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# Potential Economic and Energy Indicators of Inflection in Complexity[*]

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## Abstract

*Energy and environmental factors have often driven transitions in natural evolution and human history to more complex states which are far from equilibrium. Most of the early transitions were based on sustainable non-equilibrium states using renewable energy resources. However, the industrial revolution saw the transition from this sustainable growth pattern to the one based on limited non-renewable resources such as fossil fuels. This second-level non-equilibrium condition includes not only a complex organization dependent on energy flow but also the energy flow which is extracted from a non-renewable stock. Eventually, this latter pattern will stop when the energy stock is empty. Recent studies have indicated: 1) the importance of energy along with labor and capital in determining economic productivity; 2) a potential slow-down of growth in economies and sciences; and 3) the relatively increased pace of global technology diffusion compared with concentrated technology breakthroughs. This paper identifies indicators in energy, economic growth, and global economic disparities to connect historical trends with potential scenarios of a transition to an expanded sustainable non-equilibrium society. By transitioning back to a sustainable non-equilibrium pattern, the required complexity changes may also slow down as suggested by interpretations of Big History major events. Similar transitions have been observed and modeled in natural dynamic ecological systems.*

**Keywords:** *energy, evolution, complexity, sustainable growth, non-renewable resources.*

## Introduction

Big History connects long-term trends with recent events and understanding (Christian 2004). The long-term trends include the integrated evolution of stellar systems, life, humans, and technology. Themes in these trends include information, complexity, energy, and scales. Carl Sagan presented stages of information processing (Sagan 1977), progressing exponentially from the early

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universe to the present day. These stages were life, human, and the civilizations' technological evolution based on each stages' ability to gather and maintain information. A general model for the self-organizing universe was proposed by Erich Jantsch (1980). A model of technology progression and diffusion that has been studied is based on the logistic equation (Modis 2002) which suggests that the history of the universe might also be viewed as a logistic development of complexity. Energy flow has been identified as an important driver of the increased complexity (Chaisson 2004).

While a century seems like a small duration over the 13 billion years of the universe, much technological and social change has occurred over the last century. This acceleration of change is a continuation of the change since life started. The three periods of life, human, and technological civilization evolution started, respectively, about five billion, five million, and five thousand years ago. If this geometric sequence of acceleration continued the next two phases would be five years and then two days. This duration is clearly not sufficient to develop and test new information techniques, respond to increased complexity, generate expanding energy resources, and develop new technologies at new scales. However, Kurzweil's hypothesized Law of Accelerating Returns (Kurzweil 2001) based on his analysis of over a century of progress in computation technologies, suggests this ever-increasing rate of technological change, leading to a 'technological singularity' (Kurzweil 2005).

However, limits are being reached at the current level of technology and change. Limited natural resources are being stretched for global economic development (Brown 2003). Social response to the new technologies and global issues is hindered by new levels of uncertainty and the complex integrated nature of the problems (Linstone 1996; Tainter 1996). Instead, there is a possibility that the rate of change may slow down due to higher costs of energy and limited natural resources, the diminished rate of fundamental discovery in physical sciences, and the need for investment in environmental maintenance. Normal learning curves, or logistic growth curves, which have been observed in many technologies and social patterns, (Marchetti 1977, 1994; Modelski and Perry 2002) have an initial acceleration and then slowing with the midpoint being the inflection point. It was proposed that a society behaves as a learning system (Marchetti 1980), in that technology and idea development could also be logistic. Theodore Modis (2002) hypothesized a very different future, one having a decreasing rate of technological change, based on analyses of events from the 'Big Bang' to the present. This paper attempts to identify potential indicators of this large-scale inflection point and discusses what implications it might have.

Hints at the reason for cycles come from complex adaptive systems that exhibit nonlinear behavior far from equilibrium. The current society could be viewed as a result of an evolving complex adaptive system as it is far from equilibrium in terms of the energy flow through the system and has exhibited waves of growth, such as Kondratieff waves (Devezas and Corredine 2001, 2002; Devezas and Modelski 2003; Devezas 2006), among others with different periods, which are similar to the period doubling seen in such systems. The characteristic properties of complex adaptive systems include: (1) a resource which drives the level of complexity, such as energy use (Tainter 1996; Chaisson 2001); (2) new options at critical stages along development paths; and (3) competition and learning as the options are explored.

This paper identifies potential indicators of an inflection point in this large logistic curve. Specifically the themes of energy, social response to environmental issues, discoveries in fundamental physics, and global diffusion of technologies are explored for indications of slowing down. Fundamental physics discoveries were selected as an indicator system since these discoveries often were the bases for technological innovation. Other tests involved following the lead of Cesare Marchetti to understand if the logistic trends he observed in the 1970s in energy substitution and environmental interest continued. Some indicators of complex adaptive systems include bifurcations after discrete changes in a system driver. This was tested by exploring transitions in leadership and energy intensity use throughout modern era (last 500 years).

## Importance of Energy

History may well form a large complex adaptive system. As systems progress, new options arise for the systems may spontaneously bifurcate into two potential discrete states. While the simplest model of complex systems can be driven into chaos, more realistic models with limitations suggest a possible reversal of increasing complexity (Stone 1993). The characteristic properties of complex adaptive systems include: (1) a resource which drives the level of complexity, such as energy use; (2) new options at critical stages along development paths; and (3) competition and learning as the options are explored. Basing economics on such energy and thermodynamics concepts was begun in the 1970s by Georgescu-Roegen and continued by others, including Herman Daly (1996). Recent economic analysis has identified this useful energy measure as a major impact in determining economic productivity (Ayres and Warr 2009).

The logistic trends in the world's mix of primary energy sources were observed (Marchetti 1977) in the mid-1970s. The model accounted for the shifts in primary energy use from the early 1700s, when wood was primarily used, through the 1800s, when coal use climbed, through the early part of the 20th century, when oil became predominant and uses of natural gas and nuclear power rose. The logistic trends were extended to predict the fall of the fraction of energy from coal, the peak in the fractional use of oil, and the continued rise of both natural gas and nuclear power in the 1990s. The actual use of primary energy sources since this prediction has shown deviations, in that the relative fractions of the primary energy sources were stable since 1980. During this period, the total energy demand rose substantially, but the contributions from each primary energy source kept pace.

However, while fossil fuels will probably dominate as a source of energy for another generation, much has been done recently to increase their efficient use (Lovins 2011). In fact, it seems like energy efficiency has been growing as a substitute for raw energy. This continues the pattern of substituting different fuel sources and technologies (wood, coal, oil, and natural gas) to generate energy from the mid-1800s (LePoire 2004). The efficiency trend started to gain traction in the 1970s when two oil price shocks hit the economy. Many businesses, governments, and people realized that funds could be better invested in saving energy rather than continual normal use. The energy used now in the United States is about half what it would be without those efforts. Significant progress could be made in capturing waste heat and combined electricity and heat generation as many countries such as Japan have demonstrated.

The periodic transition in energy sources is not the only indication of energy as a major driver. The amount of energy flow to sustain people in historical societies has shown a geometric increase (Smil 1994; Niele 2005). The increase in energy usage over early agricultural societies to the present is illuminating: a human's intake of 2,500 calories per day corresponds or averages to about 100 watts (W) (*i.e.*, about as much energy as a large incandescent light bulb uses). The average energy consumption per capita in the United States stands at 15 kilowatts (kW) of energy (including commercial, industrial, and residential use), or about 150 times a person's food energy intake/use per day. This measure corresponds to about 3.5 factors of Feigenbaum's number and suggests there might be three or more transitions, or bifurcations, where the energy flow increases by a factor of about five. These transitions might include the early commercial transition after the decline of the Roman Empire which depended on human labor (often slave labor) for energy. The Western Europeans were more motivated to explore mechanical and energy extraction to help reduce their physical efforts, leading to utilization of water, wind, and wood along with mechanical machines. This activity led to a shortage of wood in Western Europe (especially in England and the Netherlands) after the recovery from the Black Plague, which created the need to import vast amounts of wood and timber from further North and East as was traded by the Hanseatic traders (Bernstein 2004). An estimate of wood consumption in the middle of the Northern Renaissance (in 1670) is four cubic meters ($m^3$) per capita. These energy sources could have supplied approximately 500 W of energy consumed per person in the late Renaissance, or about a factor of five times greater than the 100 W consumption rate of one person.

The energy consumption per capita then increased again as fossil fuels became extensively used (Nakicenovic, Grübler *et al.* 1998; Podobnik 2006). The use of coal enabled the industrial revolution. By 1860, the energy use in the United States was up to about 3.5 kW per capita, a factor of seven above the late Renaissance level. Over the course of the 20th century, oil and natural gas, along with nuclear power and hydroelectricity, were added to use. The oil crises in the 1970s prompted a more efficient use of energy resources, with the result that the productivity of energy resources increased by about a factor of 1.6 (Devezas *et al.* 2008). This increase in raw energy resources use and combined with more efficient use led to an increase of a factor of about five in energy use per person in the United States.

Currently, various energy experts recommend a range of potential paths, including continuation of fossil fuels, nuclear, wind, improvement in energy efficiency, and the development of new technologies (Heaberlin 2004; Lovins 2011). The economic viability is a major criterion for an energy solution. There is insufficient knowledge to determine the technology viability, environmental impacts, and economic implications of many new technologies over a long enough period at large-scale deployment. Since this knowledge, research, and experience take time to gather and implement, it seems that a bridge is needed to link current energy efficiency with newer fossil fuel extraction and use methods. The measurement of energy return on energy invested is one tool that is helpful in constructing this bridge. For example, corn-based ethanol production requires a large amount of energy input for the fertilizer, mechanical farming equipment, transportation, and processing. The energy extracted compared to the energy invested in this production is almost equal. Another example is the investment in equipment to increase efficiency. In hybrid cars, the battery is expensive and heavy with more complicated controls. At what point is the investment in this equipment energy cost effective? This bridge give us some time to solidify our understanding and processes, to apply foresight techniques, and develop long-term solutions (Ayres and Ayres 2010). The scope and timing means that this is not an isolated problem to be solved independently with engineering certainty but rather requires new views, new collaborations, and planning methods that come with significant uncertainty.

## Trends in Addressing Environmental Issues

The issues of energy use and environmental sustainability are deeply entwined. Analysis of the collapse of complex agricultural societies identified a major cause as the marginal return on investment of resources, such as energy, as societies grow larger and more complex (Tainter 1988). He suggested that many agricultural societies collapsed by overextending their reach into non-sustainable systems. The impact of environmental degradation has been an important factor in the development and decline of civilizations (Chase-Dunn and Hall 1997; Diamond 2005; Ponting 2007). Most of these analyses focused on agricultural societies because of their simplicity relative to industrialized societies.

In the 20th century, three key environmental issues arose at different times and different political scopes: (1) the sanitary phase of rapidly growing urban centers in the early 20th century; (2) national concern with clean air and water with action peaking in the early 1970s; and (3) international concern over transboundary issues (*e.g.*, wildlife) and atmospheric release (*e.g.*, chlorofluorocarbons, sulfur dioxide, and carbon dioxide) with treaties peaking in the mid-1990s (Marchetti 1986; Paehlke 2003; LePoire 2006). However, throughout the 20th century these issues arose faster but took longer to resolve, which is an unsustainable pattern.

This leads to questions concerning the ways of understanding waves, their connections, and their directions. Specifically, what is the next environmental phase and how will it be organized? A prediction based on logistic learning trend is that new issues, such as global climate change, trade, inequality, and environmental degradation, need to be addressed at a quicker pace as the world population and energy demand increases. If the interval between the last two phases, in 1970 and 1996, is repeated, then the next environmental phase would peak in just over another decade.

The three identified periods of environmental interest had different spatial scales: local, national, and international. It would be interesting to look at the trends in both the elevated interest duration and the time between the peaks of the periods. The data suggest a completed logistic growth period, with the midpoint being 1972 and a 22-year duration. Including this, the time between the periods drastically diminished, about halving, from about 57 years (1915 to 1972) to 23 years (1972 to 1995) (LePoire 2006).

What might be next? There are many dimensions to be considered, including new technologies, better understanding, new governance models, and new levels of environmental complexity. New technologies, including combinations of genomics, robotics, artificial intelligence, and nanotechnology, offer potential environmental benefits and risks.

The environmental interest and activities in the previous century seem to indicate a pattern of periodic interest as technologies are developed, environmental problems arise, and social responses are formulated. A critical factor for determining the continuation of this pattern is the relative rate of technology development compared to the social response. Possible leading indicators of the next period of environmental interest include new social mechanisms such as the incorporation of environmental impacts in economic accounting and the responsible development of new technologies.

## Logistic Development of Fundamental Physics

Do scientific fields develop faster as more is known? Or are they develop similar to a logistic pattern? The logistic pattern would include three major phases: 1) a slow early progress as definitions are determined; 2) a relatively constant progress once the fundamental issues have been defined, and then 3) a final slower pace as the remaining issues are resolved. To gather more evidence to address these questions, a leading indicator was identified and analyzed (LePoire 2005). Fundamental physics discoveries and its later developments into applied physics are the source for most technological advances. Fundamental physics history has been quite well documented through research papers and biographies.

The methodology used an independent list of historical physics discoveries which were categorized into traditional subfield and evaluate each subfields progress via logistic growth patterns. The events in the history of physics as listed on a website were assigned to the 12 subfields of classical gravity, classical mechanics, optics and wave physics, thermodynamics, electrodynamics, atomic physics, special relativity, nuclear physics, general relativity, quantum mechanics, high-energy particle physics, and string physics.

A logistic pattern was discovered with the inflection point being around 1925 identified as the 'Golden Age' of physics with a simultaneous development in general relativity, quantum mechanics and nuclear physics. The characteristic transition time (*i.e.,* time to go from 20 per cent to 80 per cent completion) was found to be about 210 years.

Other logistic analysis has looked at patent rates to suggest that technological innovation peaked in the early 20th century. This reflects the major qualitative technological changes in the early 20th century in transportation with cars and planes, communications with phone and radio, medicine with X-rays and antibiotics, and energy with increasing fossil fuel usage combined with electrical distribution. While new technologies such as biotech, nanotechnology, robotics/ artificial intelligence lead to new products, the change is more quantitative than qualitative. For example, the phone has been modernized with cell service and combination with computer advances but the ability to easily communicate is still the basis of the technology.

## Modern Leadership Transitions

The trend of simple characteristics of population and relative productivity are examined within the nations that formed the sequence of leading capitalist countries (LePoire 2010). The population influences both the scale and complexity of the state organization. For example, a larger population produces more only if it is efficiently organized. Therefore, the historical sequence of leading nations does not start with most populous nation but instead with a limited population where new organizational structures could be explored. The diffusion of technological and social ideas from these leading countries might be demonstrated by their relative productivity and resource use. The trends are then analyzed with regard to how they might indicate potential future directions and factors.

To test the relative speed of intensification and diffusion, the relative productivity (defined as the ratio of gross domestic product [GDP] per capita of a region to the global average) is explored. The relative productivity is plotted as a function of GDP (with a log-scale) instead of as a function of time. If the GDP grew exponentially at a constant rate, the *x* scale would be proportional to the time difference. Since the GDP grew slower at earlier times, this graph emphasizes the more recent, quicker, and more dynamic global economy. As expected, before the modern era, the relative productivity was initially quite uniform. (In 1500, the GDP was about $250 billion.) Then it diverged, with Western Europe's productivity increasing, followed by that of its Western colonial offspring (the United States, Canada, and Australia), and then by that of Japan (in the 1970s). The relative productivity of Asia (except for Japan) and Africa decreased. The productivity of the two remaining areas (Latin America and Eastern Europe) hovered around the average relative productivity. The recent dynamics reveals a sharp rise in non-Japanese Asian productivity, although it is still below the average. If innovations were to diffuse around the world faster than the rate at which current leaders could generate any additional competitive advantage, the expectation would be that the relative productivity would converge again. However, current data show that the increasing competitive advantage is still growing. It is possible that with rapid change and growth in China, India, Russia, and Brazil, this trend might soon reverse. Indications of slower growth in developed countries since the 1970's have recently been seen when environmental impacts are also considered (Heinberg 2011).

The three state trends investigated – population, relative productivity, and energy use – suggest that a global transition is close to the inflection point. The estimates are based on population limits, limits on the progress rate and diffusion rate of technological innovations, and the environmental limits on energy use. This conclusion is not surprising since the global system seems to be nearing its furthest extent from equilibrium.

## Conclusions

Big History trends of accelerating change and complexity with related increases in energy use may not be sustainable. The indications of potential slowdown in the rate of change in economies, technology, and social response were investigated. This is not to say that change will stop, just the rate of change will not accelerate. In fact, at the inflection point in a logistic learning curve only half of the discoveries have been made. Since there were three major phases in life, human, and technological civilization, the continuation of the logistic curve would suggest three more phases. The direction of the development of technologies points to the next phase including enhanced human technology through advanced biotech and computer integration.

Like any transitions, the path forward may not be clear with various potential options being explored. If this is an inflection point, the transition may be more difficult since the expectation of growth and acceleration are not met. The inflection also indicates the approaching fundamental limits of resources and understanding. As the limits are approached, the systems of economies, energy, environment, and social organization become more interdependent leading to complex nonlinear system issues.

A rapid change is not necessarily good. It tends to push systems away from efficiency because there are little long-term expectations. Also learning in changing fields is quickly obsolete, especially when the change occurs at timescales shorter than a generation. An organization might allocate many resources to prepare for many potential scenarios that are never realized. If the rate of change slows down, the complexity might decrease.

Energy resources have played an important role through the events in Big History. The current period of dependence on fossil fuels has enabled a major leap in technology and understanding. The global nature of the exploration, extraction, and transportation of these fuels has added complexity in the form of military and economic conflicts. However, the advance of science and technology during this phase has also offered a potential advanced renewable and sustainable energy technologies that might simplify energy issues. If the inflection occurs, there will be many options in how to handle the issues in growth, jobs, technology, energy, and the environment. Big History does not provide the solutions but does offer trends, indications, and a deep perspective on these challenges.

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