Policy Analysis

No. 715 December 20, 2012

Humanity Unbound
How Fossil Fuels Saved Humanity from Nature and Nature from Humanity

by Indur M. Goklany

Executive Summary

For most of its existence, mankind's well-being was dictated by disease, the elements and other natural factors, and the occasional conflict. Virtually everything it needed—food, fuel, clothing, medicine, transport, mechanical power—was the direct or indirect product of living nature.

Good harvests reduced hunger, improved health, and increased life expectancy and population—until the next inevitable epidemic, crop failure, natural disaster, or conflict. These Malthusian checks ensured little or no sustained growth in population or well-being.

Then mankind began to develop technologies to augment or displace living nature's uncertain bounty. Gradually food supplies and nutrition improved and population, living standards, and human well-being advanced haltingly. The Industrial Revolution accelerated these trends. Mankind broke its Malthusian bonds. Growth became the norm. Population exploded, along with living standards and well-being.

Technologies dependent on cheap fossil fuels enabled these improving trends. Nothing can be made, transported, or used without energy, and fossil fuels provide 80 percent of mankind's energy and 60 percent of its food and clothing. Thus, absent fossil fuels, global cropland would have to increase by 150 percent to meet current food demand, but conversion of habitat to cropland is already the greatest threat to biodiversity. By lowering humanity's reliance on living nature, fossil fuels not only saved humanity from nature's whims, but nature from humanity's demands.

Key to these developments was that these technologies accelerated the generation of ideas that spawned even better technologies through, among other things, greater accumulation of human capital (via greater populations, time-expanding illumination, and time-saving machinery) and faster exchange of ideas and knowledge (via greater and faster trade and communications).

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Fossil fuels helped transform the human world from one that was dependent on living nature for virtually its entire well-being, and thereby trapped in nature's Malthusian vise, to one that escaped that vise.

Introduction

For most of mankind's existence, human well-being was defined by climate, weather, disease, other natural factors, and the occasional conflict. Virtually everything that humanity depended on was the recent product of living nature (which the economic historian Edward Wrigley calls "the organic economy").[1] It supplied humanity with all its food, fuel, clothing and skins, and much of its medicine and material products. Living nature also supplied the sustenance for the animals—oxen, horses, donkeys, camels, even elephants—that human beings had drafted to supplement these needs and to serve as beasts of burden to transport themselves and their goods, till the soil, and provide mechanical power.

Food for human beings and feed for animals were, then as now, the direct or indirect product of recent photosynthesis in plants. Virtually all fuel was obtained via woody products. Houses were built from logs and other vegetation, supplemented by clay, earth, and stones. The few worldly goods humans possessed were also mostly from recent photosynthetic products (e.g., wood, natural fiber, skin, or bone), barring the occasional trinket or luxury good made of some exotic metal or stone. No wonder the gods who controlled the weather and rain—Zeus, Jupiter, Indra, Thor—were the mightiest in the pantheons of ancient civilizations.

When climate and weather cooperated, harvests were adequate, hunger was reduced, health improved, more children survived to adulthood, life expectancy increased, and the population grew—until the next epidemic, the next climatic, weather or other natural disaster, or the next war or breakdown of civil order inevitably led to death and disease, disrupted agriculture, or both.

These Malthusian checks—so-called because the Reverend Thomas Robert Malthus identified them in his 1798 essay on population as nature's cruel checks for population growth—ensured that in pre-industrial societies 30 percent or more of the population died before reaching age 15.[2] Population, therefore, grew at a glacial pace. If population grew too large or living standards outstripped subsistence levels for long, these checks brought them back to subsistence levels. There was, thus, little or no progress in the average person's well-being—best indicated by life expectancy—from one generation to the next.

All this started to change when mankind began to develop technologies that would augment or displace the goods that it received from living nature.[3] Gradually the supply and nutritional quality of food was increased and population growth rates started to rise, as did living standards and human well-being. The Industrial Revolution accelerated those trends. Today, mankind has transcended the Malthusian checks. Its population has exploded, as has its standard of living, yet human well-being has never been higher and it continues to improve.

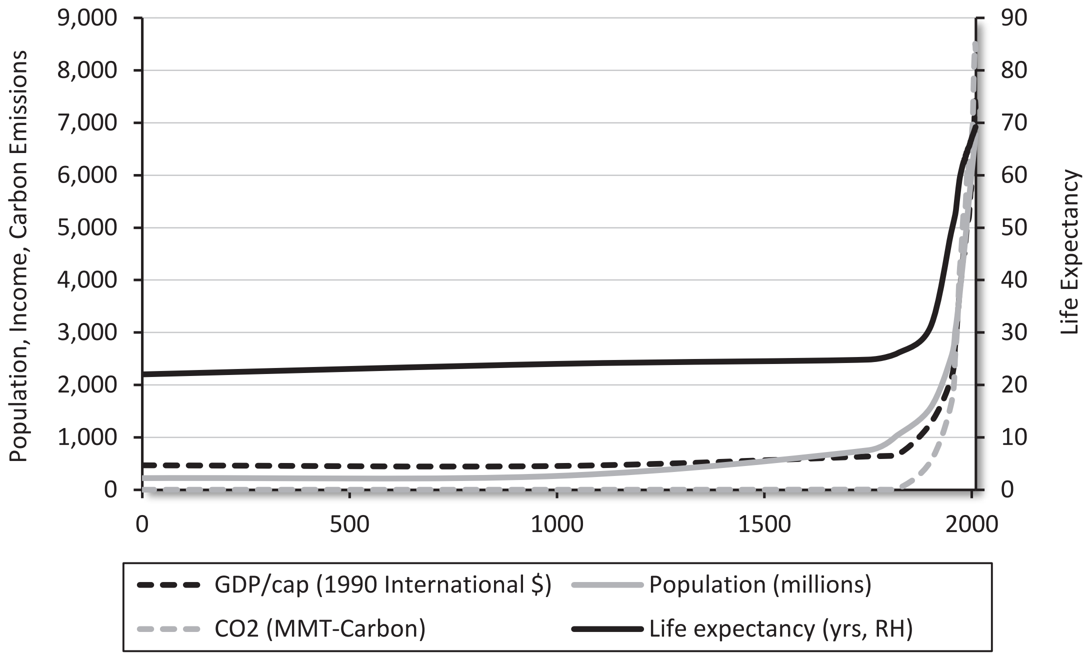
This paper describes how fossil fuels helped accomplish this grand transformation from a world that was dependent on living nature for virtually its entire well-being, and thereby trapped in nature's Malthusian vise, to one in which mankind has escaped this vise. It identifies the technologies that mediated this transformation, how they depend directly or indirectly on fossil fuels to fulfill mankind's hunger for food, energy, and materials, and how they accelerated the generation of ideas that spawned these technologies.

It shows that these technologies, by lowering humanity's reliance on living nature, inevitably ensured that human well-being is much less subject to whims of nature (as expressed through the weather, climate, disease, and other natural disasters) and that the amount of land converted to human use was limited, thereby containing mankind's footprint on the world.

A Brief History of Human Progress

Figure 1 shows trends in four indicators that *collectively* indicate humanity's progress

Figure 1
Global Progress, 1 A.D.–2009 A.D. (as indicated by trends in world population, gross domestic product per capita, life expectancy, and carbon dioxide [CO_2] emissions from fossil fuels)



Sources: Updated from Indur Goklany, "Have Increases in Population, Affluence and Technology Worsened Human and Environmental Well-being?" *Electronic Journal of Sustainable Development* 1, no. 3 (2009); based on Angus Maddison, *Statistics on World Population, GDP and Per Capita GDP, 1-2008 AD*, University of Groningen, 2010, http://www.ggdc.net/MADDISON/Historical_Statistics/vertical-file_02-2010.xls; World Bank, *World Development Indicators 2011*, http://databank.worldbank.org/; T.A. Boden, G. Marland, and R. J. Andres, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, http://cdiac.ornl.gov/trends/emis/overview_2008.html.
Notes: Data are sporadic until 1960. This figure assumes that trends between adjacent data points are linear.

(or lack of it) through the ages, beginning in 1 A.D. The indicators are global population, average life expectancy (the best single indicator of human health and well-being), and gross economic product per capita, or income, which is the best indicator for the standard of living or material well-being. Elsewhere it has been shown that virtually every indicator of human well-being, such as levels of hunger, infant mortality, life expectancy, education, economic freedom, and child labor—improves as income rises.[4] These improvements are generally non-linear and typically improve with the logarithm of income. They advance very rapidly at low levels of income, after which the improvements are more gradual. Even that nebulous and most subjective of indicators—happiness—apparently behaves similarly.[5]

Figure 1 also shows that global carbon dioxide emissions from fossil-fuel combustion are correlated with the three indicators of human progress over the last quarter of a millennium. Prior to that, these anthropogenic emissions were, for practical purposes, nil compared with today's levels.

Examination of the figure suggests that the trajectory of human progress to date can be broken into at least three periods.

The Malthusian Trap: The World through the Middle Ages. Life expectancy, the surrogate for human well-being, fluctuated around 20–25 years for much of mankind's existence. Ancient Greece had a life expectan-

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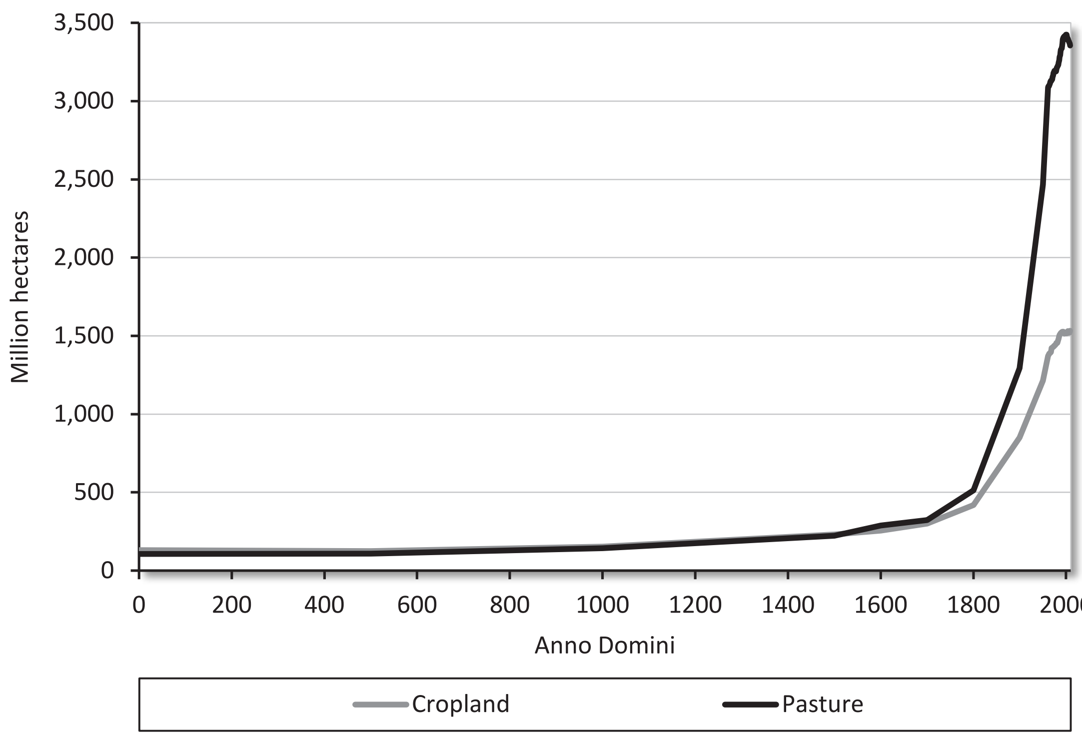
cy around 18 years, and Rome had 22 years.[6] From 33 A.D. to 258 A.D., life expectancy in Egypt—Imperial Rome's breadbasket—averaged 24 years, the same level as global life expectancy in 1000 A.D.[7]

During the first millennium A.D., world population grew from 230 million to 270 million, a compounded growth rate of less than 0.02 percent per year.[8] Average income was largely unchanged. According to the economic historian Angus Maddison, it might even have shrunk marginally, from the equivalent of $470 in 1 A.D. to $450 in 1000 A.D.[9] By today's standards, the world was mired in poverty and, except for brief spells, virtually everyone survived at the subsistence level. Humanity was trapped in Nature's Malthusian vise.

Stretching the Malthusian Bonds: From the Middle Ages through the Enlightenment. Over subsequent centuries, however, humanity started to stretch its Malthusian bonds—to insulate itself against the vagaries of weather and climate and nature's other whims, and to manage common diseases.

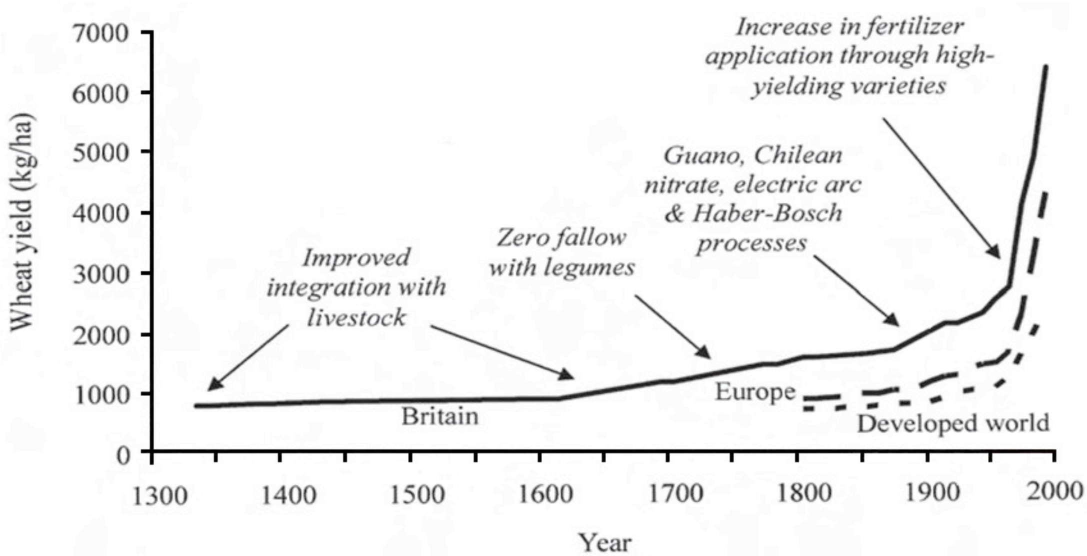
More land was converted to agriculture (Figure 2).[10] Improved cropping techniques and livestock management slowly increased yields (Figure 3).[11] Crops were translocated from one area to another, and adapted to their new homes. Maize, potatoes, yams, manioc, and tomatoes journeyed from the New World to the Old, while wheat, rice, rye, and oats went in the opposite direction.[12] This Columbian Exchange also involved livestock: chicken, cattle, horses, donkeys, and domesticated pigs were introduced to the New World, and turkeys to the Old. More roads were built, canals were constructed, new and more accurate navigation techniques were developed, and shipping technologies were advanced. These advances in

Figure 2
Global Crop and Pasture Land, 1 A.D.–2009 A.D.



Sources: Kees Klein Goldewijk et al., "The HYDE 3.1 Spatially Explicit Database of Human-induced Global Land-use Change over the Past 12,000 Years," *Global Ecology and Biogeography* 20 (2011): 73–86; FAO, FAOSTAT, http://faostat.fao.org/.

Figure 3
Wheat Yield in Britain, Europe, and the Developed World, 1300–1990



Source: N. B. J. Koning, et al., "Long-term global availability of food: continued abundance or new scarcity?" *NJAS Wageningen Journal of Life Sciences* 55 (2008): 229–292.
*Britain: Until 1800, England; since 1800, the United Kingdom.
**Europe, excluding Russia.
***The developed world, excluding Japan and South Africa.

transportation facilitated greater trade and commerce, including trade in staple grains. These changes combined to increase the amount of food and nutrition available for consumption, which freed a larger portion of the population to engage in tasks other than agriculture, to congregate in towns, and to specialize, all of which increased human capital.

Trade and commerce were advanced further by the invention of the double-entry bookkeeping system, development of banking, insurance, joint-stock companies and stock exchanges, and greater acceptance of paper money.

With the introduction of the printing press in Europe, books began to multiply. In the following half century, the price of books in Europe fell by two-thirds.[13] That helped proliferate knowledge and its offspring, technology, while retarding technological regression.

Such regression is not unusual in the annals of history. It had occurred time and again over the centuries, such as in Europe in the Dark Ages, following the fall of the Western Roman Empire. Anthropologists have also noted other instances where, through isolation or loss of human capital, societies have regressed technologically. For example, isolated polar Inuits lost the technology for making kayaks and bows and arrows when those with the critical expertise expired during an episode of the plague. These skills, however, were reestablished by migrants from Baffin Island.[14]

The trend toward constant accretion of knowledge was reinforced by an increase in literacy, aided in many areas by the printing press, the Reformation, and replacement of Latin by the vernacular. The replacement of Latin itself signaled a less dogmatic approach toward acquiring and advancing knowledge, which spilled over into the understanding of natural phenomena. Universities were established. People traded not only goods but also ideas, inventions, and methods of thought and analysis—exchang-

Improvements in agriculture, trade, and technology combined to increase the amount of food available, freeing people from agricultural tasks. As they congregated in towns and specialized, human capital was increased.

Average income had increased to $640 by 1750, only a 0.05 percent increase per year from 1000 A.D.

es that grew with population density, literacy, the increase in the volume of books and trade. The scientific method was advanced.

New medicines and medical techniques were introduced. The notion of property rights was developed. Technologies to harness wind and water power were improved.

In the meantime, in response to the scarcity of fuel wood from the deforestation caused by the demand for wood for fuel and the construction of ships and buildings, coal—a hitherto niche fuel—was beginning to be used more widely. Initially it was used for heating and cooking in the home and in non-contact (external) heating for manufacturing processes (such as lime manufacturing, glassmaking, or blacksmithing) in the general vicinity of surface coal deposits. By the 18th century, however, coal was being used in England in steam engines to convert heat energy to mechanical energy—a fundamental breakthrough that would eventually allow humanity to reduce, if not dispense with, human and animal power to transport goods and people and to do mechanical work. But because these new-fangled engines were very inefficient, their use was initially restricted to specialized high-value applications, specifically to increase coal output by pumping accumulated water out of coal mines.[15]

Cumulatively, these innovations and developments gradually reinforced the trend toward increased and more nutritious food supplies and greater economic activity. Most of the advances in food supplies and nutrition, however, went to sustain a larger population. Global life expectancy barely rose from 24 to 25 years from 1000 to 1750, while the world's population had almost tripled to 760 million. This translates into a compounded increase of 0.14 percent per year since 1000 A.D. Although modest by current standards, this increase was eight times the rate for the previous 1,000 years, as indicated in Table 1.

Average income, however, rose much less rapidly. By 1750 it had increased to $640, only a 0.05 percent per year increase from 1000 A.D. Carbon emissions from the use of fossil fuel energy, unknown during the first millennium, were at an estimated 3 million metric tons by 1750 (see Figure 4).

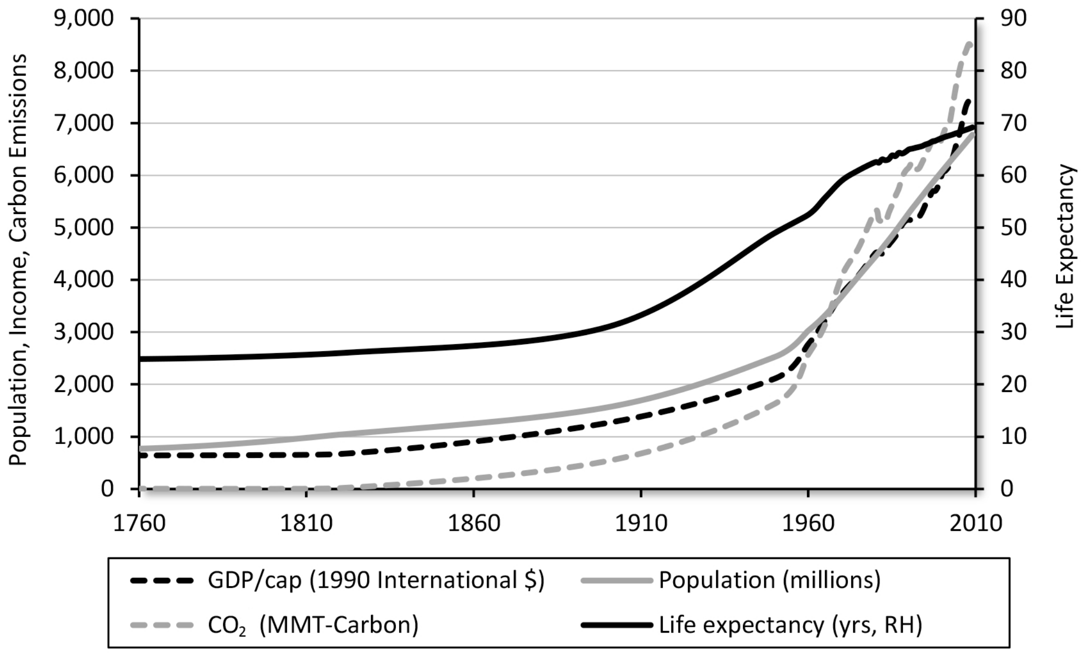
Progress, however, was uneven around the world. England had progressed much further than any other nation save the Netherlands. By 1710, coal accounted for half the energy consumed in England and Wales.[16] Their average income grew at an annual rate of 0.36 percent during the 18th century; income reached $1,710 in 1750.[17] The previous half century had seen their population grow at a relatively healthy rate of 0.25 percent per year and the average life expectancy over the previous quarter century was 35 years, substantially higher than for most other countries.[18] In 1750, most of the global carbon emissions were from coal burned in Britain.[19]

Table 1
Average Annual Rate of Increase for Various Time Periods

	1 A.D.–1000 A.D. (%)	1000 A.D.–1750 A.D. (%)	1750 A.D.–2009 A.D. (%)
Life Expectancy	0.01	0.00	0.41
Income	0.00	0.05	0.98
Population	0.02	0.14	0.88
Carbon Dioxide Emissions			3.23

Sources: Angus Maddison, *Statistics on World Population, GDP and Per Capita GDP, 1–2008 AD*, University of Groningen, 2010, http://www.ggdc.net/MADDISON/Historical_Statistics/vertical-file_02-2010.xls; World Bank, World Development Indicators 2011, http://databank.worldbank.org/; T. A. Boden, G. Marland, and R. J. Andres, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, http://cdiac.ornl.gov/trends/emis/overview_2008.html.

Figure 4
Global Progress, 1760–2009 (as indicated by trends in world population, GDP per capita, life expectancy, and carbon dioxide (CO_2) emissions from fossil fuels)



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Notes: Data are sporadic until 1960. This figure assumes that trends between adjacent data points are linear. Life expectancy is a surrogate for human well-being; living standards are depicted by affluence, or GDP per capita; and CO_2 is a proxy for fossil-fuel usage.

Such was the world that Malthus was born into, just as it was stretching—and about to slip—its Malthusian bonds.

Escaping the Malthusian Trap: The Industrial Revolution and Beyond. The increases in the rates of growth for population, life expectancy, and material well-being through 1750, virtually imperceptible by today's norms, were but a harbinger of things to come. Modern economic growth was gathering steam. Its next phase, the Industrial Revolution, was about to explode, and with it population, human well-being, and incomes—first in England, then Western Europe and its various colonies and ex-colonies, and then the rest of the world.

From 1750 to 2009, global life expectancy more than doubled, from 26 years to 69 years; global population increased 8-fold, from 760 million to 6.8 billion; and incomes increased 11-fold, from $640 to $7,300. Never before had the indicators of the success of the human species advanced as rapidly as in the past quarter millennium, as shown in Table 1. Concurrently, carbon dioxide emissions grew by 2,800-fold, increasing from 3 million metric tons to 8.4 billion metric tons (Figure 4).

Today, the Industrial Revolution is being succeeded by a post–industrial revolution. Figure 5 illustrates human progress in the United States from 1900 to 2009. Over this

From 1750 to 2009, global life expectancy more than doubled, global population increased 8-fold, and incomes increased 11-fold.

Escaping the Malthusian trap and associated advances in human progress were accompanied by an increase in carbon dioxide emissions of three orders of magnitude. These improvements occurred because of—and not despite—fossil fuels.

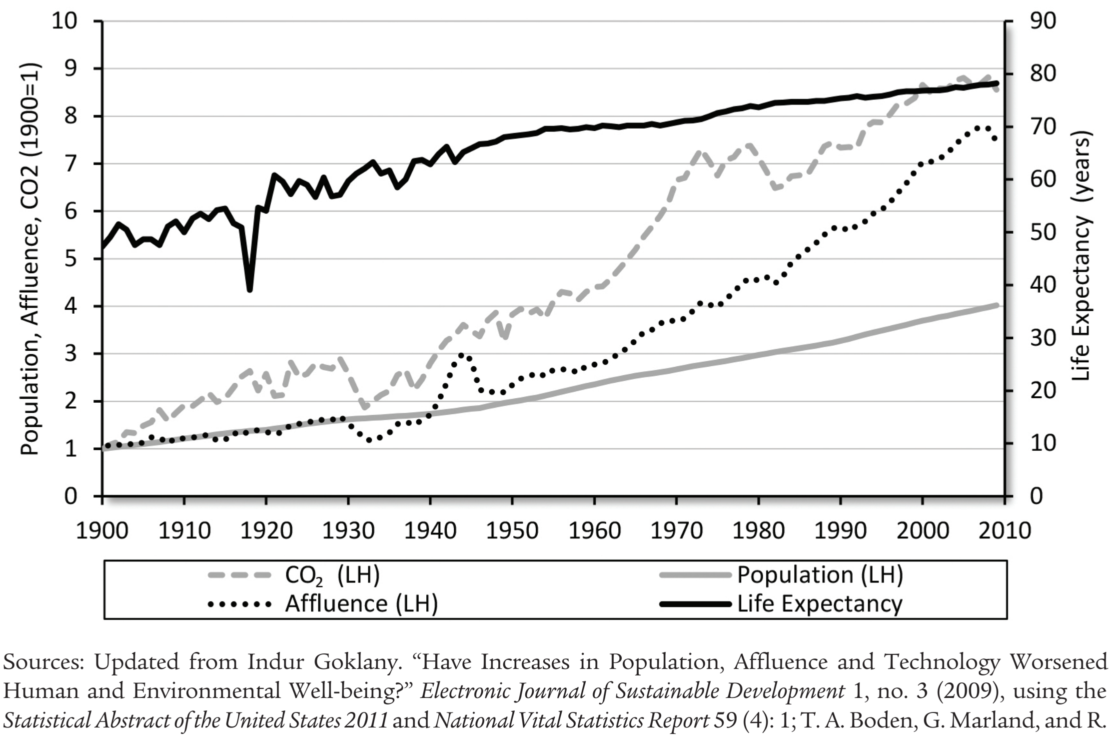
period, population quadrupled, U.S. life expectancy increased from 47 years to 78 years, and incomes (denoted "affluence") grew 7.5-fold while carbon dioxide emissions increased 8.5-fold. Yet, far from experiencing a Malthusian collapse, Americans now have more creature comforts, they work fewer hours in their lifetimes, their work is physically less demanding, they devote more time to acquiring a better education, they have more options to select a livelihood and live a more fulfilling life, they have greater economic and social freedom, and they have more leisure time and greater ability to enjoy it. And these trends are evident not just in the United States but, for the most part, elsewhere as well.[20]

Living standards started to surge worldwide later than in the United States. Since the 1950s, global living standards have been advancing more rapidly than population (see Figure 4). The population growth rate peaked in the 1960s and, according to most projections, it could start leveling off this century.[21]

More importantly, consistent with the trends in life expectancy and incomes, other major indicators of human well-being—infant, child, and maternal mortality; prevalence of hunger and malnutrition; child labor; job opportunities for women; educational attainment—show that humanity is far better off today that it was before the start of industrialization.[22] Mankind has escaped nature's Malthusian trap, at least for the time being.

Notably, this escape and the associated advances in human progress were accompanied by an increase in carbon dioxide emissions of three orders of magnitude. I will show below that these improvements occurred, in large part, because of—and not despite—fossil fuels.

Figure 5
U.S. Carbon Dioxide Emissions, Population, GDP per Capita, and Life Expectancy at Birth, 1900–2009



Sources: Updated from Indur Goklany. "Have Increases in Population, Affluence and Technology Worsened Human and Environmental Well-being?" *Electronic Journal of Sustainable Development* 1, no. 3 (2009), using the *Statistical Abstract of the United States 2011* and *National Vital Statistics Report* 59 (4): 1; T. A. Boden, G. Marland, and R. J. Andres, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, http://cdiac.ornl.gov/trends/emis/overview_2008.html; The Conference Board, *Total Economy Database*™ (2010), http://www.conference-board.org/data/economydatabase/.
Notes: Life expectancy is a surrogate for human well-being; living standards are depicted by affluence, or GDP per capita; and CO_2 is a proxy for fossil-fuel usage.

Fossil Fuels and the Reduced Dependence on Living Nature

Before humanity extricated itself from the restraints that kept its growth and well-being in check, it had to develop technologies to reduce its dependence on the direct or indirect products of recent photosynthesis. This was enabled by technologies that either amplified nature's bounty or bypassed it altogether for a wide variety of products (and services),[23] supplemented by devices or practices that would store today's products for future use when nature, sooner or later, would fail to deliver.

Food. Every activity requires energy. Even human *inactivity* requires a minimum level of energy to keep basic bodily functions going.[24] The amount of energy needed to sustain this inactivity is called the basal metabolic rate (BMR). It takes food to replace this energy.

Insufficient food, which is defined in terms of the BMR, makes populations more susceptible to infections and other diseases, which, ironically, raises the body's demands for more energy (that is, food). Societies where food supplies are inadequate have high rates of infant and maternal mortality, poor health, and low life expectancies. Thus, consuming sufficient food is the first step to human survival and, beyond that, good health.[25]

Increasing food supplies, therefore, was critical to raising humanity's numbers and well-being. This was initiated with the development of agriculture. Over subsequent millennia, humanity increased the amount of land used for crops and pasture (Figure 2) while also improving agricultural practices to increase yields from both crops and livestock (Figure 3).

As shown in Figure 4, the increase in population and improvements in human well-being and living standards commenced before the world started to use fossil fuels in significant amounts. By 1900, an estimated 850 million hectares of cropland were being cultivated to feed a global population of about 1.7 billion people. Since then, although population has quadrupled and the world is much better fed, cropland only increased 80 percent.

This was possible because of the technological augmentation of nature's bounty resulting from tremendous improvements in the productivity of virtually every segment of the food and agricultural sector, from the farmer's field to the consumer's fork. Many of these productivity increases were driven directly or indirectly by fossil fuels.[26]

Agricultural yields on the farm are driven by fertilizers, pesticides, water, and farm machinery. Each of these inputs depends to some extent on fossil fuels. Fossil fuels provide both the raw materials and the energy for the manufacture of fertilizers and pesticides; farm machinery is generally run on diesel or another fossil fuel; and irrigation, where it is employed, often requires large amounts of energy to operate pumps to move water.

To gauge the contribution of fossil fuels to agricultural production, consider that a comprehensive review of fertilizer performance in the *Agronomy Journal* concluded that the "average percentage of yield attributable to fertilizer generally ranged from about 40 to 60% in the USA and England and tended to be much higher in the tropics."[27] Another study in *Nature Geosciences* estimated that, in 2008, fertilizer made from synthetic nitrogen was responsible for feeding 48 percent of the world's population.[28]

As one can see in Figure 3, the acceleration in yields increased around the 1920s, which followed the commercialization of nitrogen fertilizers manufactured via the Haber-Bosch process. This energy-intensive process fixes nitrogen from the air by reacting it under extremely high pressure with hydrogen (obtained from natural gas), generally over an iron catalyst. In recognition of its potential contribution to feeding humanity, the co-inventor of this process, Fritz Haber, received the 1918 Nobel Prize for

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In 2007, the global food and agricultural system delivered, on average, two and a half times as much food per acre of cropland as in 1961.

Chemistry,[29] despite the fact that the same process prolonged World War I by allowing Germany to manufacture explosives and ammunitions even after the British Navy had blockaded its access to Chilean saltpeter, which until then had been critical for its manufacture. (Fritz Haber also pioneered Germany's wartime poison-gas effort.)[30]

The distinguished plant scientist, E. C. Oerke, using data for 2001–03, estimates that 50 to 77 percent of the world's wheat, rice, corn, potatoes, and soybean crops would be lost to pests in the absence of pesticides. Pesticides have reduced these losses to 26–40 percent.[31]

Irrigated lands, with average crop yields 3.6 times higher than rain-fed areas, are responsible for a disproportionately high share of production relative to their acreage.[32] Where irrigation is not accomplished entirely through gravity, it can be a very energy-intensive operation.[33] Similarly, the manufacture and operation of farm machinery requires energy. And in today's world, energy for the most part means fossil fuels (see below).

Beyond increasing yields on the farm, fossil fuels have increased food availability in other ways. The food and agricultural system depends on trade within and between countries to move agricultural inputs to farms and farm outputs to markets. In particular, trade allows food surpluses to be moved to areas experiencing food deficits. But transporting these inputs and outputs in the quantities needed and with the speed necessary for such trade to be an integral part of the global food system depends on relatively cheap fossil fuels.[34]

About one-third of the food that is produced is lost or wasted in the food supply chain between the farm and eventual consumption.[35] These losses would have been much higher but for spoilage-reducing technologies such as refrigeration, rapid transport, containers, and plastic packaging.[36] But refrigeration and rapid transport are energy-intensive: plastic, which is ubiquitous in food packaging and storage, is made from petroleum or natural gas, and virtually every container, whether it is made of clay, glass, metal, cardboard, or wood, requires energy to make and shape. These technologies are often overlooked partly because loss and waste are not included in familiar agricultural statistics such as crop yields or production figures. Nevertheless, lower losses and waste increase available food supplies and the overall efficiency of the food and agricultural system.

Additional CO_2 in the atmosphere should also contribute to higher food production.[37] Although there are uncertainties related to the quantitative relationship between higher yields and higher CO_2 concentrations, there is no doubt that the latter increases yield.[38] This is unsurprising since CO_2 is plant food, a fact established over two centuries ago by Nicolas Théodore de Saussure in his pioneering book, *Recherches Chimiques sur la Végétation*.[39]

Moreover, because the health of the population has improved, the amount of food needed to maintain a healthy weight for each individual has declined. This is because additional food is needed to replace the nutrients lost because of sickness, with some illnesses (e.g., water-borne diseases) reducing them more than others.[40] Mechanical and electrical appliances have also reduced the demand for human effort, which translates into reduced demand for food.

One may get a sense of the cumulative contribution of these technologies to the world food supply if one considers that between 1961 and 2007, global population more than doubled from 3.1 billion to 6.7 billion and food supplies per person increased by 27 percent, yet the total amount of cropland increased by only 11 percent.[41] In effect, in 2007, the global food and agricultural system delivered, on average, two and a half times as much food per acre of cropland as in 1961. New and improved technologies, coupled with greater penetration of existing technologies since 1961, account for 60 percent of total global food supplies.

Had the productivity of this sector not improved since 1961, the world would have needed to cultivate another 2.2 billion hectares of cropland in 2007 to produce the same amount of food. This is equivalent to the combined land area of South America and the European Union.

Much of this can be attributed directly or indirectly to fossil fuels. However, the full effects of fossil fuels may be even greater because the above calculation does not account for the pre-1961 yield increases from various fossil fuel–dependent technologies identified above. As indicated in Figure 3, the developed world had already captured some of these increases by 1960.

Clothing and Textiles. Until the late 19th century, all the clothing, garments and textiles used by mankind were made from the products of living nature, such as plant fiber (e.g., cotton, flax, jute), wool (from goats, sheep, and other livestock), skins, or silk. Synthetic fibers started to become commercial in the first few decades of the 20th century. Today, synthetic fibers such as polyester, nylon, vinyl, and acrylic account for about 60 percent of global fiber production.[42]

Polyester alone accounts for 80 percent of the global market share of synthetic fibers. Nylon, acrylic, and polyolefin (including polyethylene) account for another 18 percent of global synthetic fiber production by volume.[43] Each of these is produced from raw materials derived from petroleum products.

Because of the widespread use of synthetic fibers, skins and furs are widely regarded as outmoded, unfashionable, and unnecessary. This may be partly responsible for the rebound of beavers and other wildlife.

Cotton accounts for 78 percent of natural fibers.[44] However, the production of cotton, like that of other crops, depends heavily on fossil fuels. In addition to being an important consumer of fertilizers, cotton farming has traditionally been a major user of pesticides. For instance, the 6 percent of India's cropland that was devoted to cotton was responsible for 37 percent of its pesticide use.[45]

Based on 2001–03 data, Oerke estimates that because of pesticides, a potential global cotton crop loss of 82 percent was reduced to 29 percent.[46] The recent widespread adoption of genetically modified cotton that protects itself from plant pests is, however, likely to have reduced the use of pesticides on cotton.

To summarize, just as for food production, it would be impossible to sustain current quantities of production of clothing and other textiles without major additional conversion of habitat to cropland. No less important, for many uses such as water-resistance, insulation, and weight minimization, natural fibers are, for the same cost, inferior to synthetic fibers. For example, synthetic fibers have brought to the masses winter outerwear with properties that even the wealthiest could not afford a century ago.

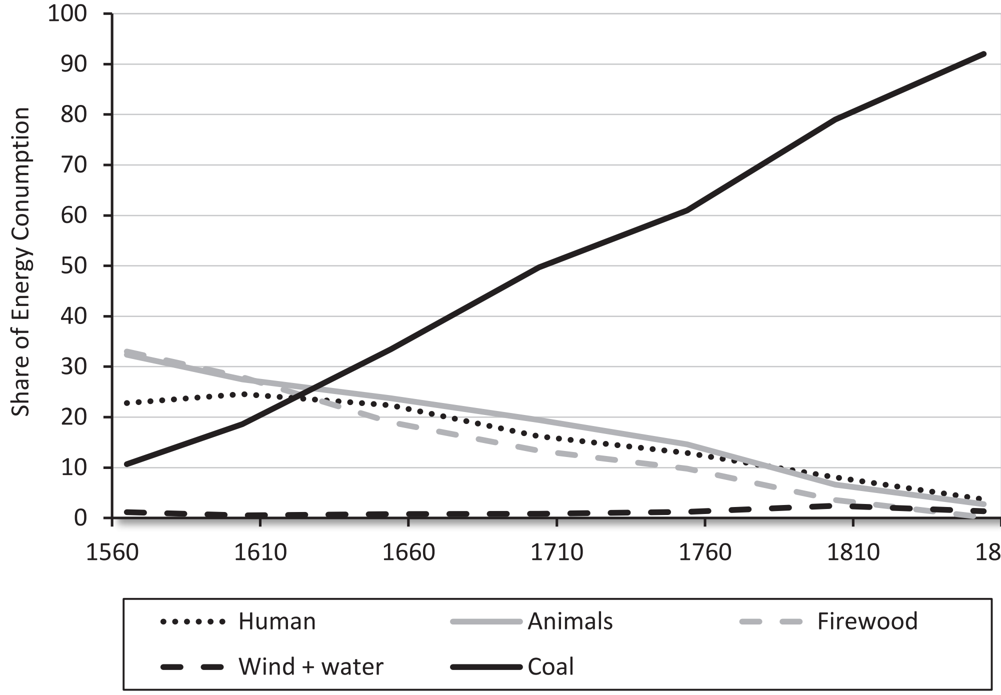
Fuel and Energy. Humanity's fuel and energy services were traditionally obtained from human power, animal power, and wood, supplemented in some places by water, wind, and geothermal power (e.g., Iceland).

Figure 6 shows the trend in energy consumption by source for England and Wales from the 1560s through the 1850s. In the 1560s, human power provided 23 percent of energy consumption; animal power, 32 percent; firewood, 33 percent; wind and water, 1 percent; and coal provided 11 percent of the total energy consumed. By the 1750s, the combined contribution of human and animal power had been halved to 28 percent, while coal's contribution had more than quintupled: by the 1860s, coal was responsible for over 90 percent of energy consumption. The share from wind and water was never very high for most places, if data for England and Wales are any guides. In the three centuries examined in the figure, their combined share never exceeded 3 percent of total energy consumption.[47]

England and Wales' turn to coal started in earnest in the late 16th century, long before the Industrial Revolution.[48] This turn commenced because the region was already suffering from a shortage of wood due to the demands of a growing population for wood

The share of energy from wind and water was never very high for most places. From 1560 to 1860, in England and Wales, their combined share never exceeded 3 percent of total energy consumption.

Figure 6
Contribution of Various Forms of Energy to Total Energy Consumption, England and Wales, 1561–70 to 1850–59



Source: E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010), p. 94.
Note: Based on averages for various decades.

Since the late 16th century, the mix of fuels has shifted from wood and human- and animal-based energy toward fossil fuels and, to a lesser extent, nuclear power.

for heating and cooking, timber, and wood charcoal, among other things.[49] Since then, the mix of fuels has shifted from wood and human- and animal-based energy toward fossil fuels and, to a lesser extent, nuclear power.

Other countries benefited from England's advances in coal-combustion technology and, over the centuries, followed suit, as illustrated for the United States in Figure 7.[50]

Figure 8 shows the contributions of "modern" energy sources to U.S. primary consumption from 1775 to 2009, which excludes the contributions of human and animal power. The split in 1850 was 7 percent for fossil fuels and 93 percent for non-fossil fuels.[51] Today, despite the government's heavy-handed intervention in the marketplace through subsidies and mandates designed to increase the share of renewable energy sources, the split is 81 to 19 in favor of fossil fuels. Since 11 of the 19 percent from non-fossil fuels are from nuclear energy, the current nonrenewables to renewables split is 92 to 8, almost exactly the reverse of the situation in 1850.[52]

These splits are similar to that for the world. According to the International Energy Agency, 81 percent of world's energy comes from fossil fuels, living nature provides 10 percent, 6 percent comes from nuclear, and the remainder comes from other renewables.[53] Thus, for both the United States and the world, energy use, for practical purposes, is synonymous with fossil fuels.

In the absence of fossil fuels, the world would have had to rely on renewables and/or nuclear. Renewables, however, are much more land-intensive, and any effort to increase their use would necessarily have involved massive conversion of land to energy generation.[54] The fact that currently the world relies primarily on fossil fuels rather than renewables, despite relatively generous subsidies and stringent mandates that favor the latter, indicates that renewables are not economically viable on larger scales.

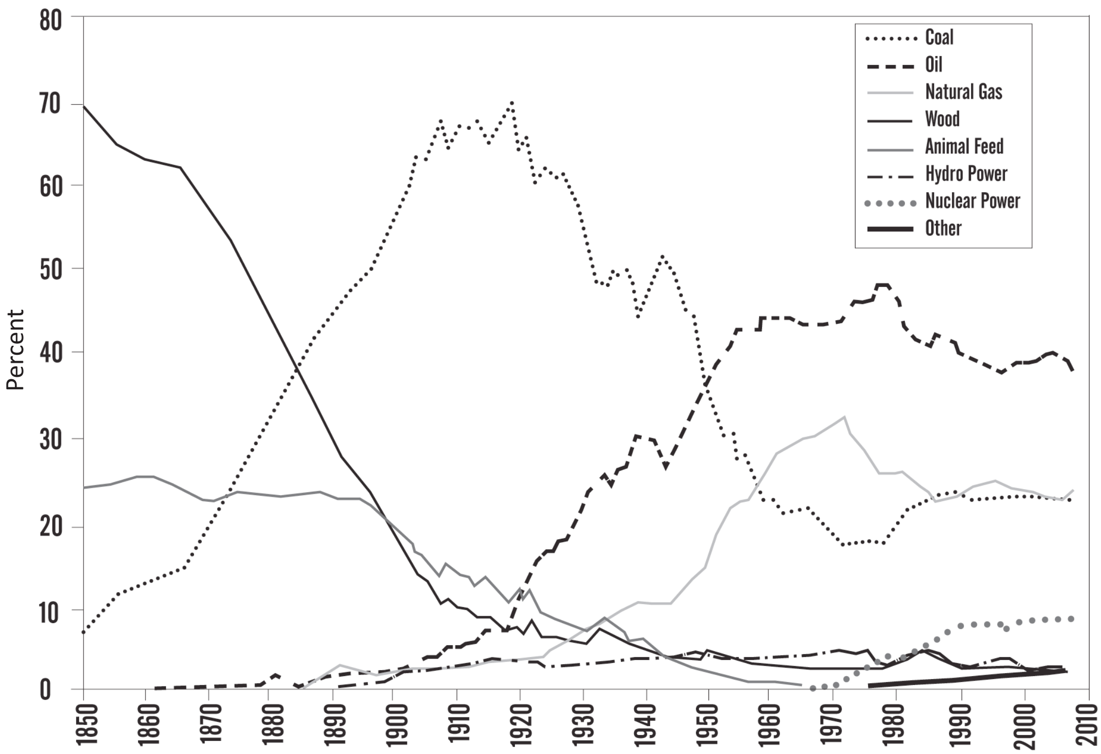
Based on the U.S. Energy Information Administration's 2011 study on subsidies for electrical generation,[55] the Institute for Energy Research calculates that in 2010, fossil fuels received a subsidy equivalent to $0.64 per megawatt-hour (MWh) of electricity produced, solar and wind received $776 and $56.3 per MWh, respectively, and nuclear received $3.14.[56]

Transportation and Other Work. A critical component of the energy sector is the energy used to transport people and goods, and to do other work in the home, on the farm, in industry, and elsewhere. Initially, human beings provided most of the energy for these activities. But once they figured out how to domesticate animals and harness their energy for such tasks, animals were conscripted to perform these tasks. One of the legacies of this period is the continued use of "horsepower" to rate the power output of various engines and machines, at least in the English-speaking world.

Although the use of animal energy for transportation and other work has, for the most part, been phased out in the industrialized world, it is still common in many developing countries. But it is being abandoned there as well, because it cannot compete against fossil-fuel driven internal combustion engines and electric powered devices. On farms and in cities, machines are displacing oxen, mules, and horses. Today, trucks

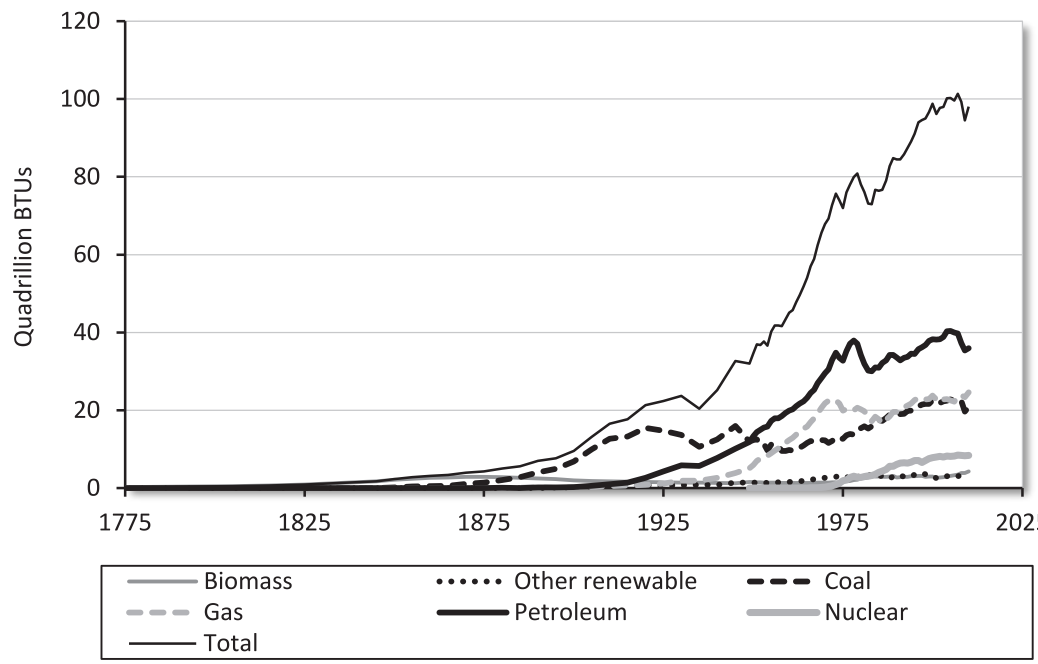
In the absence of fossil fuels, the world would have had to rely on renewables and/or nuclear. Renewables are much more land-intensive, and any effort to increase their use would necessarily have involved massive conversion of land to energy generation.

Figure 7
The Transition in the Composition of U.S. Energy Use Derived from Living Nature to Mainly Fossil Fuels, 1850–2008



Source: David I. Stern, *The Role of Energy in Economic Growth*, CCEP Working Paper 3.10, Center for Climate Economics and Policy, Crawford School of Economics and Government, Australian National University, Canberra, October 2010, p. 12.

Figure 8
U.S. Primary Energy Consumption, 1775–2010



Source: U.S. Energy Information Administration, *Annual Energy Review 2010*, Tables 1.3, 10.1, and E.1.
Note: This figure does not include estimates of energy provided by humans and animals.

From 1900 onward, the increasing use of materials by the United States indicates that it is correlated with carbon dioxide emissions and has increased along with the other indicators of progress.

and trains carry far more goods on the Silk Road, for instance, than camel caravans ever did. This has freed up land that would otherwise have had to be used to sustain and maintain the animals.[57]

More importantly, machinery and devices powered directly or indirectly by fossil fuels have advanced the well-being of children, women, the weak, and the disabled. Specifically, fossil fuel–powered machinery has reduced the value of child labor, helping make it obsolete in all but poor societies. And even these societies are reducing their levels of child labor. In low-income countries, it declined from 30 to 18 percent between 1960 and 2003. This has allowed children to be children and, equally significantly, they now have greater opportunity to attend school and be educated in preparation for a more fulfilling and productive life in a technologically more advanced society.[58]

Fossil fuels have also advanced equal opportunity for women and the disabled. Home appliances, powered for the most part by electricity, have reduced the time, tedium, and toil of the work that women traditionally did—and still do—in the home. In addition, power tools and machinery allow women, the disabled, and the weak to work at tasks that once would have been reserved, for practical purposes, for able-bodied men, which has expanded the former groups' economic opportunities.

Materials for Constructing and Fabricating Buildings and Worldly Goods. Materials, like food and fuel, are critical to humanity's well-being. Figure 9, which shows U.S. material use from 1900 onward, indicates that it is correlated with carbon dioxide emissions and has increased along with the other indicators of progress. In this figure, "materials" includes metals and minerals; synthetic and nonrenewable organic chemicals; cotton and other non-food agricultural materials; and paper, wood, and other forestry products. In 1900, a total of 144 million metric tons

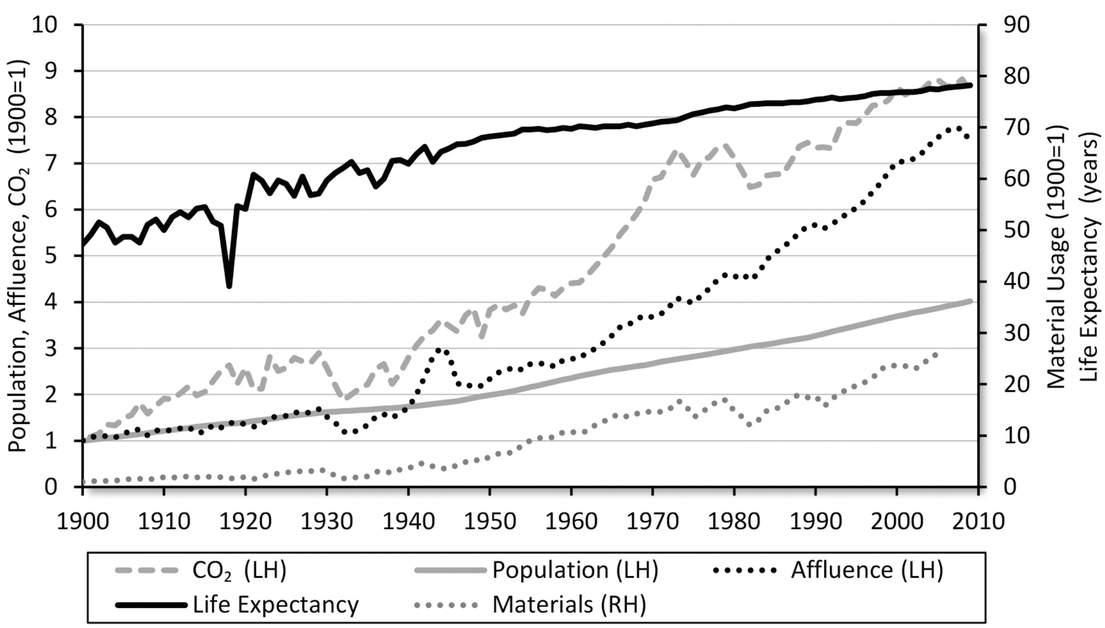
(MMT) of material was used to make products in the United States.[59] By 2006, material use had increased 26-fold to 3.8 billion metric tons (BMT). Fortunately for living nature, most of this increase was from nonrenewable sources, that is, materials derived from inorganic sources and fossil fuels.

Figure 10 indicates that materials from renewable sources (that is, agriculture and forestry) tripled over this period from 66 MMT to 188 MMT. By contrast, materials from nonrenewables registered a 46-fold increase from 78 MMT to 3.6 BMT. Consequently, the contribution of renewables to total materials decreased from 46 percent in 1900 to 5 percent in 2006 (from agriculture and forestry). Nonrenewable organic chemicals provided 4 percent of total materials, while 91 percent came from nonrenewable metals, industrial minerals, and construction materials.

The increase in the share of nonrenewables relative to renewables is due, first, to construction materials, such as cement, sand, gravel, and stone. Second, the use of metals and industrial minerals increased. Third, new materials, derived from petroleum feedstock, including vinyl, plastics, fiberglass insulation, and synthetic fibers, were developed. In addition, cement, iron, steel, and other inorganic mineral substances are often used today where previously wood might

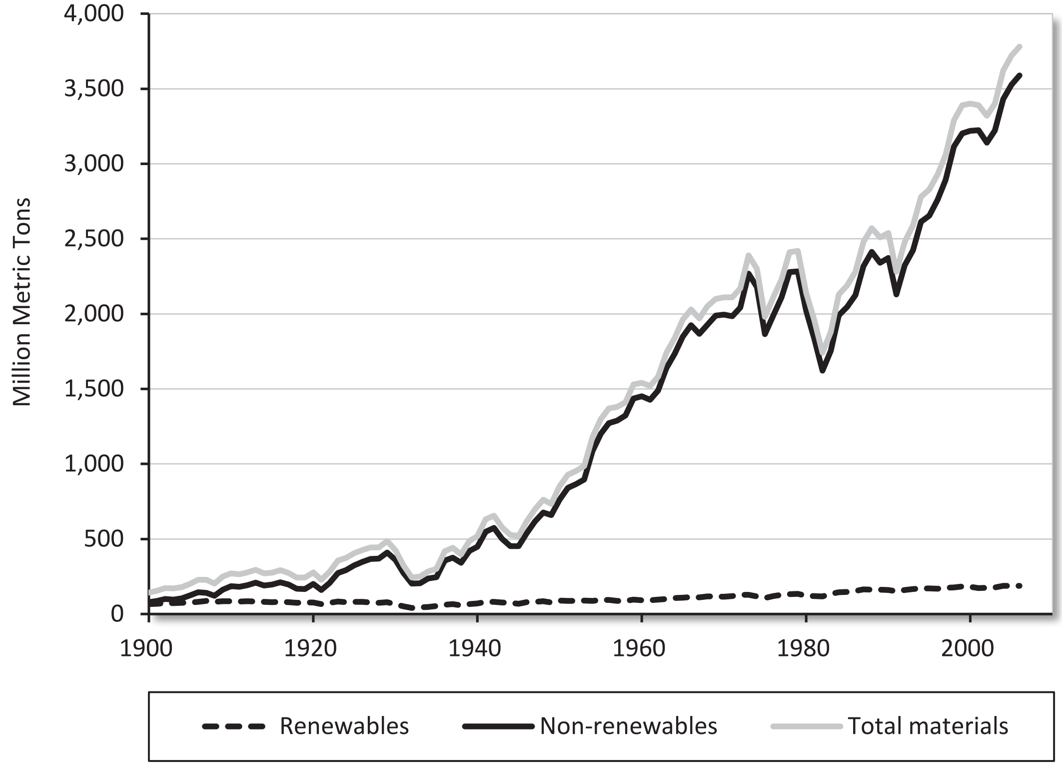
By 2006, material use had increased 26-fold to 3.8 billion metric tons (BMT). Fortunately for living nature, most of this increase was from nonrenewable sources.

Figure 9
Progress in Human Well-being, Living Standards, Material Use and Carbon Dioxide Emissions, U.S., 1900–2009



Sources: Updated from Indur Goklany "Have Increases in Population, Affluence and Technology Worsened Human and Environmental Well-being?" *Electronic Journal of Sustainable Development* 1, no. 3 (2009), using *the Statistical Abstract of the United States 2011*, and *National Vital Statistics Report* 59 (4): 1; based on Angus Maddison, *Statistics on World Population, GDP and Per Capita GDP, 1–2008 AD*, University of Groningen, 2010, http://www.ggdc.net/MADDISON/Historical_Statistics/vertical-file_02-2010.xls; Grecia R. Matos, *Use of Minerals and Materials in the United States From 1900 Through 2006*, U.S. Geological Survey Fact Sheet 2009-3008, http://pubs.usgs.gov/fs/2009/3008; World Bank, *World Development Indicators 2011*, http://databank.worldbank.org/; T. A. Boden, G. Marland, and R. J. Andres, *Global, Regional, and National Fossil-Fuel CO_2 Emissions*, http://cdiac.ornl.gov/trends/emis/overview_2008.html.
Note: Life expectancy is a surrogate for human well-being; living standards are depicted by affluence, or GDP per capita; and CO_2 is a proxy for fossil-fuel usage.

Figure 10
Renewable, Nonrenewable and Total Material Usage in the U.S., 1900–2006



Source: Grecia R. Matos, *Use of Minerals and Materials in the United States from 1900 through 2006*, U.S. Geological Survey Fact Sheet 2009-3008, http://pubs.usgs.gov/fs/2009/3008.

Regardless of whether materials are derived from renewable or nonrenewable sources, they cannot be used without energy inputs.

have been employed, for example, in houses and other structures. These developments have allowed humanity to limit its demand for timber and agricultural materials.[60]

More important, regardless of whether materials are derived from renewable or nonrenewable sources, they cannot be used without energy inputs. This is because no material can be extracted, refined, shaped, fabricated, manufactured, or processed in any fashion without the application of heat energy, mechanical energy, or both. Nor, for that matter, can any material be transported from where it is obtained, to where it is processed, to where it is used without energy.

Paper and paperboard, for example, account for almost half of all the renewable materials used in the United States.[61] But whether these products are made from virgin pulp or recycled material, they require large amounts of energy. On average it takes over 15,000 British Thermal Units (BTUs) to produce just one pound of paper, which makes the pulp and paperboard industry one of the most energy-intensive industries.[62] Not surprisingly, the five most energy-intensive industries are those that manufacture materials of one kind or another (see Table 2). But in today's world, as already noted, energy means fossil fuels.

Service and Government Sectors. Perhaps because people do not see tall chimney stacks billowing steam and smoke from the premises associated with the service and government sectors, it is a common misconception that they do not depend much on energy. But both sectors would grind to a halt without fossil fuels.

First, most workers, even in developing countries, go back and forth to work on

Table 2
The Most Energy-Intensive Industries in the United States

	BTU per pound
Ethylene	8,107
Iron and Steel	8,700
Ammonia	12,150
Paper and Paper Board	15,590
Aluminum (primary ingot)	44,711

Source: BCS, *U.S. Energy Requirements for Aluminum Production Historical Perspective, Theoretical Limits and Current Practices*, prepared for Industrial Technologies Program, Energy Efficiency and Renewable Energy, U.S. Department of Energy, http://www1.eere.energy.gov/industry/aluminum/pdfs/al_theoretical.pdf, p. 99.

some form of mechanized transportation. That requires fuel. Second, trade, transportation, and tourism—parts of the service sector—also need fuel to move goods and people. Third, the other segments of these sectors, including the information, finance, education, and government segments, would barely function without reliable electricity for lighting, computers, and telecommunications. The service and government sectors, like other sectors, also usually need heating in winter and air conditioning in summer. But all these depend on energy. And again, worldwide, energy, for practical purposes, means fossil fuels.

The Environmental Benefits of Using Fossil Fuels Rather than Living Nature

The collective demand for land to meet humanity's demands for food, fuel, and other products of living nature is—and always has been—the single most important threat to ecosystems and biodiversity.[63] Fossil fuel–dependent technologies have kept that demand for land in check. This positive aspect of the impact of fossil fuels on the environment has been ignored in most popular narratives, which instead emphasize fossil fuels' potential detrimental effects, including air, water, and solid-waste pollution, as well as any climate change associated with the use and production of these fuels. Because of this oversight, and thus lacking balance, these studies generally conclude that fossil fuels have been an environmental disaster.

To obtain a notion of the magnitude of the environmental benefits of fossil fuels, consider just the effect of fertilizers and pesticides on the amount of habitat saved from conversion to cropland because fossil fuels were used to meet current food demands. The Haber-Bosch process, by itself, is responsible for feeding 48 percent of global population and pesticides have reduced losses from pests for a range of food-related crops by 26–40 percent. Together, these two sets of technologies might therefore be responsible for feeding approximately 60 percent of the world's population, assuming that pesticides that are not manufactured with significant fossil fuel inputs would be half as effective as those that require fossil fuels. Therefore, had fossil fuels not been used, the world would have needed to increase the global amount of cropland by an additional 150 percent.[64]

This means that to maintain the current level of food production, at least another 2.3 billion hectares of habitat would have had to be converted to cropland. This is equivalent to the total land area of the United States,

Had fossil fuels not been used for agricultural production, the world would have needed to increase the global amount of cropland by an additional 150 percent.

Historian Edward Anthony Wrigley estimates that replacing coal in England and Wales in 1850 with wood would have required harvesting 150 percent of all their land.

Canada, and India combined. Considering the threats posed to ecosystems and biodiversity from the existing conversion of 1.5 billion hectares of habitat to cropland, the effect of increasing that to 3.8 billion hectares is inestimable.[65]

The above calculation underestimates the additional habitat that would have to be converted to cropland because it assumes that the additional 2 billion hectares of cropland would be as productive as the current 1.5 billion hectares—an unlikely proposition since the most productive areas are probably already under cultivation.

Moreover, even if the same level of production could have been maintained, eschewing the use of today's first-best technologies to produce fertilizers or pesticides would necessarily have meant higher food prices. That would have added to the 925 million people that the Food and Agriculture Organization (FAO) estimates are already chronically hungry worldwide.[66] Thus, fossil fuels have averted a disaster for both humanity and the rest of nature.

The movement away from wood, human and animal power, and other renewable energy sources to fossil fuels has also resulted in substantial environmental benefits. An estimated 27 percent of the land harvested in the United States for crops in 1910, for example, was devoted to feeding the 27.5 million horses and mules used on and off the farm. Had the horse and mule population in the United States expanded in proportion to the human population and crop yields stayed constant, an additional 319 million additional acres would have been needed in 1988 just to feed the additional livestock. This would have exceeded the amount of cropland that was harvested in 1988 (about 297 million acres).[67] In fact, phasing out animal power has been among the major reasons why the extent of cropland planted in the United States has not expanded since 1910, despite government subsidies to overcultivate crops.[68] Clearly, fossil fuel–based substitutes for animal power have substantially reduced pressures on habitat and ecosystems in the United States over what they would otherwise have been.[69] This should also be true for much of the rest of the rest of the world today.

The above estimates understate the reduction in habitat conversion that is the result of fossil fuel's virtual phase-out of animal power in much of the world because the assumption that it would grow in proportion to the human population ignores the fact that energy use has, in fact, grown much more rapidly (see, for instance, Figure 7). Thus, they do not include estimates of the additional land that would have to be commandeered if fossil fuels were to be replaced by renewable sources of energy and materials using current technologies had energy use stayed constant.

Historian Edward Anthony Wrigley estimates that replacing coal in England and Wales in 1850 with wood would have required harvesting 150 percent of all their land.[70] Because fossil fuel energy use is much higher today, the situation would be even worse now, if that is conceivable.

Because habitat is critical for maintaining and conserving species and ecosystems, these environmental benefits of fossil fuel–dependent technologies most likely have outweighed their environmental costs resulting from their emissions of air, water, and solid waste.[71]

In addition, the environmental damages from converting habitat to cropland is likely to be more lasting and less easily reversed than the damages from air, water, and solid-waste pollution. As the experience of the industrialized world indicates, these damages from fossil fuel combustion can be reversed at relatively reasonable cost. Moreover, if the environmental transition hypothesis is valid, because of the wealth generated from the economic surpluses from the use of fossil fuels, the probability of such reversals is increased.[72]

This hypothesis postulates that initially societies opt for economic and technological development over environmental quality because it enables them to escape from poverty and improve their quality of life by making both needs and wants (e.g., food, education, health, homes, comfort, leisure, and material goods) more affordable. But once basic needs are met, over time members of society perceive that environmental deterioration compromises their quality of life and they start to address their environmental problems. Being wealthier and having access to greater human capital, they are now better able to afford and employ cleaner technologies. Consequently, environmental deterioration can be halted and then reversed. Under this hypothesis, technological change and economic development may initially be the causes of negative environmental effects, but eventually they work together to effect an "environmental transition," after which technological change and economic development become the solutions to reducing these effects.[73]

Finally, note that despite claims that carbon-induced climate change would be detrimental to human well-being, there is no empirical evidence that higher carbon emissions have reduced global well-being or living standards in aggregate. In fact, Figures 4 and 5 suggest precisely the opposite. Human well-being and living standards have gone up remarkably even as these emissions have increased by orders of magnitude. Claims that global warming may already be responsible for killing over 150,000 people per year are based on a study whose very authors acknowledge that their methodology did not "accord with the canons of empirical science [because] it would not provide the timely information needed to inform current policy decisions on [greenhouse gas] emission abatement, so as to offset possible health consequences in the future."[74] That is, the authors sacrificed scientific quality to a policy agenda.

Empirical data also falsify other claims regarding the alleged grisly consequences of global warming, that is, that deaths and economic damages from extreme weather events will escalate, malaria will expand, or crop yields will decline and increase hunger. Specifically, empirical data show:

- Global death rates from extreme weather events declined by 98 percent since the 1920s, while economic damages corrected for population growth and wealth have not increased;[75]
- Malaria death rates were reduced by 26 percent from 2000 to 2010[76]; and
- Global crop yields increased by 160 percent since 1961.[77]

Notwithstanding their flaws, the fossil fuel–dependent technologies that stretched living nature's natural productivity and displaced some of its products not only permitted humanity to escape the Malthusian vise, but saved nature itself from being overwhelmed by humanity's demands.

Reduction in the Vulnerability of Society to Climate and Weather

Another inevitable consequence of reducing humanity's dependence on nature and relying instead on fossil fuels and inorganic materials is that climate and weather are no longer critical to humanity's well-being.

No human activities are more sensitive to climate and weather than agriculture and forestry. Agriculture, by itself, was mankind's major economic activity until the Industrial Revolution. But because of economic and technological development and the growth of the service sector—driven in large part by greater energy use underwritten mainly by fossil fuels—this is no longer the case.

In 1800, about 80–90 percent of the U.S. working population was engaged in agriculture. This had dropped to 41 percent by 1900, 16 percent by 1945, and today it is 1.5 percent.[78] This shrinkage occurred despite the increase in agricultural production because other sectors grew more rapidly. In 1900, agriculture accounted for 23 percent of U.S. gross domestic product; today it accounts for 0.7 percent.[79]

There is no empirical evidence that higher carbon emissions have reduced global well-being or living standards in aggregate. In fact, data suggest precisely the opposite.

Table 3
Reduction in Global Vulnerability to Climate and Weather
(indicated by agriculture's declining share of the economic pie for various income groups, 1980–2008)

Income Group (by percent)	Agricultural Sector's Share of GDP	
	1980	2008
Low-income countries	37.6	25.4
Medium-income countries	20.3	9.5
High-income countries	4.0	1.5
World	6.6	2.9

Source: World Bank, *World Development Indicators 2011*, http://databank.worldbank.org/.

Humanity's reduced susceptibility to weather and climate is confirmed by the long-term decline in aggregate global mortality from extreme weather events, including droughts, extreme heat and cold, floods, landslides, waves, wildfires, and storms of all kinds.

Thus, the United States has become much less dependent on—and, therefore, less vulnerable to—the climate and weather for its well-being. By the same token, climate change, which should be distinguished from "climate," is itself of lesser importance. This is also true worldwide: the same dynamic is operating in other countries. Table 3 shows that agriculture's share of gross global product is declining worldwide and for every income group.[80] That is, the world has become more immune to climate and weather.

Other fossil fuel–dependent factors have accelerated these trends. In particular, the increase in trade in agricultural products means that if an area experiences a shortfall of food, either because its productivity has always been low or it has been depressed because of weather (or manmade events such as poor agricultural policies or conflict), food shortfalls can be made up via trade.[81]

The same factors have also reduced the economic significance of the forestry sector. Currently, about 0.4 percent of the world's labor force and 1 percent of global economic product depends on forestry.[82]

Humanity's reduced susceptibility to weather and climate is confirmed by the long-term decline in aggregate global mortality from extreme weather events, including droughts, extreme heat and cold, floods, landslides, waves, wildfires, and storms of all kinds (e.g., hurricanes, cyclones, tornados, and typhoons). Despite much more complete reporting of such events and associated casualties, aggregate mortality declined by 93 percent since the 1920s.[83]

These reductions were mainly due to fewer deaths from droughts, which accounted for almost 60 percent of the deaths from all extreme weather events recorded globally from 1900 to 2010 and, to a lesser extent, from floods (which accounted for 34 percent) and storms (which accounted for 7 percent). Fossil fuels were critical to these reductions.[84] Specifically, deaths from droughts were reduced by 99.98 percent since the 1920s because thanks to fossil fuels the food and agricultural system produced more food and improved its ability to transport and distribute this food rapidly and in large quantities.[85]

Another important factor, common to all categories of extreme weather events, is better disaster preparedness and more rapid response and delivery of humanitarian aid when disaster strikes. Timely preparations and response are major factors in the reduction in death and disease that traditionally were caused by or accompanied natural disasters. Success (or failure) hinges on the availability of fossil fuels to move out people who are at risk while moving in emergency responders, food, medicine, and other critical humanitarian supplies before and after disasters. Maintaining reliable communications, which depends mainly on electricity, is another critical element of disaster response. This has been aided by improved meteorological forecasts, which rely on electricity-powered communication systems for dissemination.[86] Another critical factor for reducing casualties is the availability of energy-intensive technologies such as air conditioning and heating that allow people to cope with excessive heat and cold.

Economic development, itself dependent on fossil fuels, also allowed the United States and other developed countries to accumulate assets such as helicopters, planes, and trucks with which to mount disaster-relief efforts and offer humanitarian aid to developing countries in times of famine, drought, floods, cyclones, and other natural disasters, weather-related or not. Such aid would have been virtually impossible to deliver in large quantities or in a timely fashion absent fossil fuel–fired transportation.[87]

In fact, it is inconceivable that a successful and timely disaster-management effort can be mounted today without diesel generators; petroleum-powered helicopters, trucks, earth-moving equipment and other vehicles; heavy-duty tents made of lightweight petroleum-derived synthetic fibers for temporary shelters and hospitals; and myriad other items needed for disaster relief that depend directly or indirectly on fossil fuels.

How Did the World Escape the Malthusian Vise?

Figure 4 shows that the increased use of fossil fuel–dependent technologies paralleled humanity's progress and its escape from nature's Malthusian trap, while Figure 5 illustrates a similar story for the United States.

The improvements in human well-being in industrialized countries over the last quarter millennium and in developing countries since World War II can be ascribed to the mutually reinforcing, co-evolving forces of economic growth, technological change, human capital, and freer trade, which push and pull each other in a "cycle of progress."[88]

Figure 11 is a simplified depiction of this cycle. It shows some of the ways these forces interact with and reinforce each other and how they advance food supplies and public health. Within this cycle are other cycles, like wheels within wheels. For example, health begets wealth, and vice versa. Other coupled cycles consist of health and human capital, wealth and technology, and wealth and trade.

Since this is a cycle, it has no real beginning or end, but perhaps the first portion of this cycle that coalesced was the slow accumulation of human knowledge (capital), which led to technologies that increased both land conversion and crop yields. These, coupled with trade, increased food supplies, which in turn improved health. Since a healthier (and less hungry) population is generally more productive in whatever activity it undertakes, it became wealthier, which then helped further boost human capital. A healthier population also is generally better educated and better trained, which too increases human capital. The cycle, thus, came full circle.

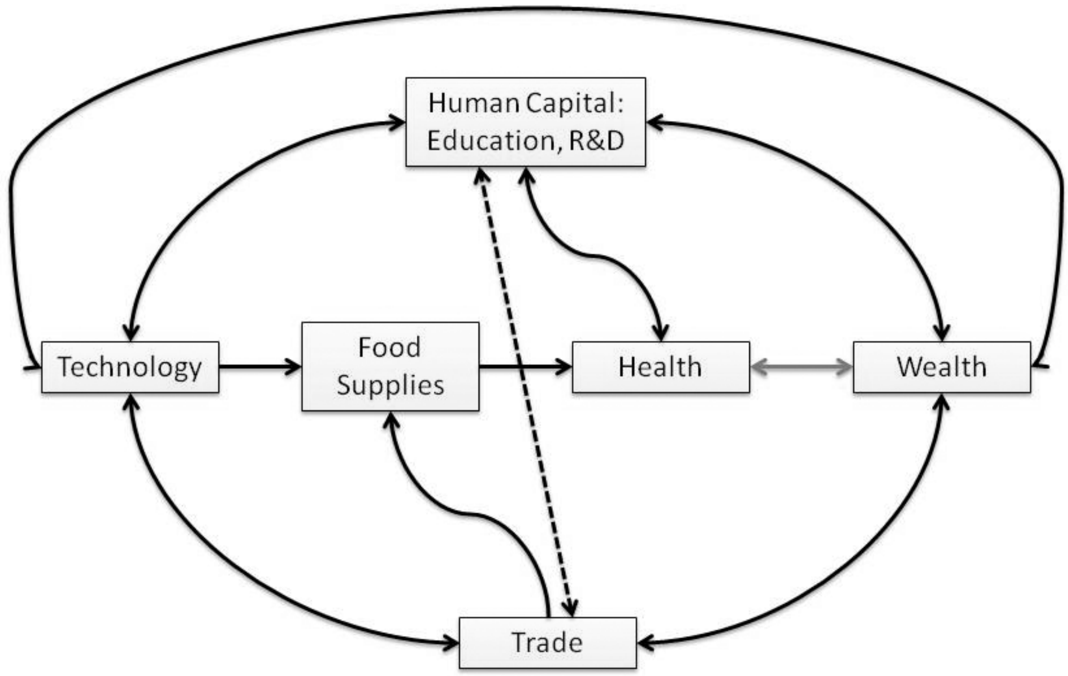
As indicated by Figures 1 and 4, fossil fuels did not start this cycle rolling, but they accelerated its progress. Today, continued progress depends on fossil fuels. Specifically, as shown above, current levels of economic activity (the proximate source of wealth), food supplies, trade, and public health—individual parts of the cycle—could not be sustained without fossil fuels.

The cycle of progress has many features identified by economists and social observers, including Charles Jones, Paul Romer, and Matt Ridley, who ascribe economic growth in general—and humanity's escape from Malthusian constraints in particular—to the growth of ideas that then spawned the necessary technologies.[89]

Jones and Romer contend that, over time, with the accretion of knowledge, human capital advanced, ideas were born, and technology advanced. This led to larger popula-

Current levels of economic activity (the proximate source of wealth), food supplies, trade, and public health—individual parts of the cycle—could not be sustained without fossil fuels.

Figure 11
The Cycle of Progress



Source: Adapted from Indur Goklany, *The Improving State of the World* (Washington: Cato Institute, 2007), pp. 91–92.
Note: This schematic illustrates how the forces of economic growth, human capital and technology interact with trade to advance food supplies and public health, and reinforce each other. Some linkages, e.g., the linkage between technology and health, are not shown. Some linkages are one-way; others are two-way. Two-way linkages indicate a subcycle.

Not only are biofuels unable to pay for themselves (hence the subsidies and mandates), but these subsidies and mandates have helped increase food prices, which has added to hunger and poverty worldwide.

tions, but more people also resulted in more ideas, which led to further technological change. At a certain point, it became possible for technologies to increase living standards despite resource constraints. These arguments had been around at least since Simon Kuznets in 1960 and Julian Simon in the 1970s.[90] But economic models capable of capturing these features adequately are of more recent vintage.[91]

Note that although the cycle depicted in Figure 11 does not explicitly have boxes for "ideas" or "population," they are implicit in the "technology" and "human capital" boxes.

The development of human capital was aided by the demographic transition, in which households traded off quantity of children in favor of quality; that is, they preferred to build their progeny's human capital.[92] In addition, the extent and speed of communication accelerated the quantity and rate at which knowledge and ideas can be exchanged, which then leads to more and faster generation of ideas and technologies.[93]

But ideas are not enough. They need to be translated into practical technologies that are adopted and used, and can be sustained in the marketplace. Equally important, for every "good" idea there is at least one or more "bad" ideas. For example, a spectacularly bad idea is that the state should control the means of production. Yet, despite access to significant levels of human capital, some societies have tried to implement this bad idea.

Yet another bad idea is providing subsidies for, and directly or indirectly mandating, the use of biofuels to replace fossil fuels. Not only are biofuels unable to pay for themselves (hence the subsidies and mandates), but these subsidies and mandates have helped increase food prices, which has added to hunger and poverty worldwide and increased the population at risk of death and disease.[94] Moreover it is debatable whether biofuels can deliver net environmental benefits.[95] A recent study by the U.S. National Research Council reaffirmed this, while noting that biofuels are also unlikely to be economically viable alternatives to gasoline, absent high oil prices, technological breakthroughs, and high carbon prices.[96]

Then there are ideas that do not pan out. Thomas A. Edison, for instance, is reputed to have tried 1,600 materials for the filament of the incandescent light bulb before alighting on carbonized bamboo.[97] That is, the vast majority of his ideas misfired. It would be another quarter of a century before the tungsten filament would be commercialized (and not by Edison).

Another great idea, championed by both Henry Ford and Edison (apparently, until they saw the light), that has not panned out so far is the electric automobile.[98] In the late 1800s and early 1900s, it seemed that the electric vehicle might be the favored replacement for the horse-drawn carriage and its associated excreta that fouled the urban landscape, but it lost out in the marketplace to the petrol-powered internal combustion engine.[99] Today, despite substantial subsidies, the electric automobile is unable to grab significant market share.

In the United States, notwithstanding direct federal subsidies of $7,500 per car (and indirect subsidies in the range of $250,000 per car), electric cars eked out a market share of 0.014 percent in 2011.[100] Similarly, in the United Kingdom, fewer than 800 electric vehicles were sold in the first nine months of 2011, despite a government subsidy of £5,000 each (equivalent to $8,000), which brought total electric vehicle registrations in that country to 1,107 out of 28.5 million cars on the road.[101]

Just as wishes cannot conjure real horses, ideas by themselves do not physically transport people. Remarkably, another failed competitor for fueling the replacement to the horse-drawn carriage was grain alcohol (ethanol). Today, despite subsidies, it remains uncompetitive on its own merits in most areas.[102]

Among the reasons why England was the among the first countries to surmount Malthusian barriers was that it had developed, perhaps through luck, a set of institutions that gave individuals a stake (or property right) in developing their ideas into useful and practical inventions. Equally important, to a greater extent than other countries, it relied on the institution of the marketplace to sort through which ideas were viable, paid for themselves, and were, therefore, self-sustaining.

By contrast, the marketplace was missing in the communist Soviet Union. Hence, despite its emphasis on developing science and technology and having abundant human capital, including some of the world's best mathematicians and theoretical scientists, its innovation and rate of economic growth lagged that of societies with freer and more open markets. The competitive marketplace also helped bring down the price of viable technologies, which led to their greater dissemination.

Complementing the economic marketplace was the development and application of the scientific method, founded on empirical verification, for analyzing and solving problems. Such prior empirical verification of ideas/technologies should have reduced the failure rate of newly introduced ideas and products in the marketplace.

How Fossil Fuels Accelerated the Production of Knowledge and Ideas

Fossil fuels have been critical for the technologies that allowed humanity's numbers to increase and its well-being and living standards to advance. But technologies are born from ideas, and fossil fuels have helped increase the quantity and quality of ideas.

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The role of cheap illumination in enhancing human capital cannot be overestimated. Illumination has given human beings something that even the gods didn't provide: it—with apologies to Albert Einstein—"expanded" time.

Population. Without fossil fuels, there would be insufficient food. As a result, the population would be in poorer health, smaller, or both. If lower food production translates into fewer people, then the world would necessarily have fewer ideas. This means less, or inferior, technology.

The connection between population and ideas seems intuitive. It is captured in that old adage, "two heads are better than one," but empirical evidence supporting this idea is difficult to come by. University of California–Los Angeles anthropologists Michelle Kline and Robert Boyd have found evidence of this connection in a novel examination of a "natural experiment" in Oceania. They analyzed marine foraging toolkits for 10 island groups and found that groups with larger populations had more complex and diverse tool kits. Malekula, the smallest island (population 1,100), had 13 total tools, while Hawaii, the largest (population 275,000) had 71.[103]

Better Health and Greater Life Expectancy. If, instead of reducing the population level, less food were to result in poorer health, that would compromise the ability to acquire and retain knowledge and training. Human capital per capita would be lowered, which, in turn, would also reduce the quality of its ideas.

Better health also translates generally into higher life expectancy, which in and of itself promotes the formation of human capital. Considering that many current candidates for advanced degrees and post-doctoral positions are in their 20s and, in some cases, their 30s and even 50s,[104] had life expectancy not increased—globally it was 25 years in 1750 and 31 years in 1900—there would have been many fewer highly educated and trained people to add to the global stock of knowledge and to train subsequent generations. Moreover, when lifespans are short, it makes less sense for either the individual or society to invest in educating the young and postponing their contribution to society, rather than putting them to work as soon as practicable. After all, the dead cannot produce, no matter how well educated they might become. Thus, higher life expectancy, a consequence of better health, advances human capital and enhances human knowledge, which then generates new ideas and technologies.[105]

Lighting. After "peak wood"—that is, the point of resource depletion where wood became increasingly unavailable and costly—but long before the notion of "peak oil" became fashionable, and even before petroleum was discovered, the world was confronting "peak blubber." Whale blubber was the fuel of choice for illumination, but whale hunting had taken its toll on their numbers and the world was running out of this precious commodity.[106] The poor had to make do with tallow candles.

Kerosene from petroleum saved the day, for both rich and poor. Today, illumination worldwide depends more on relatively cheap fossil fuel–generated electricity than any other source. In fact, the price of illumination has never been lower. In 1800 in the United Kingdom, it took the average worker six hours of labor to buy an hour of lighting from the use of a tallow candle.[107] That is, after 12 hours of labor, the average worker would have been able to afford all of two hours of lighting, with nothing left over for anything else! Today it takes half a second of work to get the same amount of illumination using a compact fluorescent bulb.[108] Lighting went from luxury to ubiquity, at least in the industrialized countries. But it remains an extravagance in impoverished areas around the world.

The role of cheap illumination in enhancing human capital cannot be overestimated. Illumination has given human beings something that even the gods didn't provide: it—with apologies to Albert Einstein—"expanded" time; that is, it has given us more time to read, learn, and be creative and productive, if we choose.

In recognition of its effects on productivity, most commercial and industrial establishments, as well as libraries, classrooms, and many laboratories, light up their premises regardless of the time of day. Not surprisingly, lighting accounts for a significant share of the U.S. electricity bill: 14 percent for the residential sector and 22 percent for the commercial sector.[109]

Mechanical Power. It's insufficient to have time to acquire human capital, if a person lacks the physical energy to do so efficiently and effectively.

Before the Industrial Revolution, much of the work done on the farm and in manufactories at home, in shops, and in industrial settings, required physical labor. (The origin of the term, "manufacture," itself reveals that it originally required human labor by hand.[110]) Even where animal power was used, a person usually had to manage and direct the animal's energy. Consequently, people generally lacked the time and energy for tasks much beyond making ends meet.

This changed with the advent of machinery and, later, home appliances powered directly or indirectly by fossil fuels. If not for such home appliances, powered for the most part by electricity, more women would be toiling for longer hours in the home. Most of these technologies would have been stillborn or available only to the wealthy, had relatively cheap fossil fuels been unavailable. These appliances include air conditioning, hot and cold running water, vacuum cleaners, dishwashers, and washing machines.

These devices have opened up options for women that seemed absent as recently as a few decades ago, in even the wealthiest countries, particularly for the less well-to-do. In effect, women's liberation was midwifed by fossil fuels. As a result, women—and their families—have even greater incentive to develop their human capital. Today, more women go on to college and graduate than men in the United States. Currently, women earn 57 percent of bachelor's, 62 percent of master's, and 52 percent of doctoral degrees.[111] Therefore, much of this human capital would be lost to mankind were relatively cheap fossil fuels not available.

As noted, power tools and machinery have leveled the playing field for women, the disabled, and the weak, enabling them to work on many tasks that were once the domain of able-bodied men. They have also reduced the value of child labor, which is helping make that practice obsolete, except in poor countries where much of the population lacks economic access to such devices. While child labor has declined, the number of children attending school has increased, adding further to the stock of human capital.[112]

Trade. Without relatively cheap fossil fuels, the volume and speed with which goods are traded would be much lower. But trade is one of the fastest methods of disseminating technologies. Introducing new technologies to new places also helps generates new ideas. Or, as Matt Ridley has noted, ideas have "sex," which then propagates new ideas.[113]

Absent trade, such devices as personal computers, notebooks, and cell phones may not have been available outside of a handful of industrialized countries, and their prices would have been higher everywhere. This would translate into lower human capital per capita. These products also contain substantial amounts of polycarbonate and other petroleum-based plastics.[114]

The simplification of Tasmania's toolkit after its isolation from Australia as the result of sea-level rise 10,000 years ago hints at the importance of trade.[115] Kline and Boyd's natural experiment in Oceania also found that island groups that had more contact—that is, more trade—also had more tools.[116] Trade, in effect, increases the size of the population and human capital from which a society may access ideas and technologies. For instance, because of trade, India's population can, and does, draw upon ideas and technologies generated in the United States, and vice versa.

Trade also encourages specialization, which advances human capital. However, if there is too much specialization and trade (for whatever reason) is then discontinued, that could lead to technological regression. Perhaps that, too, contributed to Tasmania's technological regression.

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Communications. The speed and extent of communications are among the stron-

The speed and extent of communications are among the strongest determinants of the rate of generation of ideas. The major methods of communication over the past few decades all currently depend on fossil–fuel energy.

gest determinants of the rate of generation of ideas. The major methods of communication over the past few decades, and which are still in broad use (e.g., travel, newspapers, telephones, cell phones, television, the Internet) all currently depend to one degree or another on fossil–fuel energy.

Newspapers, for example, are still printed on paper for dissemination. The pulp and paper industry is the second-most energy intensive (Table 2), and despite having ready access to wood, it supplements its energy needs with fossil fuels and electricity (most of which is also from fossil fuels).[117] Television and the Internet all rely on cheap electricity, mainly derived from fossil fuels. Moreover, televisions and the tangible objects at the interface of the Internet and the user (e.g., personal computers, laptops, even cell phones) contain substantial amounts of plastic, which are petroleum-derived products.

Detailed analysis of the total energy and fossil fuels used to produce a vintage-2000 desktop computer with a 17-inch cathode-ray-tube monitor indicates that computer manufacturing is much more energy intensive than generally recognized. The amount of fossil fuel required to manufacture this desktop system is estimated at 11 times its weight. By comparison, this ratio is 1:2 for automobiles, 2 for refrigerators, and 4:5 for aluminum cans.[118]

According to a 2007 estimate, the global information and communications technology industry accounts for approximately 2 percent of global carbon dioxide emissions, which is equivalent to aviation.[119] In 2010, data centers (for servers) alone accounted for 1.3 percent of all electricity use for the world and 2 percent of all electricity use for the United States.[120]

Comfort. Personal comfort is another factor that helps develop human capital. Without adequate heating in the winter and cooling in the summer (and appropriate clothing, most likely containing synthetic fibers to one extent or another), productivity would be compromised. Not surprisingly, where societies can afford it and weather makes it necessary, educational establishments and homes consume substantial energy to maintain premises at comfortable levels.

Conclusion

Until the last quarter of a millennium, mankind depended on living nature for all its food and clothing, most of its energy, and much of its material and medicines. She dictated mankind's numbers, well-being, and living standards. But she has never been constant. She would smile on some, but not on others. Her smiles, always temporary, would inevitably be replaced by frowns. Her Malthusian checks—hunger, famine, disease, or conflict—ensured that there was little or no progress in the human condition. Many people did not even survive into their 20s, populations grew very slowly, and living standards were generally constrained to subsistence levels.

Gradually, with the accumulation of human capital, exchange of ideas, and hard work, mankind started to commandeer more land to meet its needs and develop technologies that, in some cases, amplified Nature's bounty but, in other cases, bypassed her altogether. These led to higher food production, better health, longer lifespans, and larger populations with better living standards, which then reinforced human capital and the exchange of ideas, which begat yet more and better technologies. Thus was the cycle of progress born and set in motion.

The cycle had been moving forward in fits and starts before fossil fuels—ancient nature's bequest to humanity—became ubiquitous.[121] But fossil fuels assured progress. The cycle accelerated. Mankind's dependence on nature declined. It became less vulnerable to weather, climate, disease, and other sources of natural disasters. The Malthusian bonds that held mankind and its well-being in check started to stretch, until they were burst asunder.

Today, fossil fuels are responsible for at least 60 percent of mankind's food. They also provide 81 percent of mankind's energy supply, while nature supplies only 10 percent. Sixty percent of the fiber used globally for clothing and other textiles are synthetic, coming mainly from fossil fuels. Much (thirty percent) of the remaining—so-called natural fiber, relies heavily on fossil fuel–based fertilizers and pesticides. With respect to materials, although global estimates are unavailable, nature provides only 5 percent of U.S. materials (by weight). But even this 5 percent, just like the remaining 95 percent, cannot be processed, transported and used without energy inputs.

Without fossil fuels, humanity would be unable to feed itself, and what food there was would be costlier. There would be more hunger. There would be insufficient energy and materials available to sustain the economy at more than a fraction of its current level. Public health would suffer, living standards would plummet, human well-being would be drastically diminished, and the population would crash.

In the absence of the technologies that depend directly or indirectly on fossil fuels, humanity would have had to expand cropland by another 150 percent to meet the current demand for food. Even more land would have had to be annexed to satisfy existing requirements for energy, materials, clothing, and other textiles using nature's products.

Not only have these fossil fuel–dependent technologies ensured that humanity's progress and well-being are no longer hostage to nature's whims, but they saved nature herself from being devastated by the demands of a rapidly expanding and increasingly voracious human population.

Progress today depends on technological change; economic development; trade in goods, services and ideas; and human capital. But technology is the product of ideas, and fossil fuels have been vital for the generation of ideas. Specifically, fossil fuels have helped give us—and not just the rich amongst us—illumination, which expands our time; machines that preserve our level of energy; better health and longer life expectancies; faster and more voluminous trade in goods and ideas; more rapid communications within a wider network; and a much larger population. Reinforcing each other, they increased the stock of human capital and created more opportunities for exchanging ideas, which spawned even more ideas and technologies. And today humanity's numbers, well-being, and living standards have never been higher.

In summary, although fossil fuels did not initiate the cycle of progress and are imperfect, they are critical for maintaining the current level of progress. It may be possible to replace fossil fuels in the future. Nuclear energy is waiting in the wings but, as the high subsidies and mandates for renewables attest, renewables are unable to sustain themselves today. Perhaps, with help from fossil fuels, new ideas will foster technologies that will enable a natural transition away from such fuels.

Progress today depends on technological change; economic development; trade in goods, services and ideas; and human capital. But technology is the product of ideas, and fossil fuels have been vital for the the generation of ideas.

Notes

1. See, for example, E. A. Wrigley, *Energy and the English Industrial Revolution* (Cambridge: Cambridge University Press, 2010). I prefer the term "living nature" over "organic economy" because the former distinguishes the recent products of life in nature from those of "ancient nature." In particular, fossil fuels, which are also organic in origin, are mainly products of an ancient nature. See Indur M. Goklany, "Batteries from the Carboniferous," *Watt's Up With That?*, September 2, 2011, http://wattsupwiththat.com/2011/09/02/batteries-from-the-carboniferous/.

2. See, for example, Gregory Clark, *A Farewell to Alms: A Brief Economic History of the World* (Princeton: Princeton University Press, 2007), p. 94.

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