Economics from the Top Down

new ideas in economics and the social sciences

A Tour of the Jevons Paradox: How Energy Efficiency Backfires

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May 17, 2024

> [R]esource productivity can — and should — grow fourfold. . . . Thus we can live twice as well — yet use half as much.
>
> — *Factor Four*, 1997

When it comes to our sustainability problems, striving for greater resource efficiency seems like an obvious solution. For example, if you buy a new car that's twice as efficient as your old one, it should cut your gasoline use in half. And if your new computer is four times more efficient than your last one, it should cut your computer's electric bill fourfold.

In short, boosting efficiency seems like a straightforward way to reduce your use of natural resources. And for *you* personally, efficiency gains may do exactly that. But *collectively*, efficiency seems to have the opposite effect As technology gets more efficient, we tend to consume *more* resources. This backfire effect is known as the 'Jevons paradox', and it occurs for a simple reason. At a social level, efficiency is not a tool for conservation; it's a catalyst for technological sprawl.[1]

Here's how it works. As technology gets more efficient, it cheapens the service that it provides. And when services get cheaper, we tend to use more of them. Hence, efficiency ends up catalyzing greater consumption.

[1] Credit to Ulf Martin for inspiring the language of 'sprawl'. In a 2019 paper, he describes capitalist credit as a form of 'autocatalytic sprawl'.

Take the evolution of computers as an example. The first computers were room-sized machines that gulped power while doing snail-paced calculations. In contrast, modern computers deliver about a trillion times more computation for the same energy input. Now, in principle, we could have taken this trillion-fold efficiency improvement and reduced our computational energy budget by the same amount. But we didn't.

Instead, we took these efficiency gains and invested them in technological sprawl. We took more efficient computer chips and put them in *everything* — phones, TVs, cars, fridges, light bulbs, toasters … not to mention data centers. So rather than spur conservation, more efficient computers catalyzed the consumption of more energy.

In this regard, computers are not alone. As you'll see, efficiency backfire seems to be the rule rather than the exception. Far from delivering a cure for our sustainability woes, efficiency gains appear to be a root driver of the over-consumption disease.

The search for a sustainability cure

Humans, being fad-prone animals, excel at taking old ideas and redressing them in language that's shiny and new. Hence we get the modern obsession with 'resource efficiency'.

Of course, the word 'efficiency' is not new. However, humanity's sustainability predicament has given the pursuit of efficiency new meaning. In the before times, 'efficiency' was understood as a way to cut costs and bolster profits. But in recent decades, 'efficiency' has been rebranded as a tool for sustainability. As the UN Environment Programme puts it, the pursuit of resource efficiency can (supposedly) "decouple economic development from environmental degradation".

So where did this reinterpretation of 'efficiency' come from? Well, it was a collective effort that gained traction in the 1990s, the decade when our sustainability problems became widely discussed. Perhaps more than any other work, the book *Factor Four* (written by Ernst von Weizsäcker, Amory Lovins and Hunter Lovins) popularized the idea that efficiency could be a cure-all for our sustainability woes. Published in 1997, the book came out just as the phrase 'resource efficiency' exploded in popularity. Figure 1 shows the timing.

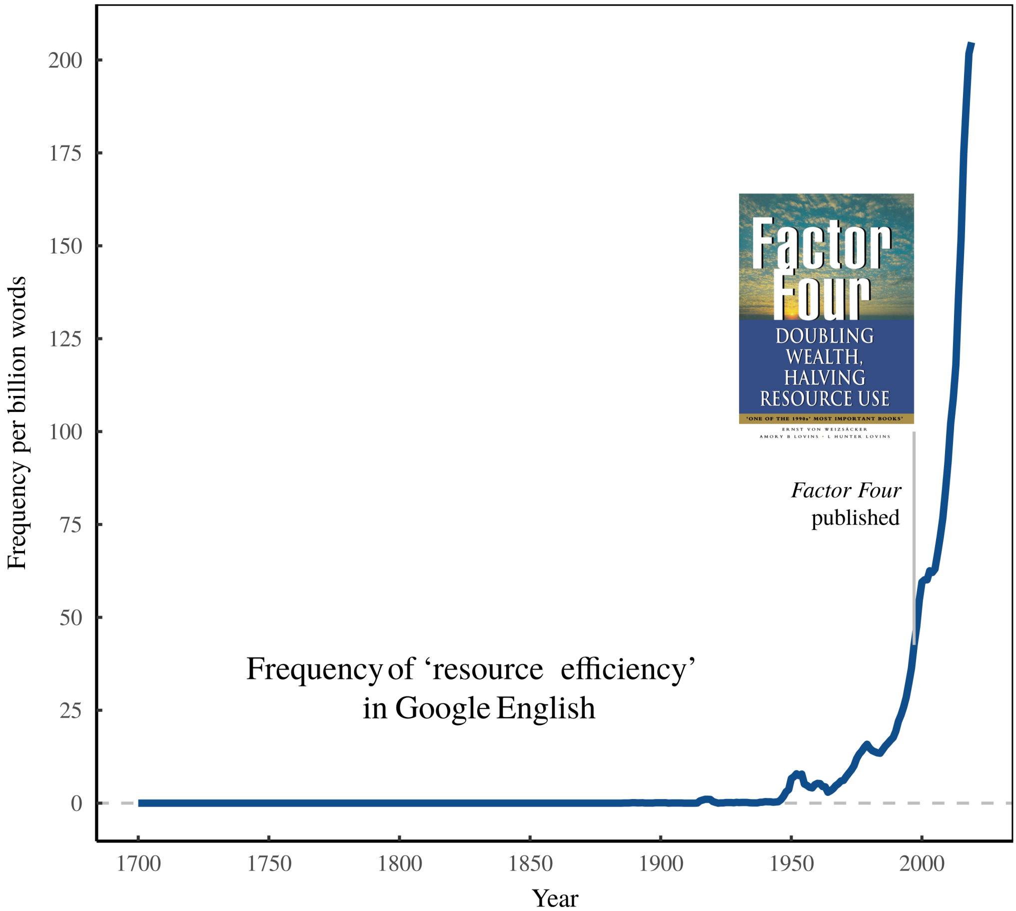

Figure 1: 'Resource efficiency' becomes a fad

The idea that efficiency could solve our sustainability problems gained traction in the 1990s. It was popularized by the 1997 book *Factor Four*, which argued that a fourfold increase in technological efficiency could double wealth while halving resource use. Sources and methods

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Factor Four's thesis was simple: if our technology were to grow four times more efficient, we could live *twice* as well, while cutting our resource budget in *half*.

Sounds compelling, right?

Sadly, there were some nagging problems. True, *Factor Four* made a well-reasoned case that many of our technologies could grow four times more efficient. But when it came to translating this efficiency into resource conservation, details were scarce.

Worryingly, the book mostly ignored the historical record. And that turns out to be a fatal flaw. You see, efficiency improvements are not a new invention; they've been happening continuously for at least three centuries. And over that time, resource use didn't shrink. It ballooned.

In what follows, we'll look at this efficiency-driven bonanza But first, let's revisit the man who first predicted that efficiency would backfire.

A neoclassical economist frets about sustainability

A century before the modern obsession with 'resource efficiency', William Stanley Jevons worried about sustainability.

Backing up a bit, Jevons is best known today as one of the founders of neoclassical economics — a co-inventor of the theory of marginal utility. But before Jevons became obsessed with counting 'utils', he was anxious that Britain was running out of coal.

In 1865, Jevons caused a minor sensation with his book *The Coal Question*. Written during the heyday of British coal mining, the book predicted that Britain would one day exhaust this precious resource. But when the coal crisis didn't pan out, the public lost interest.

Of course, Jevons was right to worry about the exhaustion of British coal ... he was just a bit early. Although he didn't live to see the day, British coal production peaked in 1913 and declined continuously thereafter. In hindsight, Jevons got the last laugh. Today, Britain produces less coal than it did in 1700. Figure 2 paints the picture.

I would argue that Jevons also got the last laugh about another idea. In *The Coal Question*, Jevons spent most of his time exploring possible ways to make coal reserves last longer. And one of the solutions he floated was to make coal engines more efficient. But instead of celebrating efficiency as a solvent for conserving resources, Jevons argued that it would have the opposite effect. Greater efficiency would *amplify* consumption:

> It is wholly a confusion of ideas to suppose that the economical use of fuel is equivalent to a diminished consumption. The very contrary is the truth.
>
> (Jevons, 1865)

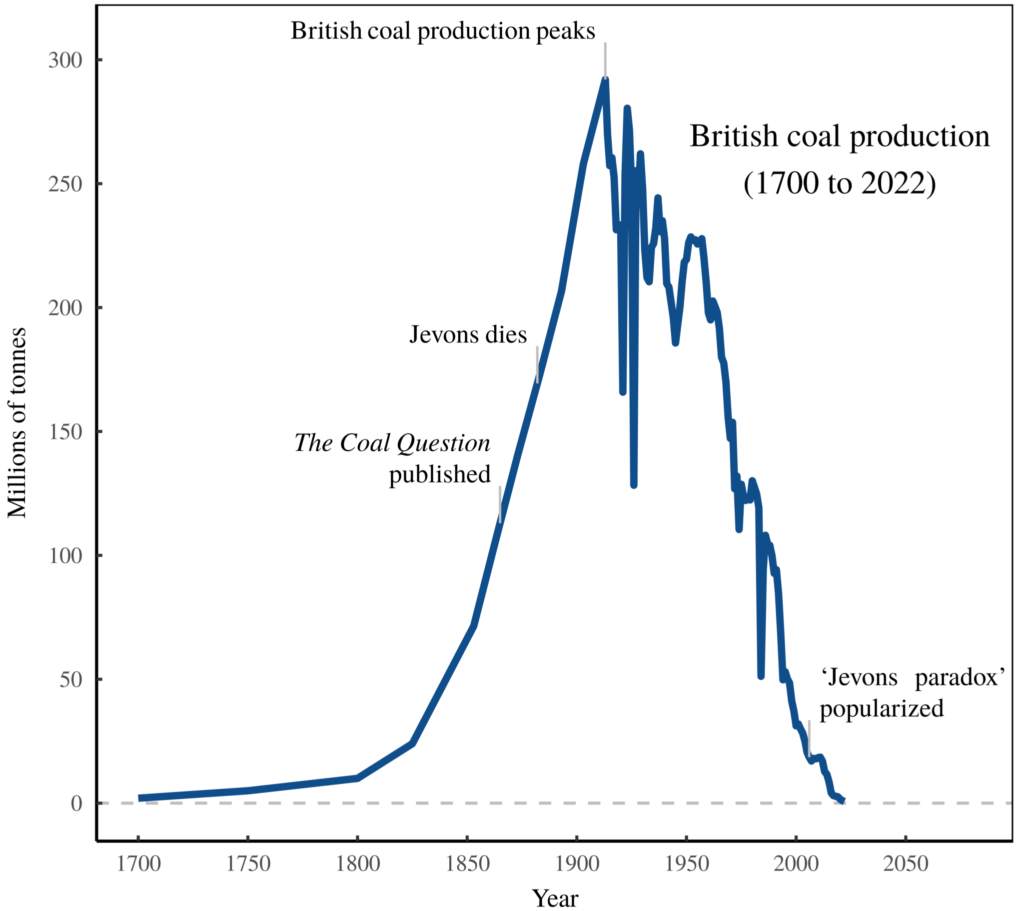

Figure 2: Jevons frets about British coal exhaustion

In 1865, William Stanley Jevons published his book *The Coal Question*, which worried about the exhaustion of British coal. Although Jevons wouldn't live to see it, British coal production peaked in 1913. A century later, when British coal was all but gone, scientists returned to Jevons' work on efficiency, coining the term the 'Jevons paradox'. Sources and methods

The reason efficiency backfires, Jevons reasoned, is that it stimulates what he called "new modes of economy". In other words, efficiency catalyzes technological sprawl.

Neglecting technological sprawl

It's the neglect of technological sprawl that ultimately undermines techno-optimist books like *Factor Four*. Although the authors were right to argue that technology can get more efficient, they were wrong about what we would actually *do* with this newfound efficiency.

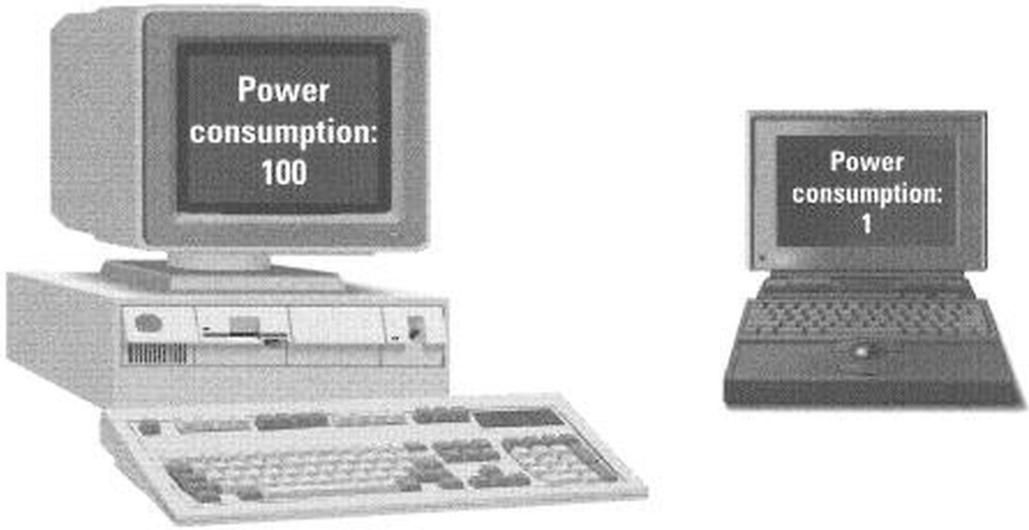

Figure 3: Switch to a laptop, reduce your electricity use one-hundredfold!
An optimistic calculation from *Factor Four*.

Let's use computers to illustrate the problem.

To the 21st-century eye, *Factor Four* contains a delightfully retro discussion about how laptop computers could be tools for conservation. "A modern laptop," the authors observed, "can ideally reduce electricity demand by 99 per cent when compared with an old-fashioned desktop computer." What's interesting is that you could make the same argument today. Except that the authors were talking about clunky, 1990s machines like the ones pictured in Figure 3.

Now, there's no question that you *could* save electricity by switching from a desktop computer to a more efficient laptop. But once you buy the new laptop, there's no law that says the old machine must stay off. Heck, your kids have been whining about having their own computer. Let them use the desktop while you work on the laptop. Actually, new laptops are so cheap that you could buy one for each family member. And look at those new iPods. Let's put *them* on the Christmas wish-list.

If this story sounds familiar, that's because it's how rising computer efficiency *actually* played out. With each generation of new device, computers could do more computation with less energy. But the end result was not resource conservation. Instead, rising efficiency catalyzed new forms of technological sprawl. Families went from having a single computer to having a sea of devices — laptops, iPods, iPads, iPhones, smart TVs, dishwashers connected to the internet, and so on.

Back to *Factor Four*. We can certainly forgive the authors for not foreseeing the specifics of how computational sprawl would play out. Yet the fact that there *would* be new forms of sprawl was utterly predictable. And that's because in 1997, rising computer efficiency was nothing new. It had been happening continuously for a half century.

Figure 4 shows the scale of progress. Things got rolling in 1946 with the birth of ENIAC, the first modern computer. When fed a watt-hour of electricity, the room-sized machine could barely muster a single computation. Fast-forward to 2009, and a three-pound laptop could take the same energy input and do a *trillion* computations. That's a stupendous increase in efficiency.

My point is that when *Factor Four* was written in 1997, the authors could have looked at the history of computational efficiency and seen what it had wrought. The answer — then and now — was *not* resource conservation. It was the continuous expansion of technological sprawl.

On the consumer end, new devices proliferated. And on the industrial end, the demand for cloud computing spawned an ever-expanding network of data centers. Today, the computational sprawl has reached comical levels. Using the most modern, ultra-efficient computers, data centers guzzle power so that half-baked chatbots can respond to your queries with answers that are plausible but wrong.

Some people call this 'progress'. But another word for it would be the continuous *backfire* of computational efficiency.

Backfire on the blockchain

Despite the ubiquity of computers, it's surprisingly difficult to pin down their collective power budget. Hence, it's difficult to measure the scale of efficiency backfire. But in *specific* applications, we do have hard numbers .. and they are jaw dropping.

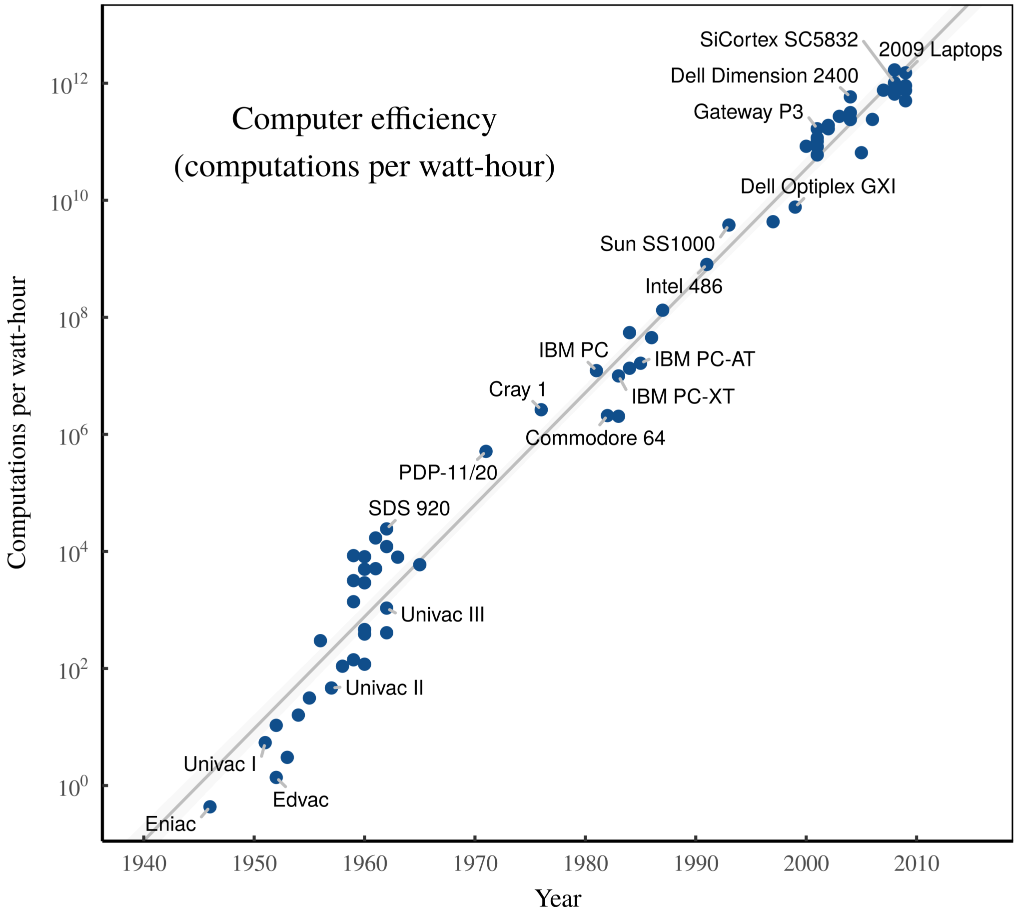

Figure 4: The evolution of computer efficiency

Since the birth of modern computers in the mid 1940s, computational efficiency (the number of computations per watt-hour) has increase by at least a factor of a trillion. Sources and methods

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One such application is the 'blockchain' — the technology that powers cryptocurrencies like Bitcoin. Now, you've probably heard that the Bitcoin network uses loads of energy. And it does. But before we look at this gluttony, let's study a (seemingly) more positive trend. Over the last decade, Bitcoin mining has grown vastly more efficient.

Figure 5 tells the story. Since 2010, the hashing efficiency of Bitcoin tech grew by a factor of a *million*. Backing up a bit, a 'hash' is the problem that Bitcoin miners solve in order to verify transactions. What's important about this algorithm is that it involves copious computation — it's nothing but brute-force trial and error. And so Bitcoin miners are under tremendous

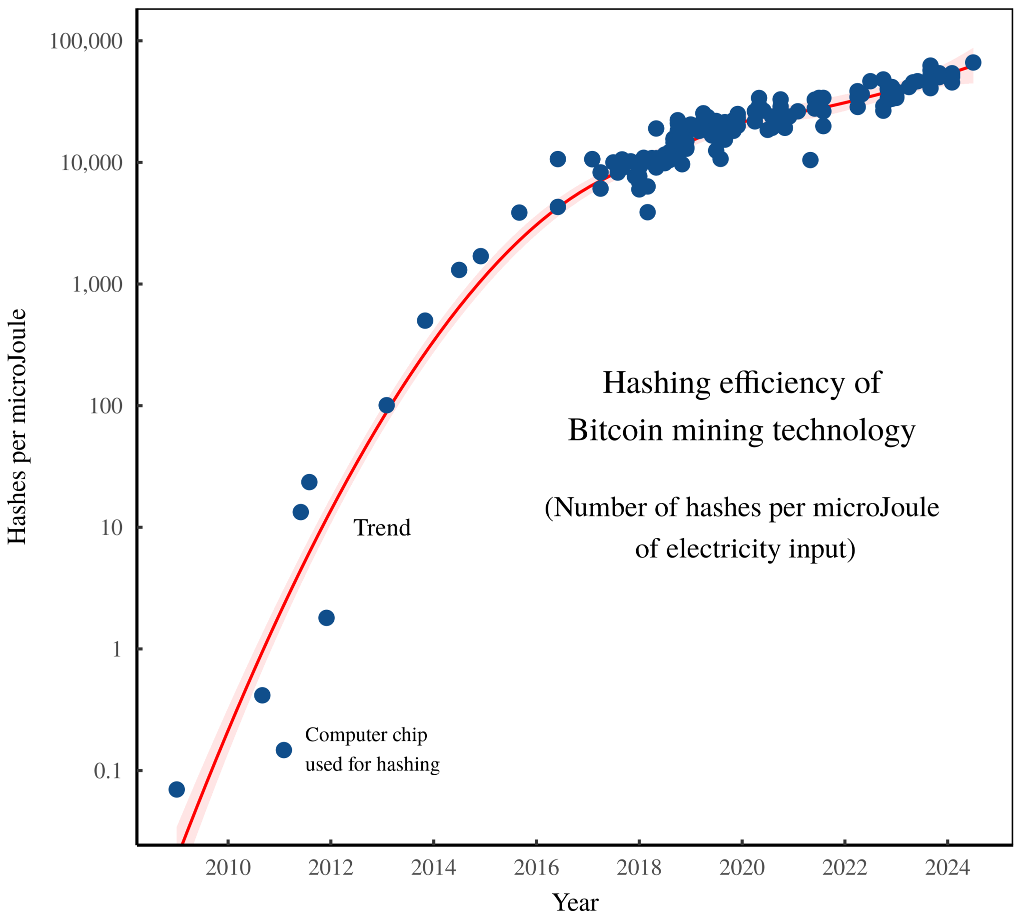

Figure 5: The rising efficiency of Bitcoin hashing technology

Each blue point represents a computer chip used for Bitcoin hashing (mining). The horizontal axis shows the chip's date of release. The vertical axis plots the chip's hashing efficiency — the number of hashes per microJoule of electricity input. In the early days of Bitcoin, standard GPUs (graphical processors) were repurposed for hashing. Soon, however, hashing was done on purpose-built chips, resulting in vast increases in efficiency. (To view the various chips behind each data point, see Figure 18 in the appendix.) Sources and methods

pressure to bolster their profits by using the most efficient technology. In 2010, that meant using standard GPUs. But today, it means using purpose-built hardware that is vastly more efficient.

Given the million-fold improvement in hashing efficiency, we can ask what it wrought. Did it cause Bitcoin miners to save spectacular amounts of electricity? Or did it induce new forms of technological sprawl?

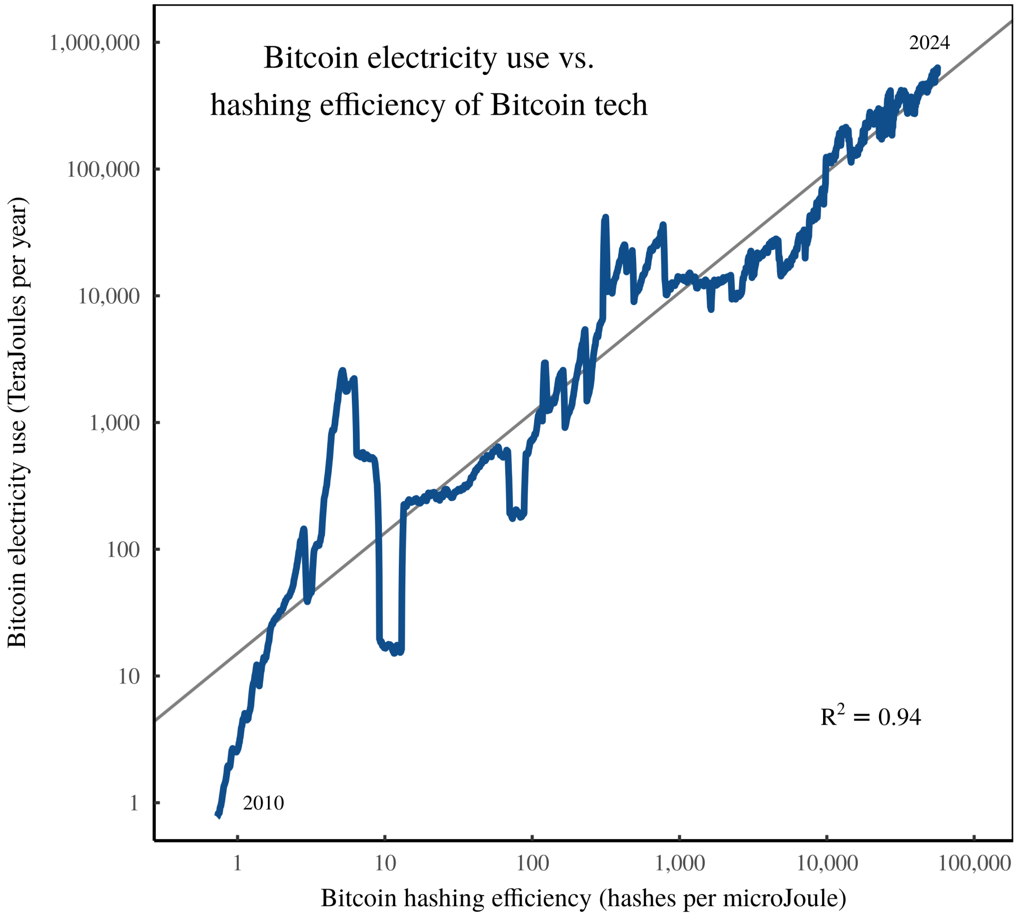

Figure 6: Bitcoin miners discover the Jevons paradox

Given the million-fold increase in hashing efficiency that occurred between 2010 and 2024 (horizontal axis), it's conceivable that Bitcoin's energy demands could have decrease by the same factor. But instead, they did the opposite, *growing* by a million-fold (vertical axis). Sources and methods

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Points to readers who guessed the latter. With more efficient technology in hand, Bitcoin miners responded by *expanding* their operations. The result, as Figure 6 shows, was that the million-fold efficiency improvements were met with a million-fold increase in Bitcoin's energy budget. As I said, jaw-dropping backfire.

The Jevons paradox comes to America

Among the spectrum of modern technology, computers are probably unique for the staggering scale of their efficiency improvements. Elsewhere, the gains have been more modest. Still, it's worth remembering that efficiency gains were not an invention of the sustainability-aware 1990s. Long before anyone cared about conserving resources, industrial tech was getting steadily more efficient.

Think of the difference between the cars of the 1910s and the cars of today. Think of what electricity generation plants looked like in 1900 and what they looked like now. Think of how powered flight went from not existing to landing on the moon in 66 years. In hindsight, the scope of this technological change is breathtaking. And the thread of efficiency runs continuously through it.

Interestingly, few scientists have attempted to look at the big picture of this efficiency thread. In other words, we know a lot about the efficiency improvements of specific machinery. But we know surprisingly little about how these improvements add up across the whole of society.

That changed in 2009 with a book called *The Economic Growth Engine*.[2] Written by economists Robert Ayres and Benjamin Warr, the book attempts to add up efficiency gains across the full range of technology. In other words, Ayres and Warr look at how much primary energy gets pumped into society. Then they estimate how much 'useful work' gets done. Take the ratio of these two quantities and you get a measure of aggregate efficiency.

[2]Permit me a brief book review. I recommend reading *The Economic Growth Engine* for two reasons. First, Ayres and Warr are extremely knowledgeable about the science of energetics, and the book is packed with useful information on this topic. Second, the book is a case study in how heterodox economists fall into conceptual traps laid by neoclassical economics.

After conducting detailed calculations of how energy gets converted into useful work, Ayres and Warr end up dumping the latter quantity into the silliest of neoclassical inventions — the aggregate production function. This function takes inputs of capital and labor and then 'explains' the growth of real GDP.

True, Ayres and Warr add 'useful work' to the standard list of inputs. However, they gloss over the gaping flaws with production functions. They religate the 'Cambridge Capital Controversy' — which demonstrated that 'capital' (and by extension, 'output') cannot be aggregated objectively — to a footnote.

Frustratingly, Ayres and Warr go on to claim that the Cambridge controversy was 'resolved', in the sense that economists arrived at an agreed upon method for 'measuring' the capital stock. But what they mean here is that neoclassical economists 'resolved' the Cambridge controversy by agreeing to *ignore* it.

Also, Ayres and Warr fail to consider the immense ambiguity involved with measuring GDP. In fact, it doesn't seem to dawn on them that the most important feature of 'economic growth' is the rise of useful work itself, and that 'real GDP' is an ideological distraction not worth explaining.

Still, reading *The Economic Growth Engine* was foundational to my own thinking, primarily because it made me realize that whenever neoclassical economics rears its head, it ruins otherwise good science.

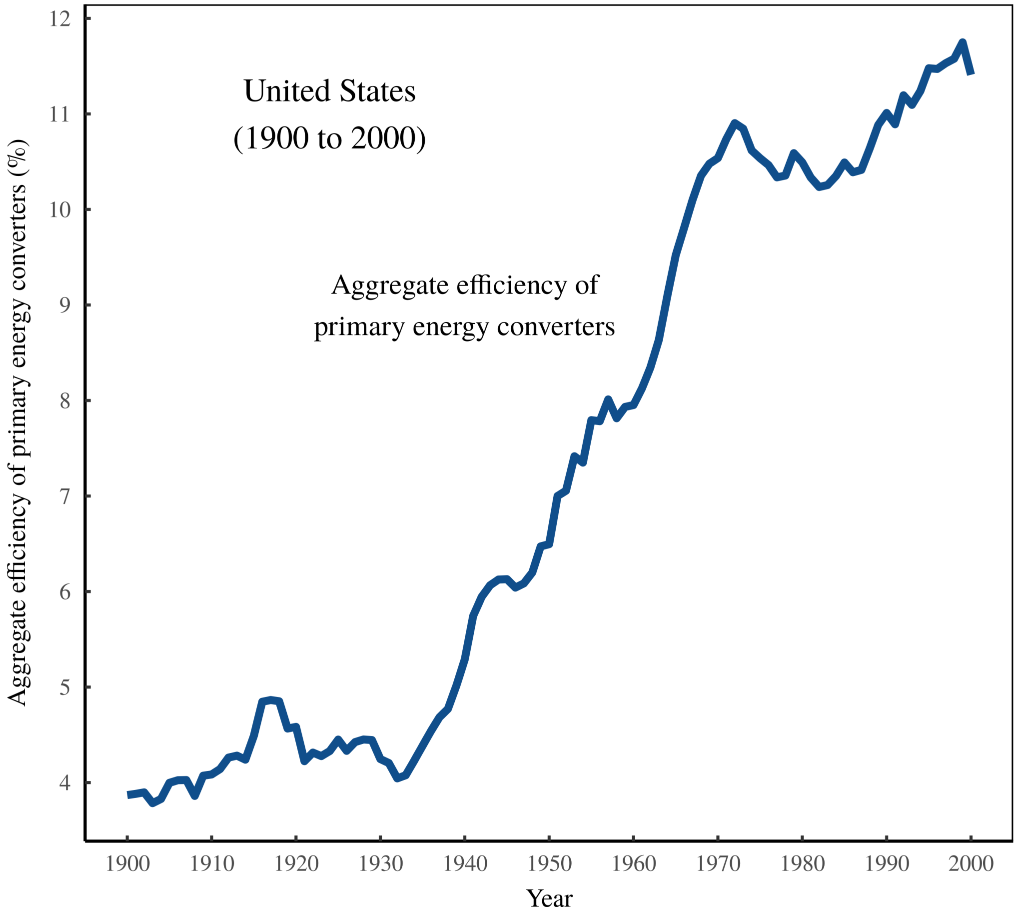

Figure 7: The aggregate efficiency of primary energy converters in the United States

Throughout the 20th century, US primary energy converters — technology like internal combustion engines, thermal power plants and various industrial processes — grew steadily more efficient. This figure show Ayres and Warr's estimates for the aggregate efficiency of these machines. Sources and methods

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Figure 7 shows Ayres and Warr's estimates of aggregate efficiency in the United States. Starting in 1900, energy-conversion technology was on average, about 4% efficient. By 2000, that value had increased to nearly 12% — a roughly threefold improvement.

So again, we can ask what these efficiency gains wrought. Did they work to conserve energy? Or did they catalyze new forms of technological sprawl?

Again, the evidence speaks for itself. As Figure 8 shows, the threefold improvement in US aggregate efficiency was met with a threefold *increase* in energy use per person. Instead of investing in energy conservation, Amer-

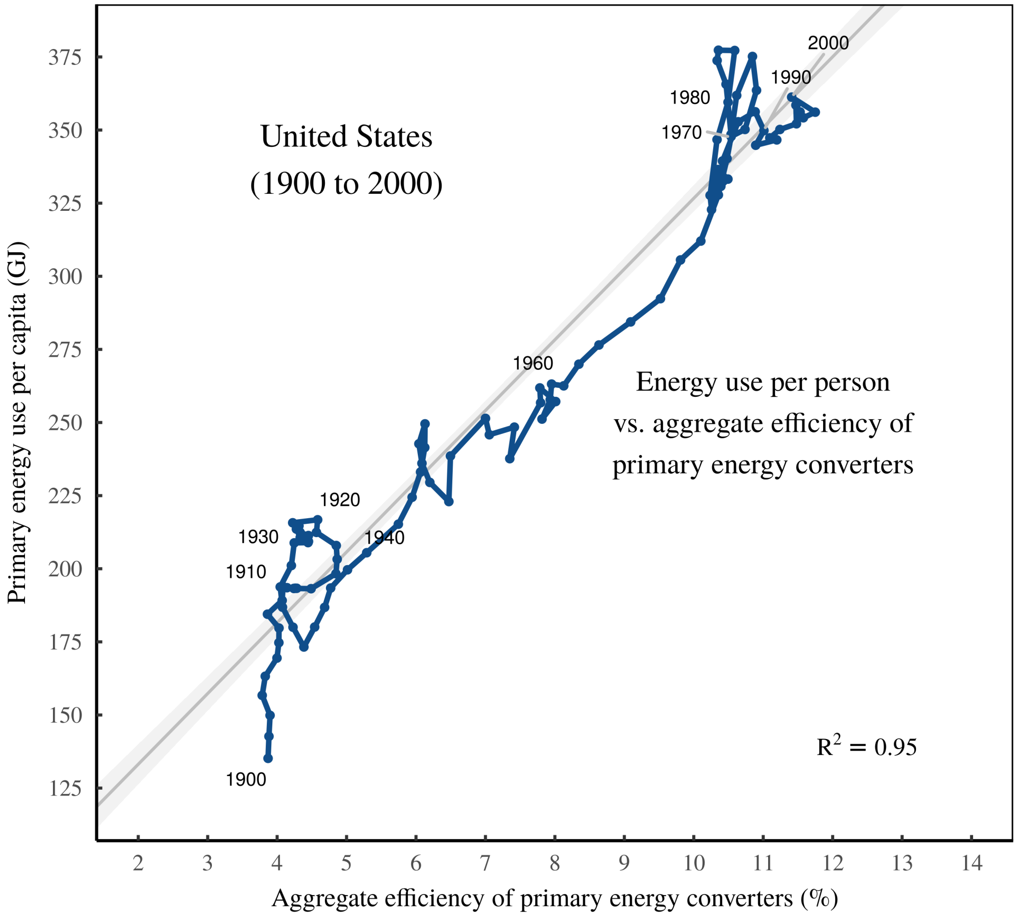

Figure 8: The United States discovers the Jevons paradox

As the efficiency of US primary energy converters increased (horizontal) access, so did its primary energy use per person (vertical axis). Sources and methods

icans took their efficiency gains and used them to catalyze new forms of technological sprawl — interstate highways, massive suburbs, theme parks, and gadgetry of every kind.

Now to be fair to Americans, their tech sprawl was uniquely bombastic. But the efficiency backfire was itself part of a common pattern. The same thing happened in the United Kingdom, in Japan, and in Austria. And while we don't yet have expansive data, I'd bet that this efficiency backfire happened in *every* country.

A world built on heat engines

Speaking of expansive, let's turn now to the global level, where we'll watch three centuries of energy-efficiency backfire. But first, I want to reflect on the technological 'stack' that supports industrial society.

In our daily lives, the top of the tech stack gets most of the attention. Phones beep notifications, computers demand our time, ovens cook our food, and washing machines clean our clothes. While this top-level tech is important, when it comes to the Jevons paradox, it's the bottom-level technology that's most crucial. And at the very bottom of the industrial stack lies the mainspring of fossil-fuel-based civilization: the *heat engine*.

For those who are unfamiliar, a heat engine is a machine that converts heat into mechanical work. It's no exaggeration to say that these machines are *the* primary driver of industrialization. Without them, fossil fuels are of limited use — they are little more than a source of heat. But *with* a heat engine, the energy contained in fossil fuels can be converted into more useful forms of work. Today, heat engines are what drive our cars, push our trains, fly our planes, and sail our ships. And heat engines generate the vast majority of our electricity.

Now, like most technologies, heat engines had humble beginnings. Just as the first computers looked like room-sized caricatures of today's sleek machines, the first heat engines were nothing like the tightly engineered machines of the 21st century. The earliest heat engines were rickety Rube Goldberg devices that leaked energy from every seam.

Case in point was the Newcomen engine, the first commercially viable steam engine. Patented in 1712, the machine was spectacularly inefficient, wasting something like 99.3% of the coal energy that went into it.[3] In fact, the Newcomen engine was so wasteful that it only worked when placed directly beside a coal mine, where it could be fed a constant stream of fuel.

At best, the Newcomen engine was the ENIAC of steam engines — a barely viable prototype that demonstrated the heat engine's potential. Better machines came later. In 1769, James Watt patented his much-improved steam

[3] Efficiency estimates for the Newcomen engine come from Vaclav Smil's book *Energy and Civilization*.

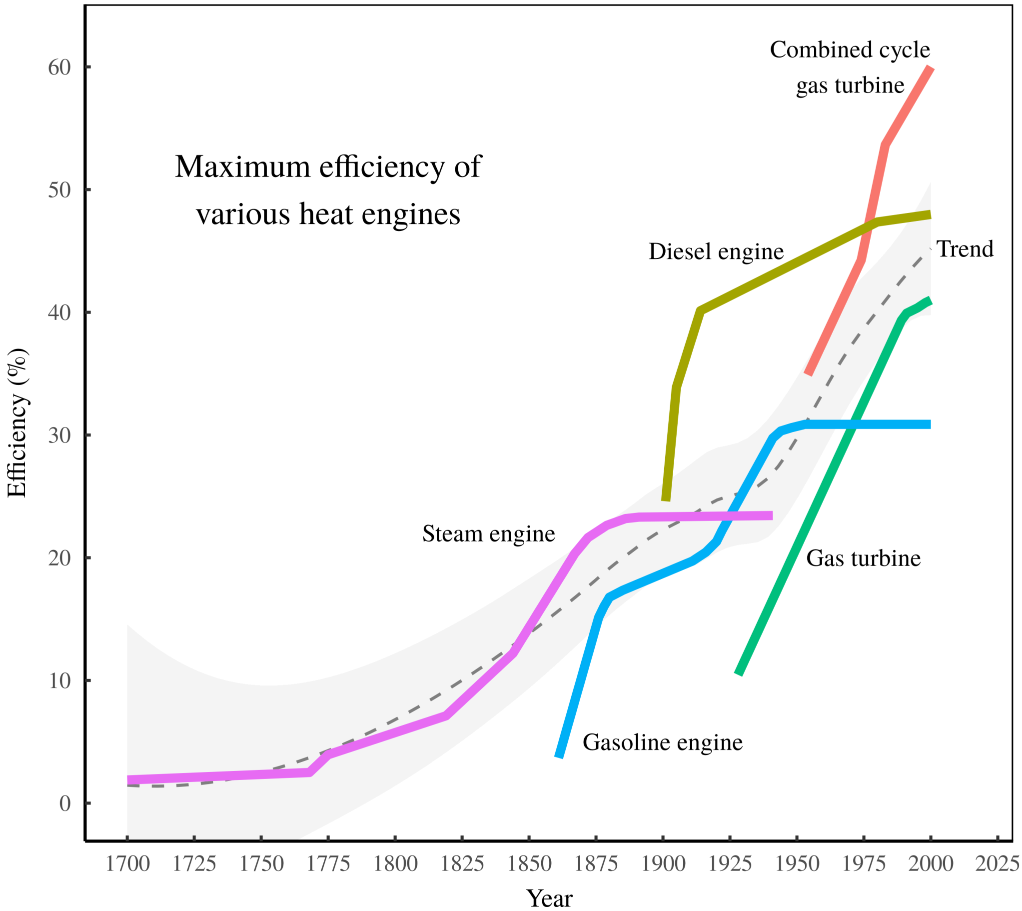

Figure 9: The arms race to make heat engines more efficient

Ever since Newcomen invented the first commercial steam engine in 1712, there's been an ongoing race to create more efficient heat engines. Initially, that meant improving the steam engine. But eventually, it meant the adoption of better machines — things like internal combustion engines and gas-powered turbines. Sources and methods

engine — a machine that wasted a mere 96% of its input coal energy.[4] And by the turn of the 19th century, an arms race had ensued, with engineers competing to design better, more efficient heat engines.

Returning to the present, Figure 9 shows the history of this heat-engine arms race. From the rickety prototypes of early industry to the hyper-optimized machines of today, heat-engine efficiency trended upward for three centuries, improving by something like a factor of forty.

[4]Fun fact: Watt's engine patent was called *A New Invented Method of Lessening the Consumption of Steam and Fuel in Fire Engines*. In other words, Watt knew that his main contribution was designing a steam engine that was more efficient.

Global investment in industrial sprawl

At this point, we're faced with a question that's becoming increasingly rhetorical. Given the vast improvements in heat-engine efficiency, did humanity invest the savings in resource conservation?

Obviously, we did not.

Instead, we used our increasingly efficient heat engines to catalyze the global sprawl of industrial civilization.

Interestingly, William Stanley Jevons was one of the first scientists to document this transformation. Looking at the demand for coal, Jevons noted that it was driven by the efficiency of steam engines. Literally. You see, one of the first uses for steam engines was to pump water out of British coal mines. This coal-driven work ensured that coal remained cheap. And cheap coal bolstered the demand for coal-powered work.

A positive feedback cycle ensued, prompting industrial sprawl that is now familiar. Farmers left the land to live in factory-filled cities. Animal-powered work was replaced with fossil-fuel powered machines. Electrification brought cheap, ubiquitous energy to the masses. And the industrial sprawl that started in Britain spread to every corner of the globe.

The result, as Figure 10 shows, was three centuries of energy-efficiency backfire. As heat engines grew more efficient, humanity consumed more fossil fuels.

Blame capitalism

Weighing the evidence, it seems clear that the Jevons paradox is a general feature of industrial society. So let's move on to the question of *why* energy efficiency backfires.

For their part, many leftists confidently blame capitalism. For example, in a 2010 article called 'Capitalism and the curse of energy efficiency', Marxist writers John Bellamy Foster, Brett Clark and Richard York scratch their anticapitalist itch. When it comes to efficiency backfire, they're convinced that capitalism is the culprit:

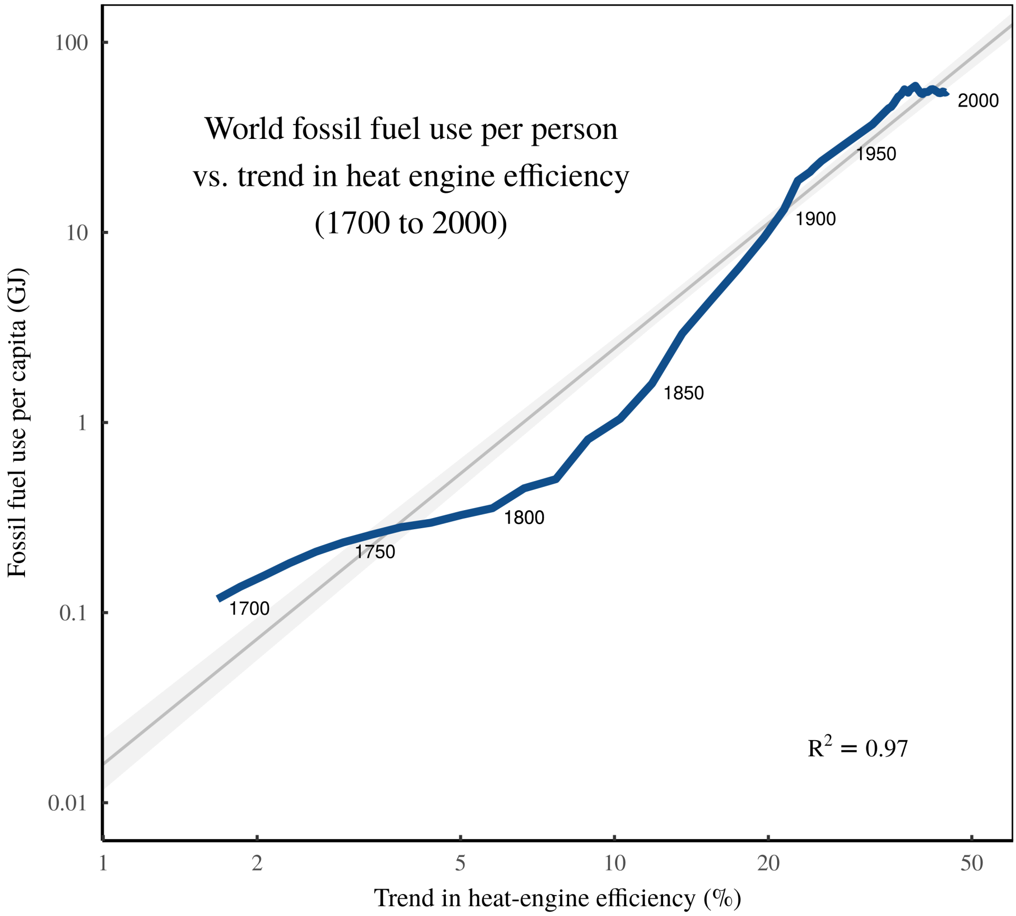

Figure 10: The world discovers the Jevons paradox

The horizontal axis the trend in heat-engine efficiency, derived from Figure 9. The vertical axis shows the world's fossil fuel use per capita. Note that both axes use a log scale. Sources and methods

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> The Jevons Paradox is the product of a capitalist economic system that is unable to conserve on a macro scale, geared, as it is, to maximizing the throughput of energy and materials from resource tap to final waste sink.
>
> (Foster, Clark, & York, 2010)

While I'm sympathetic to this blame game, the scientist in me finds it a bit presumptuous. To be sure, capitalism is unusually effective at promoting technological sprawl. But is it the *only* social system in which energy efficiency backfires?

I suspect not. Far from a being unique to capitalism, my bet is that the Jevons paradox is more general than Foster and colleagues claim. You see, humans are not the only species that play the efficiency-backfire game. The rest of life plays it as well.

Nature's feats of efficiency

To get a glimpse of the Jevons paradox's surprising universality, let's leave human myopia behind and zoom out to the rest of life on Earth. Across life's panoply, evolution has delivered some stunningly efficient designs — birds that can circumnavigate the globe, animals that can go years without food, and organisms that can survive in the most extreme environments.

Interestingly, these feats of biological efficiency become more clear when we compare them to our own attempts at mimicking nature's machinery. For example, when we use heart-lung machines to keep people alive during surgery, the machines use about 20 times more power than the organs they replace.[5] Likewise, when we use dialysis machines to replace failing kidneys, the machines use about 22 times more power than the original organs.[6]

When we try to mimic the human brain, we fare even worse. For example, when IBM's Watson beat Ken Jennings at Jeopardy, the machine used something like 45,000 watts of electricity to get the job done. In contrast, Jennings' brain (assuming it was average) ran on just 20 watts — about 2200 times less energy.[7]

[5]According to Wang et al. (2010), the average human heart consumes about 440 kcal per day, per kilogram of mass. Assuming an average heart mass of 310 grams, that equates to a metabolic rate of about 6.6 watts. I couldn't find reliable data for the metabolic rate of lungs. But assuming they're similar to skeletal muscle, they'd have a metabolic rate of about 12 kcal per day, per kilogram of mass. With an average mass of 2 kilograms, that puts the lungs' metabolic rate at around 1.2 watts. Adding both values pegs the heat and lung's metabolic rate at about 7.8 watts. For comparison, the Sorin S5 heart-lung-machine has power rating of 160 watts.

[6]Wang et al. (2010) report that the kidneys have a metabolic rate of 440 kcal per day per kilogram. Assuming an average kidney mass of 290 grams, that gives a metabolic rate of roughly 6.2 watts. In contrast Nickel et al (2017) peg the energy use of a haemodialysis machine at 0.56 kWh for a 4 hour treatment, which equates to a power of about 140 watts.

[7]According to an IBM press release, Watson ran on a cluster of ninety IBM Power 750 servers. Looking at the operating specs, each Power 750 server had a max draw of 1950 watts. Assuming a conservative draw of 500 watts per server while playing Jeopardy, that equates to a total power consumption of 45,000 watts. For comparison, Clarke and Sokoloff peg the brain's metabolism at 20 watts.

The message here is that the drive for efficient design is not unique to human culture. It's a general feature of biology, pushed by the great killer of waste, natural selection.

And so we come to the point. It's not just capitalist societies that play the efficiency game. The whole of life plays it too. But then, if the Jevons paradox is unique to capitalism, that means the rest of life ought to be *immune* from efficiency backfire. So is it?

Using efficiency to catalyze biological sprawl

To test if life is immune from efficiency backfire, we need to first define a measure of 'biological efficiency'.

Here's how I'll do it. I'll take an organism's mass and divide by its metabolism (the rate it consumes energy). I call this ratio 'biomass efficiency':

$$\text{biomass efficiency} = \frac{\text{organism mass}}{\text{organism metabolism}}$$

Biomass efficiency quantifies how much mass an organism can support per unit of energy input. For example, humans have a biomass efficiency of about 850 grams per watt. In contrast, elephants can support about 1600 grams of biomass per watt of energy input. And mice can support a mere 66 grams of biomass per watt.

Now to our question. Is life immune from the Jevons paradox?

The answer is unequivocally *no*.

Let's look first at mammals and birds — the warm-blooded species with whom we're most closely related. Across this group of animals, biomass efficiency varies from a low of 20 grams per watt to a high of 5,000 grams per watt. So if greater efficiency got parlayed into energy conservation, the most efficient animals should consume about 250 times *less* energy than the least efficient animals. But that is not what we find. Instead, more efficient birds and mammals tend to consume *more* energy. Figure 11 shows the trend.

Let's move on to our more distant cousins. Unlike mammals and birds, the rest of life generally lacks the ability to thermo-regulate (maintain a constant body temperature). And that means these cold-blooded creatures can survive on less energy. But it doesn't mean they're immune from the Jevons paradox.

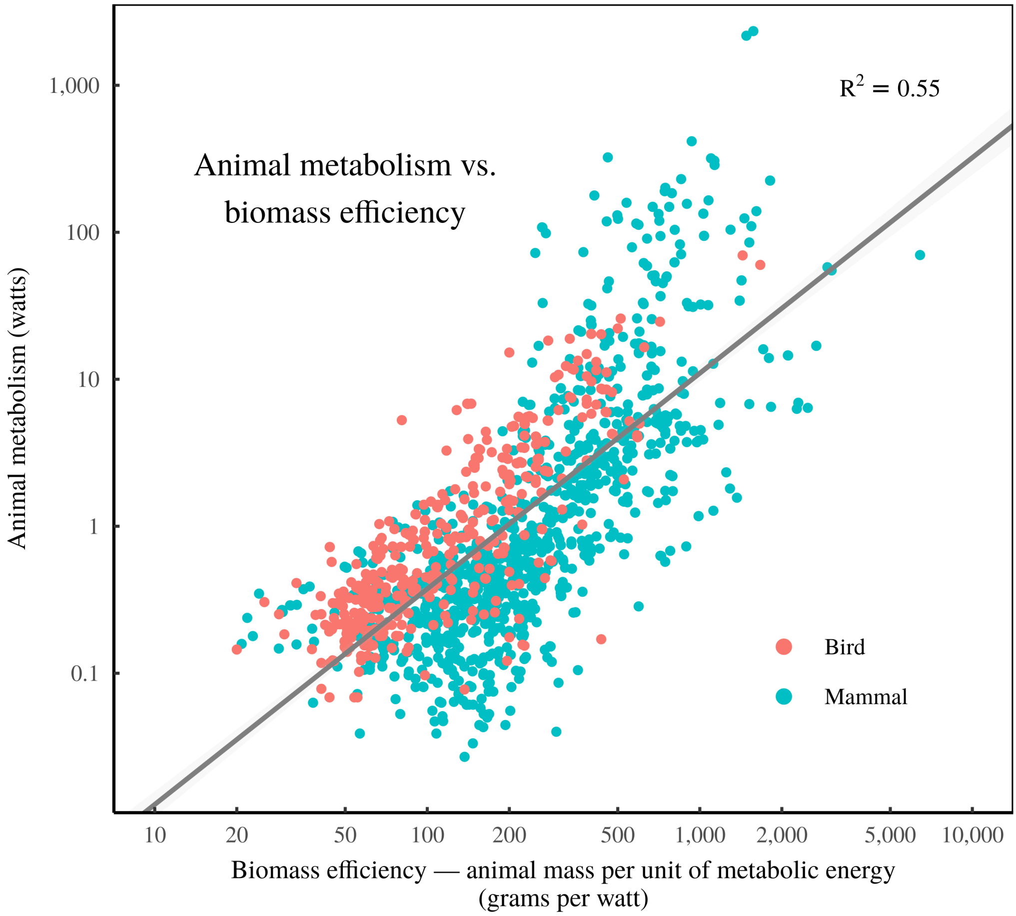

Figure 11: Mammals and birds discover the Jevons paradox

Each point represents a species of mammal or bird. The horizontal axis plots each animal's 'biomass efficiency' — the amount of biomass it can support per watt of energy input. The vertical axis shows the animal's metabolic rate — the rate that it consumes energy. Note that both axes use log scales. Sources and methods

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When we scan the panoply of life, from bacteria and amoebas to reptiles and fish, we see a now-familiar pattern. Greater efficiency is associated with *more* energy consumption. Figure 12 shows the pattern.

(Keen-eyed readers might notice that this figure doesn't show plants. Don't worry, plants also exhibit the Jevons paradox.)

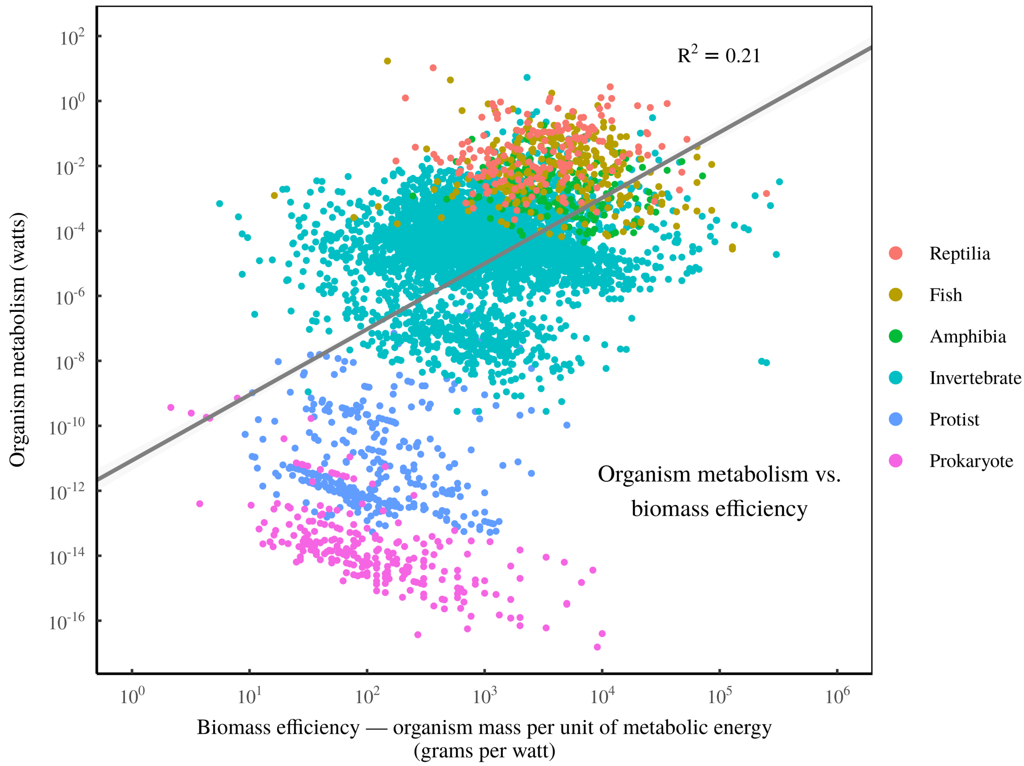

Figure 12: The rest of life discovers the Jevons paradox

Each point represents a species, with major taxa shown in color. The horizontal axis plots each organism's 'biomass efficiency' — the amount of biomass it can support per watt of energy input. The vertical axis shows the organism's metabolic rate — the rate that it consumes energy. Note that both axes use log scales. Sources and methods

Is efficiency a 'curse'?

To summarize, the backfire of energy efficiency appears ubiquitous. It's a consistent pattern throughout industrial history. And it's a recurring theme across life itself. Given this universality, does it make sense to call efficiency a 'curse'? (This is the language used by Foster and colleagues.)

I think the answer is no.

In essence, efficiency is simply a means to an end — a way to catalyze technological or biological sprawl. Whether this sprawl is a blessing or a curse depends on the setting.

In the case of life, biological sprawl is just the spread of life into many niches of size. We typically call this sprawl 'biodiversity', and we consider it a good thing. But in the case of industrial society, fossil fuels have allowed use to build more technological sprawl than the Earth can sustain. So it's less that efficiency is a 'curse', and more that anything done with fossil fuels was always destined to be unsustainable. Greater efficiency simply hastened the inevitable.

To summarize, humans play the same game as life — we use efficiency to catalyze sprawl. And for most of human history, we played the game within tight constraints, using only the energy made available by the sun. But our exploitation of fossil fuels obviously changed everything, supercharging our activity beyond what the solar budget could maintain. It's this *lack* of constraint that converts the Jevons paradox from a blessing into a curse.

Lessons from bacteria

While we're on the topic of constraints, it turns out that we can learn some lessons from the most basic form of life — the lowly bacteria. You see, these simple creatures manage to *shirk* the Jevons paradox. Figure 13 shows the pattern. As bacteria get more efficient, they consume *less* energy.

Now, I'm no microbiologist, but here's what I suspect is going on. My guess is that bacteria shirk the Jevons paradox because they are subject to tight constraints. Simply put, bacteria are stuck being *small*.

The barrier comes down to a quirk of cellular design. Since bacteria have no mitochondria, (the powerhouse of the eukaryotic cell), they're forced to metabolize energy along their cell walls. And that means their ability to harness energy is a function of their surface area. Now, as bacteria grow larger, their volume grows faster than their surface area. And that means bigness is a killer; beyond a certain size, bacteria can't harvest enough energy to support their biomass. As a consequence, they're stuck being tiny.[8]

Backing up a bit, it is the creep towards bigness that gives rise to life's efficiency 'backfire'. As organisms get larger, they tend to become more efficient. But they also consume more energy. My guess is that bacteria avoid this backfire effect because they cannot get big. In other words, they cannot create biological sprawl.

[8]For a fascinating account of how life sidestepped the size constraints that limit bacteria, see Nick Lane's book *The Vital Question*.

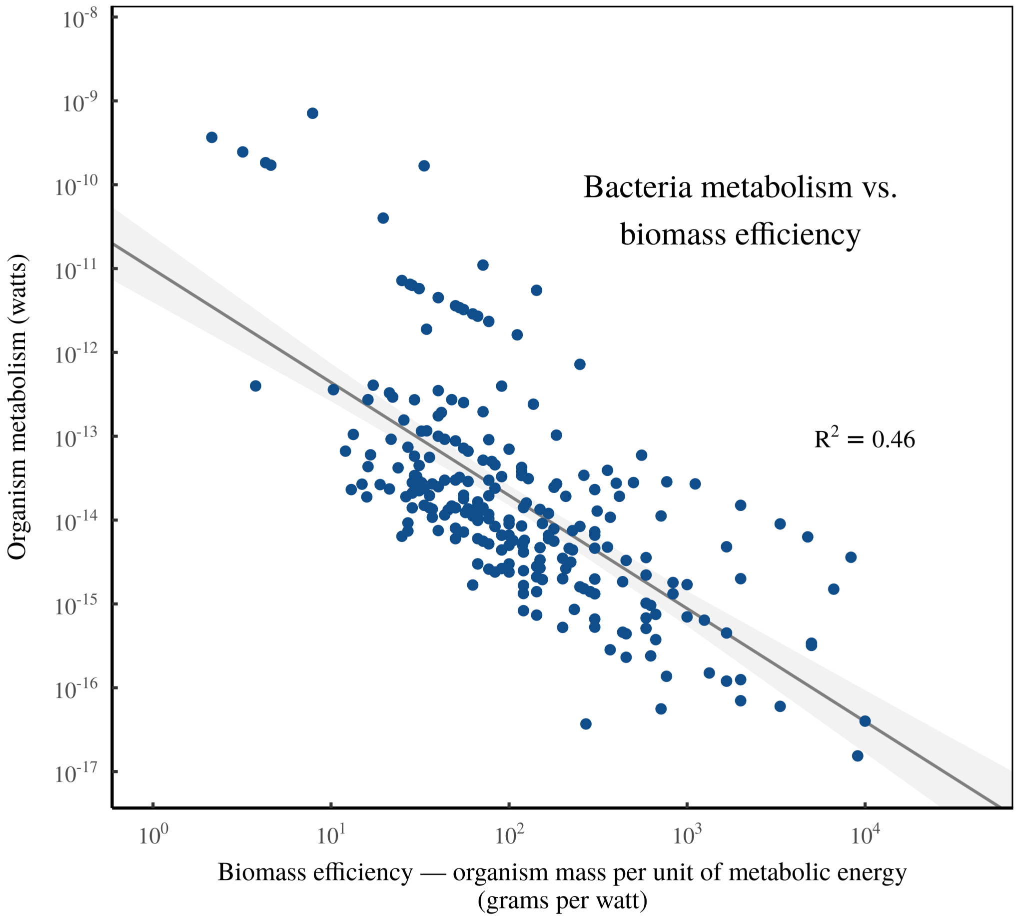

Figure 13: Bacteria shirk the Jevons paradox

As bacteria get more efficient at supporting biomass (horizontal axis), their metabolic rate decreases (vertical axis). Each point represents a different bacteria species. Note that both axes use a log scale. Sources and methods

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Constraining technological sprawl

Looking at bacteria, the lesson for humans is that if we want to avoid the Jevons paradox, we must impose constraints on technological sprawl. Of course, one way or another, those constraints are heading our way. But it would be more pleasant if the containment policy was by *design* rather than by disaster.

So how do we voluntarily constrain technological sprawl? That's the ten-quadrillion-dollar question. And I would be lying if I claimed to have a definitive answer.

For their part, degrowth writers have been mulling over the question for a while.[9] And if there's anything like a consensus among these thinkers, it's that individual action isn't enough. Instead, the road to degrowth will require drastic social change, with a focus on expanding public goods, reducing inequality, and constraining conspicuous consumption. As always, the main hurdle here is the difficulty of turning ideas into action. Sadly, I suspect that for degrowth policies to become mainstream, the unfolding ecological catastrophe will have to get much worse.

Besides limiting consumption, another option would be to steer technological sprawl in a more sustainable direction. The goal would be a complete shift to renewable energy — a shift that would put us back in line with the rest of the solar-dependant biosphere. Of course, the Jevons paradox would still apply, meaning more efficient renewable-energy infrastructure would stimulate technological sprawl. But unlike with fossil fuels, the sprawl would be constrained by the sun's energy budget.

That said, the dark side of the shift to renewables is what happens in the interim, when the fossil-fuel tap is still on. The risk is that instead of *reducing* fossil fuel consumption, renewable energy becomes another *side dish* — fries to go with the fossil-fuel big mac.

Sadly, that's exactly what's happened historically, as Figure 14 shows. Since 1965, global renewable energy consumption has exploded. And while it did, global fossil fuel use *continued* to grow.

So how should we combat this side-dish problem? In light of the Jevons paradox, here's a possible solution: *punish* fossil-fuel efficiency.

The idea is that if we continue to develop better fossil-fuel tech, the efficiency will inevitably backfire, catalyzing more fossil fuel consumption. So instead of developing this tech, we should *deprecate* it. Pull the funding for anything related to fossil-fuel efficiency and pump the money into renewable energy.

Admittedly, the policy sounds crazy. But what would be even crazier is if we kept striving for greater fossil-fuel efficiency, thinking the policy won't backfire. It always has. And it always will.

[9] On the topic of degrowth, here are two books worth reading:

1. *Less is More*, by Jason Hickel
2. *The Case for Degrowth*, by Giorgos Kallis, Susan Paulson, Giacomo D'Alisa and Federico Demaria

Unlike techno-optimist works like *Factor Four*, both books acknowledge that energy efficiency often backfires.

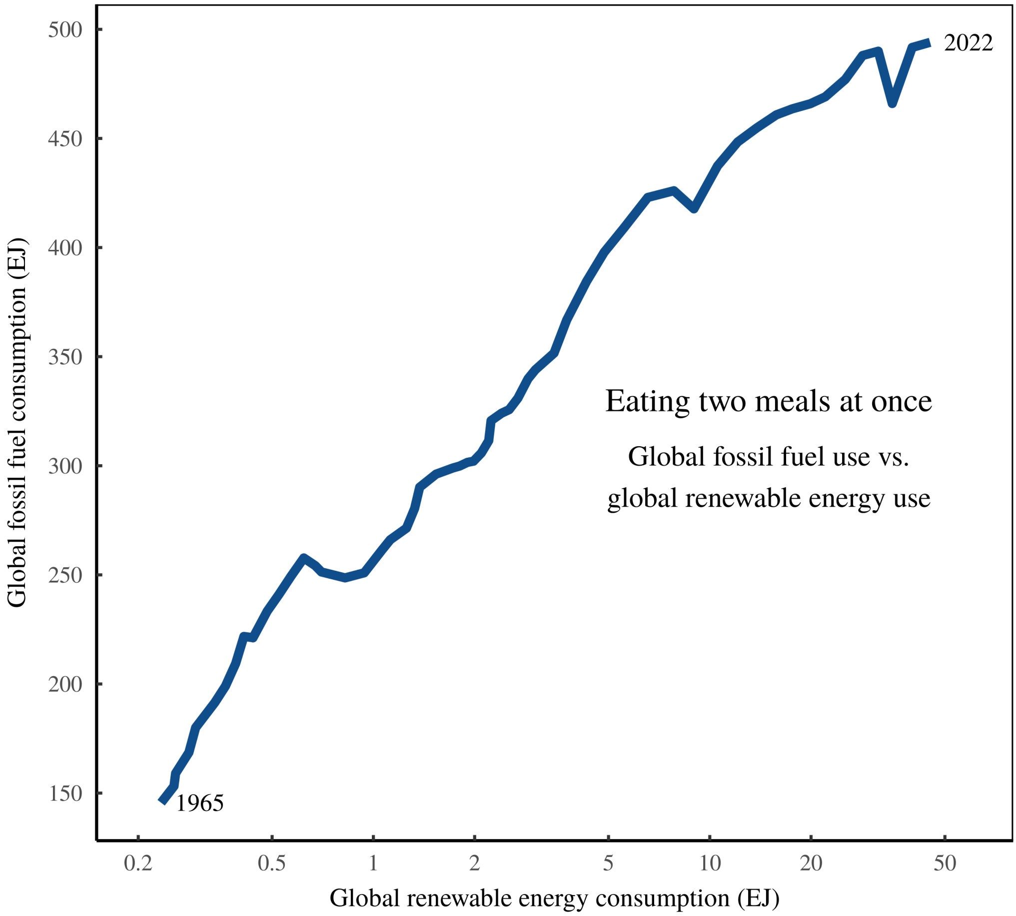

Figure 14: The spread of renewable energy hasn't slowed the growth of fossil fuels consumption

The horizontal axis shows the world's consumption of renewable energy, which has grown dramatically since 1965. (Note the log scale.) Unfortunately, over the same period, global fossil fuel use continued to expand (vertical axis). Sources and methods

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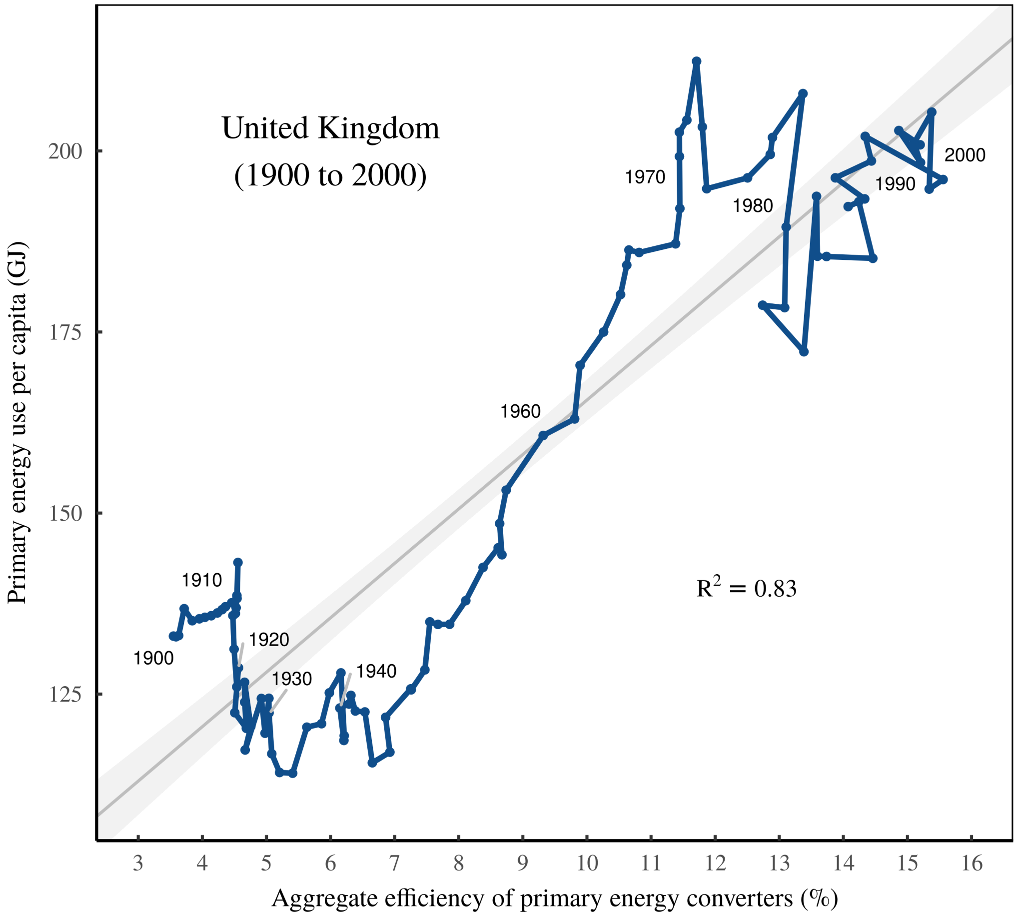

Figure 15: The United Kingdom discovers the Jevons paradox

As the efficiency of UK energy-conversion technology increased (horizontal axis), so did energy use per capita (vertical axis). Data is from Benjamin Warr's REXS database.

The Jevons paradox in the UK, Japan and Austria

In addition to the United States (Figure 8), we can see the Jevons paradox in the UK (Figure 15), Japan (Figure 16), and Austria (Figure 17). In all four countries, increases in aggregate efficiency are associated with greater energy use per capita.

My guess is that this pattern is basically universal — we'd find it in every country and every society. That said, it's only in the US, UK, Japan, Austria that we've got estimates for the aggregate efficiency of primary energy converters. On that front, the data plotted in Figures 15 – 17 comes from Benjamin Warr's REXS database.

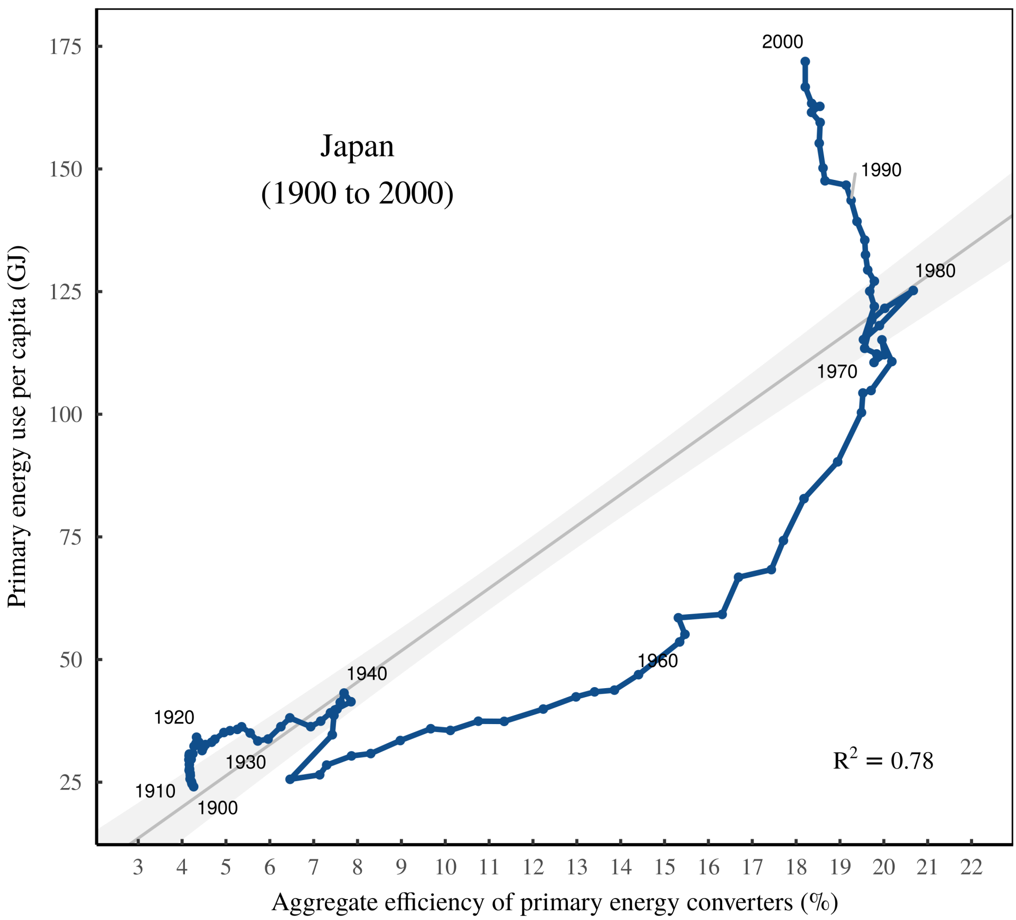

Figure 16: Japan discovers the Jevons paradox

As the efficiency of Japan's energy-conversion technology increased (horizontal axis), so did energy use per capita (vertical axis). Data is from Benjamin Warr's REXS database.

Hashing details

If you're curious about the specific chips used for Bitcoin mining, have a look at detailed labels in Figure 18. Prior to 2011, mining was done mostly with standard GPUs. But starting in late 2012, we see the invention of chips designed solely for Bitcoin mining. The efficiency of these chips grew exponentially until about 2018, after which it settled into a linear trend.

Don't forget about plants

Yes, plant's also experience the Jevons paradox. Figure 19 shows how they fit into life's spectrum.

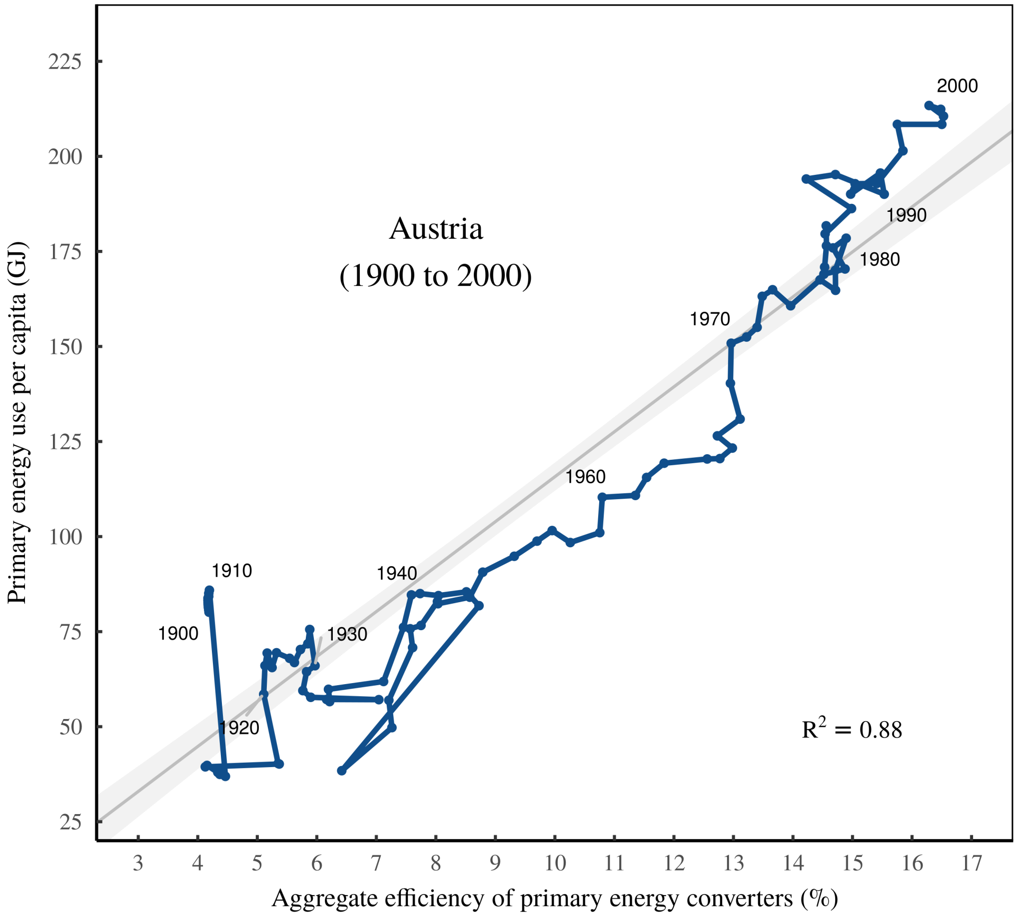

Figure 17: Austria discovers the Jevons paradox

As the efficiency of Austria's energy-conversion technology increased (horizontal axis), so did energy use per capita (vertical axis). Data is from Benjamin Warr's REXS database.

Sources and methods

Sources for Figure 1

Data for word frequency is from Google Ngrams, downloaded with the R package ngramr.

Sources for Figure 2

Data for British coal consumption is from the following sources:

- 1700 – 1912: Our World in Data, 'The death of UK coal in five charts'
- 1912 – 2022: gov.uk, 'Historical coal data: coal production, availability and consumption'

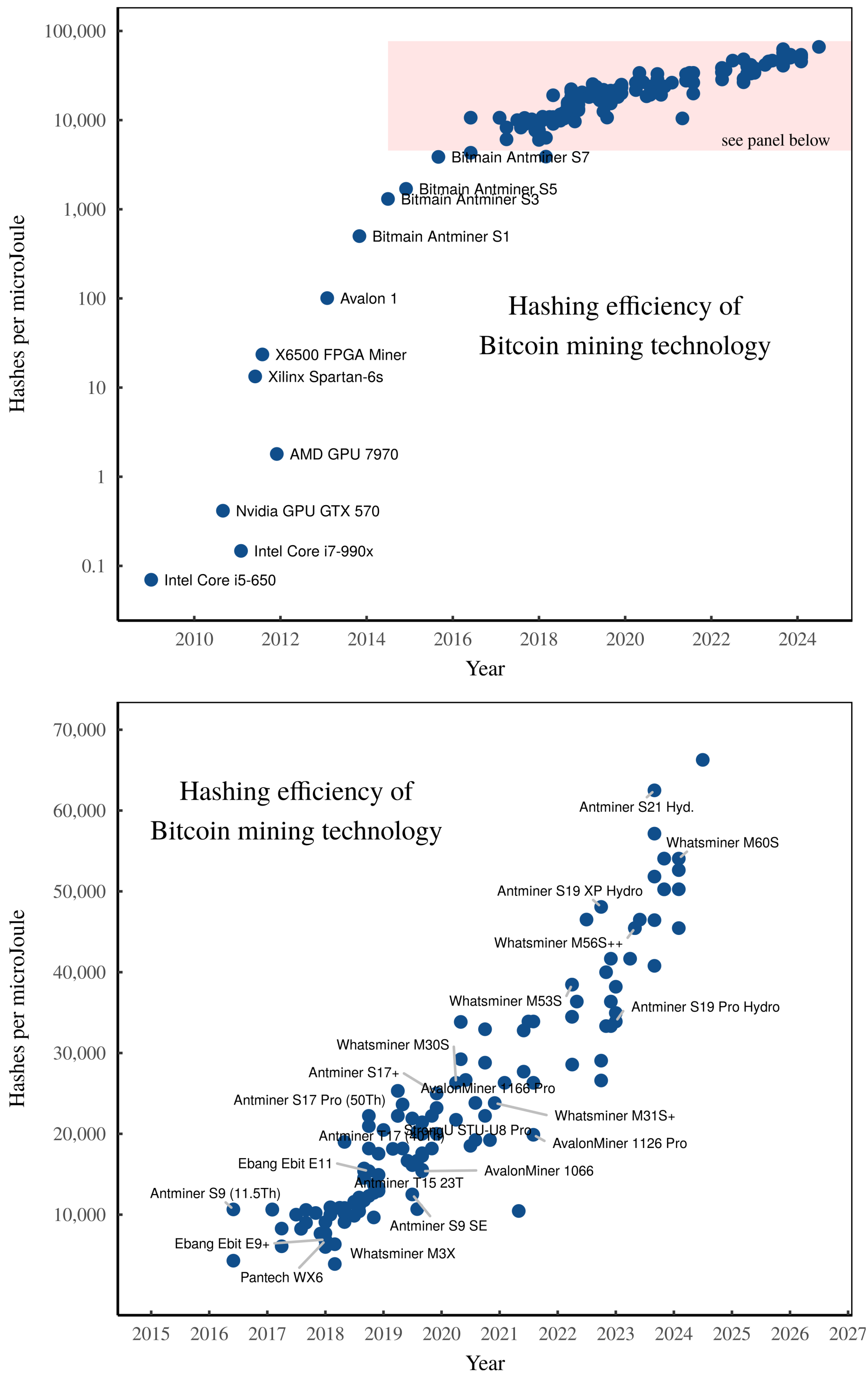

Figure 18: Hashing efficiency of Bitcoin technology

Data is from the Cambridge Bitcoin Electricity Consumption Index.

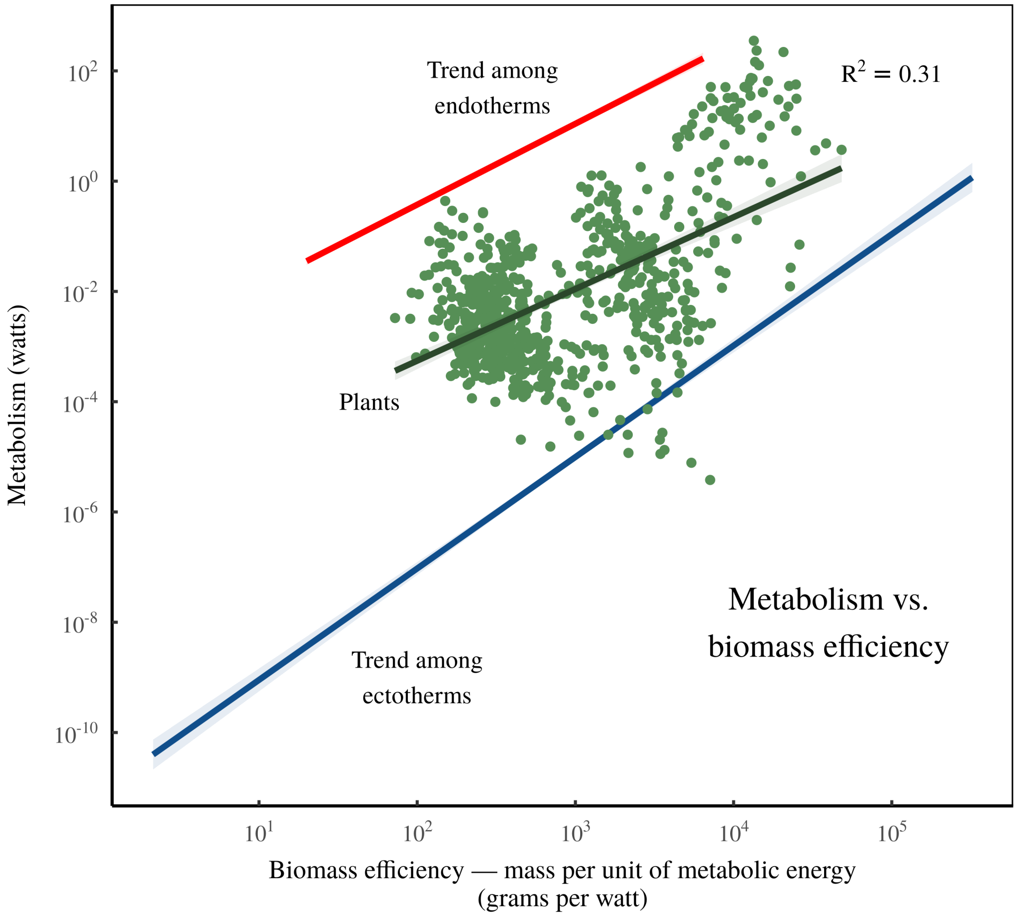

Figure 19: Plants discovers the Jevons paradox

Data for organism metabolism and mass is from Hatton et al. 2019, 'Linking scaling laws across eukaryotes'.

Sources for Figure 4

Estimates for computer efficiency are from Koomey et al, 2009, 'Assessing trends in the electrical efficiency of computation over time'. I digitized the data in their Figure ES-1.

Sources for Figures 5 and 6

Data for Bitcoin hashing efficiency and Bitcoin electricity consumption is from the Cambridge Bitcoin Electricity Consumption Index.

Sources for Figure 7

Data for the aggregate efficiency of US primary energy converters if from Benjamin Warr's REXS database. Note: Warr's original website is now dead, but fortunately has been scraped by the Internet Archive.

Sources for Figure 8

For efficiency data, see the notes for Figure 7. Data for US energy consumption per capita is from the following sources:

- Energy use, 1900 – 1948: US Energy Information Agency, Annual Energy Review 2009, Appendix E1
- Energy use, 1949 – 2000: US Energy Information Agency, Annual Energy Review, Table 1.1
- Population, 1900 — 2000: Our World in Data, 'Population'

Sources for Figure 9

Data for heat engine efficiency is from Cleveland and Clifford's article 'Maximum efficiencies of engines and turbines, 1700-2000'. Their original source data is from Vaclav Smil's book *Energy and Civilization: A History*.

Sources for Figure 10

For heat engine efficiency, see the sources for Figure 9. World fossil fuel user per capita is from the following sources:

- world population, 1700 – 2021: data is from Our World in Data, 'Population'
- world fossil fuel use, 1800 – 2021: Our World in Data, 'Energy Production and Consumption'

Note: to estimate global fossil fuel use back to 1700, I indexed it to the level of British coal production, using data from Our World in Data.

Sources for Figures 11, 12, and 13

Data for organism metabolism and mass is from Hatton et al. 2019, 'Linking scaling laws across eukaryotes'.

Sources for Figure 14

Energy data is from the BP Statistical Review of Energy, 2023.

Further reading

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