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The New York Times

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ABOUT THE AUTHOR

Vaclav Smil is Distinguished Professor Emeritus at the University of Manitoba. He is the author of over forty books on topics including energy, environmental and population change, food production and nutrition, technical innovation, risk assessment and public policy. No other living scientist has had more books, on a wide variety of topics, reviewed in *Nature*. A Fellow of the Royal Society of Canada, in 2010 he was named by *Foreign Policy* as one of the Top 100 Global Thinkers.

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How the World Really Works

A Scientist's Guide to Our Past, Present and Future

VACLAV SMIL



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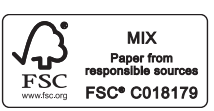
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Introduction

Why Do We Need This Book?

Every era has its claims to uniqueness, but while the experiences of the past three generations—that is, the decades since the end of the Second World War—may not have been as fundamentally transformative as those of the three generations preceding the beginning of the First World War, there has been no shortage of unprecedented events and advances. Most impressively, more people now enjoy a higher standard of living, and do so for more years and in better health, than at any time in history. Yet these beneficiaries are still a minority (only about a fifth) of the world's population, whose total count is approaching 8 billion people.

The second achievement to admire is the unprecedented expansion of our understanding of both the physical world and all forms of life. Our knowledge extends from grand generalizations about complex systems on the universal (galaxies, stars) and planetary (atmosphere, hydrosphere, biosphere) scale to processes at the level of atoms and genes: lines etched into the surface of the most powerful microprocessor are only about twice the diameter of human DNA. We have translated this understanding into a still-expanding array of machines, devices, procedures, protocols, and interventions that sustain modern civilization, and the enormity of our aggregate knowledge—and the ways we have deployed it in our service—is far beyond the comprehension of any individual mind.

You could meet real Renaissance men on Florence's Piazza Signoria in 1500—but not for too long after that. By the middle of the 18th century two French savants, Denis Diderot and Jean le Rond d'Alembert, could still gather a group of knowledgeable contributors to sum up the era's understanding in fairly exhaustive entries in their multi-volume *Encyclopédie, ou Dictionnaire raisonné des sciences, des arts et des métiers*. A few generations later the extent and the specialization of our knowledge

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advanced by orders of magnitude, with fundamental discoveries ranging from magnetic induction (Michael Faraday in 1831, the basis of electricity generation) to plant metabolism (Justus von Liebig, 1840, the basis of crop fertilization) to theorizing about electromagnetism (James Clerk Maxwell, 1861, the basis of all wireless communication).

In 1872, a century after the appearance of the last volume of the *Encyclopédie*, any collection of knowledge had to resort to the superficial treatment of a rapidly expanding range of topics, and, one and a half centuries later, it is impossible to sum up our understanding even within narrowly circumscribed specialties: such terms as "physics" or "biology" are fairly meaningless labels, and experts in particle physics would find it very hard to understand even the first page of a new research paper in viral immunology. Obviously, this atomization of knowledge has not made any public decision-making easier. Highly specialized branches of modern science have become so arcane that many people employed in them are forced to train until their early or mid-thirties in order to join the new priesthood.

They may share long apprenticeships, but too often they cannot agree on the best course of action. The SARS-CoV-2 pandemic made it clear that disagreements among experts may extend even to such seemingly simple decisions as wearing a face mask. By the end of March 2020 (three months into the pandemic) the World Health Organization still advised against doing so unless a person was infected, and the reversal came only in early June 2020. How can those without any special knowledge take sides or make any sense of these disputes that now often end in retractions or the dismantling of previously dominant claims?

Still, such continuing uncertainties and disputes do not excuse the extent to which most people misunderstand the fundamental workings of the modern world. After all, appreciating how wheat is grown (chapter 2) or steel is made (chapter 3) or realizing that globalization is neither new nor inevitable (chapter 4) are not the same as asking that somebody comprehend femtochemistry (the study of chemical reactions at timescales of 10^{-15} seconds, Ahmed Zewail, Nobel Prize in 1999) or polymerase chain reactions (the rapid copying of DNA, Kary Mullis, Nobel Prize in 1993).

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Why then do most people in modern societies have such a superficial knowledge about how the world really works? The complexities of the modern world are an obvious explanation: people are constantly interacting with black boxes, whose relatively simple outputs require little or no comprehension of what is taking place inside the box. This is as true of such ubiquitous devices as mobile phones and laptops (typing a simple query does the trick) as it is of mass-scale procedures such as vaccination (certainly the best planetary example of 2021, with, typically, the rolling up of a sleeve being the only comprehensible part). But explanations of this comprehension deficit go beyond the fact that the sweep of our knowledge encourages specialization, whose obverse is an increasingly shallow understanding—even ignorance—of the basics.

Urbanization and mechanization have been two important reasons for this comprehension deficit. Since the year 2007, more than half of humanity has lived in cities (more than 80 percent in all affluent countries), and unlike in the industrializing cities of the 19th and early 20th centuries, jobs in modern urban areas are largely in services. Most modern urbanites are thus disconnected not only from the ways we produce our food but also from the ways we build our machines and devices, and the growing mechanization of all productive activity means that only a very small share of the global population now engages in delivering civilization's energy and the materials that comprise our modern world.

America now has only about 3 million men and women (farm owners and hired labor) directly engaged in producing food—people who actually plow the fields, sow the seeds, apply fertilizer, eradicate weeds, harvest the crops (picking fruit and vegetables is the most labor-intensive part of the process), and take care of the animals. That is less than 1 percent of the country's population, and hence it is no wonder that most Americans have no idea, or only some vague notion, about how their bread or their cuts of meat came to be. Combines harvest wheat—but do they also harvest soybeans or lentils? How long does it take for a tiny piglet to become a pork chop: weeks or years? The vast majority of Americans simply don't know—and they have plenty of company. China is the world's

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largest producer of steel—smelting, casting, and rolling nearly a billion tons of it every year—but all of that is done by less than 0.25 percent of China's 1.4 billion people. Only a tiny percentage of the Chinese population will ever stand close to a blast furnace, or see the continuous casting mill with its red ribbons of hot, moving steel. And this disconnect is the case across the world.

The other major reason for the poor, and declining, understanding of those fundamental processes that deliver energy (as food or as fuels) and durable materials (whether metals, non-metallic minerals, or concrete) is that they have come to be seen as old-fashioned—if not outdated—and distinctly unexciting compared to the world of information, data, and images. The proverbial best minds do not go into soil science and do not try their hand at making better cement; instead they are attracted to dealing with disembodied information, now just streams of electrons in myriads of microdevices. From lawyers and economists to code writers and money managers, their disproportionately high rewards are for work completely removed from the material realities of life on earth.

Moreover, many of these data worshippers have come to believe that these electronic flows will make those quaint old material necessities unnecessary. Fields will be displaced by urban high-rise agriculture, and synthetic products will ultimately eliminate the need to grow any food at all. Dematerialization, powered by artificial intelligence, will end our dependence on shaped masses of metals and processed minerals, and eventually we might even do without the Earth's environment: who needs it if we are going to terraform Mars? Of course, these are all not just grossly premature predictions, they are fantasies fostered by a society where fake news has become common and where reality and fiction have commingled to such an extent that gullible minds, susceptible to cult-like visions, believe what keener observers in the past would have mercilessly perceived as borderline or frank delusion.

None of the people reading this book will relocate to Mars; all of us will continue to eat staple grain crops grown in soil on large expanses of agricultural land, rather than in the skyscrapers imagined by the proponents of so-called urban agriculture; none of us

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will live in a dematerialized world that has no use for such irreplaceable natural services as evaporating water or pollinating plants. But delivering these existential necessities will be an increasingly challenging task, because a large share of humanity lives in conditions that the affluent minority left behind generations ago, and because the growing demand for energy and materials has been stressing the biosphere so much and so fast that we have imperiled its capability to keep its flows and stores within the boundaries compatible with its long-term functioning.

To give just a single key comparison, in 2020 the average annual per capita energy supply of about 40 percent of the world's population (3.1 billion people, which includes nearly all people in sub-Saharan Africa) was no higher than the rate achieved in both Germany and France in 1860! In order to approach the threshold of a dignified standard of living, those 3.1 billion people will need at least to double—but preferably triple—their per capita energy use, and in doing so multiply their electricity supply, boost their food production, and build essential urban, industrial, and transportation infrastructures. Inevitably, these demands will subject the biosphere to further degradation.

And how will we deal with unfolding climate change? There is now a widespread consensus that we need to do *something* to prevent many highly undesirable consequences, but what kind of action, what sort of behavioral transformation would work best? For those who ignore the energetic and material imperatives of our world, those who prefer mantras of green solutions to understanding how we have come to this point, the prescription is easy: just decarbonize—switch from burning fossil carbon to converting inexhaustible flows of renewable energies. The real wrench in the works: we are a fossil-fueled civilization whose technical and scientific advances, quality of life, and prosperity rest on the combustion of huge quantities of fossil carbon, and we cannot simply walk away from this critical determinant of our fortunes in a few decades, never mind years.

Complete decarbonization of the global economy by 2050 is now conceivable only at the cost of unthinkable global economic retreat, or as a result of extraordinarily rapid transformations relying on

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near-miraculous technical advances. But who is going, willingly, to engineer the former while we are still lacking any convincing, practical, affordable global strategy and technical means to pursue the latter? What will actually happen? The gap between wishful thinking and reality is vast, but in a democratic society no contest of ideas and proposals can proceed in rational ways without all sides sharing at least a modicum of relevant information about the real world, rather than trotting out their biases and advancing claims disconnected from physical possibilities.

This book is an attempt to reduce the comprehension deficit, to explain some of the most fundamental ruling realities governing our survival and our prosperity. My goal is not to forecast, not to outline either stunning or depressing scenarios of what is to come. There is no need to extend this popular—but consistently failing—genre: in the long run, there are too many unexpected developments and too many complex interactions that no individual or collective effort can anticipate. Nor will I advocate any specific (biased) interpretations of reality, either as a source of despair or of boundless expectations. I am neither a pessimist nor an optimist; I am a scientist trying to explain how the world really works, and I will use that understanding in order to make us better realize our future limits and opportunities.

Inevitably, this kind of inquiry must be selective, but every one of the seven key topics chosen for closer examination passes the muster of existential necessity: there are no frivolous choices in the lineup. The first chapter of this book shows how our high-energy societies have been steadily increasing their dependence on fossil fuels in general and on electricity, the most flexible form of energy, in particular. Appreciation of these realities serves as a much-needed corrective to the now-common claims (based on a poor understanding of complex realities) that we can decarbonize the global energy supply in a hurry, and that it will take only two or three decades before we rely solely on renewable energy conversions. While we are converting increasing shares of electricity generation to new renewables (solar and wind, as opposed to the long-established hydroelectricity) and putting more electric cars on the roads, decarbonizing trucking, flying,

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and shipping will be a much greater challenge, as will the production of key materials without relying on fossil fuels.

The second chapter of this book is about the most basic survival necessity: producing our food. Its focus is on explaining how much of what we rely on to survive, from wheat to tomatoes to shrimp, has one thing in common: it requires substantial, direct and indirect, fossil fuel inputs. Awareness of this fundamental dependence on fossil fuels leads to a realistic understanding of our continued need for fossil carbon: it is relatively easy to generate electricity by wind turbines or solar cells rather than by burning coal or natural gas—but it would be much more difficult to run all field machinery without liquid fossil fuels and to produce all fertilizers and other agrochemicals without natural gas and oil. In short, for decades it will be impossible to adequately feed the planet without using fossil fuels as sources of energy and raw materials.

The third chapter explains how and why our societies are sustained by materials created by human ingenuity, focusing on what I call the four pillars of modern civilization: ammonia, steel, concrete, and plastics. Understanding these realities exposes the misleading nature of recently fashionable claims about the dematerialization of modern economies dominated by services and miniaturized electronic devices. The relative decline of material needs per unit of many finished products has been one of the defining trends of modern industrial developments. But in absolute terms, material demands have been rising even in the world's most affluent societies, and they remain far below any conceivable saturation levels in low-income countries where the ownership of well-built apartments, kitchen appliances, and air conditioning (to say nothing about cars) remains a dream for billions of people.

The fourth chapter is the story of globalization, or how the world has become so interconnected by transportation and communication. This historical perspective shows how old (or indeed ancient) the origins of this process are, and how recent is its highest—and finally truly global—extent. And a closer look makes it clear that there is nothing inevitable about the future course of this ambivalently perceived (much praised, much questioned, and much criticized)

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phenomenon. Recently, there have been some clear retreats around the world, and a general trend toward populism and nationalism, but it is not clear how far these will continue, or to what extent these changes will be modified due to a combination of economic, security, and political considerations.

The fifth chapter provides a realistic framework for judging the risks we face: modern societies have succeeded in eliminating or reducing many previously mortal or crippling risks—polio and giving birth, for example—but many perils will always be with us, and we repeatedly fail to make proper risk assessments, both underestimating and exaggerating the dangers we face. After finishing this chapter, readers will have a good appreciation of the relative risks of many common involuntary exposures and voluntary activities (from falling at home to flying between continents; from living in a hurricane-prone city to parachuting)—and, cutting through the diet industry nonsense, we will see a range of options of what we could eat to help us live longer.

The sixth chapter will look first at how unfolding environmental changes might affect our three existential necessities: oxygen, water, and food. The rest of the chapter will focus on global warming, the change that has dominated recent environmental concerns and has led to the emergence of new—near apocalyptic—catastrophism on one hand, and complete denials of the process on the other. Instead of recounting and adjudging these contested claims (too many books have already done so), I will stress that, contrary to widespread perceptions, this is not a recently discovered phenomenon: we have understood the fundamentals of this process for more than 150 years.

Moreover, we have been aware of the actual degree of warming associated with the doubling of atmospheric CO_2 for more than a century, and we were warned about the unprecedented (and unrepeatable) nature of this planetary experiment more than half a century ago (uninterrupted, accurate measurements of CO_2 began in 1958). But we have chosen to ignore these explanations, warnings and recorded facts. Instead, we have multiplied our reliance on the combustion of fossil fuels, resulting in a dependence that will not be severed easily, or inexpensively. How rapidly we can change this remains unclear. Add to this

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all other environmental worries, and you must conclude that the key existential question—can humanity realize its aspirations within the safe boundaries of our biosphere?—has no easy answers. But it is imperative that we understand the facts of the matter. Only then can we tackle the problem effectively.

In the closing chapter I will look to the future, specifically at the recent opposing propensities to embrace catastrophism (those that say there are just years left before the final curtain descends on modern civilization) and techno-optimism (those that predict that the powers of invention will open unlimited horizons beyond the confines of the Earth, turning all terrestrial challenges into inconsequential histories). Predictably, I have little use for either of these positions, and my perspective will find no favor with either doctrine. I do not foresee any imminent break with history in either direction; I do not see any already predetermined outcomes, but rather a complicated trajectory contingent on our—far from foreclosed—choices.

This book rests on two foundations: abundant scientific findings and half a century of my research and book-writing. The first includes items ranging from such classic contributions as the pioneering elucidations of energy conversions and of the greenhouse gas effect from the 19th century, through to the very latest assessments of global challenges and risk probabilities. And this far-reaching book could not have been written without my decades of interdisciplinary studies distilled in my many other books. Rather than resorting to an ancient comparison of foxes and hedgehogs (a fox knows many things, but a hedgehog knows one big thing), I tend to think about modern scientists as either the drillers of ever-deeper holes (now the dominant route to fame) or scanners of wide horizons (now a much-diminished group).

Drilling the deepest possible hole and being an unsurpassed master of a tiny sliver of the sky visible from its bottom has never appealed to me. I have always preferred to scan as far and as wide as my limited capabilities have allowed me to do. My main area of interest throughout my life has been energy studies, because a satisfactory grasp of that vast field requires you to combine an understanding of physics,

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chemistry, biology, geology, and engineering with an attention to history and to social, economic, and political factors.

Nearly half of my now more than 40 (and mainly more academic) books deal with various aspects of energy, from wide-ranging surveys of general energetics and energy throughout history to closer looks at individual fuel categories (oil, natural gas, biomass) and specific properties and processes (power density, energy transitions). The rest of my output betrays my interdisciplinary quests: I have written about such fundamental phenomena as growth—in all of its natural and anthropogenic guises—and risk; about the global environment (the biosphere, biogeochemical cycles, global ecology, photosynthetic productivity, and harvests), food and agriculture, materials (above all, steel and fertilizers), technical advances, and the progress and retreat of manufacturing, and also about ancient Roman and modern American history and Japanese food.

Inevitably, this book—the product of my life's work, and written for the layperson—is a continuation of my long-lasting quest to understand the basic realities of the biosphere, history, and the world we have created. And it also does, yet again, what I have been steadfastly doing for decades: it strongly advocates for moving away from extreme views. Recent (and increasingly strident or increasingly giddy) advocates of such positions will be disappointed: this is not the place to find either laments about the world ending in 2030 or an infatuation with astonishingly transformative powers of artificial intelligence arriving sooner than we think. Instead, this book tries to provide a foundation for a more measured and necessarily agnostic perspective. I hope that my rational, matter-of-fact approach will help readers to understand how the world really works, and what our chances are of seeing it offer better prospects to the coming generations.

But before you plunge into the specific topics, I have a warning as well as a possible request. This book teems with numbers (all metric) because the realities of the modern world cannot be understood only by qualitative descriptions. Many numbers in this book are, inevitably, either very large or very small, and such realities are best treated in terms of orders of magnitude, labelled with globally

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valid prefixes. Should you not have a grounding in these matters, the appendix on understanding numbers, large and small, takes care of that, and hence some readers might find it profitable to begin this book from its end. Otherwise, I'll see you in chapter 1 for a closer, quantitative look at energies. It's a perspective that should never go out of fashion.

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1. Understanding Energy

Fuels and Electricity

Consider a benign science fiction scenario: not travel to distant planets in search of life, but the Earth and its inhabitants as targets of remote monitoring by an exceedingly sapient civilization that sends its probes to nearby galaxies. Why do they do this? Just for the satisfaction of systematic understanding, and perhaps also to avoid dangerous surprises should the third planet orbiting around an unremarkable star in a spiral galaxy become a threat, or perhaps in case they should require a second home. Hence this planet keeps periodic tabs on Earth.

Let us imagine that a probe approaches our planet once every 100 years and that it is programmed to make a second pass (a closer inspection) only when it detects a previously unobserved kind of energy conversion—the changing of energy from one form to another—or a new physical manifestation dependent on it. In fundamental physical terms, any process—be it rain, a volcanic eruption, plant growth, animal predation, or the growth of human sapience—can be defined as a sequence of energy conversions, and for a few hundred million years after the Earth's formation the probes would see only the same varied, but ultimately monotonous, displays of volcanic eruptions, earthquakes and atmospheric storms.

Fundamental shifts

The first microorganisms emerge nearly 4 billion years ago but passing probes do not register them, as these life forms are rare and remain hidden, associated with alkaline hydrothermal vents at the ocean's floor. The first occasion for a closer look arises as early as 3.5 billion years ago, when a passing probe records the first simple, single-celled photosynthetic microbes in shallow seas: they absorb near-infrared

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radiation—that which is just beyond the visible spectrum—and do not produce oxygen.[1] Hundreds of millions of years then elapse with no signs of change before cyanobacteria begin to use the energy of the visible incoming solar radiation to convert CO_2 and water into new organic compounds and release oxygen.[2]

This is a radical shift that will create Earth's oxygenated atmosphere, yet a long time elapses before new, more complex aquatic organisms are seen 1.2 billion years ago, when the probes document the rise and diffusion of brilliantly colored red algae (due to the photosynthetic pigment phycoerythrin) and of much larger, brown algae. Green algae arrive nearly half a billion years later, and because of the new proliferation of marine plants the probes get better sensors to monitor the sea floor. This pays off, as more than 600 million years ago the probes make another epochal discovery: the existence of the first organisms made of differentiated cells. These flattish, soft, bottom-dwelling creatures (known as Ediacaran fauna after their Australian domicile) are the first simple animals requiring oxygen for their metabolism and, unlike algae that are merely tossed by waves and currents, they are mobile.[3]

And then the probes begin to document what are, comparatively speaking, rapid changes: instead of passing over lifeless continents and waiting hundreds of millions of years before logging another epochal shift, they begin to record the rising, cresting, and subsiding waves of the emergence, diffusion, and extinction of a huge variety of species. This period starts with the Cambrian explosion of small marine bottom-dwellers (541 million years ago, dominated first by trilobites) through the arrival of the first fishes, amphibians, land plants, and four-legged (and hence exceptionally mobile) animals. Periodic extinctions reduce, or sometimes almost eliminate, this variety, and even just 6 million years ago the probes do not find any organism dominating the planet.[4] Not long afterwards, the probes nearly miss the significance of a mechanical shift with enormous energetic implications: many four-legged animals briefly stand or awkwardly walk on two legs, and more than 4 million years ago this form of locomotion becomes the norm for small ape-like creatures that begin spending more time on land than in trees.[5]

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Now the intervals between reporting something noteworthy to their home base shrink from hundreds of millions to mere hundreds of thousands of years. Eventually the descendants of these early bipeds (we classify them as hominins, belonging to the genus *Homo*, along the long line of our ancestors) do something that puts them on an accelerated path to planetary dominance. Several hundred thousand years ago, the probes detect the first extrasomatic use of energy—external to one's body; that is, any energy conversion besides digesting food—when some of these upright walkers master fire and begin to use it deliberately for cooking, comfort, and safety.[6] This controlled combustion converts the chemical energy of plants into thermal energy and light, enabling the hominins to eat previously hard-to-digest foods, warming them through the cold nights, and keeping away dangerous animals.[7] These are the first steps toward deliberately shaping and controlling the environment on an unprecedented scale.

This trend intensifies with the next notable change, the adoption of crop cultivation. About 10 millennia ago, the probes record the first patches of deliberately cultivated plants as a small share of the Earth's total photosynthesis becomes controlled and manipulated by humans who domesticate—select, plant, tend, and harvest—crops for their (delayed) benefit.[8] The first domestication of animals soon follows. Before that happens, human muscles are the only prime movers—that is, converters of chemical (food) energy to the kinetic (mechanical) energy of labor. Domestication of working animals, starting with cattle some 9,000 years ago, supplies the first extrasomatic energy other than that of human muscles—they are used for field work, for lifting water from wells, for pulling or carrying loads, and for providing personal transportation.[9] And much later come the first inanimate prime movers: sails, more than five millennia ago; waterwheels, more than two millennia ago; and windmills, more than a thousand years ago.[10]

Afterwards, the probes don't have much to observe, following the arrival of another period of (relative) slowdown: century after century, there is just repetition, stagnation, or the slow growth and diffusion of these long-established conversions. In the Americas and in Australia (lacking any draft animals and any simple mechanical

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prime movers), all work before the arrival of Europeans is done by human muscles. In some of the Old World's preindustrial regions, harnessed animals, wind and running or falling water energize significant shares of grain milling, oil pressing, grinding, and forging, and draft animals become indispensable for heavy field work (plowing above all, as harvesting is still done manually), transporting goods, and waging wars.

But at this point, even in societies with domesticated animals and mechanical prime movers, much of the work is still done by people. My estimate, using necessarily approximate past totals of working animals and people and assuming typical daily work rates based on modern measurements of physical exertion, is that—be it at the beginning of the second millennium of the Common Era or 500 years later (in 1500, at the beginning of the early modern era)—more than 90 percent of all useful mechanical energy was provided by animate power, roughly split between people and animals, while all thermal energy came from the combustion of plant fuels (mostly wood and charcoal, but also straw and dried dung).

And then in 1600 the alien probe will spring into action, and spot something unprecedented. Rather than relying solely on wood, an island society is increasingly burning coal, a fuel produced by photosynthesis tens or hundreds of millions of years ago and fossilized by heat and pressure during its long underground storage. The best reconstructions show that coal as a heat source in England surpasses the use of biomass fuels around 1620 (perhaps even earlier); by 1650 the burning of fossil carbon supplies two-thirds of all heat; and the share reaches 75 percent by 1700.[11] England has an exceptionally early start: all the coalfields that make the UK the world's leading 19th-century economy are already producing coal before 1640.[12] And then, at the very beginning of the 18th century, some English mines begin to rely on steam engines, the first inanimate prime movers powered by the combustion of fossil fuel.

These early engines are so inefficient that they can be deployed only in mines where the fuel supply is readily available and does not require any transportation.[13] But for generations the UK remains the most interesting nation to the alien probe because it is an exceptional

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early adopter. Even by 1800, the combined coal extraction in a few European countries and the United States is a small fraction of British production.

By 1800 a passing probe will record that, across the planet, plant fuels still supply more than 98 percent of all heat and light used by the dominant bipeds, and that human and animal muscles still provide more than 90 percent of all mechanical energy needed in farming, construction, and manufacturing. In the UK, where James Watt introduced an improved steam engine during the 1770s, the Boulton & Watt company begin to build engines whose average power is equal to that of 25 strong horses, but by 1800 they have sold less than 500 of these machines, merely denting the total power provided by harnessed horses and hard-working laborers.[14]

Even by 1850, rising coal extraction in Europe and North America supplies no more than 7 percent of all fuel energy, nearly half of all useful kinetic energy comes from draft animals, about 40 percent from human muscles, and just 15 percent from the three inanimate prime movers: waterwheels, windmills, and the slowly spreading steam engines. The world of 1850 is much more akin to the world of 1700 or even of 1600 than that of the year 2000.

But by 1900 the global share of both fossil and renewable fuels and of prime movers shifts considerably as modern energy sources (coal and some crude oil) provide half of all primary energy, and traditional fuels (wood, charcoal, straw) the other half. Water turbines in hydro stations generate the first primary electricity during the 1880s; later comes geothermal electricity, and after the Second World War nuclear, solar, and wind electricity (the new renewables). But by 2020 more than half of the world's electricity will still be generated by the combustion of fossil fuels, mainly coal and natural gas.

By 1900, inanimate prime movers supply about half of all mechanical energy: coal-fired steam engines make the greatest contribution, followed by better-designed waterwheels and new water turbines (first introduced during the 1830s), windmills and brand-new steam turbines (since the late 1880s), and internal combustion engines (gasoline-fueled, also first introduced in the 1880s).[15]

By 1950, fossil fuels supply nearly three-quarters of primary energy

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(still dominated by coal), and inanimate prime movers—now with gasoline- and diesel-fueled internal combustion engines in the lead—provide more than 80 percent of all mechanical energy. And by the year 2000 only poor people in low-income countries depend on biomass fuels, with wood and straw providing only about 12 percent of the world's primary energy. Animate prime movers hold only a 5 percent share of mechanical energy, as human exertions and the work of draft animals are almost completely displaced by machines fueled by liquids or by electric motors.

During the past two centuries, the alien probes will have witnessed a rapid global substitution of primary energy sources, accompanied by the expansion and diversification of fossil energy supply, and the no less rapid introduction, adoption, and growth in capacity of new inanimate prime movers—first coal-fired steam engines, then internal combustion engines (piston and turbines). The most recent visit would see a truly global society built and defined by mass-scale, stationary, and mobile conversions of fossil carbon, deployed everywhere but in some of the planet's uninhabited regions.

Modern energy uses

What difference has this mobilization of extrasomatic energies made? Global primary energy supply usually refers to total (gross) production, but it is more revealing to look at energy that is actually available for conversion into useful forms. To do this, we need to subtract preconsumption losses (during coal sorting and cleaning, crude oil refining, and natural gas processing), non-energy use (mainly as feedstocks for chemical industries, and also as lubricating oils for machines ranging from pumps to aircraft turbines and as paving materials), and losses during electricity transmission. With these adjustments—and rounding heavily to avoid impressions of unwarranted accuracy—my calculations show a 60-fold increase in the use of fossil fuels during the 19th century, a 16-fold gain during the 20th century, and about a 1,500-fold increase over the past 220 years.[16]

This increasing dependence on fossil fuels is the most important

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factor in explaining the advances of modern civilization—and also our underlying concerns about the vulnerability of their supply and the environmental impacts of their combustion. In reality, the energy gain was substantially higher than the 1,500-fold I just mentioned, because we must take into account the concurrent increase in average conversion efficiencies.[17] In 1800, coal combustion in stoves and boilers to produce heat and hot water was no more than 25–30 percent efficient, and only 2 percent of coal consumed by steam engines was converted into useful work, resulting in an overall conversion efficiency of no higher than 15 percent. A century later, better stoves, boilers, and engines raised the overall efficiency to nearly 20 percent, and by the year 2000 the mean conversion rate was about 50 percent. Consequently, the 20th century saw a nearly 40-fold gain in useful energy; since 1800 the gain was about 3,500-fold.

To get an even clearer picture of the magnitude of these changes, we should express these rates in per capita terms. The global population rose from 1 billion in 1800 to 1.6 billion in 1900 and 6.1 billion in the year 2000, and hence the supply of useful energy rose (all values in gigajoules per capita) from 0.05 in 1800 to 2.7 in 1900 and to about 28 in the year 2000. China's post-2000 rise on the world stage was the main reason for a further increase in the global rate to about 34 GJ/capita by 2020. An average inhabitant of the Earth nowadays has at their disposal nearly 700 times more useful energy than their ancestors had at the beginning of the 19th century.

Moreover, within a lifetime of people born just after the Second World War the rate had more than tripled, from about 10 to 34 GJ/capita between 1950 and 2020. Translating the last rate into more readily imaginable equivalents, it is as if an average Earthling has every year at their personal disposal about 800 kilograms (0.8 tons, or nearly six barrels) of crude oil, or about 1.5 tons of good bituminous coal. And when put in terms of physical labor, it is as if 60 adults would be working non-stop, day and night, for each average person; and for the inhabitants of affluent countries this equivalent of steadily laboring adults would be, depending on the specific country, mostly between 200 and 240. On average, humans now have unprecedented amounts of energy at their disposal.

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The consequences of this in terms of human exertion, hours of physical labor, time for leisure, and the overall standard of living are obvious. An abundance of useful energy underlies and explains all the gains—from better eating to mass-scale travel; from mechanization of production and transport to instant personal electronic communication—that have become norms rather than exceptions in all affluent countries. Recent changes on a national scale range widely: as expected, they are lower for those high-income countries whose per capita energy use was already relatively high a century ago, with a greater increase in nations that have seen the most rapid modernization of their economies since 1950, most notably Japan, South Korea, and China. Between 1950 and 2020 the United States roughly doubled the per capita useful energy provided by fossil fuels and primary electricity (to about 150 gigajoules); in Japan the rate had more than quintupled (to nearly 80 GJ/capita), and China saw an astounding, more than 120-fold, increase (to nearly 50 GJ/capita).[18]

Tracing the trajectory of useful energy deployment is so revealing because energy is not just another component in the complex structures of the biosphere, human societies, and their economies, nor just another variable in intricate equations determining the evolution of these interacting systems. Energy conversions are the very basis of life and evolution. Modern history can be seen as an unusually rapid sequence of transitions to new energy sources, and the modern world is the cumulative result of their conversions.

Physicists were the first to recognize the fundamental importance of energy in human affairs. In 1886, Ludwig Boltzmann, one of the founders of thermodynamics, spoke about free energy—energy available for conversions—as the *Kampfobjekt* (the object of struggle) for life, which is ultimately dependent on incoming solar radiation.[19] Erwin Schrödinger, winner of the Nobel Prize in Physics in 1933, summed up the basis of life: "What an organism feeds upon is negative entropy" (negative entropy or negentropy = free energy).[20] During the 1920s, following this fundamental insight of 19th- and early 20th-century physicists, the American mathematician and statistician Alfred Lotka concluded that those organisms that best capture the available energy hold the evolutionary advantage.[21]

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In the early 1970s, American ecologist Howard Odum explained how "all progress is due to special power subsidies, and progress evaporates whenever and wherever they are removed."[22] And, more recently, physicist Robert Ayres has repeatedly stressed in his writings the central notion of energy in all economies: "the economic system is essentially a system for extracting, processing and transforming energy as resources into energy embodied in products and services."[23] Simply put, energy is the only truly universal currency, and nothing (from galactic rotations to ephemeral insect lives) can take place without its transformations.[24]

Given all of these readily verifiable realities, it is hard to understand why modern economics, that body of explanations and precepts whose practitioners exercise more influence on public policy than any other experts, has largely ignored energy. As Ayres noted, economics does not only lack any systematic awareness of energy's importance for the physical process of production, but it assumes "that energy doesn't matter (much) because the cost share of energy in the economy is so small that it can be ignored . . . as if output could be produced by labor and capital alone—or as if energy is merely a form of man-made capital that can be produced (as opposed to extracted) by labor and capital."[25]

Modern economists do not get their rewards and awards for being preoccupied with energy, and modern societies become concerned about it only when the supply of any main commercial form of energy appears to be threatened and its prices soar. Google's Ngram Viewer, a tool that allows you to see the popularity of terms that appeared in printed sources between 1500 and 2019, illustrates this point: during the 20th century the frequency of the term "energy price" remained quite negligible, until a sudden spike that began in the early 1970s (caused by OPEC's quintupling of crude oil prices; details of which follow later in this chapter) and peaked in the early 1980s. Once prices fell, a similarly steep decline followed, and by 2019 the term "energy price" was mentioned no more frequently than it was in 1972.

Understanding how the world really works cannot be done without at least a modicum of energy literacy. In this chapter I will first

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explain that energy may not be easy to define but that it is easy not to make the commonly encountered error of conflating it with power. We'll see how different forms of energy (with their specific advantages and drawbacks) and different energy densities (energy stored per unit of mass or volume, critical for energy storage and portability) have affected different stages of economic development, and I'll offer some realistic appraisals of the challenges faced by the unfolding transition to societies relying less and less on fossil carbon. As we'll see, our civilization is so deeply reliant on fossil fuels that the next transition will take much longer than most people think.

What is energy?

How do we define this fundamental quantity? The Greek etymology is clear. Aristotle, writing in his *Metaphysics*, combined *ἐν* (in) with *ἔργον* (work) and concluded that every object is maintained by *ἐνέργεια*.[26] This understanding endowed all objects with the potential for action, motion, and change—not a bad characterization of a potential to be transformed into other forms, be it by lifting, throwing, or burning.

Little changed over the following two millennia. Eventually, Isaac Newton (1643–1727) laid down fundamental physical laws involving mass, force, and momentum, and his second law of motion made it possible to derive the basic energy units. Using modern scientific units, 1 joule is the force of 1 newton—that is, the mass of 1 kilogram accelerated by 1 m/s^2 acting over a distance of 1 meter.[27] But this definition refers only to kinetic (mechanical) energy, and it certainly does not provide an intuitive understanding of energy in all of its forms.

Our practical understanding of energy was greatly expanded during the 19th century thanks to the era's proliferating experiments with combustion, heat, radiation, and motion.[28] This led to what is still the most common definition of energy: "the capacity for doing work"—a definition valid only when the term "work" means not only some invested labor but, as one of the leading physicists of the era put it, a generalized physical "act of producing a change of configuration in a

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system in opposition to a force which resists that change."[29] But that, too, is still too Newtonian to be intuitive.

There is no better way to answer the question "what is energy?" than by referring to one of the most insightful physicists of the 20th century—to the protean mind of Richard Feynman, who (in his famous *Lectures on Physics*) tackled the challenge in his straightforward manner, stressing that "energy has a large number of *different forms*, and there is a formula for each one. These are: gravitational energy, kinetic energy, heat energy, elastic energy, electrical energy, chemical energy, radiant energy, nuclear energy, mass energy."

And then comes this disarming but indubitable conclusion:

> It is important to realize that in physics today, we have no knowledge of what energy *is*. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, and when we add it all together it gives . . . always the same number. It is an abstract thing in that it does not tell us the mechanism or the *reasons* for the various formulas.[30]

And so it has been. We can use formulas to calculate, very accurately, the kinetic energy of a moving arrow or of a cruising jetliner, or the potential energy of a massive boulder that is just about to tumble down from a mountain, or the thermal energy released by a chemical reaction, or the light (radiant) energy of a flickering candle or a pointed laser—but we cannot reduce these energies into a single, easily described entity in our mind.

But the slippery nature of energy has not troubled the armies of instant experts: ever since the early 1970s, when energy became a major topic of public discourse, they have opined on energy matters with ignorance and zeal. Energy is among the most elusive and most misunderstood concepts, and a poor grasp of basic realities has led to many illusions and delusions. As we have seen, energy exists in various forms, and to make it useful to us we need to convert one form of it into another type. But treating this multifaceted abstract as a monolith has been the norm, as if different forms of energy were effortlessly substitutable.

Some of these substitutions are both relatively easy and beneficial.

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Replacing candles (the chemical energy of wax transformed into radiant energy) with electric lights powered by electricity generated by steam turbines (the chemical energy of fuels transformed first into heat and then into electric energy, which is then transformed into radiant energy) resulted in many obvious benefits (a safer, brighter, cheaper, more reliable kind of energy). Replacing steam- and diesel-powered railroad engines with electric drive has allowed less expensive, cleaner, and faster transportation: all sleek, high-speed trains are electric. But many desirable substitutions remain more expensive, or possible but realistically unaffordable for some time to come, or impossible at required scales—no matter how loudly their promoters extol their virtues.

Electric cars are a common example of the first category: now readily available, the best models are quite reliable, but in 2020 they were still more expensive than similarly sized vehicles powered by internal combustion engines. In terms of the second category, as I will detail in the next chapter, synthesis of the ammonia needed to produce nitrogenous fertilizers now depends heavily on natural gas as the source of hydrogen. Hydrogen could be produced by the decomposition (electrolysis) of water instead, but this route remains nearly five times as expensive as when the element is derived from abundant and inexpensive methane—and we have yet to create a mass-scale hydrogen industry. And long-distance electricity-powered commercial flight (equivalent to a kerosene-powered Boeing 787 from New York to Tokyo) is the outstanding example of the last category: as we will see, this is an energy conversion that will remain unrealistic for a long time to come.

The first law of thermodynamics states that no energy is ever lost during conversions: be that chemical to chemical when digesting food; chemical to mechanical when moving muscles; chemical to thermal when burning natural gas; thermal to mechanical when rotating a turbine; mechanical to electrical in a generator; or electrical to electromagnetic as light illuminates the page you are reading. However, all energy conversions eventually result in dissipated low-temperature heat: no energy has been *lost*, but its utility, its ability to perform useful work, is gone (the second law of thermodynamics).[31]

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All forms of energy can be measured in the same units—joule is the scientific unit; calories are often used in nutritional studies. In the next chapter, when I detail the massive energy subsidies going into modern food production, we will encounter the truly existential reality of different energy qualities. Producing chicken requires energies whose total is several times higher than the energy content of the edible meat. Although we can calculate the subsidy ratio in terms of energy quantities (joules in/joules out)—there is, obviously, a fundamental difference between inputs and outputs: we cannot digest diesel oil or electricity, while lean chicken meat is an almost perfectly digestible foodstuff containing high-quality protein, an indispensable macronutrient that cannot be replaced by an equal amount of energy from lipids or carbohydrates.

There are many choices available when it comes to energy conversions, some far better than others. The high densities of chemical energy in kerosene and diesel fuel are great for intercontinental flying and shipping, but if you want your submarine to stay submerged while crossing the Pacific Ocean then the best choice is to fission enriched uranium in a small reactor in order to produce electricity.[32] And back on land, large nuclear reactors are the most reliable producers of electricity: some of them now generate it 90–95 percent of the time, compared to about 45 percent for the best offshore wind turbines and 25 percent for photovoltaic cells in even the sunniest of climates—while Germany's solar panels produce electricity only about 12 percent of the time.[33]

This is simple physics or electrical engineering, but it is remarkable how often these realities are ignored. Another common mistake is to confuse energy with power, and this is done even more frequently. It betrays an ignorance of basic physics, and one that, regrettably, is not limited to lay usage. Energy is a scalar, which in physics is a quantity described only by its magnitude; volume, mass, density and time are other ubiquitous scalars. Power measures energy per unit of time and hence it is a rate (in physics, a rate measures change, commonly per time). Establishments that generate electricity are commonly called power plants—but power is simply the rate of energy production or energy use. Power equals energy

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divided by time: in scientific units, it is watts = joules/seconds. Energy equals power multiplied by time: joules = watts × seconds. If you light a small votive candle in a Roman church, it might burn for 15 hours, converting the chemical energy of wax to heat (thermal energy) and light (electromagnetic energy) with an average power of nearly 40 watts.[34]

Unfortunately, even engineering publications often write about a "power station generating 1,000 MW of electricity," but that is impossible. A generating station may have installed (rated) power of 1,000 megawatts—that is, it can produce electricity at that rate—but when doing so it would generate 1,000 megawatt-hours or (in basic scientific units) 3.6 trillion joules in an hour (1,000,000,000 watts × 3,600 seconds). Analogically, an adult man's basal metabolic rate (the energy required at complete rest to run the body's essential functions) is about 80 watts, or 80 joules per second; lying prone all day a 70-kilogram man would still need about 7 megajoules (80 × 24 × 3,600) of food energy, or about 1,650 kilocalories, to maintain his body temperature, energize his beating heart, and run myriad enzymatic reactions.[35]

Most recently, a poor understanding of energy has the proponents of a new green world naively calling for a near-instant shift from abominable, polluting, and finite fossil fuels to superior, green and ever-renewable solar electricity. But liquid hydrocarbons refined from crude oil (gasoline, aviation kerosene, diesel fuel, residual heavy oil) have the highest energy densities of all commonly available fuels, and hence they are eminently suitable for energizing all modes of transportation. Here is a density ladder (all rates in gigajoules per ton): air-dried wood, 16; bituminous coal (depending on quality), 24–30; kerosene and diesel fuels, about 46. In volume terms (all rates in gigajoules per cubic meter), energy densities are only about 10 for wood, 26 for good coal, 38 for kerosene. Natural gas (methane) contains only 35 MJ/m^3—or less than 1/1,000 of kerosene's density.[36]

The implications of energy density—as well as of fuel's physical properties—for transport are obvious. Ocean liners powered by steam engines did not burn wood because, everything else being

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