The Jus Semper Global Alliance
In Pursuit of the People and Planet Paradigm
Sustainable Human Development
April 2026
ESSAYS ON TRUE DEMOCRACY AND CAPITALISM

Technological Dynamics of Growth and Stability

Erald Kolasi

Photo by Wolfgang Weiser on Unsplash

How does technological change produce economic growth? And how does this growth affect the broader ecosphere in which it's embedded? These are the central questions to which we now turn. Recall that, in the ecodynamic synthesis, growth means the expansion and diversification of useful energy forms, where useful energy can be anything from mechanical work to electricity. The AFR *(aggregate flow rate)* is the total measure of the energy converted by a particular economy in a given year, so growth just means an increase in the AFR. We can think of technology as the set of all biophysical systems, productive methods, and intellectual abilities that allow human beings to convert energy from a preexisting form to another form. Nature doesn't hand us pottery, tables, and cars. These things must be built and manufactured from raw materials, and that process involves everything from labour power to machines and vehicles. For example, coal power plants burn coal to produce electricity, so we'd say that they've converted coal into electricity. For another case, natural cotton fibres first need to be carded and spun so they can be straightened and strengthened, then the resulting threads are woven into finished articles of clothing.

The main focus in this chapter is to analyse the intersection between ecological dynamics and technological change. It would be a mistake to see technological change as being exclusively a socially immanent phenomenon, which in this context means a process that's happening within human society. Societies interact with the natural world in highly complex ways, and those interactions also affect the pace and direction of technological development. The main point is that technological change has no inherent goal; technology is an immanent and emergent feature of the nexus between the social and ecological worlds. Technological changes are shaped and constrained by political conflicts, class struggles, as well as ecological primers that induce different modal adaptations. Nor is technology merely a fixed set of products at a given point in time; as part of the conversional process, it's also a method of adaptive engineering in the face of complex problems and challenges. Nevertheless, technological change is a process embedded within society, hence it both affects and depends on social, political, and cultural relations, such as trade, commerce, and money. To sustain the energy-intensive and multidimensional conversional stages of their broader coronets, people usually establish new institutions and organisational structures. Labour relations change and new social hierarchies are erected. If a new conversional process requires more labour-intensive work, then new forms of management and administration will also be required to control and direct the available labour power. That process can lead to the verticalisation of hierarchy, with new layers of management needed to control the conversional process. Changes in the conversional process necessitate changes in specialisation and the division of labour. If a new conversional process requires greater energy flows and extends longer across time and space relative to an earlier process, it can lead to new modal patterns, social hierarchies, and organisational structures. That's because a complex and extended conversional process that requires multiple stages of transformation needs different people who can master or supervise the different stages.

The concept of "technological innovation" is ubiquitous in modern society, but it's also more controversial and open to interpretation than one might normally think, and there's no universal agreement on its empirical definition. Some scholars have tried to measure innovation at the national level by analysing the number of patents produced by a particular country, the idea being that more approved patents indicate the invention of more valuable methods and technologies. But this metric certainly has major flaws, especially for the United States. One study estimated that almost 30 percent of all American patents would be found invalid if challenged in court.[1] Indeed, for many years in the 2010s, roughly half of all software patents taken to court were struck down and invalidated. The United States Patent and Trademark Office has a notorious history of approving ridiculous patents, including for products like urinal headrests and odours that supposedly cure male impotence. R&D funding is another metric that has been used to study technological innovation. Nevertheless, it too has many problems. Spending lots of money pursuing a technological objective doesn't always lead to innovation. Just look at the money that's been wasted on nuclear fusion without any concrete results. Moreover, corporations often play around with the meaning of R&D. Pharmaceutical companies spend the vast majority of their "research" funds on developing variants of preexisting drugs so that they can extend patent protections that would otherwise expire, posing a serious threat to profits.[2] Independent studies show that these variants are hardly ever more effective than the older versions of the drugs, although the industry funds many of its own flawed studies that eventually make their way to the FDA. Big Pharma then turns around and argues that they deserve their ridiculous profits because they spend so much on innovation. The truth is that a lot of what gets labelled as "R&D funding" is going toward projects that have no direct impact on technological change. And finally, there's a common trope that deserves to be mentioned in the neoclassical theory of growth: total factor productivity (TFP).This is supposed to be the share of economic growth that cannot be explained by labour and capital inputs. For all practical purposes, it's understood as the share of economic growth that's explained by technological progress and innovation. In reality, it's just an algebraic factor that appears in neoclassical aggregate "production" functions, which reveal nothing about production because they're little more than accounting identities that are true by definition.[3] TFP is perhaps the most egregious intellectual embarrassment of modern macroeconomics. It implies absolutely nothing about technological innovation and should therefore never come up again in any serious discussion on the subject.

---

[1] Shawn Miller, "Where's the Innovation? An Analysis of Quantities and Qualities of Anticipated Obvious Patents," Virginia Journal of Law and Technology 18 (2013).

[2] See Donald Light and Rebecca Warburton, "Demythologizing the high costs of pharmaceutical research," BioSocieties 6 (2011): 34-50.

[3] See Jesus Felipe and F. Gerard Adams, "The Estimation of the Cobb-Douglas Function: A Retrospective View," Eastern Economic Journal 31 (2005): 427-45.

Theories of Technological Change

The subject of technological innovation has aroused no shortage of theories. Technology has been analysed as everything from a kind of knowledge to a particular set of empirical examples. The historian Alex Roland defined technology as the systematic and goal-oriented manipulation of the natural world, writing that technology "has four components: materials, technique, power, and tools or machines. Thus, technology is the process of applying power by some technique through the medium of some tool or machine to alter some material in some useful way."[4] It's quite a mechanistic conception of technology as tools and techniques that are applied to change some underlying material. A historical example of this conception would be the adoption of the heavy plow in medieval Europe, which caused a large increase in agricultural productivity and population growth, according to historian Lynn White and other scholars.[5] Another famous historian of technological development, Thomas Hughes, claimed that technology is "the effort to organise the world for problem solving so that goods and services can be invented, developed, produced, and used."[6] This kind of view hints at the more social, economic, and even political aspects of technological development. Thinking along these lines, the theorist Langdon Winner suggested that technological systems are the embodiment of social relations, even political ones. He famously claimed that technologies are forms of life and that "we do not use technologies so much as live them. One begins to think differently about tools when one notices that the tools include persons as functioning parts."[7] Socialist thinkers have also contributed much to our understanding of how technology relates to labour and class. In volume 1 of Capital, Marx famously analysed the role of technology in the production process, arguing that capitalists use automation as a way of replacing or controlling their labour force, thereby reducing labour costs and temporarily boosting profits.

Theorists of complex systems view the process of technological change as a set of entangled interactions between various components, agents, social groups, and institutions. Thomas Hughes introduced the concept of a reverse salient, which is a component of a technological system that functions abnormally and therefore prevents the full development of the system. A major historical example of a reverse salient were the boilers used in the first steam engines. Because early boilers relied on low-quality metals and poor construction techniques, they could not fully support the operation of high-pressure steam engines, largely because that high-pressure gas would find its way through small cracks and crevices, causing massive explosions. It wasn't until the early nineteenth century that industrial ironworks had improved enough to allow for the construction of quasi-stable boilers, thus partially facilitating the diffusion of high-pressure steam power. One of the more popular theories on technological development is path dependence. According to this view, the development of technology follows a clear historical pattern, implying that the future depends on the past. History matters, in other words. The innovation of future tools, products, and methods follows from the development of previous tools, products, methods follows from the development of previous tools, products, and methods; there's a "path" from one to the other, so to speak. A classic though controversial example of path dependence is the QWERTY keyboard, which remains in use despite the higher efficiency of alternative keyboards.

The basic point is that technological change is generally gradual, additive, and cumulative, not sudden and revolutionary. Rarely is something completely new invented; existing technological components are instead combined and integrated into hybrid devices and designs, which can be considered new in the sense that they perform novel

---

[4] Steven Pomeroy, An Untaken Road (Annapolis, MD: Naval Institute Press, 2016), 19.

[5] Lynn White Jr., Medieval Technology and Social Change (London: Oxford University Press, 1962). See also Thomas Barnebeck Andersen, Peter Sandholt Jensen, Christian Volmar Skovsgaard, "The heavy plow and the agricultural revolution in Medieval Europe," Journal of Development Economics 118 (2016): 133-49.

[6] Brian C. Black, To Have and Have Not: Energy in World History (Lanham, MD: Rowman & Littlefield, 2022), 110.

[7] See Langdon Winner, "Artifice and Order," in Technology and Values, ed. Craig Hanks (Oxford: Wiley-Blackwell, 2010), 82.

functions or solve previously intractable problems. Consider the flywheel, one of the simplest yet most powerful technologies humans have ever created. A flywheel is a rotating disk that's used to conserve rotational kinetic energy. Flywheels are basically used in devices that rotate to help modulate their speed of rotation. Over time, flywheels have been attached to pottery wheels, watermills, steam engines, and internal combustion engines. Your car engine has one right now. Whenever you start your engine and get going on your drive, the pistons getting pushed by the combustion strokes are turning a crankshaft mechanism that is attached to a flywheel. The metallic flywheel helps to conserve the rotational energy of the crankshaft even when you're no longer pressing on the gas pedal, which prevents the engine from stalling and gives you a smooth drive. The crankshaft itself is another great example, as it has existed at least since the Middle Ages and has been widely used to convert linear reciprocating motion into rotational motion for multiple mechanical devices and components.

Other popular theories hold that technological change is evolutionary; just as organisms that are well adapted to their environment will survive and produce offspring, technological systems that are selected by their wider social environment will survive while others disappear. Indeed, theories of technology have been richly shaped and influenced by the work of numerous biologists. Humberto Maturana and Francisco Valero introduced the concept of autopoiesis to describe systems that are capable of self-reproducing their elements and parts, such as cells.[8] By contrast, allopoietic systems use energy and resources to produce other things, like a factory that produces cars. An entire economy can be seen as an autopoietic system consisting of allopoietic components. In an effort to better describe how life works, the biologist Stuart Kauffman introduced the idea of gradient-driven autocatalytic sets.[9] An autocatalytic set is a collection of molecules that undergo chemical reactions through a processing sequence driven by gradients with the external environment. In this context, the term processing sequence means a sequentially activated of biochemical reactions that produce special molecules that further catalyse, or speed up, at least one of the reactions in the set. The external gradient keeps driving this self-organised feedback loop by providing the necessary energy flows, without which the autocatalytic sets could not be activated. The broader environment is absolutely critical in shaping the physical functions and processes of all autocatalytic sets. The flow-cycle model of the ecodynamic synthesis is highly analogous, as natural energy flows are in effect biophysical gradients that facilitate the dynamic evolution of our conversional networks, which operate through globally coherent activation sequences, or modal patterns that are the equivalent of autocatalytic sets for large-scale anthropogenic energy systems.

Modal Adaptation and Conversional Spectralisation (MACS): The Relationship Between Technological Change and Growth

Ecology is the fundamental causal matrix behind the major historical changes in human society. The social and natural worlds are highly complex and nonlinear dynamical systems that are entangled together through intricate feedback loops. Recall that all economies are dissipative systems: they absorb vast amounts of energy from the natural world, use a portion of that energy to organise and sustain their internal structure, and dump most of the consumed energy back out to natural sinks in the global ecosphere. The ecosphere is capable of handling and assimilating a great deal of human waste and low-grade energy without getting severely destabilised. However, our current age of industrial capitalism is

The ecosphere is capable of handling and assimilating a great deal of human waste and low-grade energy without getting severely destabilised. However, our current age of industrial capitalism is testing that proposition in every possible way.

---

[8] See Humberto Maturana and Francisco Valero, Autopoiesis and Cognition (Dordrecht: D. Reidel Publishing Company, 1980).

[9] Stuart Kauffman, "Autocatalytic sets of proteins," Journal of Theoretical Biology 119 (1986): 1-24.

testing that proposition in every possible way. If the “useless” energy dumped by civilisation into the natural world overwhelms the capacities of natural sinks and reservoirs, the result will be chaos throughout the global biosphere, much more so than what we’ve already seen in recent times. To help prevent that sobering possibility, we need to understand how the biophysical dynamics of technological change affect the scale dynamics of energy expansions and contractions. By stabilising and modulating those scale dynamics effectively, we can indeed prevent most of the harmful impacts associated with the recent bionomic disruption while ensuring the prosperity of global civilisation for millennia to come.

Ecological primers cause changes in the underlying resource base or in the labour relations and modal patterns that have developed around existing resource bases.

Let’s begin with the ecodynamic theory of technological change and economic development, which works as follows. First, ecological primers cause changes in the underlying resource base or in the labour relations and modal patterns that have developed around existing resource bases. A resource base is any collection of natural primary energy supplies available for extraction, including things like fossil fuels, wind energy, solar energy, and water energy. A major example of ecological priming is the warming that occurred after the last Ice Age, which led to the proliferation of plants, animals, rivers, and lakes all over the world, thereby becoming the dominant factor in the transition from a nomadic existence to an agricultural one. Another example is the outbreak of a major epidemic, which can cause large death tolls and can change how the surviving individuals work and use technology. The Black Death is a major example of this kind of historical process, as the extreme labour scarcities it induced in Western Europe led to the proliferation of labour-saving technologies. Ecological primers and disturbances can change the underlying resource base through diversification or induced scarcities. “When existing resources become scarce, societies typically try to compensate by trading with others, by switching to new resources, or by exploring and fighting to seize control of additional resources. When natural resources multiply and diversify, societies typically have more materials to collect, process, and manage. The new resource base typically has different energy qualities and characteristics compared to the old base, such as different energy and power densities or different spatial distributions. The change in energy quality then produces a change in modal flows and labour relations, mostly because people need to carry out modal adaptations to extract and process the new resources for predefined social needs. The rise of industrialisation in England during the 1600s, 1700s, and early 1800s is a major historical example of this process, and one which I’ll thoroughly cover in chapter 9. These broader ecological and social changes can induce many kinds of changes in technological development, but there’s one in particular that is critical to the evolution of all economic systems: changes in the way that energy is converted.

I’ll call this process spectralisation, where spectralisation is defined as the diversification and variation in the conversional methods of existing technologies in response to changing social and ecological conditions. A modern example of conversional spectralisation has been the transition from gas-powered vehicles to battery-powered electric vehicles, since it involves a change in the way that cars convert energy as they move and perform other functions. Another example of spectralisation was the emergence of wind turbines and solar panels for producing electricity, a notable change from the conversional methods used by coal power plants, which rely on burning coal to generate hot steam that drives a turbine. But not all changes to technological forms are conversional in nature. For about a decade, Ford’s Model T cars were only painted black because that turned out to be the cheapest option. By the 1920s, increased competition from other automakers persuaded Ford to use a broader spectrum of colors. But the transition from black to colored cars is not conversional spectralisation, because there were no changes in the underlying methods of converting energy. Another example of something that’s not conversional spectralisation are smartphone cases; they change all the time without any corresponding changes to the underlying technologies that power the operation of the smartphones. Likewise, logistical chains like roads and railways do not convert any energy themselves; they merely facilitate the conversion of energy by other technologies, such as cars and trains. Spectralisation can happen along different economic scales and implementation vectors. On the scale side of things, we may speak of microlevel spectralisation, which affects the conversional processes of specific technologies, or macrolevel spectralisation, which may refer to conversional transitions for entire economies, like when trains and automobiles gradually replaced horses for personal transportation. At a conceptual level, it's also important to differentiate spectralisation from the similar concept of technological diffusion. The latter concept is about *the spread and adoption of an already existing technological form across society. By contrast, spectralization is about the initial emergence and creation of new conversional technologies.* Another important difference is that although diffusion can apply to any technology, spectralisation is something that applies specifically to new technological methods of converting energy. The two concepts may nevertheless overlap in significant ways on certain occasions, especially since the diffusion of preexisting technologies across society can affect the spectralisation of new conversional methods.

The examples above are meant to reinforce the basic point that there are plenty of economic and technological changes that do not involve conversional spectralisation. But even though not all technological innovations are spectralisations or even involve spectralisation, it's nonetheless true that spectralization is the core driver behind technological innovation because all economic systems are conversional networks, and thus changes to the conversional technologies that power those networks will have massive effects on the aggregate properties of the coronets themselves. The central idea behind spectralisation is that conversional variety overcomes technical obstacles by channeling, modulating, and converting energy flows for the purpose of achieving different social objectives. People create tools, machines, and devices with new conversional pathways to overcome various energetic constraints and engineering challenges. Spectralised technologies are used to bypass chokepoints, bottlenecks, and reverse salients by synthesising preexisting components and devices into novel combinations. The theoretical framework of modal adaptation and conversional spectralisation (MACS) describes technological change as a chaotic and dynamic response to converging social and ecological conditions. As these conditions change, people respond by adapting and modifying their modal flows and labour relations. These adaptations can result either in changes to the applied methods on preexisting technologies, or to the gradual development of entirely new technologies, which arise as contingent solutions to various problems that are discovered during the recursive and differential implementation of new modal patterns and flows. Through this process of modal adaptation, people develop new biophysical methods for harvesting, extracting, and converting natural resources into finished products. Modal adaptation and conversional spectralisation are the two fundamental elements of technological growth and innovation. In the MACS framework, modal adaptations and spectralisation form a synergistic feedback loop in which changes in adaptations can drive forward spectralisations and likewise changes in spectralisations can cause changes in adaptations.

The causal pathways by which spectralisation overcomes energetic constraints can be highly diverse. For example, a device might be changed to convert energy more efficiently or a vehicle might be changed to transport more goods using the same volume of space, allowing people to save on production costs. But spectralisation might also simply produce higher levels of exergy [available energy]and useful energy in the absence of any corresponding efficiency gains.

Likewise, spectralised technologies might produce both efficiency and exergy gains over time. Spectralisation can thus lead to the expansion of an energy system through efficiency-driven gains, exergy-driven gains, both together, or through exergetic expansions that are enough to compensate for any corresponding declines in efficiency. Spectralisation can boost efficiency and productivity gains because it gives people more control over the flow of energy. Economic incentives and social-institutional structures then provide selection pressures that result in the proliferation of certain conversional pathways over others, leading to standardised technologies and devices that come to dominate a conversional network, and therefore the economic system more broadly. The end result is that high rates of spectralisation generally expand the scale of an energy system. However, forms of conversional spectralisation that are carefully guided and controlled by the right mix of social factors do not necessarily need to produce larger energy systems. There's no inherent teleology or end-state in what spectralisation does for society; it can produce different outcomes depending on how we guide it going forward. The spectralisation of conversional methods and devices can lead to many kinds of changes across society, including changes related to infrastructure and built environments, such as the emergence of railroads after the invention of high-pressure steam engines or the construction of paved roads and highways after the invention of cars. Infrastructure often develops in response to the spectralisation of conversional technologies, because society adapts logistical and transportation systems to facilitate the rise of a new conversional network.

Whether it's the rise of watermills and windmills or the development of steam engines and personal computers, the spectralisation of technology has generally, though not always, produced more energy-intensive societies. To understand why spectralisations inflate the scale dynamics of energy coronets, it's useful to know that conversional methods have a high degree of entanglement with upstream and downstream economic activities. For example, a conversional process from any device requires energy inputs, since it involves the conversion of energy from one initial form to another. A different, spectralised conversional process may therefore require different inputs. Those new inputs have to be extracted, processed, or distributed using different methods, and executing those methods requires more energy. This extra throughput will raise the AFR of the economy unless there's corresponding downscaling effects in other sectors. What's more, the outputs of the spectralised process may also change, and they would then need to be distributed and consumed via different modal adaptations across the nodes of a given coronet. Of course, spectralisation begins at the level of individual devices and components. But these microlevel spectralisations can profoundly affect the scale dynamics of conversional networks if they manage to broadly diffuse across the economy. Under modern capitalism, this process of diffusion and technological management unfolds because of various social selection mechanisms guided by the dynamics of class conflict, social power, and geostrategic rivalries. This process is described in much greater detail in chapter 8.

Under modern capitalism, this process of diffusion and technological management unfolds because of various social selection mechanisms guided by the dynamics of class conflict, social power, and geostrategic rivalries.

To better understand the effects of spectralisation on energy scale dynamics, let's consider a concrete example: the macrolevel transition to renewable energy sources like wind, solar, and hydro. As of 2021, renewables provided an impressive 28 percent of the world's total electricity generation, up from a share of 20 percent just eleven years earlier.[10] The rate of growth in the last few decades has been astonishing. This macrolevel transition in the global economy is being driven by numerous microlevel spectralisations involving technologies like electric batteries, wind turbines, and solar panels. It's also changing the input and extraction dynamics on which the global economy depends, as the raw inputs to the new coronets are shifting from fuel-based sources to material-based sources. Renewable technologies rely heavily on critical minerals like cobalt, lithium, nickel, copper, and rare earth elements, including yttrium, scandium, and the lanthanides.[11] According to the International Energy Agency, a typical electric vehicle requires six times the

---

[10] IEA, World Energy Outlook 2022 (Paris: IEA, 2022), 279, https://www.iea.org/.

[11] The term "rare earth" element is misleading because many of these elements are not scarce at all. Some of them are far more abundant than things like copper and gold. They're called "rare earth" because they're not heavily concentrated in mineral ore deposits, unlike other metals. Instead, they're scattered around the Earth in smaller concentrations. The lanthanides are 15 metallic elements from lanthanum to lutetium in the Periodic Table, with atomic numbers from 57 to 71.

mineral inputs of a conventional gas-powered vehicle.[12] The typical onshore wind plant needs nine times more minerals than a conventional gas-fired power plant.[13] Since 2010, every new unit of power generation has required on average 50 percent more mineral resources.[14] But despite the impressive scale of this transition, the world is still using more energy, emitting more greenhouse gases, and setting new records in the atmospheric concentration of carbon dioxide and other greenhouse gases. That's in large part because the transition to renewables is still heavily dependent on fossil fuels, as raw minerals are mined and transported using vehicles powered by fossil fuels. Likewise, wind turbines and solar panels are still largely built in factories operating on electricity generated by coal-fired and gas-fired power plants. Furthermore, distributing all the new electricity produced by wind and solar farms will require the installation of additional grid capacity. This distributional barrier has been a major problem in the United States, as thousands of renewable energy projects have been delayed because of bureaucratic mismanagement and an insufficient electric grid.[15] Fewer than 20 percent of all proposed wind and solar projects in the United States actually come to fruition.[16]

Microlevel spectralisations affect the individual devices that interact within a broader coronet, such as prime movers. In a general sense, a prime mover is any initial source of motive power, such as a windmill or an internal combustion engine, that receives a flow of energy and then uses that energy to drive machinery or perform some other tasks. In engineering specifically, prime movers are engines that convert fuel to useful energy. For our purposes, I'll define prime movers as the dominant energy converters of a given economy—in other words, they're the most energyintensive devices operating in the economy. Prime movers have changed radically over time, as documented by Vaclav Smil in Energy and Civilisation. For much of human history, human muscles provided the peak power capacities available, at roughly 100 watts (W). Draft animals like oxen and horses reached about 400 W in the third millennium BCE. By the year 1000 CE, horizontal waterwheels had become the leading prime movers, generating about 5,000 W of power. In 1800, the biggest steam engines had blown through 100,000 W and retained their dominance throughout much of the nineteenth century. In more recent times, steam turbines have become the dominant prime movers, with the biggest units producing more than 1 GW, or one billion watts. In contrast to prime movers, contingents are relatively low-energy devices that depend on prime movers in order to successfully convert energy and operate normally. A personal computer is a great example of a contingent device. It operates in part because of massive steam turbines producing vast amounts of electricity, which is then distributed through various modal flows to the different residential, commercial, and industrial districts of an economy. Personal cars and vehicles are another common example of contingent technologies; they can only operate because of highly processed fuels or electric charge carriers that have undergone multiple stages of conversion in their modal flows across the economy. Industrial machines can also be considered contingents, and in that sense contingents act on raw materials to create finished manufacturing products that are sold in regional and global markets.

Technology exists in the context of financial and commodity markets that are controlled and engineered by certain groups to yield certain results.

The spectralisation of prime movers can have important downstream effects on economic activity, as prime movers effectively dictate the exergy capacity of the whole system. However, the spectralisation of contingents can also profoundly affect the spectralisation of prime movers. That's because technology exists in the context of financial and commodity markets that are controlled and engineered by certain groups to yield certain results. The modal flows and

---

[12] IEA, The Role of Critical Minerals in Clean Energy Transitions (Paris: IEA, 2021), 5, https://www.iea.org/.

[13] Ibid.

[14] Ibid.

[15] Brad Plumer, "The U.S. Has Billions for Wind and Solar Projects. Good Luck Plugging Them In," New York Times, February 23, 2023.

[16] Ibid.

dynamical cycles of modern capitalism are therefore organised for the purpose of producing and delivering large volumes of contingent devices and products in a timely and efficient manner.

In the past two centuries, we've lived under an energy-intensive technological regime of catalytic spectral spectralisation. The spectralisation of technology under capitalism is catalytic in two primary ways. First, increasing spectralisation has the effect of accelerating and intensifying modal flows across the coronets of a given economy. In other words, conversional processes under capitalism are modified to enlarge and speed up cycles of production and distribution. That's because spectralisation generally leads to a greater demand for energy services to build, operate, and maintain the spectralised technologies. In the meantime, older technologies or energy systems don't go away; they're simply shifted and transferred for the purpose of achieving other tasks and objectives. Modern civilisations no longer need horses for transportation, where ground vehicles and airplanes have taken over, but horses are nevertheless still used for competitive racing and other commercial events. Second, capitalist economies are generally catalytic in the sense that technological innovations in one economic sector often catalyse and speed up changes and innovations in other sectors, thus expanding the energy scale of the overall system. For a common example, if one particular company or economic sector spectralises a particular technology that happens to reduce production costs, other companies and sectors will inevitably follow in order to stay competitive. The result is not just that spectralised technologies diffuse across the economy and therefore consume more energy, but that an increase in the rate of spectralisation itself becomes a major feature of economic development under capitalism. Even in the presence of economy-wide efficiency gains, higher rates of spectralisation under capitalism will increase the aggregate energy scale of our civilisation, thus imposing greater pressure and more disruptions on the natural cycles of the biosphere. These intense disruptions will then reverberate on human civilisation itself, causing it to buckle and bend from all the collective ecological pressure that's rapidly building up.

Efficiency and Technological Innovation

Many people today believe that we can carefully manage and mitigate the ecological crisis we face through clever technological innovations. One of the more popular arguments inside the circles of technocapitalism is the idea that civilisation can just keep humming along through gains in energy efficiency. The idea that we can do more with less is seductive, but there are several reasons why this strategy will fail over the long run, if we choose to keep pursuing it. The most fundamental reason is that nature imposes absolute physical limits on efficiency that no amount of technological progress can overcome. The recent breakdown in Moore's Law because of quantum effects is a notable example.[17] Another one is the efficiency barrier that the Carnot cycle represents for all practical heat engines.[18] Second, even if aggregate efficiencies improve through amazing technological innovations, they're likely to do so too slowly given the timing

Aggregate efficiency gains for entire economies are almost always associated with higher levels of energy use and consumption, not less.

---

[17] Tom Simonite, "Moore's Law Is Dead. Now What?" MIT Technology Review, May 13, 2016, https://www.technologyreview.com/. Moore's Law is the observation that the number of transistors in an integrated circuit should double every two years, which is something that did indeed happen for a few decades. But as more and more transistors are packed into the same area, electrons will start tunneling across different regions of the semiconductor and weaken or disrupt the fidelity of the electric currents that are necessary for logical computation. Chipmakers and tech companies are finding ways around these quantum limitations. One method they've used is simply making computer chips bigger; that's the strategy NVIDIA adopted with its latest generation AI chip, called Blackwell, which made its public debut in 2024 and is expected to pack an astonishing 208 billion transistors in a single unit, making it by far the world's most powerful computer chip as of this writing. But the broader strategy has been to rely on accelerated and parallel computing, which features the distribution of computing tasks across multiple cores packed into the same mainframe. By spreading out intensive computing operations across different computer chips working together, it becomes possible to generate ultra-fast computational speeds even with the constraints holding back Moore's Law.

[18] Peter Atkins, Four Laws That Drive the Universe (Oxford: Oxford University Press, 2007), 51-52. The Carnot limit, or Carnot efficiency, is the highest possible efficiency that an ideal thermodynamic engine can have. As real-life engines are by definition not ideal, they will never be able to surpass the efficiency barrier of the Carnot limit.

constraints on implementing the new and ambitious energy policies required to get us out of our current mess. And third, aggregate efficiency gains for entire economies are almost always associated with higher levels of energy use and consumption, not less. This last claim appears to be quite paradoxical, so let's explore it first.

We sometimes drive longer distances when fuel efficiency improves. We often power more appliances when electricity becomes cheaper. Those who are proud of energy savings at home, through recycling and other similar activities, are more than happy to take vacations by jumping on an airplane and flying halfway around the world. People often take energy savings in one area and exchange them for expenses in another. What we end up doing with energy efficiency gains can sometimes be just as important as the gains themselves. In ecological studies, this phenomenon is generally known as the Jevons Paradox, which reveals that the intended effects of efficiency improvements do not always materialise.[19] First formulated in the nineteenth century by the British economist William Stanley Jevons, the paradox states that increases in energy efficiency are generally used to expand accumulation and production, leading to greater consumption of the very resources that the efficiency improvements were supposed to conserve. The argument behind the paradox is that boosting efficiency leads to cheaper goods and services, which encourages more demand and more spending, leading to the consumption of more energy.[20] Jevons described this effect in the context of coal power and steam engines. He observed that efficiency improvements in steam engines had encouraged more consumption of coal in Britain, implying that boosting energy efficiency did not actually lead to energy savings.

Increases in energy efficiency are generally used to expand accumulation and production, leading to greater consumption of the very resources that the efficiency improvements were supposed to conserve.

In economics, variations of this paradox are known as the rebound effect. For example, if a 5 percent rise in fuel efficiency leads to a 2 percent decline in fuel consumption, then the rebound would be 60 percent. The Jevons Paradox, also called "backfire" among economists, would occur if a rise in fuel efficiency actually produces an increase in fuel consumption. Most neoclassical economists accept that some rebound effects are real and significant, but they largely reject the notion of backfire. Neoclassical studies have concluded that microeconomic rebound effects hover around 20 to 40 percent whereas macroeconomic rebound effects are much larger, at around 50 to 60 percent, though in some cases they could reach even higher.[21] It should be emphasised that the results of these studies are not very useful, for several reasons. First, they're highly sensitive to the time horizon under consideration. Government policies or autonomous efficiency improvements might lead to net energy savings for ten years or so, then completely backfire fifty years down the road. Simply put, the studies make assumptions about demand patterns in the economy that are unlikely to hold for long periods of time. Second, these studies are generally terrible at discerning boundary effects. Efficiency policies or improvements might lead to net energy savings for one particular company, or in one particular country, but those same improvements can then spill over and produce higher energy consumption among other companies and countries. As energy scientist Carey King puts it: The smaller the system boundary used for analysing the backfire effect, the less relevant the paradox appears. To fully conceptualise the Jevons Paradox, your boundary must include the entire world economy, or every single device that consumes energy.[22] In a comprehensive review of the literature on the

To fully conceptualise the Jevons Paradox, your boundary must include the entire world economy, or every single device that consumes energy.

---

[19] John Bellamy Foster, Ecology Against Capitalism (New York: Monthly Review Press, 2002), 94.

[20] Ibid.

[21] For a prominent paper, see Kenneth Gillingham, David Rapson, and Gernot Wagner, "The Rebound Effect and Energy Efficiency Policy" Review of Environmental Economics and Policy 10 (2016). Also refer to Terry Barker et al., "The macroeconomic rebound effect and the world economy," Energy Efficiency 2 (2009): 411-27.

[22] Carey King, The Economic Superorganism (New York: Springer International, 2020), 230.

subject, the moderate UK Energy Research Centre claimed, rather prematurely, that the most extreme versions of the rebound effect probably no longer apply to developed economies. However, the research group also argued that large rebound effects across our economies can still occur. They reached the following conclusion: “It would be wrong to assume that … rebound effects are so small that they can be disregarded. “Under some circumstances, such as energy efficient technologies that significantly improve the productivity of energy intensive industries, economywide rebound effects may exceed 50 percent and could potentially increase energy conversion in the long term.”[23] Even if one conceded that backfire is impossible, the mere fact that significant economy-wide rebound effects are indeed possible should give all of us pause about the utility of efficiency strategies in combating the ecological crisis and climate change.

For all these nuances, much of this argument is actually a red herring. The fundamental problem is that the entire debate obscures a more important unknown: the problem of whether efficiency improvements, even if they don’t backfire, can come fast enough to alleviate the worst consequences of the ecological crisis, which are still ahead of us. In other words, the central problem in this discussion is about time. Can we make huge efficiency gains in the short period of time required to take serious action and forestall some of the more devastating consequences of the bionomic disruption? Do we really want to stake the future of global civilisation on the fringe promise that massive efficiency gains on a global scale can be realised within a couple of decades, contrary to all historical evidence? Given the economic and political incentives prevalent in our current age of capitalism, it’s unlikely that our love affair with efficiency can actually provide concrete solutions to the profound challenges that we face. That’s because the aggregate efficiency of an economic system is an inertial quantity that changes at a glacial pace, regardless of whether it’s increasing or decreasing.

We see this exact process playing out right now with greenhouse gas emissions, although our ecological crises extend far beyond this problem. Political and business leaders have been hoping for years that technological progress will somehow deliver both higher rates of economic growth and a sharp reduction in greenhouse gas emissions. Things have not gone according to plan. The United Nations has long warned that an “unacceptable” gap exists between the pledges from national governments and the emission reductions needed to prevent some of the worst consequences associated with climate change.[24] In 2022, carbon dioxide emissions reached a record high globally, completely defying even the relatively modest goals of the Paris Agreement.[25] Unsurprisingly, atmospheric levels of carbon dioxide, methane, and nitrous oxide—collectively the most dangerous greenhouse gases—also reached new highs in 2022, setting the stage for even more global warming down the road. The challenges with boosting efficiency are easier to understand when we view capitalism on a global scale: although many developed nations have made modest yet measurable improvements with their aggregate efficiencies, these gains have been completely washed away by developing economies that are still in the process of industrialisation.[26] Evidently, substantial changes in the aggregate efficiency of the global economy are unlikely to materialise in short periods of time under the capitalist regime. Technological growth under capitalism will deliver some additional progress on efficiency, but certainly not enough to prevent the worst consequences of our ecological crises.

One of the best ways to understand the inertia of aggregate efficiencies is to compare energy efficiencies under capitalism with those from nomadic days, more than 10,000 years ago. Recall that human muscles performed the largest share of the work in nomadic societies, and the efficiency of our muscles is roughly 20 percent, perhaps much more

---

[23] Steven Sorrell, The Rebound Effect (London: UK Energy Research Centre, 2007), 92.

[24] Fiona Harvey, “UN Warns of ‘Unacceptable’ Greenhouse Gas Emissions Gap,” The Guardian, October 31, 2017, https://www.theguardian.com/us.

[25] Cathy Bussewitz, “Carbon dioxide emissions reached a record high in 2022,” Associated Press, March 2, 2023.

[26] Nijavalli H. Ravindranath and Jayant A. Sathaye, Climate Change and Developing Countries (New York: Springer, 2006), 35.

under special circumstances.[27] For comparison, most gasoline-powered combustion engines have a thermodynamic efficiency of roughly 15 percent, coal-fired power plants come in at a global average of about 30 percent, and the vast majority of commercial photovoltaics are somewhere around 15 to 20 percent.[28] Variations exist for all of these numbers, depending on a wide array of physical conditions. Nevertheless, when it comes to efficiency, we can safely conclude that the dominant prime movers and contingents of capitalism can hardly do much better than human muscles, even after three centuries of rapid technological progress. Large gains in efficiency are extremely difficult to achieve, in both physical and economic terms, because they require enormous investments and resources. Although impressive efficiency gains happen occasionally in the history of capitalism, they have always been subordinated to efforts at expanding useful energy output and the scale of production more broadly.

From time to time, amazing innovations come along that set new standards for future technologies, but an amazing innovation does not represent the entire economy. The Watt steam engine was a major improvement over previous models, but its thermal efficiency was only 5 percent at best and its diffusion across the English economy was rather slow.[29] For another example, Tesla motors themselves have a phenomenal operating efficiency, but the electricity needed to run the cars often comes from much more inefficient sources, such as coal power plants. In 2013, a person driving a Tesla in Ohio or West Virginia would have produced roughly the same carbon emissions as someone driving a Honda Accord, given the dirty energy mix in those states.[30] The aggregate efficiency of modern economies remains relatively low because elite capitalists are interested in increasing their profits and production levels, not in making the enormous investments required to generate significant improvements in efficiency. As long as the current economic order remains in place, capitalism will continue to thrive on energy-scale expansion and intensive dissipation, with efficiency improvements merely secondary and incidental to the wider project of plundering the natural world and profiting from that plunder. Since efficiency gains alone are unlikely to improve the outlook of global civilisation in the face of the bionomic disruption, we need to think more comprehensively about the future direction of technological change and what technology should be doing for civilisation.

A person driving a Tesla would have produced roughly the same carbon emissions as someone driving a Honda Accord.

The Future Direction of Technological Change

To wonder about the future of technology is to wonder about the future of society as a whole. There's no shortage of opinions and narratives about the future direction of technological innovation.[31] There are multiple camps in these debates, and the debates themselves unfold along multiple vectors. Perhaps the most prominent vector is directed at the underlying resource base that human civilisation should adopt in the future. For debates along this vector, there's one side that has concluded that fossil fuels are absolutely necessary for the future success of human civilisation, and therefore the proper way to combat their harmful effects is by directly intervening in the ecosphere, either through solar radiation management or

Most of these debates have in common that they're happening within the ideological framework of capitalist economies.

---

[27] Zhen-He He et al., "ATP Consumption and Efficiency of Human Single Muscle Fibers with Different Myosin Isoform Composition," Biophysical Journal 79 (2000): 945-61.

[28] On the efficiency of internal combustion engines, see Efstathios E. Stathis Michaelides, Alternative Energy Sources (New York: Springer, 2012), 411. For coal-fired power plants, see R. Sandström, "Creep Strength of Austenitic Stainless Steels for Boiler Applications," in Coal Power Plant Materials and Life Assessment, ed. A. Shibli (Amsterdam: Elsevier, 2014), 128. On the efficiency of photovoltaic cells, see Friedrich Sick and Thomas Erge, Photovoltaics in Buildings (London: Earthscan, 1996), 14.

[29] Robert T. Balmer, Modern Engineering Thermodynamics (Cambridge: Academic Press, 2011), 454.

[30] Will Oremus, "How Green Is a Tesla, Really?," Slate, September 9, 2013, http://slate.com.

[31] For an excellent discussion of these issues, see Carey King, The Economic Superorganism (New York: Springer International, 2020), 59-115.

through widespread greenhouse gas removals. These ideas are collectively known as geoengineering, and I'll say more about the concept shortly. Another camp argues that we need to implement a rapid and radical transition away from fossil fuels and toward renewable energy sources, such as hydro, wind, and solar. Others maintain that we can follow a kind of hybrid approach where we develop both fossil fuel and renewable technologies, the "everything goes" strategy. Another vector of debate is directed at the role that technological innovation should play as a response to our ecological crisis. The most popular camp in this debate believes that humans are eternally clever and resourceful; combine that ingenuity with the social mechanism of capitalist markets and civilisation can then always extricate itself from any crisis. What most of these debates have in common is that they're happening within the ideological framework of capitalist economies. In other words, they assume that capitalism is the underlying economic system we should aim to preserve, and what really matters is the technological parameters under which capitalism develops in the future. For the most part, they're very narrow debates about technological tinkering, leaving aside the more important issue of what political and economic regimes are going to manage, supervise, and direct these various technological paths.

The reason why elites frame the potential solutions to our common global problems as a simple matter of technological tinkering is simply because that's what would allow them to preserve their wealth and power, to preserve the status quo from which they benefit. Capitalists are the apex predators of the ruling classes, and capitalists anywhere and everywhere are masters of deception and distraction. Focusing the debate on the Promethean potential of technology has become a specialised ritual for sidestepping more difficult conversations about the structural distribution of power in modern society. By now it's hard to keep track of all the technological breakthroughs that are supposed to save us. Maybe it's wind and solar. Maybe it's carbon capture and storage. Maybe it's solar radiation management. Maybe it's ocean fertilisation. Maybe it's next-generation nuclear power plants. Maybe it's high-temperature superconductors. Maybe it's hydrogen fuel cells. Maybe it's nuclear fusion. Maybe it's electric vehicles. Maybe it's solar panels in space beaming energy down to Earth. Maybe it's all of them. Maybe it's something else. Maybe it's Elon Musk. Maybe it's Santa Claus or Harry Potter. Fictional characters have just about the same odds of getting the job done as all these other things. It's impossible to cover the intricate nuances of all these proposals in a single chapter, so here I'll focus on two big things: renewable technologies and geoengineering.

Among those who have correctly decided that we eventually need to ditch fossil fuels, at least for the majority of our energy production and economic activities, there are still further debates around what should replace them. The two broad camps in this debate are those who support renewables like wind and solar and those who support nuclear power as the salvation strategy for our civilisation. There are many critics who contend that wind and solar are too unreliable for the energy demands of a modern electric grid.[32] They're supposedly "intermittent" sources of energy, and the implication is that other sources, like nuclear power plants and coal-fired plants, are more stable. The reality is very different. All sources of energy are intermittent at different timescales. Let's consider France, a nation that produces roughly 70 percent of its electricity from nuclear power, a higher share than in any other country.[33] In 2019, every French nuclear plant was shut down on average for almost 100 days because of planned repairs or other emergency issues; that figure rose to 115 days in 2020 when French nuclear plants generated less than 65 percent of the electricity they theoretically could have produced.[34] In 2022, the power output of the French nuclear industry fell below 50 percent capacity, reaching a thirty-year low.[35] Chronic underinvestment from Électricité de France (EDF), the state-backed company running the nuclear power system, is a major contributing factor to the recent failures, but the sheer

---

[32] Ibid., 96-99.

[33] Liz Alderman, "French Nuclear Power Crisis Frustrates Europe's Push to Quit Russian Energy," New York Times, June 19, 2022.

[34] Amory Lovins and M. V. Ramana, "Three Myths About Renewable Energy and the Grid, Debunked," Yale Environment 360 (2021). https://e360.yale.edu/.

[35] Liz Alderman, "French Nuclear Power Crisis Frustrates Europe's Push to Quit Russian Energy," New York Times, June 19, 2022.

complexity of nuclear power doesn't help. Many French nuclear plants are suffering from corrosion and faulty welding seals. Furthermore, as I mentioned in a previous chapter, many nuclear power plants around the world are heavily reliant on cool rivers to keep their reactors in check, and global warming is going to make those rivers warmer and warmer as time goes on, thus sabotaging electricity generation from much of the nuclear industry. This is not a hypothetical problem; it's a major issue that many countries, including France, have already experienced.

Nuclear power advocates often tout the advanced features of nuclear technology, but that technological complexity is actually a great reason not to rely on nuclear power as a substitute for fossil fuels. Precisely because nuclear power plants are so complex to design and build, they are plagued by ridiculous cost overruns, construction delays, and challenging operational and maintenance issues that last throughout their lifetimes. For example, EDF builds nuclear plants in other European countries. It built one in Finland that started operating in 2022 but was supposed to be ready thirteen years earlier, in 2009. The nuclear industry in the United States has suffered from the same problems. The planned expansion of the VC Summer nuclear power plant in South Carolina went disastrously after its main contractor went bankrupt in 2017.[36] The expansion has since been scrapped, with nothing to show after billions of dollars wasted, and the entire affair eventually devolved into accusations of fraud, lawsuits, recriminations, and various legal settlements. The expansion of the Vogtle plant in Georgia has experienced some of the same issues. Everywhere you look around the world, the nuclear industry is in shambles and can't get its act together.

In February 2021, when a massive winter storm knocked out power all over the U.S. state of Texas, wind and solar energy sources generally outperformed their fossil fuel counterparts.[37] Indeed, the scale of the disaster was amplified largely because of frozen natural gas pipelines and a lack of weatherisation among power plants using fossil fuels. Looking at the System Average Interruption Duration Index (SAIDI), an indicator that measures grid reliability, also confirms this point. In 2020, Germany had a SAIDI of just 0.25 hours, one of the lowest in Europe.[38] By contrast, the United States, where nuclear power provides 20 percent of electricity, had a SAIDI of 1.28 hours in 2020, roughly five times the outage rate of Germany. In contrast to the typical drivel that surfaces on this issue, renewable energy sources are indeed a highly reliable source of energy and can be successfully used to manage intermittency issues when fossil fuel and nuclear power plants become unavailable. Just as important, multiple studies have shown that the broad adoption of nuclear power would lead to much higher greenhouse gas emissions than the broad adoption of wind and solar. It's certainly true that the nuclear industry would have a smaller carbon footprint than the current fossil fuel industry does, but the uncertainties surrounding future emissions from the expansion of nuclear power are huge.[39] It's almost certainly the case that the diffusion of nuclear power would produce much larger GHG emissions than the corresponding diffusion of wind and solar.[40] Given all these problems, it's fairly obvious that nuclear power should not be our main strategy going forward, although in highly select cases nations should still continue to build some nuclear power plants to supplement the core strategy focused on the expansion of renewable energy sources.

The most fruitless debates, however, are the ones involving supporters of the current fossil fuel regime. For this crowd, there's no sense of urgency and no energy transition required to deal with our ecological problems. Instead, they would deal with these problems by implementing geoengineering solutions designed to cool down the planet and suck out

---

[36] King, The Economic Superorganism, 93.

[37] Ibid.

[38] Ibid.

[39] See Benjamin K. Sovacool, "Valuing the greenhouse gas emissions from nuclear power: A critical survey," Energy Policy 36 (2008): 2950-63. Also refer to Ethan Warner and Garvin Heath, "Life Cycle Greenhouse Gas Emissions of Nuclear Electricity Generation," Journal of Industrial Ecology 16 (2012): S73-S92.

[40] For a recent comprehensive study on the subject, see Francesco Pomponi and Jim Hart, "The greenhouse gas emissions of nuclear energy," Applied Energy 290 (2021): 116743.

greenhouse gases from the atmosphere while at the same time continuing to intensively burn fossil fuels. Geoengineering is large-scale anthropogenic intervention in the natural systems and energy flows of the global ecosphere for the purpose of managing the harmful effects of our economic activities. Overall, there are two broad geoengineering proposals on the table: solar radiation management (SRM) and carbon dioxide removal (CDR). The basic goal of SRM strategies is to somehow change the chemical composition of the atmosphere or the planet's surface so that more sunlight is reflected back into space. A prominent proposal is to inject stratospheric aerosols—small particles that reflect sunlight—into the upper atmosphere. There are several big red flags associated with SRM strategies. Perhaps the most serious is that they risk severely destabilising the global hydrological cycle, which would lead to massive droughts around the world.[41] Another major problem is what's known as the termination shock, the point in time when we have to stop doing SRM. That's going to cause a huge and sudden shock to global temperatures, because once we pull back whatever we're doing to reflect sunlight back into space, much more sunlight will start hitting the surface again and temperatures will go back up almost right away. One might wonder why have to stop doing SRM at all. Why can't we just keep going with it forever? The answer is related to the first point above. Sooner or later, continuing to engage in SRM will virtually destroy the natural cycles of the biosphere, so we'll have no choice but to stop it or roll it back significantly, which will inevitably produce a termination shock that wallops global civilisation.

In contrast to SRM, CDR strategies are focused on removing carbon dioxide from the atmosphere. A major example of a CDR proposal is afforestation, which would require a global effort to plant as many trees as possible, thus expanding the natural ground sinks for carbon dioxide. Countries such as China have had some limited success with this strategy, but it's doubtful it could work quickly enough for the entire world. Another idea is ocean fertilisation, a strategy that calls for people to add critical nutrients in special locations around the world's oceans as a way of promoting the growth of microorganisms that would then suck out even more carbon dioxide from the atmosphere. This strategy has proven to be mostly unreliable, mainly because the vast majority of the carbon sucked up by the ocean would stay near the surface, therefore making it likely to end up back in the atmosphere.[42] Very little carbon would reach deep into the ocean where it could be naturally sequestered. And yet another example, perhaps the most prominent one, is carbon capture and storage ((CCS), which refers to the process of building specialised facilities or installing devices in power plants that are designed to remove greenhouse gases from the atmosphere. CDR proposals now form a major component of all IPCC models about future climate scenarios. There's a popular assumption among politicians and capitalists around the world that we can just keep burning fossil fuels with reckless abandon, because we can always just pull out that carbon from the atmosphere later or prevent it from getting there in the first place.

One of the more popular CCS strategies has been bioenergy carbon capture and storage (BECCS). It works by burning cultivated crops to generate electricity and then capturing the resulting carbon dioxide and sequestering it underground, so that it never gets into the atmosphere. As of 2023, BECCS facilities were capturing roughly two megatons of carbon dioxide per year, a trivial amount compared to the roughly 50 gigatons of greenhouse gases that are emitted globally every year. According to the International Energy Agency, carbon removal through BECCS facilities will reach roughly 40 megatons a year by 2030, which is far less than the 250 megatons a year envisaged in the IEA's own Net Zero by 2050 scenario.[43] Beyond the fact that BECCS implementation is ridiculously behind schedule, it's worth questioning whether that implementation is a good idea in the first place. Implementing BECCS on a global scale could be disastrous for global civilisation as it would require vast amounts of new lands, roughly the size of Australia, to be set aside for crop cultivation and electricity generation. It would also be extremely costly. The climatologist James Hansen has estimated

---

[41] John Bellamy Foster, "Making War on the Planet," Monthly Review 70 (2018): 1-10.

[42] Ibid.

[43] IEA, Bioenergy with Carbon Capture and Storage (Paris: IEA, 2022), https://www.iea.org/.

the financial costs of setting up BECCS in this century to be hundreds of trillions of dollars.[44] And because BECCS will likely be established in farmlands with crop monocultures dominated by big agribusiness, there will almost certainly be massive amounts of new greenhouse gas emissions associated with harmful land use changes. The traditional counterpart to BECCS is simply CCS, which is designed to capture and store carbon dioxide at power plants. It suffers from some of the same basic problems. Regarding the implementation of CCS, energy scholar Vaclav Smil has concluded that "in order to sequester just a fifth of [2010] CO2 emissions we would have to create an entirely new worldwide absorption-gathering-compression-transportation-storage industry whose annual throughput would have to be about 70 percent larger than the annual volume now handled by the global crude oil industry, whose immense infrastructure of wells, pipelines, compressor stations, and storage took generations to build."[45] Overall, it's safe to conclude that CCS strategies are little more than carefully orchestrated propaganda from the fossil fuel industry designed to prolong their profits and the current economic order from which they benefit.

It's safe to conclude that CCS strategies are little more than carefully orchestrated propaganda from the fossil fuel industry designed to prolong their profits and the current economic order from which they benefit.

Given all these challenges, a renewable strategy based on the "Holy Trinity"—wind, solar, and hydro—is the most plausible and realistic path forward in the future. Whether humanity takes it is another matter. That these three should be the core components of our future energy strategy does not mean that other energy sources cannot be used. And if we're going to implement this strategy, then the way we decide to deploy and develop it needs careful consideration. Because it takes energy to produce more energy, scaling up new coronets based on renewable energy sources could also end up becoming vastly energy-intensive, unless the transition to renewables is properly managed and constrained through a political and economic process rooted in the realities of the planetary biosphere. For example, transitioning to renewables will require using additional land, constructing large solar and wind farms through complex machinery, the mining and production of new minerals and elements, and the expansion of transportation networks through global trade. These changes will need to be balanced by downscaling effects in other economic sectors, because in the absence of any strategic constraints from state power, this vicious energy-technology spiral would simply aggravate our current civilisational problems even more. A possible countervailing constraint is to implement a vast reduction in global beef production, which requires enormous tracts of land for the cultivation of crops that are used to feed cattle. This is just one possible change; the larger point is that there are many complex dimensions to land use dynamics that humanity would have to think through as it carries out an energy transition away from the fossil fuel addictions of modern capitalism. A radical and rapid transition toward renewable energy can and must take place, but only if it's accompanied by massive cutbacks in aggregate energy use via the decommissioning of more coal-fired and gas-fired plants and the political imposition of new limits on the transportation sector, along with other forms of industrial policy, to manage and ensure the stability of market prices and other financial indicators.

A radical and rapid transition toward renewable energy can and must take place, but only if it's accompanied by massive cutbacks in aggregate energy use.

For another example, hydroelectric dams operating in warm climates and low altitudes actually emit large quantities of greenhouse gases, especially methane, in large part because of decaying organic matter confined in the water reservoirs. Some hydropower facilities produce more greenhouse gas emissions than coal-fired power plants. If we're going to expand renewable energy capacity by building additional hydropower facilities, then we should focus on building them

---

[44] Foster, "Making War on the Planet," 1-10.

[45] Vaclav Smil, "Global Energy: The Latest Infatuations" American Scientist 99 (2011).

in cooler climates and higher altitudes, where water reservoirs are likely to hold fewer organic materials capable of decomposing and of releasing harmful gases like methane. That's why Norway's hydropower plants, which produce roughly 90 percent of the country's electricity, have extremely low life-cycle GHG emissions comparable to typical solar and wind farms.[46] It makes sense to build hydropower capacity in places like Norway, Russia, and Canada. But from the perspective of a stable biosphere, it's much more difficult to do it in places like Brazil, which has long toyed with the idea of constructing dams along the Amazon. That's not to say it's impossible. But if it's going to be done in an ecologically beneficial way, it needs to be much more carefully planned than it has been so far. It's also important to remember as we decommission fossil fuel plants in the future that they do have some advantages over wind and solar, such as flexibility and demand management. If there's too much electricity in the grid, we can simply turn off a coal plant and it won't produce anything. Even with significant improvements in energy storage technologies, it's harder to generate the same level of flexibility with wind turbines and solar panels. Thankfully, hydropower offers precisely that level of maximal flexibility because any hydro plant can be toggled on and off as necessary. What's more, pumped hydro storage is one of the best-established methods of energy storage and is rapidly spreading around the world.[47] It works by pumping water from one reservoir to another reservoir located at a higher elevation, then storing the water there until it's needed later. At that time, the water is released back to the lower reservoir, driving a turbine that produces electricity along the way. The best part is that pumped storage doesn't even need natural rivers or lakes to work. Any site that can store water will do.

The other major consideration is that even though we need to rapidly downscale the fossil fuel industry, it's not a good idea to eliminate it right away. One reason is because the pollution generated by burning fossil fuels results in layers of particles in the atmosphere that prevent some solar radiation from reaching the surface of the planet. That process has a cooling effect on global temperatures.[48] If we turned off all refineries and fossil fuel power plants tomorrow, global temperatures would rapidly accelerate upward for a short period of time, leading to chaos in the global economic system. Another major constraint on the immediate elimination of fossil fuels is transportation. Although electric batteries for ground-based transportation have made enormous strides by now, we don't have commercially viable equivalents for air transportation or merchant shipping. The Chinese company CATL, the world's dominant EV battery manufacturer, did announce in early 2023 that it would begin mass producing a nextgeneration battery with an energy density that could reach up to 500 watt-hours per kilogram, roughly double the energy density of the best batteries on the market.[49] CATL also claimed that this battery could be used in passenger aircraft. But even if that's the case, it could take years for the technology to be considered reliable enough for widespread adoption in the airline industry. And that's why targeted spectralisation is so important; we need different social management strategies for different industries. Electricity generation can undergo a radically quick transition toward renewables; there's no technological barrier there at all. It's purely social and political barriers that are the problem. But we have to be careful with transportation, because there the technological barriers are indeed more serious.

Electricity generation can undergo a radically quick transition toward renewables; there's no technological barrier there at all. It's purely social and political barriers that are the problem.

---

[46] Mafalda Silva and Ingunn Saur Modahl, "The inventory and life cycle data for Norwegian hydroelectricity," Norwegian Institute for Sustainability Research, 2019, https://norsus.no/.

[47] Mira Rojanasakul and Max Bearak, "Is It a Lake, or a Battery? A New Kind of Hydropower Is Spreading Fast," New York Times, May 2, 2023.

[48] See Rachel DuRose, "The terrible paradox of air pollution and climate change," Vox, September 17, 2023. https://www.vox.com/.

[49] "Dan Gearino, "A New Battery Intended to Power Passenger Airplanes and EVs, Explained," Inside Climate News, May 18, 2023, https://insideclimatenews.org/."

In contrast to the catalytic spectralisation of late-stage capitalism, we need strategic, balanced, and targeted spectralisation that harnesses innovation in critical industries but carefully manages technological change in others. Under the capitalist regime, it's easy for network and market effects to rapidly escalate, driving up energy use to extremely high levels and therefore dissipating more energy to our external environments. If we want to target technological innovation in a few industries, it has to be balanced by countervailing constraints in other industries. Achieving such targeted spectralisation cannot happen in the context of the existing power relations in late-stage capitalism. We need new political and economic institutions that prioritise the long-run stability of our biosphere as well as the economic concerns of workers worldwide. And to get there, we'll need to better understand the complex relationship between society, energy, and technology—that is, to understand how the actions of the social institutions that govern our lives affect the energetic and technological dynamics that are increasingly governing the global ecosphere.

We need new political and economic institutions that prioritise the long-run stability of our biosphere as well as the economic concerns of workers worldwide.

Related links:

- The Jus Semper Global Alliance
- Monthly Review
- Erald Kolasi: The Ecological State
- Erald Kolasi: The Physics of Capitalism
- Erald Kolasi: Energy, Economic Growth, and Ecological Crisis
- John Bellamy Foster: The Long Ecological Revolution
- John Bellamy Foster: Marxism and Ecology
- John Bellamy Foster and Brett Clark: The Expropriation of Nature
- Álvaro J. de Regil: Geocratia, the Paradigm that Pursues the Well-being of People and the Planet, Not the Market
- Álvaro J. de Regil: The Unbearable Unawareness of our Ecological Existential Crisis

- **About Jus Semper:** The Jus Semper Global Alliance aims to contribute to achieving a sustainable ethos of social justice in the world, where all communities live in truly democratic environments that provide full enjoyment of human rights and sustainable living standards in accordance with human dignity. To accomplish this, it contributes to the liberalisation of the democratic institutions of society that have been captured by the owners of the market. With that purpose, it is devoted to research and analysis to provoke the awareness and critical thinking to generate ideas for a transformative vision to materialise the truly democratic and sustainable paradigm of People and Planet and NOT of the market.

- **About the authors: Erald Kolasi** is a writer and independent researcher focusing on the nexus between energy, technology, economics, complex systems, and ecological dynamics. His first book, The Physics of Capitalism, came out from the Monthly Review Press in February 2025. He received his PhD in Physics from George Mason University in 2016.

- **About this paper:** This paper is a republication of chapter 7 from the author's book, "The Physics of Capitalism." It has been republished with the author's special permission, for which we are grateful. This paper has been published under Creative Commons, CC-BY-NC-ND 4.0. You are welcome to reproduce the material for non-commercial use, crediting the author and providing a link to the original publisher.

- **Quote this paper as:** Erald Kolasi: Technological Dynamics of Growth and Stability – The Jus Semper Global Alliance, April 2026.

- **Tags:** Democracy, Capitalism, Economics, Marx, Ecology, Ecodynamics, Spectralisation, Physics, Energy Consumption, Technological Efficiency.

- The responsibility for opinions expressed in this work rests only with the author(s), and its publication does not necessarily constitute an endorsement by The Jus Semper Global Alliance.

◆