The Economic Growth Engine

How Energy and Work Drive Material Prosperity

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Preface and acknowledgments

This book has had a very long gestation. The senior author (R.U.A.) has spent much of his time during the last 40 years or more – amidst numerous distractions – trying to understand the fundamental relationship between technology and economics. Some of that history is recapitulated in the book. However, the author's learning experience during a year at Resources for the Future, Inc. (RFF) during 1967–8 was crucial. In particular, it was a line of research initiated by Allen V. Kneese at RFF that has led us finally to this point. It was during that period that the senior author began to see that the economy is truly a physical system that converts raw materials into goods and services, subject to the laws of thermodynamics. It has taken most of the rest of the time since 1968 to understand how and why our conceptualization is inconsistent with standard neoclassical economic theory. Enlightenment has been very slow in coming, and even now it would be foolish to claim 'Eureka!' But since the two of us joined forces in 2001, we have made some progress – enough, we think, to warrant publication of some results.

During the past decade we have received valuable intellectual stimulation from discussions with a number of persons deserving special thanks, including (in alphabetical order) Kenneth Arrow, Christian Azar, Jeroen van den Bergh, Jonathan Cave, Paul David, Nina Eisenmenger, Karl-Erik Erickson, Marina Fischer-Kowalski, Arnulf Gruebler, Andrey Krasovskii, Reiner Kuemmel, Katalin Martinàs, Nebojsa Nakicenovic, Shunsuke Mori, Adam Rose, Warren Sanderson, Heinz Schandl, Leo Schrattenholzer, Gerry Silverberg, David Simpson, Alexander Tarasyev, David Toman, Chihiro Watanabe and Eric Williams. None of them is responsible for any errors or misunderstandings on our part.

The collection, compilation (and occasional correction) of the US and Japanese exergy/work database that underlies Chapters 3, 4 and 7 is primarily due to Leslie W. Ayres. Ms Ayres has also provided a great deal of personal support to one of us, not to mention computer expertise when needed.

Chapter 9 is partly the work of Jie Li, a Ph.D. student at Princeton, who was a member of the Young Scientists Summer Program at IIASA, in 2005. It was she who (under the direction of Robert Ayres) carried out the statistical analysis in the published paper that finally resulted (Li and Ayres 2007) and which is the basis for the results presented in this book.

We also gratefully acknowledge financial support for one or both of us from the European Commission (project TERRA), the European Science Foundation (ESF) and the Austrian Central Bank (through the University of Klagenfurt, Center for Social Ecology), INSEAD, and especially the International Institute for Applied Systems Analysis (IIASA) in Laxenburg, Austria. If any single institution can be regarded as the 'foster parent' of this book, it is IIASA.

Introduction

In the year 2000 at the end of the Clinton Administration the US federal budget had a surplus of 1 percent of GDP. By 2007 the surplus had become a deficit of over 6 percent of GDP, a figure more usually associated with Latin America. Part of the swing from surplus to deficit was due to the military spending to finance the war in Iraq. Another part was due to the huge new 'homeland security' program. A third part was due to the continued outsourcing of manufactured products (and exodus of manufacturing jobs) from East Asia. The Bush Administration's tax cuts for the wealthy was another major cause. The overvalued US dollar, propped up by its role as the major reserve currency of the world, has played a role. The budgetary deficit has been compensated in part – but only a small part – by the anti-recession policy of the Federal Reserve Bank, resulting in extraordinarily low domestic interest rates for several years (2001–04). That policy permitted (indeed encouraged) excessive consumer spending, which, in turn, generated steady growth in the US GDP (and kept tax returns from collapsing) until the end of 2007.

But the low interest rates, together with lax, or lack of, regulation, permitted some clever financial operators to create a real estate boom that soon became a 'bubble'. This was driven by huge numbers of sub-prime 'teaser' mortgages, which were sold by predatory lenders to unqualified people who should not have been buying houses in the first place. There were two results, clear in retrospect, but somehow neither predicted nor expected. One was a five-year boom in US house prices that persuaded even 'sensible' investors to take on variable rate mortgages in the expectation of selling out at higher prices before the rate adjustments came into force. Many real estate investors will now lose both their homes and their savings. Real estate prices are falling and the 'wealth effect' on spending has gone into reverse. The US economy is now in recession.

The other result of the cheap money policy was that many of the variable rate mortgages that had been sold to people with poor credit ratings were packaged with other mortgages in the form of 'mortgage-based securities' and sold by brokers to insurance companies and pension funds. These securities were treated, for a while, like AAA or AA rated bonds, because the rating agencies never examined the credit ratings of the individual borrowers. As a result, many financial institutions now have 'assets' based on assumed revenue streams that have suddenly become very uncertain. These securities have uncertain values. The financial institutions that own such securities are now (Winter 2009) in varying degrees of trouble. A further consequence of that fact, in turn, is that banks are suddenly reluctant to lend. It looks like a global repetition of the collapse of the Japanese 'bubble economy' in 1989–90. The dollar is weak. The US government seems incapable of doing anything to prevent this. How far will it go? Nobody knows.

What point are we making? Simply that economic theory has lagged rather far behind reality. However, we hasten to add that our focus is on the longer term; we have relatively little to say about short-term fluctuations.

According to most professional economists, the post-2000 acceleration in labor productivity – literally, output per (non-farm) man-hour – is very good news for the economy in the long run. The reason for this rosy assumption, at bottom, is that long-term historical trends suggest a correlation between productivity, growth and wealth creation. But sadly, whereas employment did increase slowly in the past few decades, the recent dramatic increase in US labor productivity (before 2008) has yielded very little increase in employment whereas the downturn has increased unemployment drastically. The French experience since the official 35-hour week was instituted (supposedly to create more jobs) has been similarly discouraging.

For some reason the historic link between output (GDP) growth and employment has been weakened, if not broken. We think that the historical 'engine' of economic growth has (so to speak) run out of steam. It is getting harder and harder to create jobs, outside of the import/retail trade area. The unwelcome implication of this is that 'raw' human labor, on average, is no longer a scarce or essential resource, except perhaps in some types of agriculture. Nor, it seems, is capital a scarce resource in the modern world. Capital has become cheap because capital accumulated in the past can be used as collateral for new loans, while still being productive in the present. Moreover, in recent years, institutions have been created that permit borrowing well in advance of hypothetical future earnings that are projected to flow from both current and past investments. In short, financial capital can, and does, increase much faster than savings from current income. Is this flood of capital being invested in wealth creation through new technology? Or are we exploring for oil (as it were) on Wall Street? Is the new capital being invested mainly in financial instruments, mergers and acquisitions, private equity and hedge funds?

Most people nowadays believe in economic growth for much the same reason they believe in God or in the power of prayer: it is politically proper. US currency is imprinted with the phrase 'In God we Trust'. Faith is widely regarded as a moral virtue. Faith is a cousin of confidence, and consumer confidence is said to be growth-friendly, at least in the short term. But in economic affairs clear sight, sensible policies and a bit of luck are needed too. Let us start with clarity. The key point to understand is that government (and private sector) economists assume that future economic growth will continue indefinitely at something like historical rates.

What justifies this assumption that growth is automatic? The answer is, simply, that the easiest assumption about the future, *ceteris paribus,* is that it will be like the past. Given a 200-plus year history of steady economic growth, it is fairly natural to assume that the historical trend will continue. Governments, businesses and institutions are now, and have been for several decades, effectively addicted to the presumption of perpetual and inevitable economic growth. Any suggestions that growth might not continue indefinitely (or that it might not be a good thing for society) are ignored or disparaged. Periods of turmoil, such as the recent past, are invariably regarded as exceptional. Analysts and pundits of all stripes speak of 'recovery' as though the US economic experience from 1999 through 2007 was merely like suffering from a cold, or perhaps, a mild case of the flu. We think, on the contrary, that it was (and is) symptomatic of a deeper disease.

It is important to recognize that there is no quantitatively verifiable economic theory to explain past growth. This is a fairly shocking statement, so it is worthy of repetition for emphasis. To be sure, we can say quite a lot about growth stoppers. But there is no theory, based on general behavioral laws, to explain quantitatively why some economies grow, but some grow faster than others and some do not grow at all.

To be sure there is a qualitative theory, widely accepted and rarely challenged. It goes like this: consumers save part of their current incomes in order to invest. Investment creates productive capacity. The purpose of saving and investment is partly to provide a safety net against times of trouble and partly to enjoy increased consumption (higher income) in the future. There is a well-established tradeoff between the desire to enjoy income in the present and greater income in the future. It is called the discount rate, because most people will discount future income that they might not be alive to enjoy or that might be wiped out by events beyond their control or because of simple short-sightedness. In order to induce society as a whole to save and invest, the prospects for future economic growth must be attractive enough to compensate for the loss of current consumption. But if growth is assumed to be automatic, then the incentive to save and invest disappears. The Chinese now save almost 45 percent of current income, in order to assure that they will be better off in the future. The US savings rate is zero or negative, because most Americans seem to be convinced that economic growth happens without effort, and (thanks to a lot of 'shop until you drop' urging by politicians and economists) that saving is negative for growth whereas current consumption favors growth. Besides, if one can simply borrow and spend the savings of others, as the US has been doing for decades, why save?

Energy

Apart from lack of savings other factors are at work. There have been fairly major departures from the overall growth trend, during wars, the Great Depression, and the oil embargo of 1973–74. The problem is to understand how they interact.

In contrast to the neoclassical economic model, the real economic system depends on physical material and energy inputs, as well as labor and capital. The real economic system can be viewed as a complex process that converts raw materials (and energy) into useful materials and final services. Evidently materials and energy do play a central role in this model of economic growth. This process has stages, of which the first stage is to convert raw materials into finished materials and raw fuels into finished fuels and electricity. In fact, this book argues that over the past two centuries, successive improvements in the efficiency of these various conversion stages have accounted for most of the economic growth our Western civilization has experienced. Just as many durable goods markets are approaching saturation, there is evidence that opportunities for further technological improvements in the energy- and materials-conversion stages of the economic system are simultaneously approaching exhaustion.

We said earlier that the 'engine' of growth is running out of steam. To explain that statement we need to characterize the 'engine' in potentially quantifiable terms. The growth engine is a kind of positive feedback system. Demand growth for any product or service, and hence for raw materials and energy services, is stimulated by declining prices. Lower prices enable present consumers to buy more, and marginal consumers to enter the market. (Higher prices have the opposite effect: they induce consumers to buy less or seek cheaper alternatives.) Increased demand induces suppliers to add new capacity (that is, new factories), which also tends to result in greater economies of scale, and savings from 'learning by doing', thus enabling further decreases in prices. Production experience also cuts costs by stimulating technological improvements in the production process itself. Finally, firms may invest in R&D to cut manufacturing costs or to increase product quality, which also helps sales. Evidently the system feeds on itself, which is why it can be described as a positive feedback loop or cycle. The details are discussed at length in subsequent chapters of this book.

However a significant share of the cost reductions since the early 19th century has occurred at the second stage of production, where crude fossil fuels are converted into a more highly processed form of energy, which we can call 'useful work'. Work, in the technical sense, is the service obtained from raw energy by first-order conversion. Power, a slightly less misleading term, is simply the rate at which work is performed, or work done per unit time.

In any case, fossil hydrocarbon prices are more likely to increase than to fall in the future. Emission controls are becoming a significant element of costs to electric power producers, refiners and other industrial fuel users. Another more urgent problem is the approaching 'peak oil', that is, the time when global output peaks and begins to decline. To be sure, the age of oil is not yet ended. Still, several independent lines of argument suggest that global peak production will occur between 2010 and 2020 (for example, Campbell 2004; Deffeyes 2001; Strahan 2007). As production drops, prices may fluctuate but the long-term trend will be likely up rather than down.

Of course rising prices will eventually bring some new 'unconventional' sources into production, such as bio-fuels, Greenland Shelf oil, Venezuelan heavy oil, Athabaska tar sands and Green River oil shale. But bio-fuels compete with food production. Demand for ethanol, created by government actions, is – together with rising demand for meat consumption from China – already driving up corn and wheat prices dramatically. The other unconventional sources are said to be potentially larger than the global stock of liquid petroleum. But the costs of recovery are likely to be much higher than current costs and the energy-return-on-investment (EROI) will be much lower. Extremely large amounts of capital (and energy) will be required. This creates a potential supply bottleneck; it may take a number of decades before new sources could reach the output levels of today. And higher oil prices will soon be accompanied by higher prices for gas and coal, since oil will have to be replaced by other fuels wherever feasible.

To summarize: In this book, we attempt to characterize economic variables, where appropriate, in terms of primary physical properties, namely *mass* and *exergy*. The term 'exergy' is used here, and throughout the book, rather than energy, because it is what most people really mean when they speak of energy. (We explain the terminology below.) We specifically address the economic implications of the First and Second Laws of Thermodynamics. The First Law, says that mass/energy are conserved quantities. It is primarily useful as an accounting tool, closely analogous to double entry bookkeeping, but it has powerful implications as well. On earth, where nuclear reactions are insignificant in mass terms, the First

Law says that all the mass that flows into any transformation process – including any economic process – must end up either as a useful product, a stock change or a waste. In fact most materials extracted from the earth's surface end up as wastes. *Wastes, both material and energy, are a pervasive accompaniment of all economic activity.*

The Second Law, sometimes called the entropy law, says that the availability of energy to do useful work is reduced by every transformation process, whereas the non-useful component increases. *Entropy* is a measure of that increasing non-useful component. The technical term for the useful component is *exergy*. But, according to the First Law, energy is a conserved quantity, which means that it doesn't increase or decrease. The energy content of a physical entity or system does not change during a transformation process, such as production or consumption. However exergy is the useful component of energy; it is the component that can perform useful work. Exergy is not conserved. In fact, it is partially 'used up' in every transformation or process.

It follows that *every production process is dissipative*. A continuous process requires a continuing flow of exergy to keep going. Capital equipment without an activating flow of exergy is inert and unproductive. In the eighteenth century, the main product of every economy was agricultural: food or animal feed. The primary exergy input was sunlight, which was free. At that time productive capital consisted mainly of land, tools and animals, apart from a few smelters, water mills and windmills. So the exergy flow at the time was mostly invisible, being embodied in human or animal labor. It was natural for the early economists to consider capital (including land and animals) and labor to be the primary factors of production.

However, since the industrial revolution, mechanization – beginning with the steam engine – has increased enormously. Machines have largely replaced humans and animals as power sources. These machines required coal, at first, and more recently petroleum, natural gas or electric power. In short, the mechanized industrial economy depends upon inputs of exergy. Without exergy inputs, there can be no production. It follows, then that *exergy should be considered as an independent factor of production, along with capital and labor.*

The standard economic theory of growth, developed since the 1950s, retains the two traditional factors of production but does not include exergy. However this standard theory, based on increasing capital stock and increasing labor inputs, does not actually explain the growth that has occurred. To remedy the deficiency, economist have introduced an exogenous multiplier called 'technical process' or, more recently 'total factor productivity'. In fact, most of the growth seems to be due to this exogenous multiplier.

One theoretical innovation in this book is the explicit introduction of *exergy efficiency* as an economic variable. We noted above that exergy is defined as potential useful work, that is, the amount of useful work that could be performed, in principle, by a given amount of energy. A moment's thought suggests that there can be a big difference between the amount of work actually performed and the amount that could theoretically be performed. The difference is lost work, mainly as waste heat. The ratio between actual work done and the potential amount of work that could be done in theory, is the *exergy efficiency*. We have estimated the work done by the US economy since 1900, and the exergy efficiency of that work. Not surprisingly the efficiency has increased fairly dramatically, corresponding to a significant reduction in the waste as a fraction of the total.

The final innovation discussed in this book is the introduction of useful work actually performed, instead of exergy input, as the third factor of production. The justification for this is simply that the input exergy is mostly unproductive (that is, waste heat), whereas the work actually performed by the economy is the productive component. It turns out that with this innovation, past US economic growth can be explained very well by the three factors, capital, labor and energy without needing to invoke exogenous 'technical progress' or 'total factor productivity'.

The question is: what will be the impact of rising energy (exergy) prices on economic growth? Standard theory says that there is little or no link between energy costs and growth. We disagree. Our results suggest that the link is much stronger than conventional theory admits. We think that economic growth in the past has been driven primarily not by 'technological progress' in some general and undefined sense, but specifically by the availability of ever cheaper energy – and useful work – from coal, petroleum (or gas). These energy-related price declines can no longer be expected to drive economic growth in the future. Clearly higher energy prices will – other things being equal – result in reduced demand for energy and therefore for energy services and all the other goods and services that depend on energy inputs.

As Alvin Weinberg once said, energy is the ultimate resource. It is essential. It is needed for every economic sector and activity, and there is no substitute. The implications of non-substitutability will be discussed extensively in this book.

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