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Excerpt
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Introduction

Save the Planet! This slogan has been often repeated, and with good reason. The world we live on seems to be under heavy assault on numerous fronts, ranging from biological extinctions to potential shortages of key natural resources. Energy use and its consequences currently rank among the most pressing of these concerns, and not surprisingly are among the most hotly debated and divisive issues of the day. Our use of fossil fuels lies at the heart of the debate, largely because fossil fuels supply the vast majority of our current energy use (~86 percent in the United States). It has also become increasingly clear that emissions from the burning of fossil fuels are altering the composition of the atmosphere, carrying the potential for catastrophic climate change.

So how did we get to this point? We live in a world made possible by the use of fossil fuels, but it was not always so. Prior to the 19th century virtually all energy was "green" energy, mostly derived from standing biomass in the form of agricultural crops and native vegetation. This biomass could be burned directly for warmth or fed to animals and humans to produce mechanical power (the horse still represents the reference point for some power measurements today!). Most people worked in the fields, went to sleep when it got dark, and rarely traveled far from their homes. This lifestyle may have been dull, but the boredom generally did not last very long. Average life expectancy at birth was far lower than today, estimated at forty years or less. Famine and pestilence were ever-present threats, and few means were available to combat them.

Dramatic change began with the Industrial Revolution, during the late eighteenth to early nineteenth centuries. The initial rise of machines was powered largely by coal, which fueled steam engines. The origins of the Industrial Revolution are undoubtedly complex, but it clearly occurred most rapidly in countries possessing rich supplies of coal (most notably Britain, Germany, and the United States). Coal conveys significant advantages over earlier biomass fuels: It has higher energy density, its availability is not limited by arable land surface area or growing season, and it can be mined relatively cheaply. The technology originally built around coal was also responsible for the large-scale commercialization of crude oil; for example, a steam engine was used to drill the first modern oil well in the United States (operated by Edwin Drake in Titusville, Pennsylvania, 1859). Although oil and natural gas have since taken over much of the position once occupied by coal, coal-fired steam turbines continue to supply a major share of our electricity.

Today we tend to take for granted that we will always be warm and well fed. We enjoy the luxury of free time, because most farmwork and other heavy labor is done using machines. We barely think about the ease of traveling tens or hundreds of miles by automobile and cannot easily imagine living without this ability. Average people can safely and cheaply travel to another continent for a week's vacation. The same journey would have cost their not-so-distant ancestors many months in travel time, a large part (if not all) of their wealth, and possibly even their lives. Average life expectancy in the United States nearly doubled during the 20th century, and world population nearly quadrupled. These increases were unprecedented in human history, and coincided with a tenfold increase in gross domestic product per capita in industrialized countries. During the same period the use of fossil fuels increased by a factor of nearly 8 (Figure 1.1). To a large extent these recent transformations were all powered by the unprecedented bounty of fossil fuels.

It is highly doubtful that most people would want to return to the living conditions of the 18th century, even it were possible for the current population to do so. We are therefore confronted with a very challenging problem: How can we sustain the historically unprecedented level of energy consumption of the past century and thereby continue to enjoy its benefits? Equally important, how can we extend these same benefits to the billions of people who presently consume energy at a far lower rate than those in the United States and other highly developed countries? In the past few decades it has become apparent that the "energy problem" also encompasses another distinctly different but equally important question: how to avoid or remediate the unwanted consequences of large-scale energy use. Climate

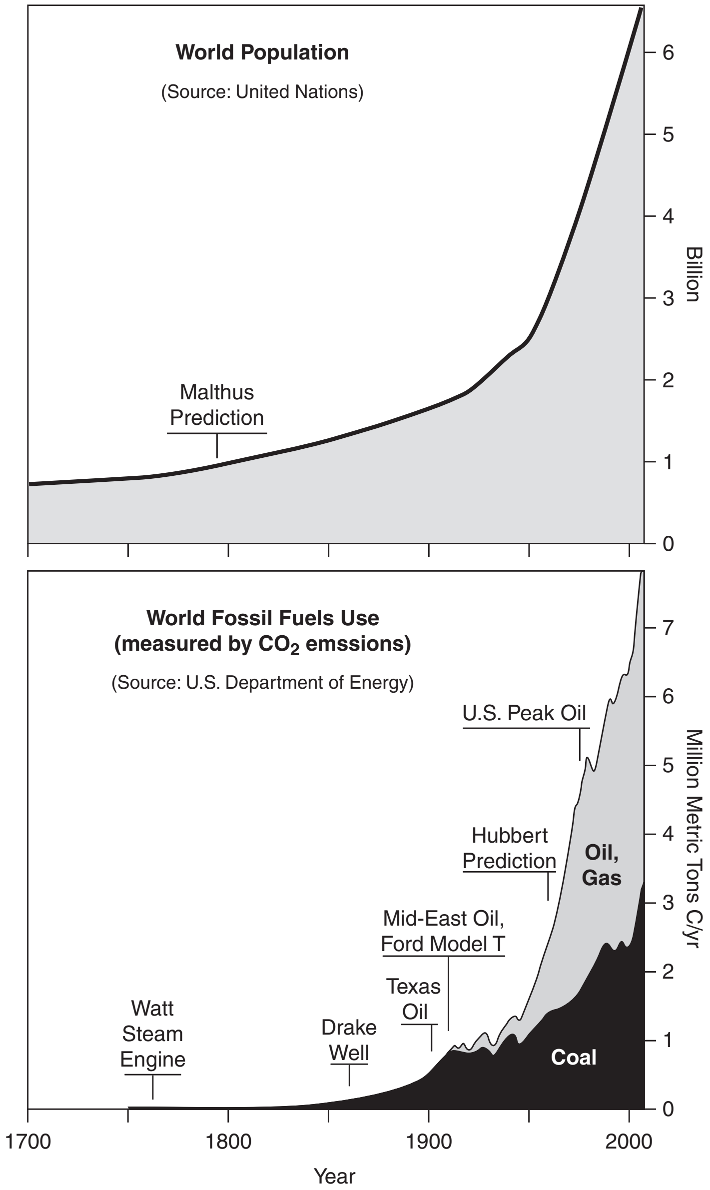

Figure 1.1. Historical growth in world population and consumption of fossil fuels, represented as carbon emissions (data sources: United Nations; Oak Ridge National Laboratories Carbon Dioxide Information Center).

changes related to the burning of fossil fuels currently loom as the most serious example of the latter. However, it is only prudent to assume that any form of energy production will incur its own unique environmental costs, especially when scaled to the present magnitude of fossil fuel use.

Just how much oil and other fossil fuels remain? It seems obvious to ask this question since we've been riding a wave of oil up to this point. Will that wave continue, or is it about to crash on the shore? Everyone knows that fossil fuels must be finite, because the planet itself is finite. A rational person might surmise that a fixed resource that is being consumed at a known rate will not last forever, and that its time of depletion should be more or less predictable. The well-publicized concept of "peak oil" is built around this reasoning, and on the assumption that the decline of oil will be a historical mirror image of its rise. Shell Oil geophysicist M. King Hubbert, who first proposed the peak oil concept, famously predicted that U.S. oil production would peak in either 1965 or 1970. In fact, it peaked in the early 1970s, emboldening others to make similar predictions of an imminent decline in world oil production (according to one such prediction world oil production should have peaked in 2005). Adding weight to the expectation of global peak oil is the decline in the discovery of giant oil fields that began in the 1970s to 1980s. The majority of oil is produced from the largest fields, so a decline in discoveries presumably signals an eventual decline in global production.

Doomsaying is perhaps among the oldest of professions, but it has not been among the most successful. The idea of peak oil has intellectual roots that go back at least as far as 1798, when Thomas Robert Malthus warned that world population growth would soon outpace growth in food production, leading in turn to widespread famine, pestilence, and poverty. This feared catastrophe failed to materialize, largely because Malthus did not anticipate the impact of the technological revolution that was already under way. Accurate prediction of oil futures has turned out to be similarly problematic, with dire warnings of shortage extending back nearly to the beginning of large-scale oil production itself. For example, global oil shortages were widely believed to be imminent during World War I, and in 1921 George Otis Smith, then director of the U.S. Geological Survey, warned, "The estimated reserves are enough to satisfy the present requirements of the United States for only 20 years." Far from running out of oil, present U.S. production rates are approximately 2.5 times higher now than they were in 1921, and in fact are about 2 times higher than predicted by Hubbert in 1956.

Can peak oil and global warming both be problems at the same time? After all, with nothing left to burn there would be no new CO_2 emissions to the atmosphere. Because fossil fuel availability and global warming represent two sides of the same coin, running out of oil might actually be a good thing for the environment. Unfortunately for the atmosphere there is not much sign of this happening yet. More ominously, no one is even talking about peak *coal,* and it appears that the known reserves are sufficient to sustain our current use rates for centuries. Recent high oil and natural gas prices have also revived interest in fossil fuel resources that are more difficult to recover but potentially very large in magnitude, such as oil sand, oil shale, and shale gas. New technologies for extracting these "unconventional" fossil fuels are evolving rapidly and dramatically altering our perception of fossil fuel reserves.

Without fossil fuels, is it even possible for us to continue living in the style to which we have become accustomed (and for the rest of the world to catch up)? This simple question unfortunately does not have a simple answer. Nuclear power currently ranks #2 behind fossil fuels, and it may be ready (like the famous car rental company) to "try harder." Like oil, nuclear power depends directly on a finite natural resource, but at first glance uranium reserves appear to be large enough to last for millennia. M. King Hubbert himself was an early supporter of the expansion of nuclear power. His 1956 paper, entitled "Nuclear Energy and the Fossil Fuels," was presented as an argument for nuclear power as a long-term replacement for fossil fuels. However, the rosy assessment of nuclear's potential presented by Hubbert (and others since) depends on counting all available uranium. Uranium in fact takes several different forms, the most common of which have atomic masses of 235 and 238. Only ^{235}U is currently used to generate power in the United States, because the reactor designs required to use ^{238}U are more costly and create enriched plutonium (which can be used in nuclear bombs) as a part of their normal fuel cycle. ^{235}U represents only 0.7 percent of the natural uranium supply however, leading to the startling implication that useful uranium reserves could become depleted within a matter of decades!

Moving further down the list (and closer to the 18th century), "renewables" are the fastest growing energy sector today. Renewable energy for the most part derives from sunlight, which can be harnessed either directly by solar collectors or indirectly by plants, moving water, or moving air. No one expects the Sun to stop shining, and so it is reasonable to believe that in addition to being renewable these energy sources will also be sustainable over long periods. In fact, these are the only energy sources for which sustainability can be historically proven; all were familiar (in primitive form) to the ancient Greeks. Renewables have never before been called upon to supply the majority of energy needs of a modern industrial society, however. Their present rapid growth is possible in part *because* their relative contribution is so small. Will this childhood growth spurt continue into adolescence and adulthood? Can the substantial technological barriers to large-scale production be overcome? What will be the environmental costs of renewable energy produced at a magnitude that replaces fossil fuels? These questions are only beginning to be explored.

So far there appear to be no clear winners for replacing fossil fuels, or at least no single winner. However, there are many smaller players that could help either to reduce the use of fossil fuels or to reduce their negative impact. We are therefore led to a diversified energy future, in which stabilization (or reduction) of CO_2 emissions is an overarching objective. This diverse future can be represented graphically by "stabilization wedges," as originally proposed by Socolow and Pacala in 2004 (Figure 1.2). Each wedge represents a different, partial solution to the larger problem of CO_2 emissions. The wedges can represent new alternative energy sources, reductions in net release of CO_2 from fossil fuels, or more efficient energy use. The relative sizes of the wedges vary, depending on who does the projecting, but most projections start with the assumption that future world energy demand will continue to grow geometrically at rates similar to those of the recent past.

But are all wedges created equal? Presumably not; each wedge has its own particular benefits and costs, which can be both economic and environmental. Some proposed solutions could even turn out to be more harmful in the long run than the problem they are intended to fix. The sheer complexity of scientific, economic, and political issues created by a diversified energy portfolio can be dizzying. The ongoing debate over corn ethanol, which presently consumes roughly 40 percent of U.S. corn production, serves as an excellent case in point. Some detractors claim that it is not an energy source at all, because the energy consumed in its production exceeds the energy content of the resultant fuel. Proponents have argued otherwise, concluding that for every 1 unit of energy invested, perhaps 1.5 units of energy are returned. This is a good thing, right? Maybe. Good, in that it adds 50 percent leverage to

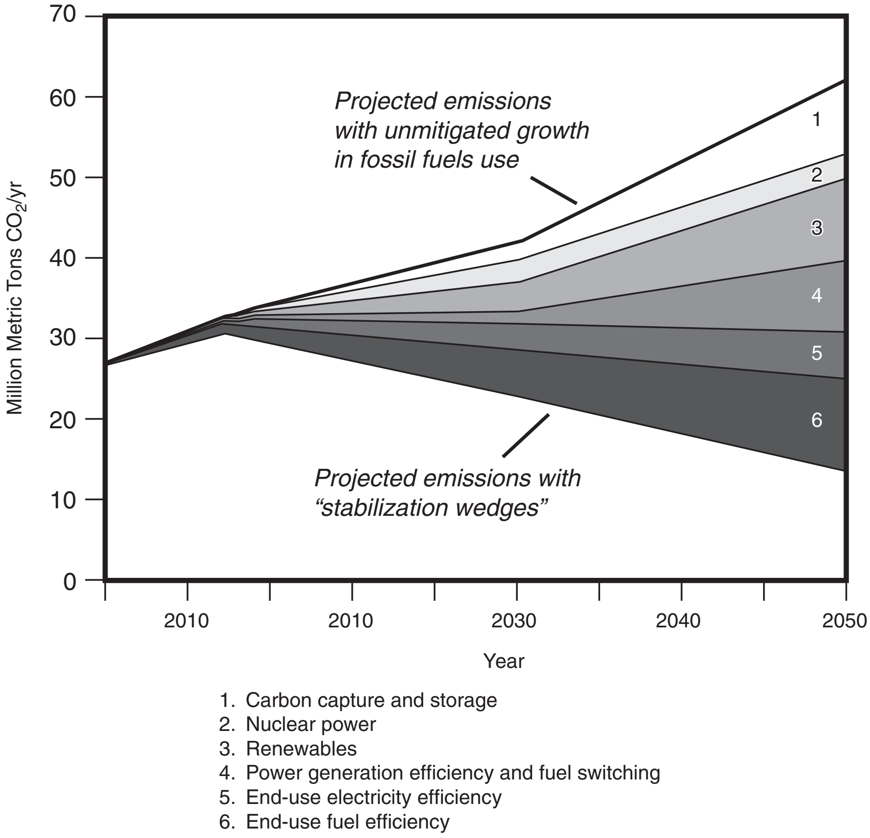

Figure 1.2. CO_2 stabilization strategies (modified from International Energy Agency 2008).

energy obtained from fossil fuels, possibly resulting in lesser CO_2 emissions. Also good if corn ethanol helps to build a technological bridge to superior cellulose-derived fuels, which are expected to have better energy returns. Bad however, in that corn ethanol and other biofuels consume huge amounts of water, require extensive use of fertilizers, and may promote soil erosion. A 1.5:1 energy return ratio means that about three acres must be put into production to recover the amount of solar energy captured by one acre of corn, effectively multiplying any environmental consequences threefold.

Confused yet? The slopes only get slipperier when economic and political considerations are applied. Are corn and ethanol subsidies vital to support American farmers, or are they a giveaway to big agribusiness? Are biofuels an important step toward reducing our dependence on foreign oil, or do they just drive up food prices? All of these views (and more) have their proponents, none of whom is shy about speaking up. The same can be said for most other energy systems, including fossil fuels. In some cases the advocates may be speaking from a genuine belief that their solution is in the best interest of the largest number of people. In other cases the motivation probably derives from more mundane self-interest. It can be truly difficult to know whom (if anyone) to believe, and the physical, economic, and political realities of energy have become entangled into a kind of Gordian knot. According to legend, Alexander the Great sliced apart the original Gordian knot with a stroke of his sword, and from there went on to rule over most of the known civilized world. Regrettably, solving the energy problem will probably not be so easy as Alexander's conquests.

Before we can even hope to conquer the energy problem we need to understand it better. The Earth itself can help in this regard. Everyone can agree that Earth resources such as fossil fuels are finite, and that the long-term history of the Earth over millions of years has determined their availability. There is plenty of room for debate over the precise natural abundance of such resources, how long they might last, or whether we should really be using them at all. However, we can at least point to some concrete observations that are not likely to change and that are not really subject to debate. For example, fossil fuels are not renewable over time frames that humans normally think about. The discovery rate of giant oil fields is declining, but production of "unconventional" oil and natural gas is increasing. Burning of fossil fuels results in relatively rapid release of carbon that originally required millions of years to remove from the atmosphere. Such observations help to illuminate and clarify related energy issues in terms of physical constraints imposed by the natural history of the Earth.

Similar logic can be applied to virtually all energy systems, because all consume natural resources in one way or another. This may sound like a rather radical statement; doesn't renewable by definition mean *not* dependent on finite natural resources? Yes and no. The energy itself is certainly infinite for practical purposes, assuming the Sun doesn't burn itself out any time soon. However, the means of gathering and using this energy generally are certainly not infinite. For example, the soil and water needed to grow crops for biofuels are both limited natural resources. Soil quality has already been degraded by agriculture in many parts of the world (Figure 1.3), and once gone it cannot be quickly restored. Rainfall continually replenishes surface water supplies, but agriculture in areas such as the Great Plains of the United States relies heavily on irrigation by groundwater. The

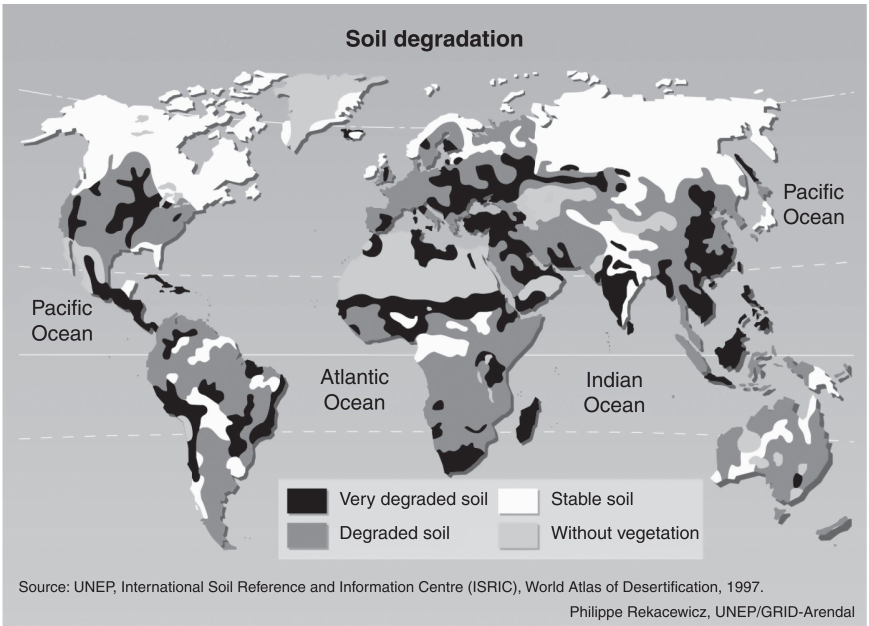

Figure 1.3. World soil quality map (Philippe Rekacewicz, 2007, UNEP/GRID).

major aquifer there is being rapidly depleted and may require thousands or tens of thousands of years to naturally recharge. Even in areas with plentiful rainfall, fresh water supplies are often considered an endangered resource because of competition between urban and agricultural uses, the environmental impacts of water usage, and contamination.

Geology also exerts first-order control on the availability of a variety of other renewable resources. For example, regional patterns of sunshine and wind intensity are governed in part by the geometric configuration of the continents, which profoundly influences the circulation of the ocean and atmosphere. The geologic history of the continents has also determined the fine-scale availability of wind resources, as a result of the dependence of wind resource quality on topography. Even tidal energy is dependent on geologic history, because effective use of tidal energy requires favorable coastline geometries to amplify tides. Moving deeper, the connection of geology to geothermal energy should be obvious in places with active hot springs. Less obvious is the fact that geothermal energy systems often rely on natural groundwater circulation that can take hundreds or thousands of years to renew.

Earth resources also govern our ability to dispose of the by-products of energy production. Practically speaking, only three places are available to dispose of things we don't want: the atmosphere, the ocean, and the solid Earth. If we don't want to put the CO_2 released from fossil fuels into the first, we must then consider one of the other two. As it happens, the ocean is already absorbing about one-third of anthropogenic carbon emissions. It has been suggested that this fraction could be increased by either stimulation of uptake of CO_2 by organisms in surface waters or by direct injection of CO_2 into deep waters. Neither of these approaches has yet been fully explored, and the potential for unanticipated consequences is largely unknown.

In contrast, industrial-scale injection of CO_2 into the solid Earth has been routinely practiced for decades. Ironically, the purpose has not been to reduce atmospheric greenhouse gases, but instead to stimulate greater rates of oil production. No apparent ill effects have resulted so far, and the CO_2 appears to stay buried. This experience has lent encouragement to the idea of larger-scale injection of captured CO_2 from power plants or other point sources. This is essentially petroleum geology in reverse, returning exhumed carbon to its original resting place. Whether geologic carbon storage can be eventually deployed on the massive scale required to have a noticeable effect on the atmosphere remains to be seen. Several pilot projects and a considerable amount of research are currently aimed at addressing questions of reservoir capacity, protection of groundwater resources, leakage back to the atmosphere, and cost.

Underground storage may also be the preferred option for dealing with the by-products of nuclear power generation. The basic requirement for geologic disposal seems relatively simple: long-term isolation of nuclear waste from the surface environment and from potential water supplies. The implementation of underground waste repositories has been anything but simple, however, because of a unique combination of political and technological challenges. For example, the Yucca Mountain site in southern Nevada was designated as a future national waste repository in 1987 but met strong local opposition from the start. The project was finally cancelled in 2009 after an estimated $30 billion in research and development expenditures over a period of more than twenty years.

One of the more challenging technical requirements of the Yucca Mountain site was that it maintain a specified level of integrity over time periods of up to *1 million* years. To put this time interval in perspective, the pyramids of Egypt are only about five thousand years old. Twenty thousand years ago the geography of North America looked radically different than it does today. Glacial ice sheets up to