unequal do we want the world to be, how unequal do we think it is, and how unequal is it really? Across countries, across the political spectrum, across methods, the literature keeps returning the same shape.

On what we want: Michael Norton and Dan Ariely asked more than five thousand Americans to design an ideal spread of wealth. Their ideal gave the top fifth about 30% of the wealth and the bottom fifth about 10%. Remarkably enough, the agreement held across Bush voters and Kerry voters, rich and poor, men and women, all within a few points of each other. They were also asked to choose blind between the American distribution and the Swedish one. Even more remarkably, 92% of Americans preferred the Swedish one.[41]

Another study extended the question to CEO pay across forty countries. The median person wanted the big boss to earn about five times as much as an unskilled worker, not the hundreds-fold many bosses actually earn. The Danes wanted two to one, the Americans seven to one. And the whole distance between far-left and far-right voters was the difference between three and four.[42] You might almost think part of the dissent is manufactured.

On what we think of the distribution: the Americans who wanted the top fifth to have 30% thought it had roughly 60%. They thought the big boss cashed in roughly thirty times as much as unskilled workers, instead of the seven times they preferred.

On what is: in the US the top fifth has about 84%, instead of the 60% they thought and the 30% they preferred. And the CEO made three hundred times more than unskilled workers, instead of the thirty times more they thought and the seven times more they preferred.[43] People in the US, Britain

and Australia consistently underestimate how unequal their countries are. More importantly, it is *perceived* inequality, not the real thing, that predicts whether people say the gap is too wide. Misperception, not reality, is what moves the politics.[44]

The inequality gets starker when you look at a smaller slice at the top. The richest tenth of the world's adults owns roughly three-quarters of all household wealth. The richest one percent, some sixty million people, owns roughly half of the world.[45] In the United States the top one percent holds more than the bottom ninety combined.[46] The distribution has drifted a very long way from the one people say they want.

One caveat. Kimmo Eriksson and Brent Simpson argued that asking people to assign percentages across fifths is an unnatural task that flattens the answers. Asked in plain wealth terms, they said, people give ratios closer to reality.[47] The exact magnitudes wobble under that critique. The direction does not. What people want is much less unequal than what they perceive, and what they perceive is much less unequal than reality.

Show them how unequal things really are and support for doing something about it rises. But the step from new belief to new policy is partial and slow.[48]

For our energy system design this matters enormously. Almost all of us would like the profits to stay with regular people instead of rich ones. And if we make energy inequality and injustice visible, people are likely to want to do something about it.

What we decide behind a veil

Norman Frohlich and Joe Oppenheimer asked groups in the US, Canada and Poland to agree on a rule for splitting money. They had to do it *before* learning which of them would end up rich or poor under it. We call this deciding behind a Rawlsian veil. The twist in the experiment was that the total pie would grow more if they allowed for more inequality.

The floor is what the poorest people earn. Rawls thought his veil would lead people to raise it as much as possible, irrespective of total wealth. That way they could be sure they would not end up relatively poor. But few people chose that.

On the other end of the spectrum were the wealth maximizers. They chose the economic default: as much growth as possible, irrespective of what it does to the income distribution. But just 5% of people chose that.

Instead the result is strikingly consistent. The large majority chooses what the authors call maximise-the-average-with-a-floor. Grow the pie for the average person as much as possible, and guarantee that nobody drops below a decent minimum.[49] Not pure equality, not pure growth, but a floor, and earned room above it.

Add the Bergen finding and the inequality research and it becomes clear what the design for our new energy system must deliver:

1. Clear information about inequality
2. A floor nobody falls beneath
3. Limited inequality and the rich must earn it through effort instead of luck

A universal floor beats charity to the poor

One more thing about that floor. Don't create it by giving energy charity only to the most energy-starved families, because that way you turn most people against it. Gøsta Esping-Andersen compared welfare states. He found that the Nordic ones cut poverty most deeply not through targeted compassion for the poor but through universal entitlements paid to everyone.[50]

Walter Korpi and Joakim Palme sharpened it into the paradox of redistribution. Systems that aim benefits only at the poor end up redistributing less than systems that pay everyone. The reason is simple. Programmes targeting just the poor lose the political backing of the middle class, while a universal floor locks in their support.[51,52]

This goes against how most countries do it now. The poorest households fill out a form proving how poor they are, and then they get money. The Korpi-Palme result predicts what comes next. The scheme is fiddly to claim, awkward to be seen using and easy to cut once it loses support.[53] It also misses many of the households it is meant for: the ones too harried or proud to file the form.[54] Some kind of universal entitlement to energy, awarded automatically to everyone, is more politically stable. It also fits our human nature better. We'll get into it in chapter 28.

Fairness across the generations

The fairness instinct extends toward people who do not yet exist. Erik Erikson called the adult drive to invest in what will outlast us generativity. It is one of the sturdiest findings of psychology.[55] We care about our children, and about the children who will come after them.[56] We register unfairness across generations on the same circuit as any other unfairness, once the framing makes it legible.[57,58] A society that hurts the future to flatter the present strikes most people as plainly unfair the moment they see it set out that way.[59]

Economists give this caring for future generations a number: the discount rate. It sets how much less the future counts than the present. The next chapter shows what they did with it. Here it matters that each of us uses several different discount rates. Which one depends on what "self" is in charge at a certain moment.[60,61] The impatient "now self" craves instant gratification. It has a high discount rate, comparable to shareholders in a company.[62,63] The "reflective self" is closely tied to long term wellbeing. It has a much lower discount rate, comparable to governments planning long term infrastructure.[64]

So when we are caught up in our daily struggles we tend to forget about the future. But once we take a step back, most of us really care about future generations.[65] Economists are focused on shareholders, GDP growth and whether we choose product A over product B. But these are all "now self"

measurements.[66] When we reflect on real wellbeing, most of us care about our grandchildren's grandchildren a lot.[67] We just built an accounting system that cannot hear them.[68] The repair belongs in a design with low discount rates, not in a lecture on willpower.[69]

We are a small-group animal

Henri Tajfel showed that we only need a flimsy excuse, like a coin toss, to create in-groups we care about more and out-groups we care about less.[70] Sherif's Robbers Cave, for all its engineered hostility, also showed the antidote. Hostility between two groups dissolved when they had to cooperate on a task neither could manage alone. Shared achievement builds trust.[71] Robin Dunbar put a rough ceiling on the whole business. Stable social relationships top out at around 150 people. That number keeps reappearing across hunter-gatherer bands, army companies and Christmas-card lists.[72,73]

I'm not claiming city neighbourhoods will turn into close-knit tribes when we organise them into neighbourhood holons. But a street or a building is well suited for the kind of cooperation our evolutionary history prepared us for. Warm reciprocal cooperation is close to our natural state and needs little scaffolding.[74]

On a larger scale, among thousands of strangers who will never meet, that warm machinery does nothing. Something cooler and more impersonal has to take over.[75]

The trick is to match each tier to the cooperation that comes naturally there: warm and personal within small groups, fair and impersonal in large groups or between groups.[76] Chapter 25 works this out for the tiers of the energy system. We need an energy system design that respects our human nature in that way.

Why strong institutions are still needed

If people are so cooperative, empathic and fair, why do we need a state at all? The answer hides inside the very experiments that show the kindness and fairness.

An extreme example is what the body does to a mother with child. Her kindness towards the child becomes almost boundless, but her ruthlessness to anyone perceived as threatening the child... Well, let's just say: don't threaten her child. More widely we are talking about in-group empathy and out-group adversity.

And the fairness instinct is a *want*, not an automatic outcome. It comes bundled with something fierce: a willingness to punish unfairness even at personal cost.[77] That fairness instinct is the engine of cooperation among strangers. It is also a recipe for blood feud when there is no neutral party to appeal to.

Finally there are the free riders, jerks and criminals. There are relatively few of them, but they can mess it up for a lot of other people.

So yes, we need institutions that have power over us. But the empirical reason is nearly the reverse of the motto of Hobbes. Hobbes claimed the state was needed to suppress a brutal nature. The evidence says we need the state, meaning impartial rules, courts and enforceable agreements, to *channel* a fairness instinct. Left without a referee, that instinct escalates into tit-for-tat.

Elinor Ostrom spent a career documenting communities that governed shared resources for centuries: Spanish irrigators, Swiss alpine herders, Maine lobstermen. She found that durable cooperation never survived on goodwill alone. It also needed the communities to make rules and monitor them.[78] But not because we are inherently evil and need to be suppressed! As she put it in her Nobel lecture: a core goal of public policy "should be to facilitate the development of institutions that bring out the best in humans."[79]

This brings us back to the Tongan boys on their island. They needed no warden, but even they made rules that they kept each other to: a rota, a shared fire, a way of settling quarrels. And they were six people who could see one another all day. Scale that up to millions trading energy across a continent and the rules can no longer be informal. But their job is

unchanged: to be the neutral referee that lets an empathic, fairness-wired species actually arrive at the fairness and flourishing we crave.

The grid operator, the market rule, the regulator… they should not be the Leviathan disciplining wolves. We should design them to be Ostrom's scaffolding: an impartial structure that brings out the best in us instead of controlling us. The goal of our new energy system design should not be to abolish the referee. It should be to let the game run as much as possible and to bring in the referee only when needed. And we should make sure the referee can never become a toll-extracting tyrant that gets in the way of our natural tendency to cooperate.

Understanding yourself is hard

In order for humans to flourish, they have to accept that they might not be as rational and free-willed as they often think.

Timothy Wilson showed that setting goals, sizing up situations and launching actions are mostly done unconsciously. The role of the conscious self is often limited to composing a plausible story about why we did it after the fact.[80] His advice to anyone who wants to know themselves is pointedly anti-introspective: watch what you do, and ask the people around you.

Daniel Wegner showed that the *feeling* of having willed an action is manufactured by a different brain system than the one that produced the action. It can be triggered in the lab when the two have nothing to do with each other.[81] Jonathan Haidt went further. Moral judgment is mostly an instant gut response. Conscious reasoning is the press officer who supplies respectable reasons afterward. The tell is moral dumbfounding: people keep a verdict with total confidence even after every reason they offered for it has been demolished.[82]

Hugo Mercier and Dan Sperber explain why our reasoning works this way.[83] It didn't evolve mainly to find truth, but to win arguments inside a group.

Robert Sapolsky traces our acts back to the brain chemistry of a second ago, the hormones of this morning, the plasticity of years past, the womb, the genes and culture. He finds no clean slot that's available for the free-floating chooser.[84] And Antonio Damasio shows that emotion is not the enemy of good decisions but part of the apparatus. Some people have their emotional tagging knocked out by a specific brain injury. They can argue the options all day and then cannot actually choose.[85]

This means the energy system cannot be designed on the assumption that people will inform themselves, compare twelve tariffs, and behave optimally once told the stakes. Instead the energy system we design should make it easy for us to evaluate our behaviour. To determine if our behaviour helps us to achieve our goals. And if we want, it should give us tips and nudges that helped others achieve their goals better.

Fast and slow

Daniel Kahneman described how we have fast, automatic thinking and slow, deliberate thinking.[86] Fast intuition is well suited to small groups, where it translates into easy generosity. But fast intuition is too parochial for fairness across a boundary: toward strangers, statistical victims, the unborn, people in other countries. There we need slow reflection. Joshua Greene's brain imaging of trolley dilemmas catches the two systems in the act. Up-close personal dilemmas light up the emotional regions. Impersonal ones light up the machinery of deliberate control.[87]

Decisions taken after slow reflection are often more in line with our long term wellbeing. But they come with a bill, and it falls hardest on the people least able to pay it. Sendhil Mullainathan and Eldar Shafir documented the bandwidth tax of poverty. When money is short, the shortage itself eats the mental bandwidth you would otherwise spend on careful decisions. The measured hit to reasoning is comparable to losing a night's sleep or being mildly drunk.[88] And even when

you are well-to-do, you are probably not craving an energy system with deliberative procedures, opt-in cooperatives, intricate tariffs and bylaws to navigate. Each of them carries a hidden entry fee in attention and time. So we need to make the new energy system mostly automatic.

And after being denied often enough, we start to accept it as the way it's supposed to be. Amartya Sen calls this adaptive preferences: the slave and the woman with the burka become satisfied with their predicament.[89] Sen's repair is to measure not what people say they want but what they are actually *able to do and to be*. That is their capability, and it does not quietly shrink to fit the cage. We should design an energy system that maximizes people's capabilities, even when they don't have the mental bandwidth to reflect themselves out of their cage.

Applied to the energy system we should always ask: where is fast intuition enough and where do we need the slow reflective self? When using an app, fast intuition should work. But when making sure the app is cybersecure and doesn't steal your data, slow reflection is needed. For helping each other during a blackout, fast intuition is perfect and gratifying. For making sure in advance we are set up to survive the blackout, slow reflection is needed. For deciding to fast charge your car because you have a meeting in 30 minutes, nothing should stand in the way of fast intuition. For designing the algorithm that works the rest of the time, and for establishing the values and decision making rules of your energy community, slow reflection should be given free rein.

For the designers of the new energy system, thinking fast and slow presents an interesting paradox. The more the energy system can run with fast intuitive decisions or no decisions at all, the better. But creating a system that requires very little slow reflection once it's turned on will require a *lot* of slow reflection during the design phase. Especially on what makes us flourish. We are currently not doing that yet.

What we actually want: self-determination theory (SDT)

Past bare survival, what does the evidence say actually makes us flourish? The most cross-culturally tested answer is self-determination theory (SDT). Across four decades and some sixty countries, Richard Ryan and Edward Deci kept finding the same three needs. They found them in rich countries and poor, collectivist and individualist, democratic and not. Autonomy: the felt sense that the consequential choices in your life carry your own consent. Competence: the felt sense that your actions are effective, that you are getting better at things that matter. Relatedness: belonging to people who know your name.[90]

These three needs predict wellbeing far better than income does. And the mirror image holds too: chase money, status and image, and once the basics are covered, wellbeing tends to drift *down* rather than up.[91]

Research on the longer arc of a life points the same way. The Harvard Study of Adult Development followed two groups of men for eighty years. Its long-time director boiled it down even further: "Happiness is love. Full stop."[92]

Carol Ryff's map of psychological wellbeing has six parts: autonomy, mastery, growth, good relationships, purpose and self-acceptance. They name the goods that accumulate across a life and that no single purchase can deliver.[93] Martin Seligman's PERMA puts four of its five elements in the relational, long-arc category.[94] And Erik Erikson named the central task of adult life as generativity, caring for what will outlast you.[95] The things that actually produce flourishing are intrinsic, relational and slow. None of them is scarce in the economist's sense: your friendship does not use up mine. And none of them is well captured by a price.

Robert Frank's work on positional goods shows why the richer-is-better story fails for society as a whole. Above a certain point, what money buys is no longer the thing itself but the rank the thing signals. And rank is zero-sum. A society of richer people is only a society of richer rivals for the same fixed supply of standing.[96] What people actually want,

and where the real ache sits when they miss it, is to be valued by the people they care about. Wealth is the cheap proxy a price-obsessed culture keeps offering in its place. It is not a good substitute.

So if we replace homo economicus with the actual human, what does that mean for flourishing in the energy system?

- Autonomy: a system in which you generate, store and trade your own power, and can change who acts for you as easily as switching phone networks.
- Competence: a system simple enough to understand, that you can improve yourself, that shows you what your panels, electric vehicle, heat pump and battery are doing and lets you act on it.
- Relatedness: a system built at the scale of a street or a building, where you can donate excess power to people you like, where solar panels on the school or parking lot and a neighbourhood battery increase social cohesion and bring down shared costs.

A distant supplier who meters you, manages you and sells your own data back to you gives you only energy. But the energy system could give you more. It's not only about lower bills.

Designing for human flourishing

How can we align everything we've learned about what makes us flourish in a way that allows an engineer to design a better system? It's clear we can't simply make it one big optimization function, as economists have tried to do. For that to work we would have to leave out almost everything that matters, as economists have done.

When we think of it as designers, efficiency and cost should still count. But it's also about giving people the capability for creating autonomy, competence and relatedness, and about nudging the system towards equality with a floor.

That is what we want. But the instrument we use to decide what is worth doing, economics, can see almost none of it.

The current science that guides us is broken, and the next chapter is about that broken compass.

22

Economics, the Broken Compass

In 1995, a committee of economists working for the Intergovernmental Panel on Climate Change sat down to do something that sounds impossible and immoral but is a routine necessity when making policy: put a price on a human life. You cannot run a cost-benefit analysis of climate change without one. If warming will kill people, and you want to know whether preventing it should come before other things, like cancer research, you need a number. What raised eyebrows was that they picked *multiple* numbers. A life in an industrialised country went into the ledger at $1.5 million. A life in a developing country went in at $150,000. The same death, at one tenth the price, depending on where the body fell.[1]

The delegates from the developing countries noticed that their death toll was far higher, but the price put on that death toll far lower, and they rebelled. India's environment minister, Kamal Nath, called the method "absurd and discriminatory," and the negotiations nearly came apart over it.[2] The economists retorted that this was simply reality: a Bangladeshi rice farmer cannot pay what a Swiss banker can, so the life of that farmer is worth less.

What happened next is typical for economics. The IPCC did not respond to the outrage by valuing life more equally. It responded by deleting the number. The later reports simply stopped adding up the costs of deaths in dollars.[3] The moral

discomfort was resolved the way I resolve a messy drawer: by closing it. But the valuation did not leave. It is still part of the damage estimates and the carbon prices that policy runs on today. It just became invisible again.

That a life in a developing country is worth a tenth of a life in a rich country (actually it's much more extreme still, more on that later) is just one example of the problem that this chapter is about: standard economics favours the rich and ignores damage to the poor and the planet. It has been doing that for over a century, and this goes a long way towards explaining why we are still burning fossil fuels, and why my beloved Internet, which started out so open, is broken.

I found out all this by accident. I was researching renewable energy and wondered how it was possible that economics was missing learning curves and seemed incapable of running even simple simulations. These things we will cover in the next chapter, where we learn how to fix economics. In this chapter I want to focus on the deeper problem that explains a lot of the mess we are in as a society: for over a century economics has been helping the rich get richer while ignoring human flourishing, discounting the poor, and polluting the planet.

You might be thinking: can't you leave economists out of this book about energy? It's already complicated enough as it is. Sorry, but I can't. How economics guided us wrong is simply too important an explanation for the mess we are in.

I've already explained that solar and wind are abundant, can be resilient, and will increasingly be cheapest. And in the previous chapter we saw what we actually want: to flourish, with less inequality and a floor under everyone. In this chapter we will see that fossil fuels are already doing damage to the tune of at least *seven percent of global GDP*. So why are we still burning fossil fuels? The easy Hollywood answer is that fossil-fuel companies are full of rich and wicked people who have bought the politicians, and there is something to that. But it cannot be the whole story, because the Internet had no fossil-fuel lobby. It was a clean-sheet industry, born

in public laboratories, with openness baked into its founding design, and it got captured anyway. There are many more examples, and chapter 24 tells their stories. When the same accident befalls all these unrelated systems, you should stop blaming individuals and start analysing what the systems have in common. And one very important thing they have in common is the instrument corporations and politicians use to decide what is worth doing. We navigated both transitions by the same faulty compass: economics.

My claim is not that economics is a conscious fraud or that economists are villains. That would be both untrue and too flattering to real villains. My claim is narrower and, I think, harder to wriggle out of: the economics we steered by was an overconfident but underdeveloped science, and a science like that starts to behave like a belief system. It pretended to be a compass while it was little more than simple prejudice clad in mathematics. Empirical science has a way of telling truth to power, but economics lacked that empirical foundation and thus became a lackey of power: it protects the rich instead of the poor. Seven times over, the standard model made choices that look neutral and technical, and seven times over the choice leaned the same way: favouring the rich, favouring the status quo, favouring the present, favouring fossil fuels, favouring whoever already owned things. This has steered the energy system in the wrong direction.

This is a chapter detailing seven complaints about economics. Each complaint is one more reason why we are burning fossil fuel, allowing extreme energy poverty, and wrecking the planet:

1. We only count growth and ignore extraction.
2. We underestimate human deaths, damage to the environment, and other "externalities" so the dirty option looks cheap.
3. We discount the future, which makes tomorrow's damage too cheap to matter.
4. We price the lives of the poor people at a fraction of our own.

5. We deny that inequality decreases flourishing.
6. We didn't even try to take human flourishing into account.
7. We under-built clean energy because the models said it would stay expensive, and it didn't.

The people who first noticed these errors were, by and large, not economists. They were engineers who could see that the mathematics was beautiful but the results were wrong: people who could read a learning curve, who understood innovation and tipping points, and who watched both climate damage and renewable energy exceed the predictions. Others were ethicists and social scientists who noticed that economic growth was not the same as human flourishing. And now economics is slowly catching up to these other sciences, led by visionaries who are finally winning Nobel prizes.

Ignoring extraction

Open the Uber app on an iPhone, take a ride across town, and Apple takes nothing. Open a news app on the same phone, buy a subscription through a few lines of Apple's payment code, and Apple takes up to thirty percent.[4] Same phone, same card, same tap of the same thumb. The only thing that changed is whether you could have paid someone other than Apple. The ride happens out in the world, where Apple cannot wall you in, so it charges nothing. The subscription is used inside Apple's walls, so it charges nearly a third. The fee does not track what it costs Apple to provide anything. It tracks the absence of an exit.

A thirty-percent toll on everything sold through a door you cannot walk around is extraction in its purest form. And yet the compass we steer by has remarkable trouble seeing it as a cost at all. The reason is a move economics made so early and so quietly that most economists have forgotten it is a choice. Every transaction is split into two questions: how big is the pie, and who gets the slices? Growing the pie is treated as the proper business of economics. Fairly distributing the pie is handed off to politics or ethics. So, since a toll

that funnels money from millions of users and developers to the company operating the toll booth does not shrink the pie, economists are unable to see the costs to users and developers. In practice that means economists protect the toll booth owners against those who pay the toll.

The Antitrust Paradox, written in 1978 by Robert Bork,[5] influenced a generation of economists and judges. It carried this blind spot into antitrust. When a monopoly overcharges the buyers who keep buying, Bork wrote, that is "merely a shift in income between two classes of consumers."[6]

Even the judges following Bork did not go that far. They kept his label, consumer welfare, but read it as the price a shopper pays.[7] They ask people who protest the monopoly: "Can you prove the shopper paid more?" That at least counts the toll at the till, but it is narrow in two ways. Firstly, this requires whoever wants to hold the monopolist and its army of lawyers accountable to prove that new entrants would be able to produce the goods at lower costs. Good luck with that.

Four iPhone owners sued Apple over its thirty percent in 2011. It took until 2019 for the Supreme Court to rule that they were allowed to sue at all.[8] In 2025 their case was "back to square one," because their own expert could not reliably tell that "Rob Pepper" and "Robert Pepper" were the same person.[9]

Secondly, the monopolist can succeed in squeezing where the test never looks: upstream. If a farmer or an app developer depends on a supermarket chain or an app store to sell their product, the chain or the store can force them to hand over a large chunk of their hard-earned money. That money now flows from their pockets to the owner of the toll booth, but by definition it is ignored. Meanwhile, off the books, the tolls spread. American firms charged 21% above cost in 1980 and 61% by 2016, and almost all of that rise came from the biggest firms and went to the people with the deepest pockets.[10]

But the tide is slowly changing. Thomas Philippon loudly proclaims that this is how America gave up on free mar-

kets.[11] Nobel prize winner Joseph Stiglitz says that much of this is inequality-inducing rent seeking: people "grabbing a larger share of the wealth that would otherwise have been produced without their effort."[12] Nobel prize winner Angus Deaton now writes that economists leave dividing the pie up to politicians who often fail to show up, so that the economists' advice becomes "little more than a license for plunder."[13]

The 2024 Nobel went to Daron Acemoglu, Simon Johnson and James Robinson for making extraction the master variable. They hang the wealth and poverty of whole nations on whether they inherited extractive or inclusive institutions.[14,15]

The neighbouring fields confirm it. Legal scholars have spent a decade making the same case about platforms, from Lina Khan's "Amazon's Antitrust Paradox" to Tim Wu on the curse of bigness.[16,17] And courts have started to follow. In 2025 an American appeals court said Apple should charge for links to outside payment only its necessary costs, "but no more."[18] The same year a British tribunal found that Apple had overcharged about 36 million British users.[19]

That humans innately dislike extraction is what the ultimatum game of the previous chapter shows: real people, across every culture tested, reject payment if they consider the division too unfair.[20] Economists call this inequity aversion leading to altruistic punishment.[21,22]

So the cost of extraction and our aversion to it is firmly established in law, psychology, and economics itself. It's time we started doing something about it.

Cheapening human life and nature

Economists still severely underestimate the damage fossil fuels extract from human health and the planet. One anecdote in particular always reminds me of what we are up against. In 1994 William Nordhaus, who later won a Nobel prize for introducing some climate damage into economics, surveyed a group of experts on how much economic damage

severe warming would do. The answers he got split sharply along disciplinary lines. The economists guessed the damage would be mild. The natural scientists – the people who study what heat actually does to ice, crops, coasts and people – guessed the risk of catastrophe was roughly thirty times higher.[23]

Faced with that gap, Nordhaus did not wonder whether economists like himself might be missing something. On the contrary. He noted that the natural scientists leaned toward what some less excitable economists called an "apocalyptic" streak. The way he saw it, 90% of economic value was realized in "carefully controlled environments".[24] In other words, because most money is made inside air-conditioned offices, we should not worry too much about the damage of climate change to nature. He only conceded that his estimates were "modest compared with some of the scientific concerns". Like most macroeconomists he did not let this shake his self-confidence. After the financial crisis some economists started to acknowledge this overconfidence. As Nobel laureate Paul Krugman put it, economists like him "mistook beauty, clad in impressive-looking mathematics, for truth".[25] But it didn't change much. As Nobel laureate Paul Romer put it in 2016: "other economists do not care that the macroeconomists do not care about the facts".[26]

That is why I say economics behaves more like a belief system than a science. In a science, when the evidence and the theory disagree, the theory has to give. Not so in economics.

Yet even under the economists' conservative assumptions, the International Monetary Fund, not a hotbed of radicalism, concluded that the so called "externalities" (costs ignored by markets) of fossil fuels added up to $7 trillion a year in 2023. That's roughly 7% of everything the world produces![27] The damage is not just abstract and in the future. Air pollution from fossil fuels already kills over 5 million people every year, comparable to the entire population of New Zealand, mostly from breathing fossil exhaust.[28]

All this still ignores the living world, but economists are starting to notice that too. As Partha Dasgupta said in a review commissioned by none other than the British Treasury: we, and our economies, are "embedded within Nature, not external to it."[29] I consider that progress compared to Nordhaus' framing that we should not worry about nature too much, since most money is made in "carefully controlled environments".

In the end, all this results in a price we have to put on burning fossil fuels. As I said before, it sounds strange putting a price on things like life and nature. But if you have to compare different policy alternatives, you need such a price, as strange as it might feel. And the price in this case is the so called Social Cost of Carbon, or SCC, also called the carbon price. At first economists thought this social cost of carbon, or SCC, was basically negligible. They thought human progress would solve everything and nature wasn't that important anyway. But right now it's about $60 per tonne of carbon, or 6 cents per kg. What does that mean exactly?

A simple way to think of it is this: coal emits (very roughly) 1 kg of CO2 per kWh. So this adds about 6 cents to the price of one kWh of coal-fired electricity. The only regions that enact this are the EU, the UK and Canada, and there coal is quickly becoming uncompetitive. The US doesn't charge anything, but there coal is losing out against fracking gas, which is cheaper and, because of its fugitive emissions, just as dirty. In the rest of the world coal is increasingly struggling against solar and wind, but since nobody adds this SCC to its price, it gets to pollute for free and can still compete.

By now economists overwhelmingly agree the SCC is an uncounted cost that should be included. In 2019 the Wall Street Journal published an endorsement by 4000 economists, 27 Nobel laureates among them: never have so many economists endorsed something.[30]

But we are only getting started! That $60 is the SCC when you discount the future.

Discounting the future

The cost of carbon depends to a large part on how much you discount the future. The question we have to answer is this: if you cause $100 of damage a hundred years from now, how much would you be willing to pay today to avoid it? If you are brought up – like me – with the idea that you should clean up your own mess it's $100. But economists see it differently. They say: "If you lend money, for example for a mortgage you have to pay interest. This shows that something is worth less in the future." And yes, I'm paying a mortgage, so I'm familiar with that idea too.

But for causing pollution, my first choice would still be a discount rate of 0% and $100, and that puts me in the company of many distinguished ethicists and economists. Nordhaus says 5.5% is more realistic and that means you should spend less than half a dollar to avoid $100 of damages a hundred years from now. Make it 2% and you should spend $14 to prevent $100 of damage a hundred years from now.

This 2% is where economists are converging now and that moves the social cost of carbon from $60 per tonne to $190 per tonne. This is what is proposed in a careful 2022 study in Nature.[31]

And it is the model the US is using (until Trump changes it).[32] Recently over two hundred economists who study discounting were polled and again the median was 2%.[33] So that gives us an SCC of $190/tonne and coal becoming 19 cents per kWh more expensive.

One thing to note: to calculate these damages they are not using the very high warming scenarios that were mainstream just 20 years ago (like the infamous RCP8.5 that was implausible from the start)[34,35,36] but the new SSP2-4.5, which takes into account the growth of renewable energy, lowers the projected warming in 2100 to 2.7 degrees Celsius above the pre-industrial baseline and slashes the projected death toll by roughly a factor of ten.[37,38] So $190 is not an over the top estimate but thoroughly mainstream for those in the know.

No country is even close to asking markets to pay that much. If one country does it and another country doesn't, the fear is that industry will move to the country with cheap fossil fuel. And there are lobbyists, both on the country level and on the level of the IPCC. So this is all theoretical. But it's also true.

If we would be able to make fossil fuel energy producers pay for the actual damage we think they do, the costs of coal and gas would triple overnight. There would be a run on PV and wind. Coal fuelled power plants would close in a few years and gas would only run as backup for 5% of the year until eFuels were ready. So if somebody tells you renewables run on subsidies, tell them they've got it backwards: fossil fuels run on subsidy in the form of damage they don't have to pay.

Whose death counts

The now broadly accepted – but never actually implemented – discount rate of 2% moved the social cost of carbon from $60 to $190/tCO2. That alone would make fossil fuel entirely uncompetitive in a well-priced market. But there is something else, something slightly unethical, that is bothering many economists who care to deal with the issue. It's the one we opened the chapter with: how much does a poor person's life cost?

Now the underlying problem is simple: some countries are rich and some countries are poor. For example, the US and EU spend a thousand times more on healthcare per person than African countries.[39] Climate change is different from regular development aid, because it is something we are still going to cause. And yet we still value the deaths we will cause less in poorer countries.

Anyway, what we do is use Negishi weights. Basically they make sure that money doesn't leak from rich countries to countries where it helps more people.[40] So the models protect the rich instead of the poor, and they do it by design.

If we would weight the damage to rich and poor persons equally, the social cost of carbon would get far above $1000/tCO2: coal would cost $1/kWh extra, while the market prices it at less than $0.05 now![41,42]

I'm not advocating we should use these numbers. Total chaos would ensue if we did. But I consider it important to point out that the oft-celebrated free market, if correctly implemented, would make fossil fuel criminally expensive.

Ignoring equality

This complaint is about a fact so ordinary a child grasps it: one euro has more value to a poor person than to a rich one. The euro that is the difference between eating and going hungry plainly matters more than the euro that rounds up what you can pay for a new diamond necklace. Economists have a term for it: the diminishing marginal utility of income, where utility is simply their word for how much good something does you. It's like a learning curve that flattens the more you earn: every doubling of income gives you roughly the same increase in happiness. So the step from $10k to $20k per year is worth as much as the step from $40k to $80k. After that it becomes dramatically lower still. There is discussion on whether earning more than $100k makes you happier, but it's clear that if you would focus on relationships and doing things you love, it would bring you far more happiness than the very questionable increase you get from going from $200k to $400k. And that's not an opinion but an empirical observation.[43]

Almost no one disputes that this is true. But taken seriously, it is also a stick of dynamite, because the implication is that moving money from the very rich to the very poor raises the total amount of human wellbeing in the world.

So what did economics do with the dynamite? Around 1932 it put it in a drawer and labelled the drawer "not science." Lionel Robbins argued, with real cleverness, that you cannot truly compare the satisfactions of two different minds, and

that any claim resting on such a comparison is an ethical opinion, not an economic finding.[44]

So when comparing the person going hungry with the person buying their next diamond necklace, his reaction was that these are entirely different people and thus impossible for an economist to compare.

This would have been news to the babies of chapter 21, who are already willing to make that judgement when they spot unfair inequality. And of course it was such a transparent way of not inconveniencing the rich that it couldn't last. Now the mathematics of optimal taxation, thoroughly respectable and Nobel-decorated work, runs entirely on the forbidden premise that a poor person's euro is worth more. Engage with the issue honestly and the top tax rate is at least 73%.[45]

With energy we will see a similar dynamic. I have 80 solar panels on my roof, but I'm pretty sure that if I was living in extreme energy poverty and just had wood and dung for cooking, kerosene for a small lamp at night, and I had to walk somewhere to charge my phone, one solar panel to replace all that would make a far bigger difference for me than my 80 solar panels in my current rather luxurious predicament.

The lean, again, is toward the rich. Ruling the fairness question out of bounds doesn't mean you have stayed neutral. You have handed the win to whoever was already rich, and only pretended your silence was objectivity.

Ignoring flourishing

Take away the decoration, and the target of economics is to increase utility, which is approximated by money. So the goal of economics is basically: more money. And the one that money is for sits at the centre of the standard model, the creature whose satisfaction the whole apparatus exists to maximise: the homo economicus. He is a self-interested calculator who is only interested in buying more stuff, and who has no interest in other people except as a means to more money.

Economics did not start with him. In 1759 Adam Smith, professor of moral philosophy in Glasgow, opened *The Theory of Moral Sentiments* with the principles in man's nature that "interest him in the fortune of others, and render their happiness necessary to him, though he derives nothing from it except the pleasure of seeing it".[46] Seventeen years later, in *The Wealth of Nations*, he wrote: "No society can surely be flourishing and happy, of which the far greater part of the members are poor and miserable."[47]

But economics became a science in the period that most social scientists tried to emulate Newtonian physics, requiring humans to be just as predictable as, say, electrons.[48] Newton was the hero of the day. Even Smith, in an essay on the history of astronomy, wrote that Newton had made "the greatest and most admirable improvement that was ever made in philosophy".[49] In 1881 the economist Francis Edgeworth spelled out what this meant for humans: "the conception of Man as a pleasure machine may justify and facilitate the employment of mechanical terms and Mathematical reasoning in social science."[50]

In September 1901 Léon Walras, the founder of general equilibrium theory, sent the fourth edition of his book to Henri Poincaré, the French mathematician and physicist, and asked for his opinion. In a second letter, of 30 September, Poincaré explained that every mathematical theory starts from assumptions, and that it only bears fruit if you stay aware of them, as in physics. Forgetting them is how you overstep the proper limits. He did not say Walras had done so, but he added: "In mechanics, for example, one often neglects friction and regards bodies as infinitely smooth. You regard people as infinitely selfish and infinitely farsighted."[51]

In 1909 Walras printed the letter at the end of an article in which he called the procedure of pure economics "rigorously identical" to that of rational and celestial mechanics, and set the equilibrium of the market beside the equilibrium of

the celestial bodies.[52] Letting go of that Newtonian dream of equilibrium is one of the repairs in the next chapter.

In the twentieth century economists such as Frank Knight gave economic man even more of that far-sightedness: perfect knowledge and perfect foresight. The historian Mary Morgan argues that they exaggerated him this way for the sake of the mathematical theory of the economy, not to describe real economic life.[53] Instead of the science that helps us to make the most of our lives, economics became the science of optimising our worst selves.

In the last two decades economists have slowly started to accept what social scientists have been telling them for over a century: homo economicus is utterly unrealistic. Daniel Kahneman won a Nobel for showing that real humans are a bundle of biases, Richard Thaler won one for building a field on the wreckage, and no serious economist will defend the homo economicus over coffee anymore.[54]

But what economists believe at the coffee machine is not the problem. The problem is what stays welded into the machinery after the belief is gone: into the textbooks that still teach the calculator to first-year students, the welfare models that still maximise his utility, and above all the one place where the fiction was given a body.

Because in the end we did build homo economicus, out of models and laws. A company under a strict shareholder-value mandate is required, more or less by its charter, to treat everything that is not its own profit as either a resource or an obstacle. That is precisely the disposition the model assumes. The legal scholar Joel Bakan made the uncomfortable observation that if you take that behavioural profile to a psychiatrist, it matches, item for item, the clinical checklist for psychopathy: callous disregard for others, incapacity for guilt, a failure to conform to social norms, deceit for gain.[55] We told the most powerful institutions in society to do one thing: enrich themselves. Then we madly reduced any regulation that kept them from being extractive. And fi-

nally we acted surprised when they acted like the extractive sociopaths we asked them to be.

For the energy system this matters because the optimal energy system is more than the one with the lowest cost per kWh. I give presentations a lot. Of course the people coming are interested in energy, but I'm always amazed at how everybody sees different implications. There is a general feeling that energy is something that's underpinning everything and that our current system is too shaky. Most EV owners love the idea of their car being able to supply energy to their house. Some love the technical aspects of supplying and storing your own energy the way others love herbs from their own garden. Many are enchanted by the idea that in their home the lights will stay on when the grid fails. Some love the idea of leaving a better world to their children or to people suffering energy poverty. Others like the idea of giving the finger to large corporations and organizing locally. Increasingly energy independence is a thing, especially in Europe. And so there are many ways in which people could derive value from the energy system, other than by a lower price per kWh.

And there is another side of the coin too. If we do this wrong, we will not be at the table but on the menu. The energy system could increasingly resemble a kind of Facebook, where our behaviour and our assets are used to enrich a big software company that managed to build a toll booth.

The wrong forecast

Here we can be brief because we've been over this. Economists ignore learning curves. The so called Integrated Assessment Models that the IPCC bolted onto the climate models are so woefully out of date that their predictions for 2050 are often the results achieved yesterday, for example with solar, batteries, electric vehicles and people's dispositions towards them. The International Energy Agency, whose annual outlook is the most-read energy document on earth, predicted in essentially every edition from 2002

onward that solar power was about to stop growing. Every year solar kept growing, roughly doubling every couple of years. I showed my graph of those forecasts in chapter 5.[56]

Somehow the experts making these models could not bring themselves to believe the data when it told them every doubling of solar production reduced the price by 20%. But in the last 50 years solar panels have become over 500 times cheaper. And now batteries are going even faster. To feel the size of that, picture a $50,000 luxury car from 1975 costing just $100 today.

When Rupert Way, Matthew Ives, Penny Mealy and Doyne Farmer decided to include the learning curves across over 50 technologies, they reached a conclusion that ought to have been front-page news. A fast transition to clean energy is not a cost we must heroically bear for the sake of our grandchildren. It is the cheap option, full stop, before you even count a single avoided climate disaster. Compared with carrying on as we are, decarbonising the energy system quickly saves something like $12 trillion.[57] What the hell are we waiting for?

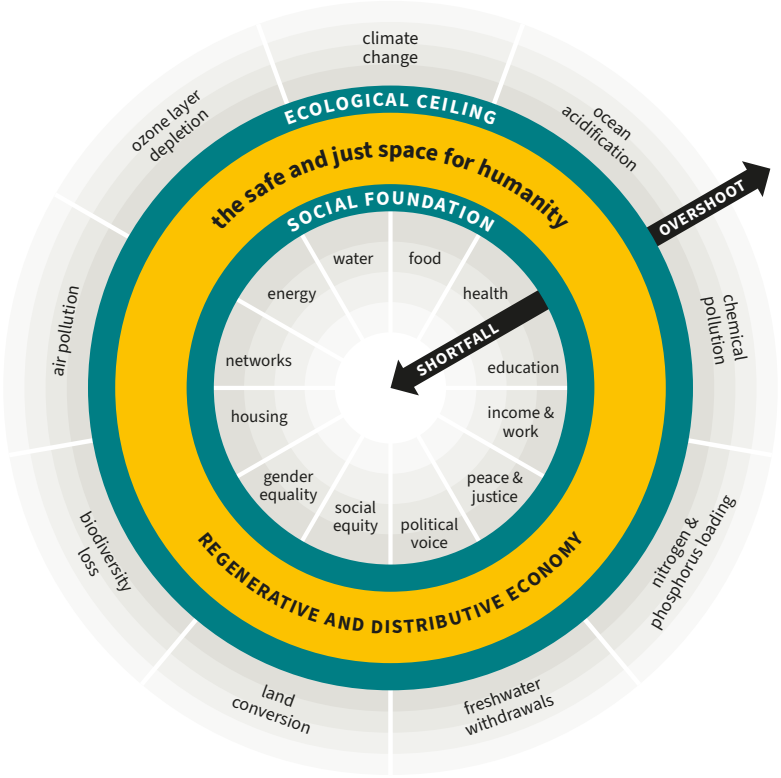
But I've seen the same thing unfold in my first telecom and Internet career. In 1980 AT&T asked the consultancy McKinsey how many mobile phones there would be by the year 2000. McKinsey studied the matter and said about 900,000. The real figure was around 109 million.[58] In 1998 the economist Paul Krugman predicted that "by 2005 or so, it will become clear that the Internet's impact on the economy has been no greater than the fax machine's."[59] The list of absurd underestimates of computers, mobile phones and the Internet can fill volumes. And the underlying reason is the same: status quo experts – like ordinary people – simply can't imagine exponential growth and learning curves. So they abuse their models until the trends in the data go away.

The intentions might not have been evil, but economics has done real harm. Many trillions in wealth were wasted and many millions of people died because of this unwillingness to do actual empirical science.

The good news is that a broken compass can be repaired. Economics can stop behaving like a belief system and grow up into an empirical science: one that measures how humans really work and points at human flourishing, our true north, instead of at more money. That is what the next chapter is about.

The doughnut

Kate Raworth's safe and just space for humanity



After Kate Raworth and Christian Guthier, *Doughnut Economics* (2017). CC BY-SA 4.0.

23

How to Bake a Doughnut

The most vivid image of where economics needs to go is the doughnut from Kate Raworth's book "Doughnut Economics".[1] Economists' first order of business should be to make sure that no human being is left in the hole of the Doughnut, because there they would live below a poverty floor that's unacceptable. Their second order of business is making sure the system does not stray outside the Doughnut, signifying that the system should perform inside planetary boundaries. Only after this floor and ceiling have been met – the space inside the Doughnut – is economics free to optimize. The optimization inside the Doughnut should aim for flourishing instead of money. That means not just focusing on material wellbeing but also on autonomy, competence and relatedness. And it means taking equality, future generations and rights into account. Previous chapters have outlined why all these things are important. This chapter will focus on actually baking the Doughnut with them.

And let me just add that creating an energy system that improves flourishing while staying above the floor and below the ceiling isn't actually that hard. The energy floor is exceedingly modest and energy abundance below the ceiling is rather trivial for a well designed energy system. My provisional theory is that economics has too many ideologues, philosophers and mathematicians and too few engineers and social scientists that take empirical science seriously.

Fortunately that is starting to change and the shift has a name: the credibility revolution. In the field's own words,

better research design is taking the con out of econometrics.[2] It means natural experiments, randomised trials and causal inference.

The Nobel prize in economics now rewards this. In 2019 it went to Banerjee, Duflo and Kremer "for their experimental approach to alleviating global poverty".[3] In 2021 it went to Card, Angrist and Imbens for natural experiments that overturned predictions of standard theory.[4]

In the energy system we no longer have to assume how households respond to electricity prices, because field experiments have measured it. The most useful finding is that information barely changes how households respond when the price jumps. Automation, a thermostat or a charger that answers the price signal by itself, delivers the response reliably.[5] Chapter 21 reached the same answer from psychology: make the new energy system mostly automatic. It is also how the holons of chapter 20 work.

Lift everyone above the floor

The floor is about material capability: energy, food, shelter, healthcare, mobility and a way to reach other people. Below a certain level, the lack of it wrecks everything else. It wrecks what Amartya Sen calls capabilities: what people are actually able to do and to be.[6] Martha Nussbaum turned that idea into a list of the basic ones: nourishment, health, education, a political voice, the ability to form relationships and to work.[7] Nothing gained elsewhere makes up for losing those, so below the floor no trade-off is allowed.

The floor is also very modest. The decent-living research worked out what a dignified material life requires: heating and cooling, clean cooking, washing, schooling, a clinic, a phone, transport.[8] Delivering that basket to every human on Earth with the best current technology takes roughly 15 gigajoules of final energy per person per year. That is the energy in about two and a half barrels of oil.[9]

Expressed as solar energy available to 80% of humanity, the need is tiny. One panel on your roof for your house,

and one for transportation. One for food production. One for clothing, education, and datacentres. One for everything else. Oh and a few beer crates' worth of batteries spread over the system.[10,11]

And most energy use is far above the floor. For comparison: the average American uses 300 GJ, or 50 barrels, about 20 times the floor. And billionaires with a private jet and superyacht routinely use 100 thousand GJ or 7000 times the floor.[12,13]

Get back below the ceiling

The ceiling is the outer edge of the doughnut. It is a wall rather than a price, because seven of the eight planetary boundaries are already breached at safe and just levels,[14] and walls, unlike prices, cannot be lobbied downward.

That sounds as if there is no room left. But we breach the boundaries mostly by what we burn and how we farm, not by how much energy we use. The sun alone delivers about ten thousand times the energy we use, as chapter 4 showed. And chapter 12 went through the planetary boundaries one by one. An energy system built on sun, wind and batteries, designed the way a proper engineer would, can give everyone abundant energy without burning anything, and better farming can take care of most of the rest.

As chapter 11 showed, every one of us could use as much energy as the average American, electrified and delivered by the sun, and the panels for that would cover about 0.4 per cent of the Earth's land. (And no, sorry, not everyone can have a private jet and superyacht yet, if we want to stay within planetary boundaries.)

Designing for flourishing

Between the floor and the ceiling is an enormous area. How do we design it? Chapter 21 wrote down what we actually run on: autonomy, competence and relatedness, fairness with a floor and earned room above it, care for people who are not born yet, and all of it in harmony with nature. To an engineer

that list is a specification. In this section I turn it into a target function: the one number a model tries to make as large as it can.

Let's start with the part that is plainly good to have more of: material capability. Above the floor, it is the only thing we maximise, so designing for flourishing is still about maximising wealth. Chapter 21 warned that one big optimization function would have to leave out almost everything that matters. This one does not: the rest of what matters enters as the floor, the ceiling, a constraint or a dial.

Autonomy, competence and relatedness, the three psychological needs that wellbeing depends on,[15] are constraints: they may not fall while material capability rises. A policy that makes us richer in kilowatt-hours and poorer in autonomy fails the test, however many kilowatt-hours it adds. Fortunately, as we saw in Part 2, autonomy organised in near-decomposable holons is ultimately more resilient and efficient, so this should not be a problem.

Then come three dials, for equality, future generations and rights. The floor, the ceiling and the constraints draw lines nobody may cross. The dials set how much the bottom of the distribution, the future and people's rights count in the space between, and on that people differ.

The first is the inequality dial. In the previous chapter we watched Lionel Robbins file the obvious, that a euro means more to the hungry than to the rich, in a drawer marked "not science". Once that comparison was banned, the test that remained was Pareto optimality: an economy counts as optimal when nobody can gain without someone else losing. A society in which some starve while others live in luxury can pass that test, as long as feeding the starving would cost the rich something. As Amartya Sen put it, a society can be Pareto optimal and still be "perfectly disgusting".[16] The repair is the inequality dial of our target function: restore the comparison, openly, and let a kilowatt-hour count for more where it lands lower. The forbidden becomes a parameter.

Setting that dial is not the job of economists. It is everyone's job. The way to set it is to ask people who do not yet know where they will land. The Vikings knew the trick. One man divides the loot, the other picks his half first, and the divider, who keeps whatever is left, suddenly divides very evenly. The fairness is forced by the geometry, not by the goodness of anyone's heart.

Rawls scaled the same geometry up to whole societies, in a move that is now called the Rawlsian veil.[17] Chapter 21 told how Frohlich and Oppenheimer then ran it with real people. Most groups chose neither an even split nor Rawls's rule of lifting the bottom as high as it can go. They chose to maximise the average, with a guaranteed floor.[18] Here it goes to work, as the calibration of the inequality dial.

That makes energy justice something you can calculate. With the inequality dial in the function, a tariff, a subsidy scheme or a grid-connection queue can be scored by what it does to the bottom of the distribution instead of to the average. The floor most people say they want becomes a design requirement you can check in a model run. Building that floor in the real world, universal, automatic and hard to stigmatise, is the job of chapter 28.

The second dial is a time dial: how much a future person counts. Ask the experts who publish on discounting, over two hundred of them, and the median pure impatience they allow is half a per cent. That is the dial itself. When they also count on future people being richer, their median discount rate comes to two per cent.[19] The US EPA adopted the same two per cent for climate damage in 2023,[20] nowhere near the five and a half per cent that shrank $100 of damage a century away to less than half a dollar in the previous chapter.

The third dial is for rights: a weight that is heavy, but not infinite. A right differs from the autonomy constraint, because it is one person's claim against what everybody else wants. Sen proved back in 1970, with nothing more than two readers and one copy of Lady Chatterley's Lover, that such claims, treated as absolute trumps, can clash with even the

mildest rule of collective choice: if everybody prefers one option to another, take it. Together they collapse the whole calculation into contradiction, leaving no best choice at all.[21] A heavy but finite weight always leaves a best choice.

The dials are value choices, and they are labelled that way. You may think a particular setting of the inequality dial too generous, or of the time dial too strict. Now we can argue about that in public, with the consequences of each setting laid out. The old economics made the same kind of choices but presented them as measurements: the time choice in a discount rate, the equality choice in Negishi weights, as chapter 22 showed.

For the energy system this means a new definition of success: energy that reaches everyone, raises flourishing and stays inside the walls of the planet. Cheap on average is no longer good enough.

Measure flourishing, even when we find it hard to look inside

It is not enough to declare flourishing the goal. We have to measure it, because the constraints of the previous section only work if we can tell when autonomy, competence or relatedness falls. Why not simply ask people what makes them flourish? Because of an awkward finding in psychology, which chapter 21 reported: we don't know. The conscious mind that answers questionnaires is a press secretary, composing plausible stories about decisions made elsewhere.[22] Mainstream economics dodged the problem by decree: whatever people buy reveals what they want, and getting it makes them better off. Both claims fail when tested, as chapter 21 showed. So if we want to aim at flourishing, we need workarounds.

Fortunately psychology has built at least six. First, speak about yourself in the third person, and you reason about your own life as wisely as you do about a friend's.[23] Second, trust what people do over what they say, because testimony about our own motives is confabulation depressingly often.[24]

Third, keep what I am separate from what I ought to want, the move clinical psychology has turned into effective therapy.[25] Fourth, switch sides until the other tribe's view fits from the inside.[26] Fifth, build scaffolding against your own confabulation: adversarial collaborations where opponents design the test together,[27] and pre-mortems where you declare the project dead in advance and explain why.[28] And sixth, when individual discipline fails, as it reliably does, build the corrective into institutions so it runs without anyone's willpower.

Anticipate learning curves and other foreseeable change

When I started modelling the energy transition I assumed economics would have the tools and I would merely borrow them. I was writing a paper about what I found, together with my friend Maarten Steinbuch, a distinguished professor in control systems and usually the smartest person in the room. I can still see him looking at me reproachfully: "So you mean to tell me that economists are using equilibrium models for something that is clearly a complex adaptive system?" The look made clear that declaring a whole discipline of scientists incompetent was not a joke he found funny. That is why the paper we wrote with Geert Verbong carries 343 references: I had to prove to him I was not making it up.[29]

In that paper we listed what the standard models must pretend the world does not contain. Humans in the models are, we wrote, "impervious to status, strategizing, populism, idealism, tribalism, hearsay, or marketing. They do not empathize with future generations or people in other countries. Furthermore, the actors function in 'ideal' markets. This means, among other things, no bankers with perverse incentives, no lobbyists, no political games, no idealists, no monopolistic tendencies, no network effects, no incumbent resistance to change, and so on." Every item on that list shapes the real energy transition.

The repair is called complexity economics. Its founding move is to stop treating the economy as a machine that settles and to start treating it as an ecosystem that evolves.[30] Brian Arthur supplied the formal heart: with increasing returns, early choices lock in, and history decides which of several possible futures you reach.[31] For energy this means that the same cheap solar can end up owned by the people who use it, or by whoever first took control of the points that everyone has to pass through. Only a model in which order matters can even show you that fork.

Increasing returns have a famous and measurable form in energy: the learning curve. Costs are not numbers you type in. They fall by a roughly constant percentage with every doubling of cumulative production. That regularity was first measured on aircraft in the 1930s, as chapter 6 told, and solar panels have obeyed it decade after decade.[32] Battery packs became cheaper than energy and transport models were still assuming.[33] The previous chapter told how Doyne Farmer's group put these learning curves into the forecast and found that a fast transition is roughly twelve trillion dollars cheaper than carrying on with fossil fuels, before counting a single avoided flood.[34] It also told how the International Energy Agency predicted the imminent end of solar growth, edition after edition. The agency has since been raising its lines toward what the learning-curve forecasters had said all along.[35] My own group now uses the same machinery on electric trucks, locating the tipping points so policy can push where pushing works.[36]

Apply agent-based modelling: model the world as it really is

An agent-based model does not squeeze a whole population into one average person. It simulates many different agents, each following its own rules, and lets you watch what happens when they meet.

Now go back to the six workarounds. An agent-based model can weld two of them, the second and the fifth,

into one instrument. It can be behaviour-watching at scale: agents calibrated on what millions of people measurably did, not on what anyone reported at the coffee machine. And it can be the pre-mortem made permanent: a place where a rule can fail in silicon, cheaply and instructively, before it fails in a country. We cannot look inside ourselves reliably, but we can watch a simulation of ourselves, and we can rehearse.

I did not expect it when I started, but an agent-based model also suits moral philosophy. Brad Hooker's rule-consequentialism, a framework from applied ethics, judges rules rather than acts. The right rule-code, the whole set of rules, is the one that produces the highest expected wellbeing once the overwhelming majority of people have absorbed it, with the cost of teaching complicated rules charged against their score.[37] Hooker works with ninety per cent internalisation[38] and ten per cent defectors, a stipulation he names as openly as we name our inequality and time dials. The measure of wellbeing is the one we met at the floor: Sen's capabilities.[39]

Now look at what Hooker's test asks for. Install a candidate rule in most of a population, keep some defectors, run the world forward, and read off the wellbeing. For decades that was a thought experiment. An agent-based model can literally run it. I haven't done it yet – I haven't built most of the models I've envisioned – but I'm sure it could be done. Take a few levers that research has measured: making luck visible, publishing who pays and who gets, dividends per head. In a model they become candidate rules you can trial against the ten steps of the slide into extraction that the next chapter describes, before anyone deploys them on actual citizens. That is what testing a vaccine against extraction means. Testing this in a standard equilibrium model is simply impossible, but in an agent-based model it's at most time consuming, although with the help of AI less and less so.

Agent-based modelling is older than you might think. In 1969 Thomas Schelling lined up tokens of two colours and gave each one a mild preference: stay unless fewer than half

of your neighbours share your colour. Then he ran the rule by hand. The line segregated. No token wanted that.[40] That is the problem with the representative agent, the single average person of the standard models: average the tokens into one representative token and the phenomenon you needed to see disappears. Energy poverty, adoption waves, lock-in, bubbles. They all live in the differences.

Agent-based models then spent decades at the margins for a dull reason: simulating millions of distinct agents was expensive. By 2009, after the equilibrium models had missed the financial crisis, Doyne Farmer and Duncan Foley could argue in Nature that the economy needs agent-based modelling.[41] Leigh Tesfatsion had already given the field its motto: growing economies from the bottom up.[42] Later Doyne Farmer literally "wrote the book" about the topic of this chapter.[43] A laptop now does what required a national laboratory in 1995. The constraint that once forced the representative agent on us is gone. What remains is mostly habit. And beautiful mathematics that some people just can't give up.

Agent-based models are also getting a tremendous boost from AI, since they are best used by people who understand the system but don't necessarily know how to code. The coding can increasingly be taken care of by AI, and this makes it possible to create far more realistic systems in far less time, made by people who actually understand what they are modelling.

And the new tools can forecast. In May 2020, with the United Kingdom newly locked down, Farmer's group simulated the British economy industry by industry, without assuming equilibrium. The model forecast that output in the second quarter would be 21.5 per cent below its level before the pandemic. The statistics office later reported 22.1 per cent.[44,45]

A trivially simple model of Dutch EV adoption I imagined and Peter Hogeveen wrote in 2017 predicted 1.1 million EVs in 2025, which turned out to be 1.05 million.[46] Full agent-

based integrated assessment models now exist,[47] and the climate scenarios used by the network of 141 central banks are built on non-equilibrium frameworks.[48] For energy the payoff can be forecasts that finally track the adoption of solar, batteries and EVs, with learning curves for their costs: the curves the old models undershot for twenty years.

Bake vaccines against extraction into the models

One more thing you should be able to do with agent-based models is watch the chokepoints and extraction develop in real time. That is the first vaccine. Give every agent in such a model its own wealth, capability and exit options, and concentration shows up as a signature in the run: a few agents' share climbing while the rest stall. Trace which transactions moved the money and which feedback loops protected it, and you are watching a chokepoint form, the third of the ten steps in chapter 24, years before the lawyers arrive.

The second vaccine is a lobbying detector. In 2017 we proposed letting different actors in the model face different effective carbon prices: high for those who follow the science, lower for policy-makers weighing what is politically survivable, negligible for companies strong enough to lobby exemptions. That is simply what the world looks like.[49] Calibrate those prices on what each actor actually does, and the gap between the price an actor truly faces and the price the science would assign becomes a map of where the lobbying is working. You can see injustice in action, and that is where fixing it starts, because you cannot fix what you cannot see.

The third vaccine is that agent-based models are easy to understand for domain experts and the people that stand to lose from extraction. An equilibrium model can only be audited by the small profession trained in its mathematics. That is how ministries end up steering by models that, in Robert Pindyck's verdict on the climate versions, "create a perception of knowledge and precision that is illusory".[50] An agent-based model is built from rules about the world, and rules can be read by whoever knows that piece of world: a

psychologist checks the belief rule, a political scientist the lobbying rule, a grid engineer whether the electrons add up. Publish the code and anyone who disagrees can fork the model and run their objection. As we put it in 2017: downloadable models are peer review for the twenty-first century.[51]

None of this makes the new tools perfect. A flexible model like this has many many knobs, and a modeller who has already chosen the answer has many many ways to reach it. Chapter 22 showed how far the discount rate moves the social cost of carbon: from $60 a tonne to $190. The DICE climate model shows how much rides on such settings. In 2020 Martin Hänsel and colleagues updated it with current climate science, with damage estimates about three times higher, and with the discounting views of the experts surveyed for the time dial. Keeping warming below 2°C then became the economically optimal path for about three quarters of those expert views. That is in direct contrast to what Nordhaus, the Nobel prize winning maker of the model, took as its outcome.[52] His optimal path led to about 3.5°C of warming by 2100. The discounting alone took between half a degree and just over a degree off the optimal warming. Agent-based models have many more dials. So the defence is not the tool but the workflow around it: open code, named dials, and enough outside readers that a thumb on the scale gets caught.

Build these models with us

The field that builds these models is far smaller than the problem it has to carry. You do not need a doctorate in economics to join it. An equilibrium model demands years inside its apparatus before you may speak. An agent-based model demands that you know how the real thing behaves, because its rules are claims about the real thing. A power-systems engineer who has stood in a substation will write a better grid agent than an economist who has only met one in an equation.

The system I would most like to see modelled like this is the energy transition: millions of different people deciding differently. A woman in rural Tanzania choosing between a kerosene lamp and a solar home system. A Rotterdam household weighing a heat pump against the boiler it already owns. A pension fund moving billions, a regulator writing connection rules, a cooperative wondering whether the neighbourhood battery pays. Rooftop solar has already been modelled at this resolution, with adoption running through real social networks that a market-share equation cannot reproduce.[53] Many of the tools are open source. The data, increasingly, are open. What is scarce is people who can use them and still remember what the target function is for. So come and join us.

An economics that computes its way toward flourishing is not a modest ambition. Maybe it will be hard. But with new modelling methods and increasing computing power and AI, far more is possible than most people realize.

Such an economics also gives us a precise test for whether a whole system is extractive, because it counts where the gains land. A system is extractive when it lowers flourishing while concentrating the gains, and generative when it raises it. That is what the next chapter is about.

24

Preventing extraction

Do you want to know the biggest disappointment of my life?

The Internet.

When I started with what I now call my first career, I was so full of hope. Everybody around me was. We really wanted to create a global village. We wanted to democratise knowledge and foster understanding between cultures. We wanted to allow a schoolchild in rural Peru to discuss agriculture with a professor in Wageningen. Instead I find myself on Twitter arguing with someone called "PatriotDad1488" who wants to convince me climate change is a hoax perpetrated by satanic baby eating elites gathering in Uncle Joe's pizzeria in New York every Tuesday evening at 7 PM.

Don't get me wrong: I still consider the Internet far superior to the old telecom system and it has given me a lot of meaningful connections. But as I'm navigating past clickbait in Microsoft Office, Amazon, Google, and Twitter I'm acutely aware large parts of the Internet have gone from a system I dreamed of, a system focussed on generating value *for* us, to a system focussed on keeping us locked in while extracting value *from* us.

Cory Doctorow aptly calls it "enshittification". He observes the same pattern again and again on digital platforms: it becomes successful by generating value for users, then starts to generate value for its business customers, finally it focusses on extracting value from all participants to maximize profits and perpetuate itself.

Centralization and institutional capture aligning to create extractive systems is of course much older than digital platforms. We are increasingly realizing that now. There is a long history of systems initially growing by generating value, then mainly providing that value to a subgroup while becoming extractive to most, and finally mainly serving themselves by oppressing and extracting value from everybody they have captured, with self-preservation becoming their highest goal. The history runs from the first agricultural states to feudal systems, priesthoods, colonial empires, utilities, fossil fuel companies, "too big to fail" finance, state bureaucracies, and academic publishers.

Getting energy right is arguably even more important than repairing Amazon, Facebook and Twitter. Bad Internet platforms extract value from creatives and give you bad habits. Lack of energy gets you dead. There's a difference.

The current energy system also funds wars and strife. Like most Europeans I'm aware of our historic role in destabilizing the Middle East and overturning Iran's democracy for wanting to nationalize the Anglo-Iranian Oil Company, now BP. We know our oil and gas purchases from Putin fund the war in Ukraine. Our oil and gas purchases from Mohammad Bin Salman in Saudi Arabia fund the least tolerant strain of Islam – Wahhabism – all over the world. Part 1 told these stories in chapters 2 and 9. And since the US under Trump is no longer considered an ally, we would like to stop buying fracked LNG from the US and instead spend the money on clean alternatives in the EU. When you have to pay someone you don't like to empower them to do things you don't like, you know you're the captive of an extractive system.

Chapter 21 showed that we register extraction once we see it: toddlers protest it, strangers pay out of their own pocket to punish it.

But one thing the rest of this chapter will not offer is villains. The people who build and defend toll booths are not evil, just your average greedy ones, and most of them believe they are providing a service. Many of them are. The test is in

the outcomes, not the intent. Decent people inside an extractive architecture produce extractive outcomes, because the rules do the sorting, not the character of the staff. I find this more hopeful than the alternative, since character is harder to redesign than rules.

Time and time again, technological progress leads to extraction, following a predictable pattern. Doctorow's three stages are the short version. First, a technology spreads because it is useful. Then people build chokepoints: places where defensible power gathers. From the chokepoints they collect rent. Finally the system hardens around the rent until even the rent-collectors are trapped inside it. I have stretched that arc into eight steps. By step six the lawyers have arrived and prevention has become surgery or war. The cheap moment to act is steps two to four, and you can only act then if you recognise them.

1. It starts with something useful

Samuel Insull, once Thomas Edison's private secretary, did more than almost anyone to electrify America. He chased economies of scale most people thought impossible, drove the price of electricity relentlessly down, and by 1929 served over four million customers across thirty-two states. He also stacked his empire into a pyramid of holding companies so baroque that when it collapsed in 1932 it wiped out the savings of some 600,000 shareholders.[1] Congress spent part of 1935 writing the Public Utility Holding Company Act as its tombstone.[2]

The useful man and the extractive man were the same man, with the same engineers and the same accountants. What changed was the architecture around them.

The East India Company ran the same arc with even worse manners. It began in 1600 as a spice-trading venture. It ended up running a private army of 200,000 men, twice the size of the British Army, and collecting the taxes of Bengal. Each step looked reasonable up close: a warehouse, then a fort to protect the warehouse, then soldiers to protect the fort, then

tax rights to pay the soldiers. When famine struck Bengal in 1770 and killed millions, the Company kept collecting and sent over a million pounds to London in the famine years.[3,4] Nobody planned this in 1600. There was never a moment when a reasonable person on the inside would have said: stop here.

Now look at our own field with that arc in mind. The electricity grid is beyond useful. It's the precondition for nearly everything we call modern. Smart meters let households see what they use and let a renewable system balance itself. These are good things and we should be glad to have them. But a grid is also monopolistic, technically obscure and wrapped in a century of rules. Essential, monopolistic, opaque. I know the people at the grid operator mean well. I've worked at one and count the former CEO as a friend. But that combination is the ideal substrate for extraction.

2. Useful things make us dependent

Once something useful works, we sensibly build our lives around it, and that transfers power. My grandparents could run a household without the grid. I could not. An EV driver depends on charging networks, authentication, roaming and payment systems. A cooperative depends on connection rules it did not write. A small business depends on tariffs it cannot influence.

Thomas Hughes showed that electricity systems are never just wires. They are machines, firms, regulators, financiers, habits and experts growing around each other for decades, until you cannot remove one part without unravelling the rest.[5] Once such a system stands, increasing returns make every extra user cheaper to serve and every alternative harder to start, which is why early choices outlive their justification.[6,7] Gregory Unruh called the energy version carbon lock-in: not an affection for coal, but a co-evolved fortress of technology, institutions, markets and training.[8]

Network science adds an uncomfortable footnote. New connections attach preferentially to the nodes that are

already best connected, so the big get bigger by simple arithmetic. The rich getting richer is not a moral failure of networks. It is their default geometry.[9] Facebook is the textbook case in living memory. It was a free place to find your friends, and every friend who joined made leaving costlier, until the company could earn $164.5 billion in one year. Roughly 99% of it came from advertising, which is to say from selling access to you.[10] Albert Hirschman taught that deteriorating systems are disciplined by two forces: customers leaving, or customers organising.[11] Dependence quietly kills the first force. You can still leave, in the sense that you can still emigrate. Then it starves the second, because isolated households negotiate one by one against institutions that negotiate for a living.

3. Dependence creates chokepoints

Timothy Mitchell observed that coal, for all its filth, gave ordinary people leverage. A strike at the pit or the railhead could stop a nation, and the eight-hour working day and the vote travelled in coal's wake. Oil moved the flow to tankers and pipelines run by far fewer hands, and the leverage moved with it, away from citizens.[12]

Solar and wind promise to reverse that long dispossession, because the fuel falls on every roof in the world for free. But when the physical chokepoints evaporate, the extractors move on to non-physical tollbooths, like the monopoly on grid connections, the monopoly on grid data, the cloud platform that manages your inverter, the dispatch algorithm, the tariff category that forbids selling your flexibility, the standard that keeps the new entrant out. Sunshine cannot be made scarce, but metering and settlement rules can be made to act as if it were.

If that sounds paranoid, remember that the chokepoint has never been the resource. Standard Oil did not own the oil. It owned the refining, roughly 90% of US capacity at its peak, and the railway rebates.[13] John Deere does not own your tractor either. It owns the software authorisation that

decides whether the tractor runs. That is how tractors looted from Ukrainian dealers in 2022 could be bricked from the other side of the world.[14,15] And Apple, as chapter 22 showed, does not only charge you for the phone in your hand but also for the door you cannot walk around. The gate is often worth more than the goods.

4. Chokepoints become property

The next step is to make the gate legal: sold, licensed, certified or regulated into an asset with owners, a valuation and a defence budget. The English gave us the template. Take the commons: the shared rights of grazing, gathering and gleaning that fed ordinary families for centuries. They were converted into private property by Acts of a Parliament composed substantially of the people doing the converting.[16] The Black Act of 1723 went as far as making some customary uses of formerly common land a hanging offence.[17] The winners did not say "we are taking this." They simply claimed history had moved on, and they had the deeds to prove it.

Modern extraction prefers subtler instruments: proprietary code, exclusive data agreements, certification bottlenecks, cloud dependencies, patent thickets. The arthritis drug Humira accumulated 311 US patent applications, 89% of them filed after the medicine was already approved. Those are patents protecting revenue, not invention.[18] Shoshana Zuboff documents the data version: the behavioural exhaust of our lives, harvested into proprietary feedstock for prediction and influence.[19] And Sheilagh Ogilvie's autopsy of the European guilds shows how long such arrangements can last: centuries, provided the rent is shared with the authority that could otherwise abolish them. Quality control was the cover story. The entry barrier was the product.[20]

In energy, note carefully what enclosure does not require: private ownership. A state-owned chokepoint can be just as opaque and just as biased toward incumbents as a corporate one. And a private asset disciplined by open standards and real exit can behave perfectly well. The type of ownership

matters far less than the architecture: who controls the dispatch logic of your battery, who holds your data, what the tariff formula rewards, who can provide or withhold certification.

5. Finance accelerates the drift

A gate that has become property pays its owner, whether or not the owner improves anything. Where customers cannot go elsewhere, part of that income can drift above what the service actually costs, and economists call that part rent. Property invites rent. It takes no plan, only an owner who knows the costs better than the customers and the regulator do.

The clearest measurement of this I know comes from the British National Audit Office. Each regional electricity network in Britain is a monopoly owned by shareholders, and the regulator Ofgem sets the return they may earn on it. Over an eight-year price control, the network companies expected an average real return on their equity of 9.2%. Ofgem's own estimate for ordinary listed companies was 5.25 to 5.75%, and a regulated network carries less risk than an ordinary company. Ofgem had set the starting return on outdated evidence about that risk, and 2.7 of the 9.2 percentage points came from spending less than the allowances and beating almost all of Ofgem's performance targets. The auditor estimated that consumers could have paid at least £800 million less.[21] The service itself was good, with fewer power cuts than in most other EU countries. Ofgem left the returns in place, because it changes a running price control only with clear evidence that consumers would gain.

From a portfolio manager's point of view, dependable revenue attached to people who cannot leave is a wonderful thing. So once chokepoints are property, finance arrives with capital and impatience, prices the expected income and buys it. From then on a lower toll means a loss for an investor who paid a fair price for it, and the regulator will hear about that loss. Bit by bit, the system gets run for the yield. Mariana

Mazzucato points at a second asymmetry. The public bore the early risk of solar, wind and batteries and has no mechanism to share the upside, so risk socialises while reward privatises.[22]

Carlota Perez would tell us to expect exactly this phase. Every technological revolution, she argues, has an installation period dominated by financial capital, speculation and concentrated gains, and a deployment period in which the gains spread through society. The second half has never arrived by itself. It has always required deliberate institutional redesign.[23] We are in the installation period of renewables right now. This book is, among other things, an argument about what the deliberate part should look like.

The Dutch grid shows how financial logic wears regulatory clothing. Grid operators earn an allowed return on their regulated asset base, the capital in the ground. Operational fixes such as flexibility contracts, smarter congestion management and price signals earn no comparable return. Annual grid investment has reached roughly €8.5 billion and is projected to double again by 2040.[24] No one is pocketing the difference: the shareholders are our own municipalities. But every year of copper-first investment locks a higher asset base into future bills. Nobody decreed that copper beats cleverness. The formula just pays better for copper.

For over ten years now I've tried to get Dutch grid operators to give me data on their cables and transformers. These are bought by a monopoly with public money. I think we have a right to know. Without that information, I can't do my research and no storage provider or aggregator can prove its alternative would be cheaper, because the counterfactual is a secret. But there's always another excuse. Even the investment plans are secret and now even the regulator is complaining about this.[25] So the choice between copper and cleverness is made by the one party that has the data, and that party is paid for copper. Frank Pasquale calls this the black box society: power hiding inside systems that the people affected cannot inspect.[26]

6. The rules get rewritten around it

George Stigler earned a Nobel prize partly for saying the quiet part in print. In 1971 he wrote: "as a rule, regulation is acquired by the industry and is designed and operated primarily for its benefit."[27] Daniel Carpenter and David Moss add the modern refinement: capture rarely involves brown envelopes. It is cognitive. The regulator spends years across the table from the regulated, learns their language, absorbs their sense of what is realistic, and eventually finds it hard to imagine the game any other way.[28] This is an almost too perfect description of how I experience the grid regulator ACM in the Netherlands.

Occasionally someone is crude enough to commit an actual crime, which is useful for calibration. FirstEnergy paid $61 million through a dark-money vehicle to pass a one-billion-dollar bailout in Ohio. The Speaker of the Ohio House got twenty years and the company paid a $230 million penalty.[29] Such cases are rare. Nearly everything else in this chapter was legal: the money is made in writing the rules, not in breaking them.

Once the rules have been rewritten around extraction a few times, citizens learn the lesson and apply it to everything, including the policies that would help them. Thomas Douenne and Adrien Fabre ran the natural experiment in France. A revenue-neutral carbon tax returning equal dividends to every household would have left most respondents better off in plain money. Seventy percent rejected it. They overestimated their losses, assumed the scheme was regressive, and discarded information showing otherwise.[30] Given what the system had already taught them about who wins, that distrust was a reasonable inference.

The same literature shows what earns acceptance: equal per-capita dividends, visible earmarking, transparent who-pays-who-gets arithmetic, and deliberative procedure.[31] It's not the tax itself but the recycling rule, what the government does with the revenue, that decides whether a carbon price redistributes downward or upward.[32]

Hold that list against the Dutch decision to end the "salderingsregeling", our net-metering scheme, from 2027. It is understandable that you want to end a situation where the grid is treated as a free battery, and you can deliver back at maximum payback, even when the grid is congested and energy prices are negative. But why no dividend mechanism? No published arithmetic of who pays whom? No deliberative procedure? No using that money to e.g. help the owners of solar panels buy batteries? Now it just looks like a money grab instead of a system optimization.[33,34] Net metering did what a subsidy for early adopters should do: it made solar panels pay for themselves while they still cost more than the alternative. Full disclosure: with eighty panels on my roof I actually received money back for a few years. So I have no quarrel with ending it now that panels are cheap. But the citizen-side scheme was unwound the moment it scaled, the incumbent-side schemes were not, and the way it was done taught Dutch citizens the French lesson one more time.

7. Counterpower weakens

Why does the diffuse majority keep losing to the concentrated few? Mancur Olson supplied the arithmetic two generations ago. A small group with millions at stake per member will organise, fund lawyers and attend every consultation, while a large group with twenty euros at stake per member stays home.[35] The toll-booth builders are organised and capitalised. The opposition is distracted, often unaware it is the opposition, frequently confused by ideology, and easy to manipulate with a well-funded story. That follows from the incentive gradient and says nothing about the intelligence of the public.

Martin Gilens and Benjamin Page tested who actually moves American policy, across 1,779 issues. Economic elites and organised business interests had substantial independent influence. Average citizens had little or none.[36] John Kenneth Galbraith argued long ago that concentrated economic power is only ever disciplined by organised power

on the other side: unions, cooperatives, watchdogs, courts.[37] Where that countervailing power thins, the gradient runs free.

In energy the asymmetry is almost comic. Incumbents sit on every standards committee and answer every consultation with institutional memory and a legal department. Households bargain alone, and without the data. And the gentle Dutch irony: our grid operators are owned by municipalities, the same municipalities that are choking on the congestion, but they are too scattered and too unorganised to do anything. The counterpower against grid operators exists on paper. Paper is where it stays.

8. The system hardens, and traps even its keepers

Give the arrangement a few decades and reversal stops being a decision and becomes an excavation. The fossil system reached this stage long ago. Pipelines, refineries, engine factories, suburban planning, training curricula and monetary flows interlocked so thoroughly that no superior alternative could compete on merit alone.[38] Inside a hardened system, people stop seeing architecture and start seeing nature. Anomalies get patched rather than heard: "intermittency is fatal" and "storage will stay expensive" survived as professional consensus years after the data had falsified both. Upton Sinclair's line is overquoted because it keeps being needed: it is difficult to get a man to understand something when his salary depends upon his not understanding it.[39]

The final twist is that the keepers get locked in with everyone else. France obliged EDF to sell nuclear power to competitors at €42 per MWh. When markets spiked past €200 in 2022, the arbitrage helped push the utility toward more than €53 billion of net debt and full renationalisation. The extractor got extracted.[40] In Britain, the retail market built to discipline incumbents shed 29 suppliers in a single year of price spikes, with £2.7 billion of failure costs socialised onto everyone's bills.[41] Even Phoebus ended as a prisoner of its own design: having organised the whole industry around the

1,000-hour bulb, no member could profitably build a better one.

That is the full slide: usefulness, dependence, chokepoint, property, rent that finance buys, rewritten rules, weakened counterpower, hardening. No villain required at any step, and at every step a hundred respectable professionals doing their jobs. Which leaves the question this chapter actually exists to answer. Chapter 21 showed that humans detest unfair extraction with rare unanimity. So why do we keep tolerating it for decades at a stretch?



The Phoebus Lightbulb Conspiracy

In December 1924 the world's leading lamp makers met in Geneva and founded a company called Phoebus. Osram was there, and Compagnie des Lampes, and the overseas arm of General Electric, and our own Philips from Eindhoven. On paper, Phoebus existed to standardise the light bulb. In practice it standardised one number: 1,000 hours. Member factories sent sample bulbs to a testing station in Switzerland, and any member whose bulbs lasted too long was fined. Average bulb life duly fell from 1,800 hours to 1,205 in under a decade.[42]

For four decades engineers had worked to make bulbs live longer. Now they were paid to make bulbs die on schedule, and their employers kept tidy minutes of the achievement. The technology had not failed. It had succeeded so completely that the only way left to grow the profits was to quietly break it, for everyone, indefinitely. It took a world war to dissolve the cartel.[43]

Why extraction defends itself

The cognitive machinery that makes us hate extraction starts defending it the moment it exists. Daniel Kahneman, Jack Knetsch and Richard Thaler showed that we value what we hold roughly twice as much as what we could gain. Hand a student a coffee mug and her selling price doubles her neighbour's buying price within minutes.[44,45] Then add status-quo bias: whatever is labelled "current arrangement" wins extra votes just for being incumbent.[46] Together they produce the political asymmetry that Alberto Alesina and Francesco Passarelli formalised: a strictly larger majority opposes reversing a policy than ever supported enacting it.[47] Fossil subsidies are not defended because anyone loves them. They are defended because removal reads as loss, and losses count double.

The defence is fiercest exactly where you would hope for solidarity. Ilyana Kuziemko and colleagues found "last-place aversion": people one rung from the bottom are the least willing to support transfers that might lift the bottom rung level with them.[48] In energy terms, that is the renter just above energy poverty watching her surcharge rise to help fund the solar credits of homeowners like me. And in that situation her resistance to the energy transition is not ignorance. It is an accurate reading of who was sent the bill.

On top of the cognitive layer sits a motivated one. John Jost and Mahzarin Banaji documented system justification: a tendency to perceive whatever arrangement exists as fair and legitimate. Paradoxically, it is found strongest in some of the groups the arrangement treats worst.[49,50] The just-world literature shows we would rather conclude that victims deserved it than conclude that the system is rigged.[51] And Jonathan Mijs found the bleak punchline: in countries where inequality rose most, the belief that success reflects merit rose with it.[52] Exactly where the distribution most needs questioning, it gets questioned least.

The lever that flips us between outrage and acceptance is the story about where the gains came from. Chapter 21's

Bergen experiments showed we accept inequality traced to effort and reject inequality traced to luck.[53] Extraction survives by running that switch in reverse: "The extractor actually did *something* for his money so it's not pure luck!"

Beneath the psychology sits the political reality that makes the cynicism rational: the rules really are tilted, as Gilens and Page measured. So citizens correctly sense rigging, cope by re-narrating outcomes as deserved, and thereby withdraw the very pressure that would force repair. The cognitive defence and the captured rules feed each other. The system does not need to buy our consent. Our own minds provide it free of charge.

This is why "build first, fix the fairness later" is the expensive option every time. The cognitive defence grows with every year a distribution stands. So the window in which an energy system can be designed cleanly is the window before millions of people hold positions they will defend as earned. Later is not cheaper. Later is when the endowment effect has been armed.

Extraction is bad engineering

On a good day, a combustion car converts about a quarter of the energy in its fuel into motion.[54] The rest leaves as heat, and the fuel leaks and sometimes burns the machine down. We do not call that immoral. We call it wasteful and flammable, and we replace it with something better. Extractive systems deserve the same verdict. They waste flourishing as friction: gatekeeping, compliance, lobbying, monitoring, lawyers. That overhead produces no light and no warmth and gets billed to the users as a cost of doing business. And they leak value upward instead of converting it into the thing on the brochure.

They also catch fire. 2008 was a fire. Enron was a fire. Winter Storm Uri was a fire: ERCOT's energy-only market design and unenforced winterisation turned a cold week in Texas into 246 deaths and an estimated $80 to 130 billion in damage.[55] Eskom is a slow fire. The Zondo Commission doc-

umented R14.7 billion looted from the South African utility, and in the worst years load-shedding has shaved around 3% off the GDP of the continent's most industrialised economy.[56,57]

The grid congestion in the Netherlands, driving businesses to bankruptcy, locking down municipalities and costing a whopping 300 billion in the coming 25 years, is an increasingly hard to control firestorm. None of these were lightning strikes. Each was the predictable output of a design whose internal incentives pointed away from its stated purpose. The question for the renewable build-out is simply whether we engineer those losses out, or shrug and leave them in the new design.

We have a moral obligation to design a good system

This is not just engineering. It's ethics. When scarcity seemed unavoidable, energy injustice could be presented as tragedy. There was not enough energy. There was not enough grid. There was not enough money. There was not enough technical capability. We had to stay within planetary boundaries. So some people had to wait. Some regions had to remain dependent. Some households could not afford electricity. Some communities had to live next to pollution. Some countries had to keep exporting raw materials while importing expensive technology. Sad, but inevitable.

Now that we know abundance is possible, it becomes obvious that scarcity was the excuse, not the underlying problem.

As chapter 21 showed, most people want a floor that ends extreme energy poverty, and yet it endures. That makes it a symptom of the problem that the current energy system is too extractive instead of generative. Designing a generative instead of an extractive new energy system is not just a better engineering job, it's a moral imperative. And even if you have access to and can afford energy: there's more to energy wellbeing than cost per kWh.

This is where we technical people become uncomfortable. We like to finish the calculation and then hand over the result. Here is the cost curve. Here is the grid model. Here is the control strategy. Here is the optimal dispatch.

But design and implementation are not value neutral. Every energy system is also a social system. It decides who may connect. Who must wait. Who gets paid for flexibility. Who carries risk. Who can see the data. Who may override an algorithm. Who owns the assets. Who writes the standards. Who is told to trust a black box. Who profits from that. These are not afterthoughts. They are design choices. And design choices harden once they are made.

Fairness cannot be bolted on later, like an optional accessory. In a greenfield situation making good design choices is relatively easy. Once ownership structures are established, they defend themselves. Once source code and protocols are proprietary, companies hire armies of lawyers and lobbyists to make sure they stay that way. Once grid rules favour large incumbents, small actors spend years begging for exceptions. Once households become dependent on opaque platforms, their bargaining power disappears. Once the financial flows are arranged upward, they do not politely rearrange themselves downward because a policy document mentions justice.

Right now, we've got a real shot at getting this right.

Let's take the shot.

No oil baron with a cigar

You may have noticed I keep returning to my own country, and since I am a typical Dutchman I can assure you it is not patriotism. The Netherlands is just a perfect control experiment I know well: a rich, competent, low-corruption state full of public-spirited engineers and civil servants who cycle to work. If extraction needed villains, we would be safe. We are not safe, which proves the point: the extraction is in the design.

Thirty regional energy strategies give siting decisions a democratic appearance while holding no enforcement power. The national evaluator found that citizens consider wind and solar parks far more legitimate when a government or a cooperative they can join owns them. Yet ownership keeps landing with national and foreign capital.[58]

The main subsidy auction allocates by euros per tonne, which structurally favours industrial scale; cooperatives were handed a side door instead, and the existence of that side door is the confession about the main door.[59] The side door is a separate, smaller, more bureaucratic scheme.[60]

When citizens do organise, it shows, which is rather the theme of the chapters ahead. The new Energiewet recognises energy communities for the first time, requires one-member-one-vote governance, and creates a legal basis for energy sharing. Those provisions exist because organised cooperatives lobbied them into existence, amendment by amendment.[61] The implementing regulations, where the geometry is actually set, are being negotiated as I write, with the usual parties at the usual table. The Dutch scholars who invented transition management concluded that Dutch practice gave incumbents too central a role in designing their own alternative.[62]

Or take that data from the grid operator I keep going on about. It *seems* it is now – finally – in the new law that grid operators should share. But the regulator is still shielding them from complying and the whole thing will probably be dragged out for years.

And the most effective instrument in the EU toolbox was left untouched. Article 16(4) of the Electricity Directive lets a member state grant citizen energy communities the right to manage their own distribution network.[63] One article in the Energiewet would have done it. The Netherlands has not even discussed it.[64] Without it I consider energy communities little more than status-quo-enhancing window dressing.

Nothing in this list is broken. Every instrument is doing what its design makes it do. That is the chapter in one sen-

tence: extraction is not a malfunction of the machine. It is a function the machine was, however absent-mindedly, built to perform.

De-enshittification is possible

But it doesn't have to be this way! The commons that chapter 21 credited with building the Internet is still standing. The Internet Protocol itself is still open and free. Wikipedia is still an encyclopaedia rather than an extraction platform. Email is still federated, even after Microsoft and Google. Linux is still the open source operating system the enshittified companies depend on.

Currently my favourite example of de-enshittification is USB-C. The European Union made one charging port the rule for the phones and small electronics sold on its market, and eventually even Apple had to cave.[65] Chapter 26 tells that story in full.

The US political system seems captured by extractive corporations.[66,67,68,69,70,71,72,73] In China the state is more able to stop private extraction[74,75,76] but worse in terms of state extraction.[77,78,79,80]

The EU's rights driven model[81] is still somewhat free to act on behalf of its citizens[82,83] and large enough[84] to put up a meaningful fight. Other EU successes are the abolition of mobile roaming,[85] mobile-number and data portability,[86] DMA,[87] GDPR,[88] right to repair,[89] and interoperable banking.[90] In energy there's mandating the CCS plug,[91] appliance efficiency labelling,[92] energy unbundling,[93] and laws giving rights to local energy communities.[94]

One of the biggest impacts this book could have is if it gave some EU bureaucrats the inspiration to come up with anti-extraction laws for the new energy system. Funny how that works.

So, de-enshittification is possible. The next energy system can be designed not to repeat the Internet's mistake. But it will only happen if we aim for that explicitly in the design. Fortunately, designing a good platform for energy creation

and distribution is actually much less complicated than designing a good platform for content creation and distribution. Because while every story is unique, every electron is the same.

From reacting to preventing

We should still expect extraction the way a shipbuilder expects rust: not as a scandal but as a property of the materials. The materials here are ordinary greed, increasing returns and asymmetric organisation, and no energy system made of humans will lack them. Expecting it changes the response. You do not hold conferences against rust. You choose materials, add sacrificial anodes, schedule inspections, and you do it at the shipyard, not in the middle of the Atlantic.

Earlier in this chapter we saw why we end up defending extraction. Research also shows what makes us stop. Make luck visible, and the merit story loses its grip. Publish who pays and who gets, and the overestimated losses that sank the French carbon dividend deflate.[95] Use fair, deliberative procedure, and acceptance follows.[96] Name windfalls as windfalls.[97]

The next four chapters turn these findings into four design principles for the new energy system:

- Power to the People!
  We should prevent and undo power grabs by "helpful" toll booth owners, whether they are grid operators or flexibility aggregators. Users should own the assets, data, code and decision making power. As long as users remain in charge and able to easily change provider, extraction can be minimized and the capability to develop autonomy, competence and relatedness is not diminished. This also helps to keep value at the customer long term, which reduces inequality and the need for more problematic redistribution later. The burden of evidence for taking power away should be on toll-booth owners like grid operators and software companies providing code.

- Radical simplicity through holons.
  By keeping the system as simple as possible, we increase de-facto capabilities, competence and autonomy for users. We also make the system more efficient, resilient and able to evolve. Holons are the blueprint for minimizing complexity as we've seen in part 2. We should enforce proper implementation with interfaces that are as light as possible. That also lowers barriers to entry.
- Sunlight is the best disinfectant.
  Data, standards and source code should be "open unless" with a heavy burden of evidence on the parties trying to keep anything secret. Nothing is as useful for taking power away, reducing simplicity and hiding extraction as closed data, standards and source code. As we will see the code we need isn't that complicated, but if closed it would be the perfect rent extraction toll-booth. Let's not let that happen.
- Universal access to energy.
  Left unattended, human systems invariably create more inequality than most people think is optimal and leave out the floor most people want. So we have to "nudge" the system towards equality and that floor from the start. The chapter explains how we can "hack" our instincts for fairness, empathy and kindness towards that result.

Remember the Phoebus engineers? They knew perfectly well how to build a better light bulb but were paid by toll booth owners to build a worse one. The energy system is not simply a light bulb but the largest machine our species will ever build. Let's make sure it's a better one.

25

Power to the People

The Hush-A-Phone was a plastic cup. You clipped it over the mouthpiece of your telephone, and the people around you could no longer hear your conversation. Harry Tuttle had been selling it from New York since the 1920s. It harmed nobody. Then AT&T noticed and invoked its tariff: nothing may be attached to the telephone that the telephone company did not supply. The regulator sided with the monopoly. It took years in court before a federal appeals panel established, in 1956, that an American had the right to put a plastic cup on his own phone. As the ruling put it, the subscriber had the right to use his telephone "in ways which are privately beneficial without being publicly detrimental."[1] AT&T's lawyers had argued, with straight faces, that the cup was a threat to the integrity of the national telephone network.

The company fought a cup because the cup threatened a principle. In those days people did not own their telephones. They rented them from the Bell System, which also owned the wire, the exchange, the repair man, and the conversation about what was possible. A decade later a Texan inventor named Thomas Carter spent years fighting the same tariff. His Carterfone was a cradle that let two-way field radios connect to the phone network, and it was equally forbidden. The regulator gave in only in 1968. From then on the network was open to any device that did it no harm.[2] The network survived the plastic cup. It also survived the Carterfone, and then the answering machine, the fax and the modem.

And through the modem, arguably, the consumer internet walked in through the door Carter forced open.[3]

What the arrangement had been worth to its owner surfaced decades later, in the small print. When the Bell System was finally broken up in 1984, customers were given the choice to keep renting their telephones. Many never understood they could stop. In 2006 a reporter found Ester Strogen, an 82-year-old widow in Ohio. She had been paying rent on two black rotary phones for more than forty years. By her family's arithmetic that came to over $14,000, for hardware worth perhaps twenty dollars. Three quarters of a million Americans were still renting phones that year.[4]

Nobody broke a law. The arrangement simply kept collecting, the way arrangements do when leaving requires a decision and staying requires nothing.

The soft-sell that holds such arrangements together is always the same sentence: "it's easier if you just let us handle it." And it is easier. Handing your wallet to someone else is also easier than keeping track of your money. The cost comes later. And it comes precisely when you want something the handler does not want to give you: a plastic cup, a modem, an end to the rental.

Chapter 24 walked down the ten steps from useful technology to hardened extraction. Then it used chapter 23's models to build instruments that catch that slide early. But instruments do not redistribute power. They only show where it sits.

So let me put the pieces of this part together. Chapter 21 described what we want: human flourishing. Chapters 22 and 23 swapped a broken compass for one that points there. Chapter 24 showed how extraction creeps in, and how to stop it. A better sense of flourishing, a better compass and a system that prevents extraction give us power to the people.

Of the four design principles, power to the people comes first, because it is the first defence that keeps extraction out. As chapter 24 told, Albert Hirschman taught that customers discipline a deteriorating system in exactly two ways. They

leave, or they organise: exit, or voice.[5] Dependence quietly kills the first and then starves the second. So the first structural defence is to keep both alive on purpose. That is this chapter.

In chapter 21 I claimed that only an energy system with the users in charge can reliably deliver human flourishing over the long term, and that this was important enough to put on the cover. This is the chapter that has to earn the cover.

Written out as design requirements, independence is a short list. We do not depend on any chokepoint we cannot route around. We can change energy providers as easily as we change telecom operators. Our data is ours and travels with us. The value of our energy and our flexibility lands primarily with us. And we choose who buys and sells on our behalf, and we can fire them.

Hold all five and extraction is hard, because a toll booth in front of people who can walk away is a bad investment. These five conditions are also chapter 21's flourishing needs in institutional form. Autonomy, competence and relatedness all presuppose a system we can act on. Give one of the five away, usually in exchange for "easier", and chapter 24's slide to extraction has taken its first step.

Leaving is a feature, and it has to be built

Today we can leave our telecom operator in an afternoon. Our number, the handle everyone uses to reach us, must by European law follow us within one working day.[6]

It is worth pausing on how logical, valuable and yet unnatural that is. Easy exit did not emerge from the market. Every rung was forced on the incumbents: the cup in 1956, the Carterfone in 1968, the breakup in 1984, portability after that. Each time the door was widened, its owners warned that the network would degrade. It did not. It got better, cheaper and more inventive, which tells us what the warnings were actually protecting.

On paper, energy is halfway there. European law gives every customer the right to switch supplier within three weeks, free of charge. It also requires that by 2026 the technical switch itself take no more than 24 hours.[7]

That is the easy half, because a supplier contract is the shallow end of dependence. The deep end is everything that does not follow us when we switch. Our consumption history. Our generation record. The permissions we granted. The flexibility contracts attached to our battery and our car. The app that knows our habits. All of that resets to zero, or worse, stays behind with the old provider. We can leave the contract. Leaving the relationship is another matter.

Europe's privacy law looks as if it solved this in 2018. The GDPR gave everyone the right to receive their data in a "structured, commonly used and machine-readable format."[8] Britain had already tested what such a right is worth. Its midata programme let bank customers download their transaction history as a file. Almost nobody did anything with it.[9]

A downloadable file is portability the way a box of paper records is a medical history: complete in principle, useless in practice. The same goal succeeded only when it was rebuilt as Open Banking: live, standardised access through interfaces that a service we authorise queries directly.[10] The lesson generalises. A right to export defeats outright hoarding and changes little else. What works is the data equivalent of number portability, where our history and our permissions follow us automatically, because the systems of would-be toll-booth owners are required to talk to each other.

Energy is climbing that ladder on three continents. The United States has had Green Button since 2011. It is one standard through which a customer can authorise any third party to pull their meter data, and it is in use at utilities serving tens of millions of households.[11] Australia extended its Consumer Data Right from banking into energy in 2022. An accredited service can now fetch a customer's consumption and tariff data and find them a better deal.[12]

The EU's Data Act has applied since September 2025. It gives users of connected devices, such as smart meters, inverters and chargers, the right to the data those devices generate. From 2027 it also bans charges for switching cloud providers.[13] None of this is charity. It is the same reflex that gave us one charging plug: the EU forcing an interface open, because no incumbent ever volunteers.

The most complete version is about to run in my own country, I am pleased to report. The Dutch Energy Act, in force since January 2026, places an independent entity, Het Normo, at the centre of energy data exchange. Het Normo is not a database. Our data stays where it was measured, with grid operators and suppliers. The entity's only job is to connect an authorised request to the source once we have consented. Consent itself runs through a portal called enKiy that works like approving a payment. It bounces us to a screen where we approve this data, for this purpose, for this long. And we can revoke at will. Its director calls it "the iDEAL of the energy sector," after the online payment system we Dutch use the way the rest of the world uses credit cards. enKiy names the eIDAS wallet as the next step.[14]

Add the meter-point identifier and we have energy's phone number: an identity plus a permission record that follows us from provider to provider instead of resetting at every switch.

My only worry is that Het Normo is a monopoly (a potential chokehold for access) that in practice is controlled by the grid operator. The grid operator can also use it to slow-walk opening up the data on what's happening on their network.

One number tells us whether any of this is real: the price of the exit. Amazon's cloud division long charged roughly nine cents per gigabyte to move your own data out, while charging nothing to bring it in. Cloudflare dissected that structure under the title "AWS's Egregious Egress" and could explain it only as lock-in.[15] One software firm leaving the cloud had to negotiate a $250,000 waiver simply to retrieve what was its own.[16] Only under the Data Act did AWS concede free

egress. Even then it was only for customers leaving entirely, on request.[17] If leaving costs more than staying, we are not customers. We are inventory with a billing address. Energy deserves the same inspection. Every termination fee is a small egress charge. So is every history that cannot move, and every dataset that stays behind. The egress charges are the architecture announcing its intentions.

Your data is the hostage

What makes energy data worth holding is how much of us is in it. A meter reading every few seconds is enough to reconstruct which television channel a household is watching. That was first shown in 2012,[18] and the identification accuracy has since been pushed above ninety per cent.[19]

Coarser data still reveals when we wake, when we shower, and when the house stands empty. In 1980 Langdon Winner argued that artifacts have politics: the architecture of a system encodes who gets to decide.[20] A smart meter that streams this intimacy to a corporate cloud and sends back a monthly bill encodes a very specific politics. We are the source of the value, and someone else is the recipient.

The same politics now ships in cardboard boxes. On 11 October 2024 the company Enel X Way closed its North American operations. It switched off the app behind JuiceBox, one of the most popular home EV chargers on the continent. The hardware kept working. But everything smart about it, like scheduling around cheap hours, monitoring and remote control, died with the server connection.[21] The owners owned the box, the copper and the receipt. The behaviour lived in a cloud they had no claim on. A device we own whose conduct depends on someone else's server is not property. It is a tenancy with a purchase receipt.

What makes this indefensible rather than merely irritating is that nothing in physics requires the tether. Everything time-critical in a home energy system already happens locally, in the device's own firmware. An inverter holds voltage and frequency on millisecond timescales without asking

anyone.[22] A charger cuts power on a fault by itself. A battery enforces its own limits. The network layer only decides the economics: charge now or in an hour. A missed message there costs cents, never safety. So when a vendor wires our devices to its servers as a condition of function, that is not an engineering necessity. It is a business model wearing an engineering costume.

Which brings us to the most valuable thing behind the meter, and it is not the electrons. It is flexibility: our battery, our car and our heat pump being free about *when*. That is precisely what a renewable system is short of. Someone will trade that freedom on the markets for us: an aggregator, an energy company, an algorithm. European law already says we may pick that someone independently of our electricity supplier, and switch without discrimination.[23]

The design test is who keeps the proceeds. If the value of our flexibility lands mainly with us, the system serves us. If it lands mainly with whoever holds the contract, we have acquired a landlord. The profile of what we can do is ours, and it should move when we move.

Decide at the lowest competent level

Which decisions belong at which level? On this, remarkably, the disciplines agree. Psychology finds autonomy a load-bearing human need: chapter 21's self-determination theory.[24] Economics has Hayek's argument that the knowledge that matters is local and cannot be summoned to headquarters.[25] European law enshrines subsidiarity: decisions taken as closely as possible to the citizen.[26] Governance has Elinor Ostrom's polycentricity. Many nested centres of decision-making, each sized to its own problem, outperform one centre that runs everything.[27] And network engineering has the end-to-end argument that built the internet: put intelligence at the edges and keep the middle simple.[28]

Five fields, five vocabularies, one design rule. We call it holarchy: decisions sit at the lowest level that can competently take them. The burden of proof should lie on whoever

wants to move one upward. Scientists agreeing across faculties is rare enough that an engineer should treat it as a measurement.

Run the rule down the energy system. At the household: a meter we can read, a tariff we can understand, and our own software deciding when to charge, store and sell, on terms we set. At the street level: the street decides when the local battery dispatches, and who has priority when it cannot serve everyone. At the neighbourhood level: a cooperative with real operational control over its collective assets, not a consultation that runs after the engineers have decided. At city and region: the rules by which communities compose into larger systems. Those rules are set by the people who live inside them, not imported from a vendor's terms of service.

The test at every rung is the same. Can the people inside change what happens? Not appeal, not petition, not vote for someone who might appoint someone. Change it.

In a research project on smart-home systems, a participant was asked what he wanted his home energy system to do. He could not name a temperature schedule or a charging strategy, but he was more than willing to accommodate others, within limits. He knew only one requirement he would not budge on: there had to be a button he could press that the system would obey. The other people and I nodded: damn straight. In the Netherlands and at the ElaadNL foundation this is now called "the overrule button". The point is not the button. It is the guarantee underneath it. Authority that operates only as long as you agree with the system is not authority. It is decoration on someone else's control loop.

Whether ordinary people can govern shared infrastructure is no longer a matter of opinion. It is one of the most thoroughly answered questions in social science. Chapter 18 introduced Elinor Ostrom's communities: Spanish irrigators, Swiss alpine grazers and Maine lobstermen, governing commons sustainably for centuries. Her eight design principles read like an energy community starter kit. Defined

boundaries. Rules matched to local conditions. The users themselves making the rules. The users monitoring them. Graduated sanctions. Cheap conflict resolution. Recognition by the state. And nested enterprises: units within units, each handling problems of its own size.[29,30] That last principle is the holon in different words. And we now understand why her institutions endure. They sit exactly where the cooperative wiring of chapter 21 fires reliably. We form ingroups on the flimsiest excuse.[31] We pay out of our own pocket to punish free-riders.[32] And the machinery works up to Dunbar's ceiling of roughly 150 stable relationships.[33] A street-scale energy holon of ten to fifty households sits comfortably inside that range. It is not asking anything heroic of human nature. It is asking what human nature, at that scale, was already inclined to do.

Give the slow self a firm seat

Above Dunbar's ceiling of 150 stable relationships the warm machinery stops. And that is where most of the energy transition's hardest decisions happen to live. The tariff between communities. The timing of a fossil phase-out that will hurt some people on the way. Cross-subsidies between prosperous and struggling districts. The design of universal access. These are decisions about strangers and about people not yet born. As chapter 21 showed, those are exactly the questions our fast intuitions answer badly and only our slow reflection answers well. Put them to a poll and we summon the fast self: loss aversion, status quo defence, the cognitive layer that chapter 24 showed protecting extraction. The French carbon tax of chapter 24 died that way. It was rejected by voters most of whom would have profited from it.[34]

The same voters produce different answers inside a different procedure. James Fishkin has spent three decades running deliberative polls. Take a random, representative sample of citizens. Give them balanced briefing material. Put them in facilitated small groups with experts they can interrogate. And poll them again afterwards. Across more than a

hundred such experiments in dozens of countries the direction is consistent. People come out better informed, more willing to carry long-horizon policies and trade-offs, and less polarised than they went in.[35,36] Deliberation does not make people left-wing or right-wing. It makes them able to sit with complexity. It is, quite literally, a procedure for eliciting the slow self.

This is not laboratory news. In 2016 Ireland convened a Citizens' Assembly: ninety-nine randomly selected citizens with a judge as independent chair. Over months of weekends it worked on the country's most poisonous question, abortion. Its recommendation to repeal the constitutional ban went to a referendum in May 2018. It passed with 66.4 per cent, a wider margin than the polls had foreseen.[37] The OECD has catalogued 289 such deliberative processes across its member countries since 1986, and finds the pattern holding at scale.[38]

From 1989 onward, Porto Alegre in Brazil ran the participatory version on its city budget. Within a decade it took sewage and water coverage from 75 to 98 per cent of households.[39] Given information, time and real stakes, ordinary citizens reliably produce decisions their own polling selves would have rejected.

France then demonstrated both halves of the lesson at once. Its Citizens' Convention for Climate gathered 150 randomly selected citizens for nine months. It paid them a daily allowance and asked them to design a socially just path to cutting emissions by forty per cent. They produced 149 worked-out proposals. President Macron promised to pass 146 of them on "without filter," vetoing only three. Then the ministerial machine did what ministerial machines do, and filtered. In 2021 the citizens were reconvened to grade the government's follow-through. They gave it marks between 2 and 3 out of 10.[40] The assembly worked. The implementation betrayed it. An assembly whose output can be filed and superseded is not slow-tier authority. It is slow-tier decoration.

Arguably it is worse than nothing, because it teaches citizens that the slow self was invited and then ignored.

In holons like Citizen Energy Communities, divide decisions between those that can be taken quickly and those requiring the slow self, and set up deliberative decision processes using a representative group. Make sure the results of this group have authority.

Three design rules follow. First, decide which processes are best done by the slow self and set up deliberative processes for them using representative samples of the affected group. Second, a seat should be default-on and paid. Summon people as for jury duty, schedule the sessions in paid working hours and cover childcare, as France to its credit did. That matters because chapter 21's bandwidth tax is real: the households with the most at stake have the least attention to spare for evening meetings.[41]

Third, the assembly's output must be structurally load-bearing. It must be connected in advance and by rule to the decision, as Ireland's was and France's was not. Authority is not the right to be consulted. It is the guarantee that the consultation counts.

Break up power before it buys the rules

Everything so far defends us against the providers we have. One more habit, borrowed from every long-lived democracy, decides which providers we get. Buying the rules takes a war chest and a single voice. Keeping them bought takes a monopoly on knowing how the system works. FirstEnergy in chapter 24 had the first two: one company with one interest, spending $61 million on a legislature it could recoup from every customer in the state. By that stage of the slide, prevention has become surgery. The cheap move comes earlier. Denying everyone that position costs nothing.

The energy version has three working parts, one per ingredient. Unbundling splits the voice. A company that owns the plant, the wires and our contract lobbies as one. Separate them, and the generator starts demanding open access to

wires it no longer owns. The retailer starts fighting the network tariffs. And the regulator hears an argument instead of a chorus.[42] Interoperability starves the war chest. A vendor whose devices work only with its own platform converts every sale into a captive, and a million captives fund a lobby. Force the interfaces open, and customers stop being conscripts. Public grid data, which I keep going on about, ends the knowledge monopoly. As long as only the operator knows where the congestion sits, every rule debate ends in "trust us", and nobody can prove the cheaper alternative existed. None of this is "the market sorting itself out." Markets do not sort themselves out when one side organises and the other does not. This is the deliberate organisation of the side that would otherwise stay unorganised.

Spot and remove the fakes

The fakes are easy to spot once we notice what they imitate: this chapter's own vocabulary. Take a utility's "community solar" programme in which the community holds no operational authority and no governance seat. That is community as a marketing word. A smart meter that reports our life to a cloud and shows us a monthly bill is not energy citizenship. The data flow is the capture. An energy community running on one vendor's black-box dispatch software is a tenancy with a cooperative logo. A platform that puts the override button behind a subscription has converted the most basic form of authority into a revenue stream. And an "energy citizens' assembly" whose report is received with warm appreciation and then set aside is the French lesson, re-staged.

None of these are exotic pathologies. They are the default output of systems designed by people whose incentives point away from the users'. Every one of them is the soft-sell wearing a new coat.

Become your own grid operator

In early May 1986 the rain came down on the Black Forest. It carried caesium from a reactor 2,000 kilometres away. In

Schönau, a small town in a valley where the firs stand dark on the slopes, the parents kept their children indoors and served them preserved food, as advised. When they asked what would change now, neither the government nor their electricity supplier had answers they considered useful.[43]

What they did next took eleven years. They founded Parents for a Nuclear-Free Future. They ran energy-saving competitions and, this being a small German town, a cabaret. The council extended the incumbent's grid licence anyway. The company had offered the town 100,000 Deutschmark for the favour. So the parents forced a referendum and won it, narrowly. They founded their own supplier, Elektrizitätswerke Schönau or EWS. It was staffed by teachers, doctors and policemen, with not one energy expert among them. They won the concession. Then they won a second referendum, again narrowly, when opponents tried to overturn it.

The incumbent valued the wires at 8.7 million Deutschmark. EWS's own appraiser arrived at 4 million. The parents paid the inflated price under legal protest, and later won the difference back in court. They raised the money through a national donation campaign whose slogan translates as "I am a disturbance." In 1997 the parents switched on their own grid, with 1,700 customers.[44,45]

Today EWS is a cooperative, one member one vote. It supplies green power to some 170,000 customers across Germany, from a town most Germans would need a map to find.[46] Look at what the parents actually rebuilt, because it is this chapter in miniature. It is also proof that independence, once fully surrendered, can still be taken back. Exit: they fired their provider in the most thorough way available, by buying the wires out from under it. Voice: two referendums, a cooperative, an annual assembly, and the everyday authority of running the system themselves. Data, value, agency: theirs, by construction. The grid that had no useful answers in 1986 and the grid that serves Schönau today are largely the same copper. What changed was not the hardware. What changed was who is on the other side of the meter.

New European legislation regarding Citizen Energy Communities or CECs makes it easier to follow their example and start your own local grid operator when you feel the big utility is not listening to you. It is one of the best possible instruments to discourage extraction and encourage local initiative. Unfortunately countries can choose not to implement CECs nationally (like the Netherlands so far, as chapter 24 showed), but I expect we will increasingly see examples like Schönau.

Everything in this chapter is a precondition, not a destination. The three chapters that follow keep the independence usable. Radical simplicity (chapter 26), so that exercising authority does not require a law degree and a free weekend. Open data, standards and source code (chapter 27), so that no vendor can stand between us and our own system. Universal access (chapter 28), so that authority is not reserved for those who could afford the entry ticket. So let's now turn to the polite soft-sell of a system made so complicated that you will be relieved to let someone else handle it.

26

Radical simplicity through holons

Somewhere in your house is a drawer full of chargers. Mine held the black snouted one for a Nokia, two incompatible Samsungs and three other phones, a Mini-USB, a Micro-USB, and a dozen I could no longer identify but did not dare throw away. Every plug in that drawer once had a justification: thinner, faster, patented, "better for the user experience". The drawer knew better. Thirty chargers were never consumer choice. They were thirty small toll booths, each collecting a margin on compatibility, and we all paid the toll one bedside table at a time.

Then the EU, an institution rarely accused of impulsiveness, finally told the industry to stop being ridiculous and pick one port. Apple objected that "strict regulation mandating just one type of connector stifles innovation rather than encouraging it, which in turn will harm consumers in Europe and around the world."[1] Since 28 December 2024 every new phone, tablet, camera and headset sold in the EU charges over USB-C; laptops follow in April 2026. Discarded chargers were costing us about 11,000 tonnes of e-waste a year, and the single port saves consumers some €250 million annually.[2] The iPhone now charges over USB-C, and innovation, as far as anyone can measure, has survived.

I open with that drawer full of chargers because the energy transition is similarly good at making things needlessly complicated. Chapter 24 showed that extraction needs opac-

ity the way a magician needs sleeves. Since outright secrecy is increasingly illegal, complexity provides the same opacity while remaining perfectly legal. That's one reason we should stay as close to reality as possible, and abstract from reality only when the abstraction simplifies: everybody shares the same reality. Every extra abstraction - be it an extra market, interface or data-field - is a potential source for consultants, complications and chokeholds. You might remember the adagium of many a teacher to their students: KISS (keep it simple stupid).

The disguise

Smuggling in complexity follows a three-step recipe. First build a system that requires specialist knowledge to navigate. Then position yourself as the specialist. Finally charge for the translation.

Many of you know how this works from your tax return. Most rich countries already know what you earned, work out what you owe, and send you the result to check, so filing takes minutes and costs nothing. The United States could do the same, and for more than twenty years the maker of TurboTax fought to stop it, lobbying to keep filing complicated while selling itself as your guide through the maze it was helping to preserve.[3] In 2022 it paid $141 million to settle charges that it had steered people away from the free filing it was meant to offer.[4]

For many experts, complexity is not a side effect. It is the product. The anthropologist David Graeber spent a career on this pattern and named it the utopia of rules: elaborate rule systems reliably serve the people who run them better than the people governed by them.[5] Energy plays the same game, except its translators get to call the maze physics, even though the real physics, voltage and frequency and Ohm's law, has been stable since the nineteenth century and asked for none of it.

That gives us a blunt test for any layer in a system: imagine deleting it. If the electricity keeps flowing, the layer

was never holding the system up. It was holding someone's income up. A load-bearing wall keeps the house standing, and knocking it out brings down the roof; a toll booth that holds up nothing but the toll needs to go. The catch is that from the outside the two look alike, and the people collecting the toll are powerfully motivated to keep you from telling them apart. So the most removable layers tend to arrive wrapped in the most sophisticated arguments for why they are essential.

Our job is to imagine knocking out every wall. And when nothing falls down in the thought experiment, that wall needs to go in reality too.

Markets stacked on markets

Electricity-market design has been piling layer upon layer for forty years, each one added for a reason that made sense at the time. The plain spot market could not, on its own, reassure anyone that enough power plants would be built, so a capacity market was bolted on to pay generators for being available. The capacity market struggled to value the rare, desperate hours when supply runs short, so scarcity pricing was bolted on top of that. And because all this leaves traders exposed to violent price swings, a layer of financial hedges, among them the financial transmission rights we are about to meet, was bolted on again.[6] Nobody sat down and chose this stack. It grew, layer patching layer, and every new layer opened a new place to play.

The taller the stack, the better the view for whoever can climb it. Look at that top layer, the financial hedges. When a power line between two regions fills up, electricity is cheaper on the crowded side than on the far side, and the gap between the two prices is real money. A financial transmission right is a ticket that pays its holder that gap, hour after hour, for years. A utility buys these tickets as insurance, to cancel out the congestion costs it expects to pay; a speculator buys them to bet. Either way, because the bet can go against

you, the market operator asks for a deposit up front, money it can seize if you cannot pay what you end up owing.

Here a three-man firm called GreenHat spotted the flaw. In PJM, the biggest electricity market in America, the deposit demanded on long-dated tickets was set close to zero. So from 2015 to 2018 GreenHat bought them by the thousand, chosen not for what they might be worth but for how little had to be put down to hold them. If the bets paid off, GreenHat kept the winnings; if they soured, there was almost no deposit to lose. Heads the firm wins, tails someone else pays. In June 2018 it came up tails. GreenHat walked away, and the roughly $179 million hole was, by the rulebook, spread across every other PJM member and, through them, their customers. The three traders later settled the manipulation case for $1.4 million between them, the regulator having concluded there was nothing more to take.[7] A review afterwards found the market operator had been, in its own consultants' word, naive.[8] Who plays a game like this? Financial traders and utilities with dedicated desks. Who pays when the hedge-of-a-hedge blows up? Everyone with a meter. The rules bar no one. The prerequisites bar almost everyone.

None of this is special to electricity. British banks spent two decades selling payment protection insurance, a product tangled enough that most buyers could not tell whether they needed it (mostly not), whether it would even pay out (often not), or what it really cost (more than they thought). Unwinding it cost the banks £38.3 billion in refunds, the largest consumer compensation in British history.[9] There are no informed buyers for a product built to resist understanding. That is not a defect in the product; it is the product. Chapter 24 already showed one energy twin: the £1.4 billion a year British households overpaid by sitting on default tariffs in a market too tangled to compare.

It's the complex solution to supply and transport issues that creates all these markets. Most of these markets would evaporate if we used holons with storage that keep their

energy local as much as possible and can solve the exchanges between them in realtime.

A country is not a copper plate

The second way complexity slips in is quieter, and it is worth seeing on its own, because the obvious reaction to it is the wrong one. Europe largely runs its electricity market as if each bidding zone, often a whole country, were a single copper plate: one price everywhere inside it, as though a wind turbine in Groningen and a steel works in Maastricht were bolted to the same sheet of metal with limitless transport capacity between them. They are not. Real power runs through real wires with real limits, and when the cheap wind sits in the north while the demand sits in the south, the wires in between fill up. The single national price pretends that traffic jam doesn't exist, so a second market, redispatch, was bolted on afterwards to pay some plants to turn down and others to turn up, undoing on the physical grid what the first market had promised on paper.

Lion Hirth and Ingmar Schlecht worked out what rational producers do once that second market exists: they see the redispatch payments coming and bid strategically in the first one. This is the inc-dec game, and the result is worth savouring. Congestion gets *worse*, not better. The windfall flows to exactly the plants sitting on the bottleneck. And it needs no cartel and no villain, because perfectly competitive firms, each one merely optimising, are paid to deepen the very problem the patch was built to cure.[10] When a market design lies about transport capacity, reality sends arbitrageurs to collect the difference.

The most expensive version on record was California. Its deregulated market of the late 1990s was, for its day, a sophisticated piece of architecture: day-ahead and real-time markets, ancillary services, retail prices capped while wholesale was left to float. In June 2000 the average wholesale price hit $143 per megawatt-hour, more than double any month in the market's first two years; by spring 2001 the state

was buying power at more than a billion dollars a month, ten times the year-earlier price, and its largest utility had gone bankrupt.[11]

Chapter 24 introduced the Enron traders who caused it with schemes named Death Star and Get Shorty. Basically they succeeded in pretending to create congestion and then pretending to solve it without actually doing something.[12]

For many people the instinctive response to all this gaming is exactly backwards. Faced with traders running rings around the market, the reflex is to blame markets and reach for a central controller. But the inc-dec game is not caused by having a market. It's caused by having a market that lies about grid capacity. The repair is to make the price tell the truth about place, pricing electricity at the actual spot on the actual grid, congested wire and all, so there is no difference between market and reality to exploit.[13] Done properly that is not one more layer on the stack; it is the removal of the gap the gamers lived in. A price that already mirrors the physics needs nothing bolted on top, and leaves nothing to arbitrage.

This is the whole principle of the chapter in one example: stay as close to reality as possible.

Why simplicity wins, formally

Complex rules do handle edge cases better. A tariff with seventeen components prices every corner case of congestion and scarcity more precisely than a tariff with one. But learning the rules is a price too.

Chapter 23 introduced Brad Hooker's rule-consequentialism, the workhorse of applied ethics: calculate the value of a rule by the wellbeing it produces after about 90% of real people have actually internalized it. Then calculate that score against the cost of internalizing the rule: teaching the rule, remembering it, applying it, monitoring it, training your successors in it, and punishing deviance.[14]

Those internalisation costs[15] are paid out of the same budget of human flourishing the rule was meant to grow. The complex rule wins its edge cases, which are rare. The simple

rule wins the internalisation, which is paid every day, by everyone. Run that calculus and simplicity stops being an aesthetic preference. It is what the optimisation returns once teaching humans appears in the books.

Apply that to the seventeen-component tariff. Its sophistication is real, and so is its bill: what users must learn to participate meaningfully, what installers must track, what a small cooperative must model before it dares sign anything. Most participants cannot pay that bill, so they stop participating meaningfully – they take the default, miss the rebate, sign with whoever knocked first. The participants who can pay it are the energy desks, who then collect the margin the complexity created. That margin is the internalisation cost of the rule-code, transferred from everyone to the specialists. That's what Hooker's calculus shows.

The same principle, by the way, applies to the many models that justify complex markets. The equilibrium models of chapter 23 must assume away networks, lobbying, learning and herding because the mathematics demand it, then bless market designs that require those assumptions to be true. By simplifying how the system is run – with holons – and by using agent based models that can stay close to reality, the need for markets that correct model simplifications disappears.

Complexity held and complexity sold

None of this is an argument for primitivism. A smartphone is one of the most complex objects ever mass-produced, and yet grandparents call their grandchildren with it. The complexity is real but it is *held* – managed on their behalf, beneath an interface that asks nothing of them. The kilowatt-hour is an abstraction, and a magnificent one: it lets you compare a tumble dryer with a toaster while knowing nothing of phase angles. Grid frequency control is complexity we keep: stray too far from 50 hertz and the grid starts disconnecting customers to save itself, so inverters and chargers handle it locally, in firmware, in milliseconds, as the previ-

ous chapter showed. The test is never "is it complex?" but "who holds the complexity, and who pays for the holding?" Held complexity serves the user. Sold complexity is the business model where your inability to understand the system is the revenue line.

What held complexity looks like is specific enough to write into law. Defaults that work for the satisficer, so the household that wants to do nothing still gets a sensible result: green power, fair price, automatic participation in balancing. Depth for the maximiser, so the cooperative that wants to model its own tariff can reach the full data in a standard format. One button to override anything – chapter 25's research participant, the man who wanted nothing except a button the system would obey, was defining this property. One screen to see everything the system did on your behalf. One sentence to explain any decision it took for you. Abstraction with these five properties is ok. Abstraction without them is not.

Holons, or where the complexity goes

Where does complexity physically live, in a machine that spans a continent? Part 2 gave the answer and Herbert Simon proved it. Recall his two watchmakers: Tempus built his watches in one go and lost the whole assembly every time the phone rang; Hora built sub-assemblies that held their own shape, and prospered. Simon showed that almost every complex system that survives – cells, brains, firms, ecosystems – is built the same way: dense interaction inside the parts, sparse interaction between them. He called it near-decomposability, and the part that keeps its mess inside while presenting a calm face outward is what this book, following Koestler, calls a holon.[16] We already explained the man was an extraordinary genius so it should probably come as no surprise that he is also the Herbert Simon that coined the term "satisficing". The man understood, twice, that the art of design is deciding what people should *not* have to think about.[17]

An energy holon, as Part 2 defined it, is a unit – home, street, neighbourhood, city – that balances itself as well as it can and presents one simple interface to the level above: here is the flexibility I can offer, here is what I need, and how I arrange things inside is my business. That thin interface is where radical simplicity stops being a slogan and becomes architecture. Inside the holon, complexity is held: the inverter mathematics, the battery management, the optimiser arguing with the weather forecast. Across the interface travels almost nothing: a price, a limit, an offer. The copper already agrees – every grid on Earth is physically built as transformers serving neighbourhoods serving regions, a perfect nested hierarchy – but today's institutions ignore the seams and run the whole thing as one Tempus watch.

The catch is that thin interfaces do not happen voluntarily, because every fat, proprietary, undocumented interface is a moat. A vendor whose cloud must approve your battery's behaviour owns you a little; a grid operator whose data formats only consultants can parse owns you a little; an energy producer that requires you to give all your trading information in return for a dynamic contract owns you a little. So proper implementation must be enforced, the way the EU enforced the charging port: define the interface, mandate it, and let everyone compete on what sits behind it.

The prize is the same as with USB-C, scaled up. Barriers to entry collapse, because joining the system means implementing one published interface rather than negotiating thirty bilateral integrations with thirty lawyers. And Apple may try to deny it from its moat but innovation accelerates. Because others can now develop better chargers. Or to go back to our energy system they can develop better battery optimisers, battery cells, inverters or energy management systems. All without asking permission and getting delayed by toll-booth owners.

Hora's watches evolve module by module, while Tempus must redesign the whole watch, every time. And the system as a whole gets *better*, not worse: Part 2 showed that nested,

self-balancing structures are both more efficient and more resilient than monoliths. Simplicity at the seams is not a sacrifice we accept for fairness. It is how you make the machine perform better. Better than the Tempus watch the grid currently tries to emulate.

The grandma test

There is a test that I think should be standard in every regulatory proceeding: "will this rule help to create solutions that we can describe in a few simple sentences, why they exist, what they offer, and what they cost?" Call it the grandma test.

Grandmothers are not simpletons. This one has raised children, run a budget through two recessions, and outnegotiated more salesmen than most market designers. She is simply not a specialist in power-system economics. She should not have to be. She is who the system is for.

A solution that passes: "We offer you money to use less when the grid is full. It's added to the app you already have to buy electricity cheap. This screen shows what will happen and what you earn. This button is your opt-out."

A solution that fails: something that binds her to clouds and aggregators, introduces vulnerabilities and secrecy, requires her to send and receive more information than is absolutely needed, isn't interoperable between appliances and energy suppliers, and can't be integrated by a third party.

Grandma can use her mobile to call her grandchild and that is also how a good energy system will present itself to her. On any mobile phone of course. Or on a wall unit. Because the software is simple and open and so is the rest of the system.

The decisions that are based on prices that change by the hour and depend on the interplay between appliances are food for computers. People are for deciding. She should be able to state her terms once, in a way that makes sense to her: warm by seven, the car full by eight, never spend more than fifty euros without asking. For the rest do what you like. And

if she pushes the overrule button the system becomes dumb again.

The system and software can stay simple and open because the house talks to the grid through a keyhole. A price comes in; an offer goes out. Whether it was the boiler or the car that answered is nobody's business but hers, and what never leaves the house cannot be leaked, sold, studied, or bundled into an interface that creates lock-in. A keyhole is also a poor target: the worst a corrupted price signal can do is shift her laundry by an hour. The fashionable alternative, a million boilers wired to one company's cloud, is a blackout waiting for a leaked password[18,19].

A simple keyhole is also simple to standardize the way thirty charging plugs became one. Different parties can easily develop open software for it and for once the landlord is her. She can evict one provider on Friday and a rival moves in on Monday; the house barely notices. Rivals competing is how the value of her flexibility ends up in her pocket instead of the middleman's.

And how does she test all this? The way she has tested every salesman at her door: say no, and watch what happens. Press the button: does it obey at once, without a fee? Pull the internet cable for a week: does the house stay warm, or does the system go dumb the way America's most popular home car charger went dumb the day its maker switched off the servers[20]? Refuse to share anything beyond the meter total: does the deal still stand? Leave: does her history come along, free of exit fees? Simplicity that survives four no's is engineering. Simplicity that punishes a no was a leash.

Of course she should not have to do these tests herself. A laboratory does it once, and the verdict becomes a label, like the coloured letter on her fridge: a measurement she has never read but knows can be trusted.[21]

A large part of simplicity comes from letting the sunlight in, and that's where we will turn next.

27

Sunlight is the best disinfectant

Picture a neighbourhood that has done everything this book asks. They pooled savings, survived the permit process, argued cheerfully about panel tilt, and now own every panel, battery and inverter outright, the way you own a house after the mortgage burns. Then they plugged it all into the energy management software that came bundled with the inverters. Turns out the software is a black box. Somewhere in the terms of service nobody read, the vendor reserves the right to sell their consumption data to electricity traders. The algorithm that decides when to charge and when to sell is proprietary, and can be changed overnight from a headquarters on another continent. The community cannot audit it, modify it, or replace it without voiding the warranty. The shop is theirs. The cash register belongs to someone else. Whose holon is this?

Notice where the trap sits. The big costs in any energy system are in hardware: panels, turbines, cables, transformers, batteries, cars. The software that steers all this costs, by my estimate, less than a thousandth of the hardware it sits on. But that thin layer is where the decisions live, and rent always migrates to the decision layer. Uber owns no cars and Booking owns no beds; they own the layer that decides, and they charge accordingly. Chapter 24 showed the ten steps by which such a toll booth hardens. The thin software layer on

top of your expensive hardware is the cheapest place in the entire energy system to build one.

Instead what we need is Linux for energy. That's an easy slogan to remember. In actuality it will be much much simpler than Linux in terms of software. Rather it will be a couple of basic apps that run on top of Linux. The reason this will require a fight is not that the task of making the software is hard. It's that powerful players don't like to let the sunlight in because that moves their power to end users.

The good news is that if we've kept up with the advice from this book so far, we've already made it pretty hard on the extracting parties. Chapter 25 kept the power with the users: your data is yours, your exit is real, your representative can be fired. Chapter 26 stripped away the complexity they like to hide in. Openness is the last nail in the coffin. In 1913 the American lawyer Louis Brandeis wrote, about bankers, that "sunlight is said to be the best of disinfectants; electric light the most efficient policeman."[1] For an energy book it is pleasing that his runner-up was electric light. This chapter applies his remedy three ways: open data, so everyone can see what is happening; open standards, so anyone can compete; open source, so you can verify what acts on your behalf.

Open data: what sunlight did to the sky

Until the spring of 2000, the United States military deliberately scrambled the GPS signal for everyone else. The system could already tell a receiver where it was to within metres, but civilians got a degraded signal, accurate to about a hundred metres, on the reasoning that precision was too dangerous to share. On 1 May 2000 the White House switched the scrambling off[2], and overnight the position error of every civilian receiver on Earth shrank roughly tenfold.

Nobody at the Pentagon had foreseen what happened next. Tractors began steering themselves along centimetre-straight furrows. Container ports, ambulances, hiking apps, dating apps and pizza delivery built themselves on a signal that asks no permission, no subscription and no means test.

The EU then went one better: its Galileo system now broadcasts a free signal accurate to about twenty centimetres, aimed squarely at the robots and autonomous machines that will need it.[3] Hoarded precision served one institution. Open precision built an economy no one predicted, least of all the people doing the hoarding. The military guarded its signal the way grid operators guard their cable data, and for the same reason: they want an information monopoly.

Energy already runs the experiment at the top of the system. Since 2015, European law obliges every transmission operator to publish load, generation, cross-border flows, outages and congestion on one platform, free for anyone to download.[4,5]

Traders, researchers, journalists and bored students all stare at the same numbers, the sky has not fallen, and the market works better for it. But on the level below it, they still treat the sunlight in a way reminiscent of a Vampire. Chapter 24 described my ten-year-and-counting fight for data on cables and transformers that were bought with public money by a monopoly. Same kind of data, same public mandate, different appetite for sunlight. Lynne Kiesling's design rule names the cure: quarantine the monopoly.[6] Grid operators have a monopoly on most of the wires and transformers. Fine. But the monopoly should not be larger than it needs to be. So they should not hamper the markets by hiding data just so they can put more cables into the ground without a second opinion.

Just to be clear: this is not about your consumption data. That's personal and chapter 25 settled whose it is: yours, shared only with whom you authorise. This is grid data: grid capacity, congestion, dispatch decisions, tariff formulas, connection queues, the algorithm that decides who waits for a connection. That is collective machinery, and it should be "open unless", with the burden of evidence on whoever wants secrecy, instead of today's "closed unless" leaving citizens to beg in vain. Extraction, chapter 24 showed, invests in fog. It's hard to lobby against a solution everyone can check,

and an open number feeds the open models of chapter 23, where anyone can rerun the calculation and call the bluff.

Open standards: doors nobody owns

In the spring of 1993 the internet had two competing ways to publish information, and the favourite was not the Web. Gopher, built at the University of Minnesota, was bigger, faster and tidier. Then the university announced it would charge commercial users a licence fee for its server software, and the internet's builders fled as if from a burning building.[7] At CERN, Tim Berners-Lee drew the lesson and pushed his employer the final step: on 30 April 1993, with a half-page document, CERN renounced every intellectual property right to the World Wide Web and placed it in the public domain.[8]

Gopher asked for a toll and is now a museum piece. The Web asked for nothing[9] and carries this sentence.

This was not a fluke of the nineties. TCP/IP, designed by committee in the 1970s and free for anyone to implement, quietly buried CompuServe, AOL and Minitel, walled gardens that were all more polished at the time and all had nothing left when their walls came down.[10] A published protocol is a door nobody owns. It is the most direct attack on a toll booth there is, because a toll booth needs a wall to lean on, and a new entrant who can read the specification walks straight through. Chapter 26 showed the EU forcing exactly this with one charging plug; USB-C is simply a door nobody owns, made mandatory.

Energy already has its doors, and a striking number were built in my small country. In 2009 the foundation of the Dutch grid operators, ElaadNL, started deploying public charging stations and refused to be locked to any hardware vendor, so it published the protocol by which a charger talks to its management system and gave it away. That protocol, OCPP, is now maintained by an alliance of more than 400 members and was adopted in 2024 as the international standard IEC 63584.[11,12]

Any charger, any backend, no permission required. The companion protocol OCPI does the same for roaming[13], so one account charges on any network, and it deliberately works peer-to-peer: its older rival was built around a mandatory central clearing house, and the protocol that did not need a middleman out-competed the one that did.

The rest of the stack exists too, and I will walk past it rather than through it. S2, a European standard born from Dutch research, lets a heat pump, an EV charger and a battery from three different manufacturers tell any home energy manager what flexibility they have to offer.[14] ISO 15118 lets the car authenticate itself the moment you plug in, and from January 2026 every new public AC charging point in the EU must speak it, with the bidirectional version following in 2027.[15] Openness as a condition of market access: the USB-C reflex, applied to energy. A list of acronyms is nobody's idea of a stirring read, but this is what de-extraction looks like in practice, and I find that rather wonderful: I applaud the tenacious people who sat through all the often boring committee work so they could make sure the toll booths would never get built.

Rough consensus and running code

How did internet standards resist capture by the richest companies on Earth? Not through good intentions. In 1992 David Clark summarised the working philosophy of the internet's standards body to a room of engineers: "We reject: kings, presidents and voting. We believe in: rough consensus and running code."[16] Rough consensus means the chair judges whether objections have been answered on their technical merits; nobody counts hands.[17] You cannot capture a process by packing the room, because the room does not take a head count, and a loud incumbent cannot veto a standard by objecting forever. David Clark might not have known it but what he describes seems to be the deliberative process that gives a seat to the slow self as described in chapter 25.

Running code does even more work. A specification does not climb the standards ladder until at least two independent teams, who never coordinated, have built implementations that actually talk to each other.[18] A paper standard written around one company's product cannot make that trip; if only one vendor can implement your standard, you do not have a standard, you have that vendor with better paperwork. Add the quieter rules and the design is complete. You participate as a person, not as a company delegate, and every finished standard is free to read[19] and free to implement. Anyone who joins must disclose patents that touch a draft[20], and working groups route around technology that cannot be implemented royalty-free, which defuses the oldest trick in the standards business: bake your patent into the specification, wait for the world to adopt it, start invoicing. And when a standards body drifts anyway, you can walk out with the standard. For example, if OCPP ever becomes a party you don't want to work with anymore, you can fork and start your own community. That option is what keeps a standard honest.

Hold the energy sector against that checklist and two bad habits show up. The first is the paywall. For example: S2 is officially EN 50491-12-2, and substations talk IEC 61850; to read the official text of any of these open standards, you reach for your credit card and pay a standards body that decides by national and corporate delegation. This makes it the sort of setup large companies like that don't want new entrants. OCPP is again the positive exception: it is now IEC 63584 and to download that standard you must pay, but the guaranteed same standard can be downloaded for free from the OCPP website.

The second habit is worse: the open protocol that phones home through one company's cloud. Much plug-and-charge authentication today hangs from a certificate chain anchored at a single private company, Hubject, and the credential your car transmits carries a persistent identifier[21], so whoever sits at that anchor can watch where and when

you charge, which is to say where you live, work and get treated. None of this is physics. Researchers from Darmstadt and Deutsche Bahn have demonstrated the same handshake with self-sovereign credentials and zero-knowledge proofs: no central gatekeeper, nothing to track, formally verified, and authorisation almost twice as fast as the incumbent system.[22] The gap between what is deployed and what is possible is not an engineering gap. It is the convenience of the hub, and the thirst for information, hardening into a chokepoint one storey above the open wire, exactly where chapter 25 found the cloud-tethered charger. Watch that storey. It is where the next toll booth is being poured.

Open source: keeping energy private and safe

Linux has been hovering at the edges of this book since chapter 21; time to look at it properly. In 1991 a Finnish student posted his hobby operating system to a newsgroup with the immortal disclaimer that it was "just a hobby, won't be big and professional".[23] As predictions go, it was not his best. Today Linux runs every one of the world's 500 fastest supercomputers[24], the majority of the world's websites[25], about ninety per cent of the public cloud[26], and, through Android, two of every three smartphones.[27]

The companies that spent the nineties insisting only proprietary software could be trusted now run their clouds on the descendants of the free thing a student gave away. Chapter 21 promised that large-scale, unpoliced cooperation could build infrastructure; this is the infrastructure.

The energy management system is like a butler with power of attorney: it sees when you sleep, knows when the house is empty, and buys and sells your energy with your money. Open source means the butler keeps a diary anyone may read. You will not read it, any more than I read the Linux kernel. But your cooperative's resident nerd will, and a master's student somewhere, and a competitor hoping to catch a rival cheating, and a regulator who finally can. Veri-

fication does not require everyone to look. It requires that anyone can.

For software wired into millions of grid-connected batteries and chargers, this is not just privacy and hygiene; it is national security. In 2024 an attacker spent years of patient social engineering becoming co-maintainer of xz, a compression library buried in virtually every Linux distribution, and slipped in a back door that would have opened hundreds of millions of servers. It was caught before deployment[28] by one database engineer, employed by Microsoft of all people, who got annoyed that his logins were taking half a second longer than usual and could trace the delay through code that was public all the way down. It was another example of Linus's law: "Given enough eyeballs, all bugs are shallow".[29]

Of course open source doesn't mean all bugs are found that fast. Heartbleed, the 2014 bug that exposed the keys of much of the encrypted web, lived in OpenSSL, software guarding roughly two-thirds of all web servers and maintained by a handful of volunteers, about one of them full-time, on some two thousand dollars a year[30] in donations. After Heartbleed the industry abruptly found millions[31] for the commons it had been freeloading on, and Germany now runs a Sovereign Tech Agency that has put over €40 million[32] into the unglamorous task of maintaining some of the most important open source libraries of the digital world. Energy should copy this reflex before its own Heartbleed. Remember: this software costs a tiny fraction of the hardware and keeping it open makes the software itself much cheaper and avoids vendor lock-in. That should interest all the grid operators and other heavy hitters.

Open source also blocks a subtler attack: malicious compliance. Microsoft's strategy against the open web in the nineties was described inside the company as embrace, extend, extinguish[33]: join the standard, add proprietary extensions until the standard means your product, and one executive reportedly explained that this was a strategy "to cut off Netscape's air supply". The modern version complies in

paperwork and defects in implementation: in April 2025 the EU issued its first fines under the Digital Markets Act, €500 million for Apple, whose app-store rules kept developers from freely telling users about cheaper options elsewhere, and €200 million for Meta's pay-or-consent construction.[34] Code-level defection can only be caught where code, or at least a conformance test anyone can run, is open. This is why energy standards have plugfests and certification suites, and why the dispatch software itself should be readable: malicious compliance needs a place to hide, and open source takes that away.

So when people say: "energy software is critical infrastructure, surely it must be locked down," they have it backwards.

The only thing closed buys you

The strongest case for closed systems is that they ship faster and integrate tighter; the first iPhone really was better than the open chaos around it. But this chapter has been one long demonstration that over a decade or two, walled gardens usually lose to open rivals on usefulness. What closed systems reliably win is the funding round. A moat is a story you tell investors: our customers cannot leave, our data is proprietary, our future revenues are defensible. Doctorow and Giblin documented the model across a dozen industries: the chokepoint is not a side effect of the business, it *is* the business.[35] So when someone designs a closed protocol for your inverter, they are not optimising your energy system. They are manufacturing collateral. The lock-in is the rent, and the rent is what the loan sharks lend against. Closed standards are not technically necessary, and the only thing they reliably help is attracting predatory finance.

Point the giants at the toll booth

Who pays to keep the commons maintained, if not the loan sharks? Joel Spolsky named the mechanism in 2002: *smart companies commoditise their complements*, because demand for your product rises when the things it needs get cheaper.[36]

IBM poured hundreds of millions into Linux not out of idealism but because a free operating system sold IBM's hardware and services, and starved rivals who wanted their operating system to be the toll booth. The trick is to find the giant for whom your commons is a complement, and point it at the toll booth.

Energy has such giants, and some of them are starting to work it out. For a grid operator or a battery manufacturer, the energy management layer is a complement, not the product: a closed EMS is a tax on their business and a leash on their roadmap. So the French transmission operator RTE founded LF Energy in 2018[37] under the Linux Foundation, and grid operators pay for open energy software the way IBM paid for Linux. This is not a research curiosity: Alliander's open forecasting software[38] predicts load on the Dutch grid in production, TenneT runs grid security calculations on open libraries[39], and OpenEMS, the most mature open energy management system, was founded by a battery maker and is now governed by an association of some seventy companies and institutes.[40] The European distribution operators' association has concluded, in public, that operators should stop committing to single vendors and integrate open components themselves.[41] None of these organisations is chasing an exit. They are managing a shared resource, which is exactly the incentive structure you want holding the code.

But there are also sharks in these alliances that see the EMS not as a complement but as the crown jewel. To make sure they don't ruin things a neutral foundation should hold the trademark, contributors should keep their copyright so nobody can relicense the commons into their product, conformance tests catch the "extend" half of embrace-extend-extinguish, and the fork stays available as the ultimate exit. ElaadNL did this very well with OCPP. And where commerce will not move, mandate, as AFIR already mandates open charging protocols. Make open interfaces a condition of grid connection and market access, and the EU turns up once

more in the role this book keeps catching it in: the unglamorous institution that dismantles toll booths.

Open unless

Data, standards and source code should be "open unless". Your private data stays yours and all other secrecy should be the exception that must argue its case. "The code is our competitive edge" is not a case but a symptom of a problem, especially in energy where we want a coordination layer free of lock-in.

So authority keeps you in charge; simplicity keeps the system legible; and openness keeps both honest over time, because authority without openness lets the vendor change the rules under you, and simplicity without openness quietly silts back up into complexity. Together they make the energy system something the internet only half managed to stay: a commons with doors nobody owns, run by software anybody can check, in daylight everyone shares.

28

Universal access to energy

Too many people in energy poverty

666 million people live beyond the reach of any electricity grid, 85% of them in sub-Saharan Africa.[1] So far that means they have no access to electricity which is increasingly *the* type of energy people need to flourish. And the availability of an electricity grid is just half the story. Measure light from orbit instead of connections on paper and you find 1.18 billion people – one human in seven – whose homes at night cannot be told apart from uninhabited land.[2] That means there is a grid but they can't afford to use it.

The textbook assumption is that these poor cannot pay for energy. The numbers say something stranger: they already pay, at the worst rates on Earth. Households without electricity spend $38 billion a year on fuel-based light, and per unit of useful light a kerosene wick costs up to 150 times more than an efficient bulb.[3] A family burning kerosene pays $12 to $18 a year to light one room badly and fill it with smoke.[4] The poorest customers in the world's energy market pay its highest prices. Nobody designed that; it is simply what happens when the only light you can afford is the kind you buy by the bottle, week by week. Or maybe when nobody offered you an LED light on solar yet.

Lighting is the smaller part of the problem. 2.1 billion people cook on open fires or rudimentary stoves, and the smoke killed an estimated 2.9 million of them in 2021, including 309,000 children under five.[5] The burden disproportionally

falls on the women and girls who gather the fuel and stir the pots. Count the sickness, the gathering hours and the climate damage and the bill reaches $2.4 trillion a year.[6] We are, collectively, paying a fortune for the privilege of poisoning the cooks.

Energy poverty does not require a missing wire. 3.8 billion people live in countries with less than 1000 kWh per person per year[7] (250 kWh at home and 750 kWh in society overall) in electrical energy. In those countries about 3 billion people are below that threshold. That means over a third of the world doesn't have enough energy for a fridge, let alone something to stop burning biomass.

It does not even require living in a developing country. In 2024, 9.2% of the EU population could not keep their home adequately warm, rising to roughly one in five in Bulgaria and Greece.[8] In the United States, 27% of households reported difficulty paying an energy bill, and one in five cut back on food or medicine to pay one.[9] The floor is missing in Lagos *and* in Liège.

Chapter 21 established what humans choose when nobody knows in advance which life they will draw: maximise the average, but put a floor under everyone.[10] That instinct is part an innate sense of fairness, kindness and empathy but it's also the oldest insurance policy in the books. And energy sits underneath nearly every capability Sen taught us to count[11]: you cannot study without light, keep medicine without cooling, or join the modern economy without a charged phone. How high the floor should be is a fair fight. That there should be one – first the floor, then the argument about everything above it – is as close to a human universal as politics gets.

Nonetheless we keep failing at delivering it: free electricity blocks, fuel subsidies that mostly warmed the already-comfortable,[12] giveaway stoves... Enough attempts failed, in enough different ways, that some serious people (without exception comfortably above the floor) now conclude floors are a mistake. I think these failed attempts again and again

show us most people are too fair, kind, empathic and decent to give up on so many of their fellow humans. We just haven't found the right formula yet. But the new energy system is about to change that. And what was considered to be the hardest part, now looks like the easiest part.

People without a grid are now the easy part!

The people with no access to a grid at all were considered to be the hardest part. The good news is that in our new energy system they are now the easiest part! Over 95% of those without a grid connection live in rural areas close to the equator.[13,14,15,16,17,18] That means they have two things in common: plenty of sun and plenty of room for solar panels.

One solar panel and a battery the size of a beer crate is enough to give a household there 1 kWh a day even in the rainy season. Enough for phones/computers, lights, refrigeration and a fan. Add two more solar panels (not more batteries) and induction cooking becomes possible. No more searching for wood and dung hours a day. No more destroying any nature left. No more poisoning lungs.

Currently three solar panels would cost about $200. The cheapest 2 kW off-grid inverters costs around $100. A five kWh battery will cost around $200 in a few years. $500 in total. Include streamlined financing and distribution and you are looking at around $700 for a family of on average seven people. $100 per person.

Such a setup could easily last 20 years and if people have to pay for it themselves they will take care of it and sell it if they don't need it anymore or upgrade. So that's $5 per person per year. Times 660 million people we are talking about 3 billion per year. Compare that to the $2.4 trillion in health damage alone and it is a truly paltry sum. If you care about nature and climate change it's also the most effective intervention possible per dollar. And it aligns with our feeling of fairness. Very few people will say: these families don't deserve $5 per person per year to solve their energy problems.

But it gets even better! Because poor households in sub Saharan Africa already pay around $10-$50 per person per year for kerosene lights and $10-$50 per year for cooking fuel. So a solar kit would only cost around a tenth of that! We don't have to present this as charity. We are only providing an organisational upgrade that gives them direct access to a cheaper universal energy source that is already directly available to them. And on top of this less sickness and enormous productivity gains because you can read at night and no longer need to go foraging for wood hours a day.

What we need to do is create competition (companies are much better and cheaper at delivering this than NGO's and governments). Standardize development, create open standards and open source software and reference designs. Provide cheap financial backing that makes risk taking cheap. In short, provide capabilities to entrepreneurs willing to tackle this while avoiding extraction. One of the simplest and most effective distribution mechanisms is a kill switch that is deactivated after the loan is finished. So when households don't provide mobile payments, their electricity stops working. As soon as the payments start, the electricity works again. Brutal but effective and cheap. And once the loan is paid off the installation is theirs forever.

That last is important because this could become an extremely extractive scheme targeting a vulnerable population. Some firms keep ownership deliberately vague, so the paying never quite ends.[19] So we have to make predatory lending schemes unattractive by withholding anything that was created open source, withholding any financial support, and by mandating against it if you are a government. What we need is something that people pay off in a maximum of five years, and then it's theirs. No strings attached. No kill switch. No lock in to a software vendor who might not provide over-the-air updates.

And it's already happening. Off-grid solar provided more than half of all new connections in sub-Saharan Africa and is already the cheapest route for roughly two in five of the

people still waiting.[20] In Bangladesh, the state-backed lender IDCOL financed 4.1 million solar home systems – the largest off-grid electrification program in history – with instalments deliberately calibrated to the kerosene spending each system replaced, and every contract ending in ownership.[21] The kerosene budget became a mortgage, the mortgage became a paid-off roof, and nobody resents a family that owns its panel.

You can argue about the bolting on of a temporary toll booth. Pay-as-you-go solar – the kit on credit, instalments by mobile money, a remote kill switch as collateral – carries financing premiums around 94% over the cash price at commercial terms, with roughly half of 2023's customers written off or more than a month behind.[22] I think we (people and governments in richer countries looking for a cheap way to counter climate change and do good) should lower these premiums by carrying the risks. And we could improve on some sense of dignity by giving people fair warning. Now it's often: miss a payment and the kill switch turns your house dark in front of the neighbours; when one provider's customers had the lockout clause explained to them, purchase interest fell from 63% to 40%.[23]

But in fairness, the kill switch is also why an uncollateralized household gets credit at all: in a Ugandan trial, digital lockout cut default by 19 percentage points.[24] So treat it like what it is – collateral. Let it do its job, then make it die. Any lease, lockout or remote-disable right should expire by law at the earlier of payoff or five years of active payments, after which the device is property, full stop. M-KOPA's original kit reached full ownership in 365 daily payments,[25] so five years is not radical. It is a ceiling on how long the sun may be rented back to its owners.

Finishing the job is a campaign on several fronts at once, and none of them requires inventing anything. Researchers first: publish open reference designs – circuit boards, battery management, charge controllers, test protocols – that any competent workshop from Nairobi to La Paz can copy

without paying for a licence. Laboratories have quietly run this experiment already: scientific equipment built from open-source designs costs roughly 87% less than its proprietary equivalents.[26] Pair the blueprints with the durability standards the field keeps asking for – replaceable batteries, available spare parts, repairability[27,28] – because a legal right to own hardware that dies in year three is a right to own junk. Chapter 27 made the general argument that open standards are how newcomers compete; here they are how a thousand local manufacturers come into existence.

Bankers second. Commercial pay-as-you-go needs effective interest around 30% just to survive its own write-offs,[29] and at unsubsidised instalments only 22% of unconnected households can afford even the smallest real system.[30] Cheap, patient capital changes that arithmetic: concessional loans and guarantees pull the rates down, and subsidies can ride payment rails that already exist instead of building bureaucracies that don't. Togo pays $4 a month straight into the instalment account of a provider the household chooses – 134,000 kits and counting[31] Rwanda's results-based subsidies reached 370,000 households.[32] And at the very bottom, subsidy can safely go all the way to free: charging $0.60 instead of nothing for a bednet cut uptake by 60 percentage points, while free distribution produced no waste[33] and made people more willing, not less, to pay later.[34] Free at the bottom does not corrupt the market. The market was never going to reach the bottom on its own.

Appliance engineers third. Every watt an appliance does not draw is panel and battery nobody has to buy: a super-efficient solar vaccine refrigerator needs one tenth the panel and battery capacity of a conventional one,[35] and the same lever works through LED lights, DC fans and televisions. Efficiency is what makes the entry kit beat kerosene on price rather than on principle. The kit must also be something people want, because the poor refuse goods that mark them as poor and stretch for goods that signal a future – households living on a dollar a day buy televisions before the things

experts call sensible.[36] The cautionary tale is the improved biomass cookstove: promoted for decades because experts approved of it, abandoned by year two because nobody wanted it, delivering no measured health gain.[37] Induction stoves are a completely different story but make them products people actually want. Maybe the first rung of a normal product line – same brand, bigger tiers above,[38] the better-off buying up and the kit carrying no poverty mark. Dignity counts.

Distribution fourth and last: sell the kit where airtime is sold, price it in mobile money, install it the same day, write the contract on one page. The kit must be the easiest purchase in the market, visible at every kiosk until nobody can fail to notice it exists. Indonesia showed what ubiquity plus a starter package does: a free initial kit and a built-out supply chain moved 50 million households from kerosene to LPG in five years.[39] Availability everywhere is not a logistics detail. It is how a floor announces itself.

Again: this is not charity. It's cheaper energy and when rural KwaZulu-Natal was electrified, female employment rose nine percentage points within five years – from a baseline of about seven, a more-than-doubling – as electric light and cooking released hours into paid work.[40] Kenya's M-Pesa lifted 194,000 households out of extreme poverty, the effect strongest where women ran the household – and the entire system presumes a charged phone.[41]

The new energy system offers an unprecedented chance to lift 660 million people out of energy poverty by giving them cheaper and ubiquitously available energy. Let's make it happen.

The complicated part: people with a grid connection

How do you help people when the problem is not access to the grid but poverty? Delhi chose an interesting option. The city gives every household its first 200 kWh per month for free and cuts the price of the next 200 kWh by half.[42] Around 4.4 million households pay nothing at all for electricity.[43]

Economists calculate the "cost" at $450 million a year.[44,45] But it's not really a cost. It's mostly a floor that keeps electricity cheap for those with little money.[46] It doesn't feel like redistribution because everyone can profit from it, leaving only a small genuine transfer to the poorest and almost nothing spent on administration. The clearest proof that it works is political. The policy helped carry Arvind Kejriwal's party to landslide victories in 2015 and 2020[47,48] and when the BJP — whose leaders had dismissed such schemes as a dangerous "revdi," or free-sweet, culture[49] — finally won Delhi in 2025 after 27 years out of power,[50] it did not scrap the subsidy. It kept it, and spent even more.[51] It illustrates that there are ways to institute a floor with dignity for all.

Or take the UK. In July 2024 the Winter Fuel Payment Britain gave to pensioners became only for the poor, shrinking the covered population from 10.8 million to 1.5 million. The government's own figures showed that the new requirement - proving you were poor - would exclude about 880,000 pensioner households who were entitled, simply because they were too proud or too unaware to apply..[52] Within weeks, 59% of the country opposed the cut.[53] Within a year the payment was back, universal by default, clawed back from incomes above £35,000 through the tax code.[54] The Institute for Fiscal Studies' verdict was that simply paying everyone "would be simple and avoid administrative overheads".[55]

But it's hard to reach people in real poverty. South Africa budgets Free Basic Electricity for 10.9 million households and delivers it to 1.75 million – one in six of those already paid for.[56] When researchers spent nine months helping 30,000 likely-eligible elderly Americans onto food stamps, ordinary conditions enrolled 6%; information plus hands-on assistance managed 18% – and the neediest were precisely the ones the paperwork screened out.[57] Britain's social broadband tariffs reached 5% of the entitled; 69% had never heard of them.[58] Chapter 21 explained the mechanism: scarcity itself taxes the bandwidth that forms and files a

claim.[59] An application form is a means test that charges its fee in attention, billed to the people who have the least of it.

Generosity should have a ceiling. Punjab made farm electricity free without limit; tubewells multiplied from 190,000 to 1.38 million and groundwater fell measurably faster than in the state next door.[60] And floors written in fixed currency rot quietly: Iran's universal cash transfer, a genuine lifeline at launch, lost most of its real value to inflation within a decade.[61]

I think most failures do at least one of five things wrong: asked people to apply, funded the block from the price it sat beneath, set no ceiling below luxury, paid in melting currency, or hid the benefit so well that nobody defended it. Flip all five and the most promising design assembles itself. A modest block of kilowatt-hours on every connection – every connection, the minister's included – delivered automatically by the meter that already knows your address. Funded from outside the energy bill: general taxation, carbon revenue, and where fairness demands it, clawed back from high incomes through a tax system that already knows what everyone earns. Sized below typical consumption, so every unit beyond the block costs full price and thrift keeps paying. Denominated in energy rather than money, so it cannot be inflated away. Printed as a named line on every bill, so everyone can see exactly what they would lose. Call it a basic energy income. And under it, non-payment stops meaning darkness: the meter throttles to the floor instead of cutting to zero, and the lights stay on while the debt gets sorted out.

No country has run that full package, but every component is in production somewhere. Defaults: when Britain switched workplace pensions from apply-to-join to automatic, participation went from 56% to 88% in a decade[62] – in the same country where applied-for help reaches one eligible household in twenty. Below-typical sizing: Germany's gas price brake covered only 80% of last year's consumption, precisely so that saving still paid.[63] Visibility: Canada

rebated its carbon tax invisibly, left roughly 80% of households net winners, and watched the policy die because the winners never noticed[64,65] Switzerland prints its CO2 rebate as a named line on a bill every resident already receives, and the levy survives.[66] The floor can be built: France keeps 1 kVA flowing for at least 60 days before any cut-off,[67] Flemish budget meters keep delivering 10 amperes when the credit runs out,[68] and EU law now requires every member state to protect the energy-poor from disconnection.[69] Smart meters can limit current today. The floor needs no new hardware, only a decision.

Some economists object that a cash transfer would be cleaner,[70] and on a blackboard it would; but it doesn't fit our psychology nearly as well, is not self-indexing, does not survive non-payment, and must be applied for. I think it's just an example of economists not having come to grips with the fact that real humans are not homo economicus. So learn what works for real people and go for a universal energy floor with (limited) inequality above.

Just two and a half days

The bill for the whole thing – universal electricity and clean cooking for everyone on Earth by 2030 – could be less than $45 billion a year.[71] Fossil fuel subsidies, explicit and implicit, run to $7 trillion a year.[72] Divide those numbers and the entire energy floor for the species costs two and a half days of what we already spend on subsidizing fossil fuels. That is not just unjust. That is a surreal and perverse miscarriage of justice. It is simply and entirely unacceptable.

This is not a sacrifice we are weighing. It is loose change we have not bothered to pick up. Imagine all the people getting more capability to add not only their own but everybody's flourishing! Imagine being able to tell your children that you helped to solve energy poverty!

29

Conclusion

This chapter is in preparation.

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