The Physics of Capitalism

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People tend to think of capitalism in economic terms. Marx argued that capitalism is a political and economic system that transforms the productivity of human labor into large profits and returns for those who own the means of production.[1] Its proponents contend that capitalism is an economic system that promotes free markets and private property.[2] Capitalism's impact is most often understood in terms of wealth and income, wages and prices, and supply and demand. However, human economies are complex biophysical systems that interact with the wider natural world, and none can be fully examined apart from their underlying material conditions. By exploring some fundamental concepts in physics, we can develop a better understanding of how all economic systems work, including the ways that the energy-intensive activities of capitalism are changing humanity and the planet.

This article will explain how the fundamental features of both our natural and economic existence depend on the principles of thermodynamics, which studies the relationships between quantities such as energy, work, and heat.[3] A firm grasp of how capitalism works at a physical level can help us understand why our next economic system should be more ecological, prioritizing stability over the long run and compatibility with the global ecosphere that sustains humanity.

Such an understanding requires a glance at some central concepts in physics. These include energy, entropy, dissipation, and the various rules of nature that bind them together. The central features of our natural existence, as living organisms and as human beings, emerge from the collective interactions described by these core physical realities. Although these concepts can be difficult to define without reference to specific models and theories, their general features can be outlined and analyzed to reveal the powerful intersection between physics and economics.

The exchange of energy between different systems has a decisive influence on the order, phase, and stability of physical matter. Energy can be defined as any conserved physical property that can produce motion, such as work or heat, when exchanged among different systems.[4] Kinetic energy and potential energy are two of the most important forms of energy storage. The sum of these two quantities is known as mechanical energy.[5] A truck speeding down the highway packs a good amount of kinetic energy—that is, energy associated with motion. A boulder teetering at the edge of a cliff has great potential energy, or energy associated with position. If given a slight push, its potential energy transforms into kinetic energy under the influence of gravity, and off it goes. When physical systems interact, energy is converted into many different forms, but its total quantity always remains constant. The conservation of energy implies that the total output of all energy flows and transformations must equal the total input.

Energy flows among different systems represent the engine of the cosmos, and they happen everywhere, so often that we hardly notice them. Heat naturally flows from warmer to colder regions, hence our coffee cools in the morning. Particles move from high-pressure areas to low-pressure areas, and so the wind starts to howl. Water travels from regions of high potential energy to regions of low potential energy, making rivers flow. Electric charges journey from regions of high voltage to regions of low voltage, and thus currents are unleashed through conductors. The flow of energy through physical systems is one of the most common features of nature. And these examples show that energy flows require gradients—differences in temperature, pressure, density, or other factors. Without these gradients, nature would never deliver any net flows, all physical systems would remain in equilibrium, and the world would be inert—and very boring. Energy flows are also important because they can generate mechanical work, which is any macroscopic displacement in response to a force.[6] Lifting a weight and kicking a ball are both examples of performing mechanical work on another system. An important result from classical physics equates the quantity of work to the change in the mechanical energy of a physical system, revealing a useful relationship between these two variables.[7]

Although energy flows can produce work, they rarely do so efficiently. Large macroscopic systems, like trucks or planets, routinely lose or gain mechanical energy through their interactions with the external world. The lead actor in this grand drama is dissipation, defined as any process that partially reduces or entirely eliminates the available mechanical energy of a physical system, converting it into heat or other products.[8] As they interact with the external environment, physical systems often lose mechanical energy over time through friction, diffusion, turbulence, vibrations, collisions, and other similar dissipative effects, all of which prevent any energy source from being converted entirely into mechanical work. A simple example of dissipation is the heat produced when we rapidly rub our hands together. In the natural world, macroscopic energy flows are often accompanied by dissipative losses of one kind or another. Physical systems that can dissipate energy are capable of rich and complex interactions, making dissipation a central feature of the natural order. A world without dissipation, and without the interactions that make it possible, is difficult to imagine. If friction suddenly disappeared from the world, people would slip and slide everywhere. Our cars would be useless, as would the very idea of transportation, because wheels and other mechanical devices would lack any traction with the ground and other surfaces. We would never be able to hold hands or rock our babies. Our bodies would rapidly deteriorate and lose their internal structure. The world would be alien and unrecognizable.

Dissipation is closely related to entropy, one of the most important concepts in thermodynamics. While energy measures the motion produced by physical systems, entropy tracks the way that energy is distributed in the natural world. Entropy has several standard definitions in physics, all of them essentially equivalent. One popular definition from classical thermodynamics states that entropy is the amount of heat energy per unit of temperature that becomes unavailable for mechanical work during a thermodynamic process.[9] Another important definition comes from statistical physics, which looks at how the microscopic parts of nature can join to produce big, macroscopic results. In this statistical version, entropy is a measure of the various ways that the microscopic states of a larger system can be rearranged without changing that system.[10] For a concrete example, think of a typical gas and a typical solid at equilibrium. Energy is distributed very differently in these two phases of matter. The gas has a higher entropy than the solid, because the former's particles have far more possible energy configurations than the fixed atomic sites in solids and crystals, which have only a small range of energy configurations that will preserve their fundamental order.[11] We should emphasize that the concept of entropy does not apply to a specific configuration of macroscopic matter, but rather applies as a constraint on the number of possible configurations that a macroscopic system can have at equilibrium.

Entropy has a profound connection to dissipation through one of the most important laws of thermodynamics, which states that heat flows can never be fully converted into work.[12] Dissipative interactions ensure that physical systems always lose some energy as heat in any natural thermodynamic process, where friction and other similar effects are present. Real-world examples of these thermodynamic losses include emissions from car engines, electric currents encountering resistance, and interacting fluid layers experiencing viscosity. In thermodynamics, these phenomena are often considered irreversible. The continuous production of heat energy from irreversible phenomena gradually depletes the stock of mechanical energy that physical systems can exploit. According to the definition of entropy, depleting useful mechanical energy generally implies that entropy increases. Formally stated, the most important consequence of any irreversible process is to increase the combined entropy of a physical system and its surroundings. For an isolated system, entropy continues to rise until it reaches some maximum value, at which point the system settles into equilibrium. To clarify this last concept, imagine a red gas and a blue gas separated by a partition inside a sealed container. Removing the partition allows the two gases to mix together. The result would be a gas that looks purple, and that equilibrium configuration would represent the state of maximum entropy. We can also relate dissipation to the concept of entropy in statistical physics. The proliferation of heat energy through physical systems changes the motion of their molecules into something more random and dispersed, increasing the number of microstates that can represent the macroscopic properties of the system. In a broad sense, entropy can be seen as the tendency of nature to reconfigure energy states into distributions that dissipate mechanical energy.

The traditional description of entropy given above applies in the regime of equilibrium thermodynamics. But in the real world, physical systems rarely exist at fixed temperatures, in perfect states of equilibrium, or in total isolation from the rest of the universe. The field of non-equilibrium thermodynamics examines the properties of thermodynamic systems that operate sufficiently far from equilibrium, such as living organisms or exploding bombs. Non-equilibrium systems are the lifeblood of the universe; they make the world dynamic and unpredictable. Modern thermodynamics remains a work in progress, but it has been used to successfully study a broad spectrum of phenomena, including heat flows, interacting quantum gases, dissipative structures, and even the global climate.[13] There is no universally accepted meaning of entropy in non-equilibrium conditions, but physicists have offered several proposals.[14] All of them include time when analyzing thermodynamic interactions, allowing us to determine not just whether entropy goes up or down, but also how quickly or slowly physical systems can change on their path to equilibrium. The principles of modern thermodynamics are therefore essential in helping us understand the behavior of real-world systems, including life itself.

The central physical objective of all life forms is to avoid thermodynamic equilibrium with the rest of their environment by continuously dissipating energy, as the physicist Erwin Schrödinger suggested in the 1940s, when he used non-equilibrium thermodynamics to study the key features of biology.[15] We may call this vital objective the entropic imperative. All living organisms consume energy from an external environment, use it to fuel vital biochemical processes and interactions, and then dissipate most of the energy consumed back to the environment. The dissipation of energy to an external environment allows organisms to conserve the order and stability of their own biochemical systems. The essential functions of life critically depend on this entropic stability, including functions like digestion, respiration, cell division, and protein synthesis. What makes life unique as a physical system is the sheer variety of dissipation methods that it has developed, including the production of heat, the emission of gases, and the expulsion of waste. This sweeping capacity to dissipate energy is what helps life to sustain the entropic imperative. Indeed, physicist Jeremy England has argued that physical systems in a heat bath flooded with large amounts of energy can tend to dissipate more energy.[16] This "dissipation-driven adaptation" can lead to the spontaneous emergence of order, replication, and self-assembly among microscopic units of matter, providing a potential clue into the very dynamics of the origin of life. Organisms also use the energy they consume to perform mechanical work by, for example, walking, running, climbing, or typing on a keyboard. Those organisms with access to many energy sources can do more work and dissipate more energy, satisfying the central conditions of life.

The thermodynamic relationships among energy, entropy, and dissipation likewise impose powerful constraints on the behavior and evolution of economic systems.[17] Economies are dynamical and emergent systems compelled to function in certain ways by their underlying social and ecological conditions. In this context, economies are non-equilibrium systems capable of rapidly dissipating energy to some external environment. All dynamical systems gain strength from some energy reservoir, reach peak intensity by absorbing a regular supply of energy, then unravel from internal and external changes that either disrupt vital energy flows or make it impossible to keep dissipating more energy. They can even experience long-term undulations by growing for some time, then shrinking, then growing again, before finally collapsing. Interactions between dynamical systems can produce highly chaotic results, but energy expansions and contractions are the core features of all dynamical systems. The energy consumed by all economic systems is either converted into mechanical work and the physical products derived from that work, or is simply wasted and dissipated to the environment. We can define the collective efficiency of an economic system as the fraction of all energy consumed that goes into creating mechanical work and electrical energy. Economies that increase the amount of mechanical work they generate can produce more goods and services. But however important it may be, mechanical work represents a relatively small fraction of total energy use in any economy; the vast majority of the energy consumed by all economies is routinely squandered to the environment through waste, dissipation, and other kinds of energy losses.

Throughout history, economic growth has depended heavily on people consuming more energy from their natural environments.[18] When humans were hunters and foragers, the primary asset that performed mechanical work was the human muscle.[19] Our nomadic way of life lasted for some 200,000 years, but underwent significant disruptions after the Ice Age. Over millennia, changing ecological conditions around the world compelled numerous groups to adopt pastoralist and agricultural strategies. Agrarian economies relied heavily on cultivated plants and domesticated animals to help generate surpluses of food and other goods and resources. These agrarian modes of production and consumption dominated human societies for almost ten thousand years, but were eventually replaced by a new economic system. Capitalism emerged and spread through colonial expansion, waves of industrialization, the proliferation of epidemic diseases, genocidal campaigns against indigenous populations, and the discovery of new energy sources. The global economy has since become an interconnected system of finance, computers, factories, vehicles, machines, and much more. Creating and sustaining this system required a major upward transition in the rate of energy throughput from our natural environments. In our nomadic days, the daily rate of per capita energy consumption was around 5,000 kilocalories.[20] By 1850, per capita consumption had risen to roughly 80,000 kilocalories per day, and has since ballooned to about 250,000 kilocalories today.[21] From a physics perspective, the fundamental feature of all capitalist economies is an excessive rate of energy consumption focused on boosting economic growth and material surpluses. The collective deployment of capital assets can generate incredible levels of mechanical work, allowing people to produce more, travel great distances, and lift heavy objects, among other tasks. Capitalism is far more energy-intensive than any previous economic system, and it has wrought unprecedented ecological consequences that may threaten its very existence. It remains uncertain how long humanity can sustain capitalism's energy-intensive activities, but there is no doubt that the fantasy of endless growth and easy profits cannot continue. All dynamical systems must eventually come to an end.

Over the last two centuries, inefficient capitalist economies have unloaded large amounts of energy losses to their natural environments, in the forms of waste, chemicals, pollutants, and greenhouse gases. The aggregate effect of all this waste and dissipation has been to fundamentally alter critical energy flows throughout the ecosphere, triggering a major social and ecological crisis in the natural world. This socioecological crisis is still in its early phases, but has already spawned calamities like deforestation, global warming, ocean acidification, and substantial losses in biodiversity.[22] Barring revolutionary changes to our socioeconomic system, this crisis will only continue and intensify. As this occurs, accumulating problems in the natural world will threaten the long-term viability of global civilization. The products we dissipate to the environment may be useless to us, but they often serve as energy reservoirs for other dynamical systems. Energy losses often have an amplifier effect on human civilization, meaning their true costs are far greater than may be visible or superficially understood. Consider the unsanitary conditions in cities throughout much of human history. Cities in pre-modern economies were typically filthy, with trash and waste overwhelming many public spaces. Yet these energy losses were a critical source of food and nourishment for a wide variety of other living organisms, especially insects and other small animals that could survive in the middle of human civilization. When these creatures became hosts to deadly diseases, human waste helped to concentrate their numbers in precisely the worst places imaginable: high-density areas like cities. As a consequence, epidemic diseases usually generated far larger death tolls than they would have otherwise, with the unimaginable carnage of the Black Death as a primary example.[23]

Today we face our own versions of this ancient problem, but on a much bigger scale. There are several kinds of gases in the atmosphere, known as greenhouse gases, able to absorb outgoing heat radiation.[24] When these gases in the atmosphere trap and emit radiation back to the surface of the planet, large numbers of photons excite the electrons, atoms, and molecules on the surface to higher energy states, in a process called the greenhouse effect. These additional excitations and fluctuations at the microscopic level collectively represent the warmth we experience at the macroscopic level. The greenhouse effect is critical because it makes the Earth warm enough to be habitable.[25] Over the last two centuries, however, wealthy and industrialized nations have been reinforcing this natural process by pumping vast amounts of new greenhouse gases into the atmosphere, in turn causing more global warming. This artificial reinforcement of the greenhouse effect has already had profound consequences for our species and others. Thermal excitations from an amplified greenhouse effect often act as a powerful energy reservoir for other dynamical systems and natural phenomena, including storms, floods, droughts, cyclones, wildfires, insects, viruses, bacteria, and algae blooms.[26]

A warming planet could also reinforce positive feedback mechanisms in the climate capable of inducing even more warming, beyond that already caused by our greenhouse gas emissions. These mechanisms, such as melting sea ice and thawing permafrost, would allow the planet to absorb more solar energy while naturally emitting vast quantities of greenhouse gases.[27] The resulting chaos would render any human attempts to mitigate global warming futile. This is precisely what should worry us: the chaos we are unleashing on the planet through the capitalist system will find a way to produce a new kind of order, one that threatens human civilization itself. As capitalism expands, the ecological crisis will worsen. The intensifying dynamical systems of nature will increasingly interact with our civilizations and could severely disrupt the vital energy flows that support social reproduction and economic activities. Regions with high population densities subject to recurring natural disasters are especially vulnerable. Cyclone Bhola killed about 500,000 people when it struck East Pakistan in 1970, triggering a series of massive riots and protests that culminated in a civil war and contributed to the establishment of a new country, Bangladesh.[28] Numerous studies have concluded that the worst drought to strike Syria in almost a thousand years was partly responsible for the social and political tensions that culminated in the current civil war.[29] The climate is a resilient dynamical system capable of assimilating many different physical changes, but this resilience has its limits, and humanity will be in deep trouble if it keeps trying to transgress them.

These arguments highlight one of the deepest flaws in modern economic theory: it lacks a scientific foundation. Orthodox economic philosophies, from monetarism to the neoclassical synthesis, focus on describing the transient financial features of capitalism, mistaking these features for immutable and universal laws of nature. Capitalist economics has largely been transformed into a metaphysical philosophy whose goal is not to provide a scientific foundation for economics, but to produce sophisticated propaganda designed to protect the wealth and power of a global elite. Any scientific explanation of economics must begin with the realization that energy flows and ecological conditions—not any "invisible hand" of the market—dictate the long-term macroscopic parameters of all economies. Important contributions along these lines have come from the field of ecological economics, especially in seminal works by the economists Nicholas Georgescu-Roegen and Herman Daly, but also from the systems ecologist Howard Odum.[30] Marx himself incorporated ecological concerns into his economic and political thought.[31] The contributions of these and other thinkers revealed that the economic features of the world are emergent properties shaped by underlying physical realities and ecological conditions, making an understanding of these conditions critical to any basic understanding of economics.

Ecological thought differs from the orthodox schools of economics in fundamental ways. Most importantly, ecological theory contends that we can no longer treat waste and dissipative losses as "externalities" and "costs of doing business," given how important these energy losses can be in shaping the dynamical evolution of economic systems. What mainstream economists call "externalities" include the physical products we dump to the environment—everything from pollutants and plastic trash to toxic chemicals and greenhouse gases. The consequences of extreme energy losses can have a profound effect on the future evolution of dynamical systems. As scientists continually stress, the energy losses from our modern economies are so large and intense that they are starting to fundamentally alter the energy flows of the entire ecosphere, from the reinforcement of the greenhouse effect to the changing chemistry of the oceans. Some of these new concentrations of energy then act as reservoirs that power the formation and operation of other dynamical systems, which often disrupt the normal activities of civilization. Hence the fundamental reason our economic actions cannot be decoupled from the natural world: if the effects associated with our energy losses become powerful enough to destroy the normal functions of our civilizations, then no number of ingenious economic policies will save us from the wrath of nature.

Most people in power today believe we can carefully manage capitalism and prevent the worst effects of the ecological crisis. A popular strain of technological optimism holds that innovation can solve the fundamental ecological problems that humanity faces. Several different solutions have been proposed to fix our ecological woes, from the adoption of renewable energy sources to more outlandish programs like carbon storage and sequestration. All these ideas share the presumption that capitalism itself does not have to change, because technological solutions will always be available to deliver more economic growth and a healthier environment. From Beijing to Silicon Valley, technocapitalists are fond of arguing that capitalism can keep humming along through gains in energy efficiency.[32] The ultimate reason why this strategy will fail over the long run is that nature imposes absolute physical limits on efficiency that no extent of technological progress can overcome. The recent breakdown in Moore's Law because of quantum effects is a notable example.[33] Another is the efficiency barrier that the Carnot cycle poses for all practical heat engines.[34]

But our most pressing concerns have to do with the underlying relationships between technological innovation and economic growth. Faith in technological solutions helps to foster further technological innovation and economic growth, increasing the overall demands placed on the biophysical world and the dissipation associated with the capitalist system. We can examine these relationships by first looking at how people and economic systems respond to efficiency gains. For a sense of whether capitalism can deliver major improvements in efficiency, we need to develop a general theory that explains how the collective efficiency of our economic systems changes over time.

When fuel efficiency improves, we often drive longer distances. When electricity becomes cheaper, we often power more appliances. Even those who proudly save energy at home through recycling, composting, and other activities are more than happy to jump on an airplane and fly halfway around the world for a vacation. People often take savings in one area and exchange them for expenses in another. What we end up doing with 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 materialize.[35] First formulated in the mid-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. Boosting efficiency leads to cheaper goods and services, which encourages more demand and more spending, leading to the consumption of more energy.[36] Jevons first 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 increased energy efficiency did not actually yield energy savings.

Variations of this paradox are known in economics as the rebound effect. Most economists accept that some versions of the effect are real, but disagree over the size and the scope of the problem. Some believe rebound effects are irrelevant, arguing that efficiency improvements do encourage lower levels of energy consumption in the long run.[37] In a comprehensive review of the literature on the subject, the UK Energy Research Centre determined that the most extreme versions of the rebound effect probably no longer apply to developed economies. However, they 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 (e.g. energy efficient technologies that significantly improve the productivity of energy intensive industries) economy-wide rebound effects may exceed 50% and could potentially increase energy consumption in the long-term."[38] The fact that significant economy-wide rebound effects are possible should give us pause about the utility of efficiency strategies in combating the ecological crisis and climate change. In fact, this entire argument obscures a more important uncertainty: the problem of whether efficiency improvements can come fast enough to alleviate the worst consequences of the ecological crisis, which are still ahead of us. Given the mechanics and incentives of capitalism, we should beware the current infatuation with efficiency optimism.

To clarify these arguments, we need a theory that explains the role of efficiency in the wider context of technological progress. The rebound effect and the Jevons Paradox focus on understanding how people and economic systems behave in response to efficiency gains. More fundamental, however, is the task of understanding the general evolution of collective efficiencies over long periods of time. The dominant theme of technological innovation throughout history has been the effort to shift the burden of energy use from human muscles to other physical and biological systems, such as animals, machines, and computers. Consider cars, bicycles, airplanes, microwaves, dishwashers, vacuum cleaners, and virtually all the "wonders" of modern life: their central goal is to exploit energy and perform tasks that would normally require the exertion of human muscles. Robots and artificial intelligence have recently become all the rage, ready to swoop in and perform menial tasks that we have no desire to do. The expansion in mechanical output facilitated by technological progress typically leads to more energy-intensive societies where those who control the means of production can generate greater surpluses and profits. Technological innovation under capitalism, in particular, has boosted the collective amount of mechanical work that economies can generate, and has also ballooned the rate of energy consumption from our natural environments. But it has not fundamentally changed collective efficiencies, implying that higher rates of economic growth have usually been accompanied by larger energy losses.

Economic systems typically use new sources of energy to expand production, consumption, and accumulation, not to fundamentally improve efficiency. From the cultivation of plants and the domestication of animals to the burning of fossil fuels and the invention of electricity, the mastery and discovery of new energy sources has generally produced more energy-intensive societies. Although any economic system may make efficiency gains, these are incidental and secondary to the wider goal of accumulation. The overall efficiency of an economic system is highly inertial, changing at a glacial pace. We see this very process playing out now with greenhouse gas emissions, although the ecological crisis extends far beyond this problem. Political and business leaders have hoped 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 year 2017 saw a substantial global rise in harmful emissions, defying even the modest goals of the Paris Agreement.[39] Even before that, the United Nations had warned of an "unacceptable" gap between government pledges and the emission reductions needed to prevent some of the worst consequences from climate change.[40] The challenges of boosting efficiency are more apparent when we view capitalism on a global scale: although many developed nations have made modest but measurable improvements in their collective efficiencies, these gains have been undercut by developing economies still in the process of industrialization.[41] Evidently, substantial changes in the collective efficiency of any economic system rarely materialize in short periods of time. Technological growth under the regime of capitalism will deliver some additional progress on efficiency, but certainly not enough to prevent the worst consequences of the ecological crisis.

One of the best ways to understand the inertia of collective efficiencies is to compare energy efficiencies under capitalism with those of humanity's nomadic days, more than ten thousand years ago. Recall that human muscles performed most of the work in nomadic societies, and the efficiency of our muscles is roughly 20 percent, perhaps much more under special circumstances.[42] For comparison, most gasoline-powered combustion engines have an 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.[43] All these figures vary depending on a wide array of physical conditions, but when it comes to efficiency, we can safely conclude that the dominant assets of capitalism hardly do better than human muscles, even after three centuries of rapid technological progress. Cost and convenience are the main reasons why technological innovation works this way, emphasizing mechanical output and the scale of production at the expense of efficiency. Large gains in efficiency are extremely difficult to achieve, in both physical and economic terms. From time to time, a James Watt or an Elon Musk comes along with an amazing invention, but such products do 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.[44] And although Musk's Tesla motors have a phenomenal operating efficiency, the electricity needed to run them often comes from much more inefficient sources, such as coal-fired power plants. If you drive a Tesla in Ohio or West Virginia, the dirty sources of energy powering it mean that your amazing technological product produces roughly the same carbon emissions as a Honda Accord.[45] The collective efficiency of capitalist economies remains relatively low because these economies are interested in growing their profits and production levels, not in making the enormous investments needed for significant improvements in efficiency.

In November 2017, a group of 15,000 scientists from more than 180 nations signed a letter sounding the alarm on the ecological crisis and what awaits us in the future.[46] Their prognosis was grim, and their proposals—intentionally or not—amounted to a wholesale repudiation of modern capitalism. Among their many useful recommendations was a call for "revising our economy to reduce wealth inequality and ensure that prices, taxation, and incentive systems take into account the real costs which consumption patterns impose on our environments." Our fundamental problem is easy to state: modern civilization uses far too much energy. And the solution to this problem is equally easy to state, but very difficult to implement: humanity must reduce the rate of energy consumption that has prevailed in modern times. The best way to drive down that rate is not through messianic delusions of technological progress, but rather by breaking the structures and incentives of capitalism, with their drive for profits and production, and establishing a new economic system that prioritizes a compatible future with our natural world.

Governments and popular movements around the world should develop and implement radical measures that will help to move humanity from capitalism toward ecologism. These measures should include punitive taxes and caps on extreme wealth, the partial nationalization of energy-intensive industries, the vast redistribution of economic goods and resources to poor and oppressed peoples, periodic restrictions on the use of capital assets and technological systems, large public investments in more efficient renewable energy technologies, large reductions in work hours, and the adoption of mass veganism among industrialized nations that no longer rely on animals for food production. The economic priorities of the ecological project should focus on improving our existing quality of life, not on trying to generate high levels of economic growth to boost capitalist profits. If human civilization is to survive for thousands of years, and not just a few more centuries, then we must drastically scale back our economic ambitions and focus instead on improving the quality of life in our communities, including our community with nature. Rather than trying to dominate the natural world, we should change course and coexist with it.

Notes

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[3] Peter Atkins, *Four Laws That Drive the Universe* (New York: Oxford University Press, 2007), Preface
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[6] Atkins, *Four Laws That Drive the Universe*, 23.
[7] Debora M. Katz, *Physics for Scientists and Engineers: Foundations and Connections*, vol. 1 (Boston: Cengage Learning, 2016), 264.
[8] William Thomson, "On a Universal Tendency in Nature to the Dissipation of Mechanical Energy" in *Proceedings of the Royal Society of Edinburgh*, vol. 3 (Edinburgh: Neill and Company, 1857), 139-42.
[9] Douglas C. Giancoli, *Physics for Scientists and Engineers* (London: Pearson Education, 2008), 545.
[10] John M. Seddon and Julian D. Gale, *Thermodynamics and Statistical Mechanics* (London: Royal Society of Chemistry, 2001), 60-65.
[11] Seddon and Gale, *Thermodynamics and Statistical Mechanics*, 65.
[12] Atkins, *Four Laws That Drive the Universe*, 53.
[13] For the famous reciprocal relations that describe heat flows, see Lars Onsager, "Reciprocal Relations in Irreversible Processes I," *Physical Review Journals* 37 (1931): 405-26. This work was the main reason why Onsager won the Nobel Prize in Chemistry. For a study of bosonic quantum gases in a one-dimensional trap, see Miguel Ángel García-March et al, "Non-equilibrium thermodynamics of harmonically trapped bosons," *New Journal of Physics* 18 (2016): 103035. For an exhaustive review of modern thermodynamics and an explanation of dissipative structures, which earned Ilya Prigogine his Nobel Prize, refer to Dilip Kondepudi and Ilya Prigogine, *Modern Thermodynamics: From Heat Engines to Dissipative Structures* (Hoboken: John Wiley & Sons, 2014), 421-41. In 2009, Alex Kleidon wrote an important theoretical study and review of the climate system using non-equilibrium thermodynamics. See Alex Kleidon, "Nonequilibrium thermodynamics and maximum entropy production in the Earth system," *The Science of Nature* 96 (2009): 1-25.
[14] A notable idea from the physicist Phil Attard looks at entropy as the number of particle configurations associated with a physical transition in a given period of time. See Phil Attard, "The second entropy: a general theory for non-equilibrium thermodynamics and statistical mechanics," *Physical Chemistry* 105 (2009): 63-173. Perhaps the most technically rigorous model of entropy imagines it to be a collection of two functions that describe the changes happening among a restricted class of non-equilibrium systems. See Elliott H. Lieb and Jakob Yngvason, "The entropy concept for non-equilibrium states," *Proceedings of the Royal Society A* 469 (2013): 1-15. The physicist Karo Michaelian provided an intuitive definition of entropy, viewing it as the rate at which physical systems explore available energy microstates. See K. Michaelian, "Thermodynamic dissipation theory for the origin of life," *Earth System Dynamics* (2011): 37-51.
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[16] Natalie Wolchover, "A New Physics Theory of Life," *Quanta Magazine*, January 22, 2014.
[17] Carsten Hermann-Pillath, "Energy, growth, and evolution: towards a naturalistic ontology of economics," *Ecological Economics* 119 (2015): 432-42.
[18] Numerous studies from around the world have revealed a powerful relationship between energy use and economic growth. For a review of the statistical relationship between energy use and GDP growth worldwide, see Rögnvaldur Hannesson, "Energy and GDP growth," *International Journal of Energy Management,* vol. 3 (2009): 157-70. For a major study on the causality between energy and income in certain Asian countries, see John Asafu-Adjaye "The relationship between energy consumption, energy prices, and economic growth: time series evidence from Asian developing countries," *Energy Economics* 22 (2000): 615-25. For a general overview of how energy use has shaped human history, see Vaclav Smil, *Energy and Civilization* (Cambridge: MIT Press, 2017).
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[22] Robert Falkner, "Climate change, international political economy and global energy policy," in Andreas Goldthau, Michael F. Keating, and Caroline Kuzemko, ed., *Handbook of the International Political Economy of Energy and Natural Resources* (Cheltenham: Edward Elgar Publishing, 2018), 77-78.
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