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FROM MY PERSPECTIVE

Turning point: The end of exponential growth?

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1. Preface

I think I can claim pretty solid credentials as a technological and economic optimist. In 1973 I took the opposing (i.e. optimistic) side in a formal debate at INSEAD about "Limits to Growth". My opponent was Alexander King, who was then the head of the Technology Division at the OECD and deputy leader of the Club of Rome. In a series of articles in recent years I have repeatedly argued against the "entropy" pessimism of Georgescu–Roegen, Herman Daly and others [1–5].

Nevertheless I am now increasingly convinced that a continuation of exponential growth until 2100 cannot be taken for granted. I tried to make the case for an imminent turning point in a book written in the late 90s, but the evidence at the time was primarily negative, in the sense that a number of then-current trends seemed to me to be unsustainable [6,7]. Today, a decade later, the evidence is far more persuasive. The US economy, in particular, is in deep trouble. It seems to me that those who still believe the future will be a straightforward continuation of the past need to address a number of serious objections. I summarize the arguments briefly in this paper. A much more extensive (and intensive) elaboration of these arguments is in progress.

2. Reasons to expect exponential growth to continue

The strongest 'pro-growth' argument is one I have made myself.[1] The argument is that the economy has a lot of inertia, whence the future is more likely to be a continuation of past trends, than otherwise. Exponential economic growth in the western world began in the late 18th century and has continued, more or less

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[1] See my defense of the 'envelope curve' forecasting methodology [8-9].

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unabated, until the present. The US has been the world's biggest economy for over a century and has been the unquestioned "locomotive" of global growth since the end of World War II. Why should this pattern not continue?

In answer to the pessimism of "Limits to Growth" [10,11] Solow, Stiglitz, Nordhaus and others – myself included – took issue with the model underlying the book. In particular, they argued that the resource limitations postulated by Meadows et al. failed to allow for technological progress and substitution possibilities [12–16]. Physicists added to the chorus of criticism e.g. [17]. Julian Simon and Herman Kahn entered the controversy, arguing that economic growth depends only on human ingenuity and ideas [18,19]. This argument has been formalized and updated especially by Paul Romer and Ray Kurzweil (Romer 1986, 1987; 1990).

The growth optimists now argue essentially that the pace of technological change, especially in information technology, bio-tech and robotics is accelerating, and that this "fact" assures that economic growth will continue and even accelerate e.g. [20]. It should be noted, here, that the spectacular evolutionary progress foreseen by Romer, Kurzweil and others focuses on information technology, health and basic science. It does not deal with ordinary everyday activities such as food, clothing, housing, transportation, or the underlying materials-intensive and energy intensive industrial activities. Nor do the optimists consider the implications of growing inequity, social unrest, religious conflict, or conflict for scarce resources.

In case technological progress in IT and bio-tech is insufficient, three other mechanisms have been proposed. They are (i) 'globalization', (ii) deregulation, and (iii) privatization. Globalization is a mixed blessing: good for some – mainly the multi-nationals (MNCs) – bad for the rest, especially the poorest people and countries. "Free trade" has been promoted as the secret to global growth for the past several decades, largely because of the very negative experience of the 1930s that resulted from the counter-productive US trade restrictions that followed the stock market crash in 1929. Since WW II there has been progress reducing tariffs and non-tariff barriers for industrial goods. However, free trade for non-agricultural goods and for capital, *but not labor*, has resulted in the movement of manufacturing, and more recently some services, away from the so-called 'rich' countries into countries with cheap labor and minimal health, safety or environmental protection. The result of this partial globalization has been a massive growth in US imports with no corresponding increase in exports. This trade deficit has not resulted in exchange rate adjustments (as theory assumes). Instead it has been financed by increasing debt which can never be repaid. This debt will eventually have to be written off somehow, or devalued by inflation. Meanwhile, the lack of development in resource exporting countries has created a huge problem of unwanted and un-assimilable immigration from the poor 'south' to the rich 'north'.

Deregulation of some sectors has had some favorable impacts, but largely by making it easier to cut costs by reducing employment. This increases the "productivity" of those still employed but does not create new jobs. Moreover, there are indications the large investment in computers and software during the 1990s is finally beginning to pay off, in productivity gains. In 1987 Nobel laureate Robert Solow was quoted in an interview as saying "you can see the computer age everywhere except in the productivity statistics" (Solow 1987). The phenomenon behind this remark became known as the "Solow Paradox", and attempts to explain it have been many. In 2003 *The Economist* asserted that the paradox has been explained at last (Anonymous 2003). It seems that labor productivity, which grew at an annual rate of barely 1.4% p.a. during 1975–1995 jumped to 2.3% p.a. in 1995–2000 and hit 6.8% in the second quarter of 2003. But, without job creation to absorb the surplus labor, productivity gains increase unemployment, especially for the less skilled. Productivity gains are a double-edged sword.

Privatization has also had some efficiency benefits, probably best exemplified in Western Europe. It has also been a source of inequity and social problems, as in Russia. There is little or no evidence that privatization has accelerated growth.

3. Reasons for skepticism

Perpetual economic growth is an extrapolation from history and a pious hope for the future, not a law of nature. There are a number of drivers of past growth in the industrialized countries that are now showing signs of saturation or exhaustion. These include:

(1) Division of labor (job specialization), as emphasized long ago by Adam Smith,
(2) International trade (globalization) as it allows economies of scale and international division of labor.
(3) Monetization of formerly unpaid domestic and agricultural labor, as a consequence of urbanization.
(4) Saving and investing (the traditional driver of growth).
(5) Borrowing from the future (by the creation of new forms of unsecured credit in massive amounts), also tends to increase consumption in the present without creating anything new.
(6) Extraction of high quality and irreplaceable natural resources and destruction of the waste assimilation capacity of nature.
(7) Increasing technological efficiency of converting resource (especially fossil fuel) inputs to "useful work" and power.

The first four trends have been largely completed in the industrial world, though barely beginning in many third world countries. Specialization of labor was very important at the beginning of the industrial revolution, but it probably peaked a century ago during the heyday of Taylorism [21]. The benefits of scale from international trade have also probably peaked. The monetization of (formerly) unpaid domestic labor (by women) and subsistence farm labor – closely correlated with urbanization – is now largely complete in the OECD countries. Much of the GDP growth in developing countries is simply due to urbanization and monetization of formerly unpaid labor.

Saving from current surplus and investing is quite out of fashion, notably in the US. The Asian countries still do it, but the US essentially stopped saving in the '90s and is currently dis-saving. That is another word for living on capital, or living on money borrowed from others. Borrowing from the future is borrowing on the basis of expectations of future income. Unsecured credit cards are the most obvious way to do this, but most stock market investing today has nothing to do with actual assets and everything to do with expected future earnings and capital gains. In other words, stock market returns in the present are based on expectations of real productivity gains in the future. The collapse of Enron resulted from counting expected future profits from so-called 'side deals' on the balance sheets as if they were current profits, resulting in a huge inconsistency between financial reports and reality.

A subtler and less understood way do this at the national level is to borrow from other countries by running a trade deficit. The US now has a huge and growing trade deficit, entirely financed by foreign investment in US government securities, by exporting countries. The deficit currently approaches $800 billion, or 7% of the US GDP *and absorbs close to three quarters of the savings of the rest of the world*. A few influential economists, including Alan Greenspan (in his last few years) and the current Chairman of the Fed, Ben Bernanke, have argued that the problem is really excess savings on the part of the developing countries, and that everybody benefits. The idea seems to be that US government bonds are a better long-term investment for China and the other exporters than domestic investment of the profits, e.g. in infrastructure. What this policy also does is to keep the cost of borrowing (in the US) low. That finances consumption, of course, as well as large mergers and acquisitions and other financial investments such as hedge funds. All of this makes the US GDP go up, but creates very few jobs. This looks superficially like “real” growth, but on deeper scrutiny it more strongly resembles a “bubble”. I do not know where the limits are for consuming the savings of the rest of the world, but I feel sure there is a limit.

Those policy-makers who see the problem hope for a “soft landing’. But that would obviously require a return to the sort of policies that resulted in large budgetary surplus during the Clinton administration. Those policies included much higher taxes and sharply reduced military spending, i.e. a reversal of all of George Bush’s policies. Given the significant deterioration in US economic strength since the ’90s it would probably also require a gradual devaluation of the dollar, significant energy conservation policies and other policies to encourage domestic investment rather than capital export. The alternative – a “hard landing” – would include a sudden devaluation of the dollar, a sharp increase in US inflation, a sharp devaluation of US bond prices, and a deep recession. Foreign creditors would see their dollar reserves cut in value at the same time as their US export markets dried up. A worldwide depression would probably follow.

Borrowing from nature, by exploiting non-renewable resources – including biodiversity – is really more like theft, because there is no possibility of repayment. This form of converting long-term assets into current income is approaching limits. We (the human race) are running out of a number of high quality resources (topsoil, fresh water, fish, virgin forests, oil and gas, and toxic waste assimilation capability) to exploit. Again there are limits. Land is limited, fresh water is limited. The atmosphere is limited. There are no substitutes. The fact that global reserves of easily recoverable petroleum, natural gas, and high quality metal ores are also finite, merely adds to the problem. Competition for land, water, fisheries and energy resources is already creating violent conflicts in some parts of the world, much of which is disguised as ethnic or religious in nature [22].

This leaves item (#7) above, together with potential (but still unrealized) progress resulting from newer technologies, as the *only* viable driver of future economic growth. We know that the technological efficiency of converting raw materials (and fuels) into useful work and power increased enormously during nineteenth century and the first half of the twentieth century. This increase in conversion efficiency resulted in cost and price reductions, not only for primary energy, but also for all energy-related products and services. In fact, virtually all products and services are dependent on energy – or energy, as converted to “useful work” – to some degree. This long-term trend has enabled the substitution of machines, powered by cheap fossil fuels, for human and animal labor. It has also facilitated large scale industrial processes, together with their economies of scale and experience, which further cut costs and prices. These cost-price reductions triggered increased demand, thanks to price elasticity. Increased demand yields still further economies of scale and experience.

One way to think about economic growth is in terms of what has been called the “rebound effect”. In brief, increasing efficiency in the past has cut costs resulting in lower prices, which increase demand. Increasing demand drives increasing investment, increasing supply and (thanks to economies of scale and experience) still lower costs. This positive feedback cycle – at the aggregate level – is nothing less than the engine of economic growth by another name. This positive feedback cycle has been the primary driver of productivity gains and economic growth throughout the past two centuries.

However, when costs rise, demand falls. Unfortunately, sources of primary energy (crude oil, gas, hydroelectricity, etc.) are no longer getting cheaper. Higher energy prices may alleviate scarcity, by reducing consumption. But higher prices also inhibit economic growth. Moreover, the rate of increase in the efficiency of energy conversion in industrial societies has slowed down significantly. The aggregate US (technical) efficiency trend shown in Fig. 1 exhibits only a minor slowdown after the mid-1970s. It is

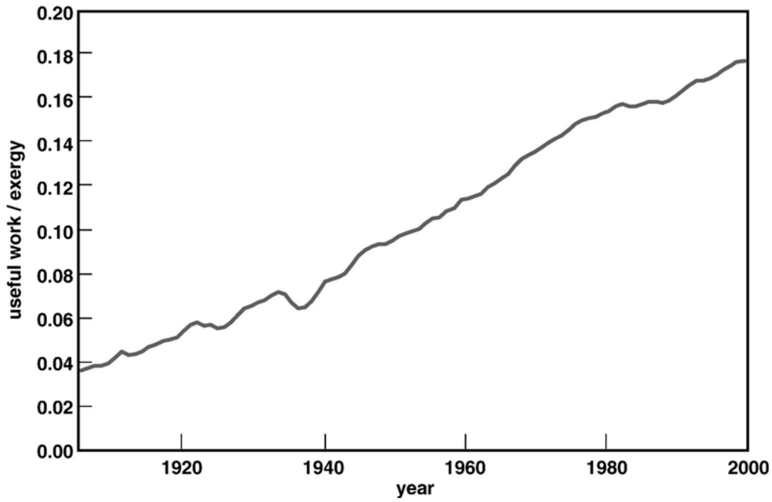

Fig. 1. Aggregate exergy conversion efficiency, $f=(\mathrm{Ub}/B)$, USA 1900–2000.

easy to attribute that change to the after-effects of the "energy crises" of 1973–73 and 1979–81. One of those after-effects is clearly visible in Fig. 2, which shows that whereas the energy intensity of the US economy (the exergy/GDP ratio) has been declining since the 1920s, the 'work intensity' (the useful work to GDP ratio) was rising steadily – apart from a wartime dip – until the high energy (oil and gas) prices of the mid-1970s. Since then the work-intensity of the economy has stopped rising. It declined sharply through the 1980s and has stabilized at a lower level since c. 1990, probably thanks to the accelerated shift from manufacturing to services. The decline in energy consumption by manufacturing has been offset by increasing energy consumption in the service sector.[2] However, it would seem that the events of the 1970s triggered a major shift in the structure of the economy.

The situation *vis à vis* energy conversion efficiency becomes still clearer when we consider the various energy (exergy) carriers individually, as shown in Fig. 3. Evidently the greatest gains in technical efficiency, especially in electric power generating efficiency, but also in internal combustion engine efficiency were achieved prior to1970. The slowdown in technological progress in the energy conversion domain seems to be due to a combination of exhaustion of the easiest options, institutional sclerosis and inappropriate regulation favoring established monopolies (especially in electric power distribution) and inhibiting innovation [23–25].

Another more illuminating way of looking at the future prospects is by representing technological progress, as energy conversion efficiency, in the form of an experience curve (Fig. 4). It is evident that the period of rapid improvement is far behind us. The "inertia" effect I mentioned at the outset applies here. Barring a miracle (i.e. a scientific breakthrough of huge proportions or a radical change in government policy) only further slowdown can be expected in the future.

What does this slowdown in the rate of technological progress, as applied to the production of "useful work" (in the thermodynamic sense) imply for economic growth? If growth is automatic and exponential,

[2] I use the word 'energy' because it is familiar, but of course energy is actually conserved. The correct term here and throughout is 'exergy' which is defined as the maximum *work output* that can be obtained from a given flow of energy under ideal conditions. Conversion efficiency is the ratio of actual work performed to theoretical maximum, which is exergy.

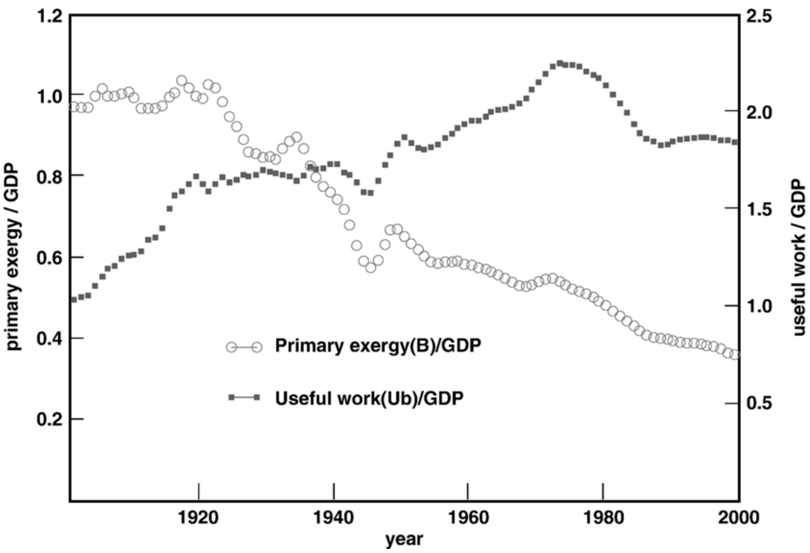

Fig. 2. Exergy and useful work intensities of GDP, USA 1900–2000.

as assumed by contemporary growth theory, it means little or nothing. However, if one of the main drivers of economic growth over the past century has been a growing supply of useful work, as I have argued, then the continued slowdown in efficiency gains means a gradual future slowdown in economic growth. Economic growth conceptualized as a continuous approach to an ever-advancing equilibrium may shift to economic decline as reaction to an increasing disequilibrium.

We have incorporated the feedback ideas in a formal economic growth model that does not assume any exogenous "progress" multiplier or total factor productivity (TFP). The model successfully reproduces the past economic growth of the US, and of Japan, from 1900 to 1998, as shown graphically in Fig. 5. The

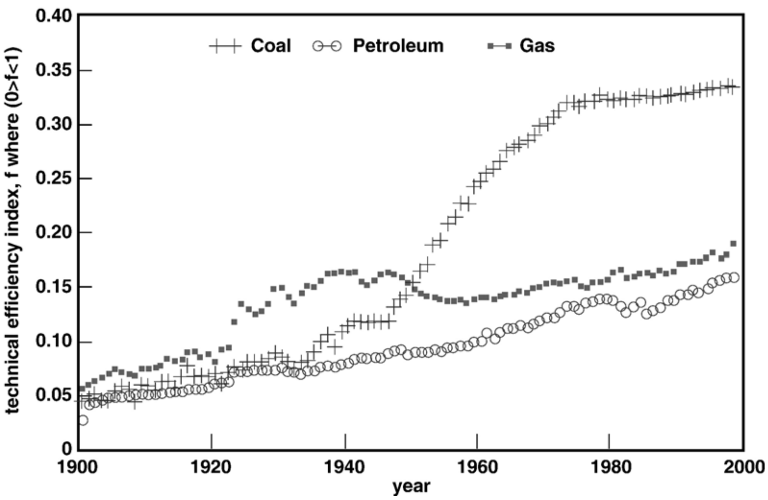

Fig. 3. Technical efficiency of major energy carriers, USA 1900–2000.

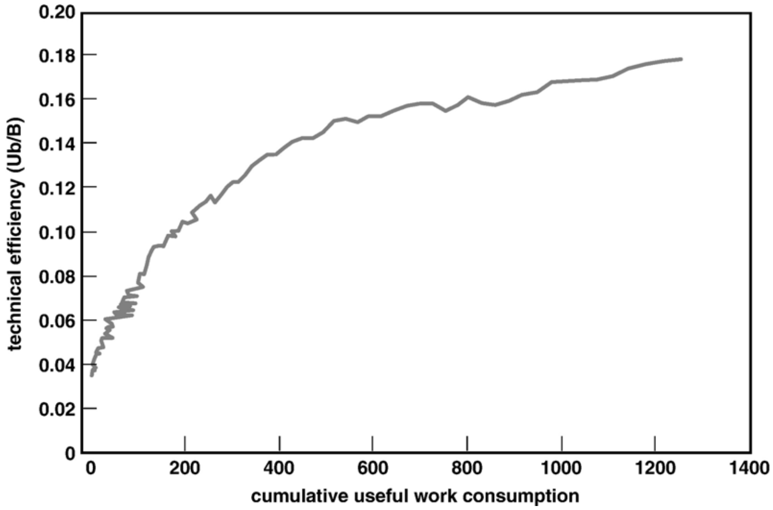

Fig. 4. Exergy conversion efficiency (f) vs. Cumulative useful work consumption, USA 1900–2000.

model can also be used to forecast the future, as illustrated graphically (for the US) in Fig. 6. This is not the place for a detailed explanation of the model. In any case the essential details can be found in journal articles or on the Internet [26–28].

Information technology has exemplified the feedback cycle and the rebound effect. Costs have fallen, prices have followed and demand has risen in consequence. But IT is not the panacea for the economy as a whole, unless it results in dramatically lower costs and increased demand for all of the other tangible goods and services that society needs. Up to now the applications of IT outside its own sector seem to be eliminating more jobs than it creates, but without significant corresponding impacts on consumer demand for products and services that would create more jobs.

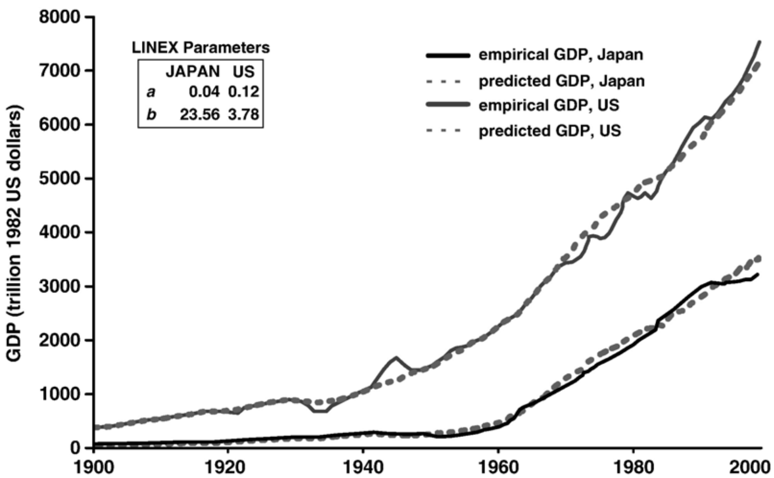

Fig. 5. Empirical and estimated GDP (using LINEX) of the US and Japan 1900–2000.

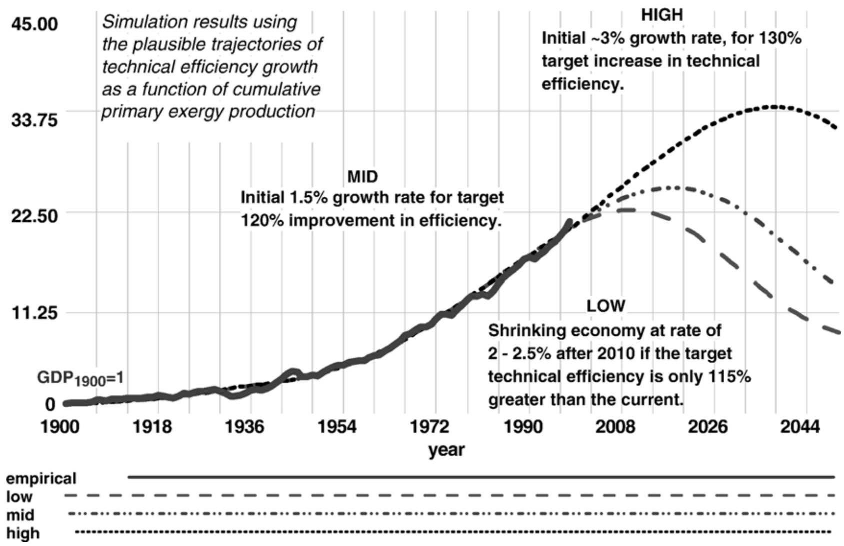

Fig. 6. Forecast gross output (GDP): USA 2000–2050.

All of these phenomena taken together, as in Fig. 6 above, suggest that US economic growth is almost certainly decelerating and could soon cease altogether. This pattern of slowdown is already visible in the other most advanced industrial countries.

4. Implications

The implications of a significant US slowdown or extended depression, accompanied by inflation, are frightening. I need mention only a few. We saw a preview of the impact of stagflation in the late 1970s. In that case, the "cure" was a sharp increase in interest rates, deliberately engineered by then Federal Reserve Chairman Paul Volcker, followed by a long decrease in oil prices from the 1980 peak. President Reagan, who had nothing to do with it, got credit for the 'recovery'. Of course, one consequence of the period of low oil prices in the late 1980s and early '90s was that investment in finding new oil and gas resources, as well as alternative technologies, slowed. The current problem is at least partly due to lack of investment in production and refining capacity. On the other hand, the high oil prices of today also reflect political instability in the middle east and, at another level, the fact that new discoveries have consistently failed to replace current consumption in the quarter century since 1980, and the gap is growing. It is hard to avoid the suspicion that the cost of finding new reserves will necessarily be rising rapidly, even as demand by China and India is also rising rapidly. The hope (by governments and industry) that near-term scarcity can be overcome by increased Saudi Arabian production may be disappointed.

The next time, we may not be so lucky. Oil prices will not drop unless, or until, demand drops, and that would happen only in the event of a major recession or depression. But the resulting drop in oil prices, even by a factor of two from present levels, is unlikely to be enough to re-start rapid global economic growth along the current trajectory. The existing sources of cheap oil will be showing clear signs of exhaustion and the "unconventional" sources, constantly touted by optimists, require huge capital investment. Capital outflows from the industrialized world for non-energy development will inevitably slow down.

Recent rapid Chinese growth has been financed largely by foreign investment and exports, mainly to the US. A collapse of the US economy would have disastrous effects on China (not to mention other exporting countries). Sudden or even rapid dollar devaluation would cut exports, and cut the financial assets of Chinese banks, many of which are already overloaded with non-performing assets. The impact on China might not be limited to economic distress. If, as usual, the worst pain is felt by those at the bottom of the ladder, (rusal peasants) there could be violent repercussions.

Cheap money to combat recession will increase the money supply and – without increased production of goods and services to match – will accelerate subsequent price inflation. Inflation favors existing debtors and hurts lenders. A cheap money policy by the Fed would help banks survive (as recently in Japan) but would not make banks more willing to lend to small businesses or individuals. Small savers would be hurt by such a policy, of course. Real interest rates are likely to be negative (as in the 1970s) for some time.

For industry, lower growth (or no growth) means reduced future profit expectations: and lower stock and share prices. Insurance companies will get into trouble. The so-called "wealth effect", operating in reverse, will cut the consumption of other goods and services, especially housing and tourism. That will also reduce employment and income, especially in places and countries that depend on visitors. Energy consumption will decline along with declines in long-distance tourism. If it happens too quickly it could trigger a wave of bankruptcies among energy producers who bet on a continuation of high prices, as well as major economic problems for petroleum exporting countries. The basic problem is that, just as growth in a feedback system drives more growth, similarly decline ("decroissance" to use the elegant French word) begets decline. If the growth engine goes into reverse, there may be no bottom to the depression, except through the intervention of exogenous events, such as war. Unfortunately a wider war for resources, pitting the Judeo-Christian West against fundamentalist and jihadist Islam, seems more plausible month by month.

Is the current malaise – to use Jimmy Carter's unfortunate but accurate term – reversible? Here is where my optimism reasserts itself. Yes, it is reversible. But it is reversible only if the approaching crisis is recognized for what it is and if appropriate actions are taken. It seems to me that the first and most important of the needed actions is to end the war in Iraq and to recognize that the "war" on terror cannot be won by military means, but only by promoting economic development, international law and religious tolerance. There are alternative energy technologies that can be further developed and promoted. If we do the right things the world will survive and will eventually recover from the foreseeable problems, thanks to statesmanship and cooperation on the part of political leaders (of which we see little current evidence). Global economic growth may begin again, as it did after World War II, but without the destruction. However, the hyper-inflation of the early 1920s followed by the boom, the 1929 bust, and the Great Depression, created many of the conditions that led to the Nazi takeover in Germany, encouraged Japanese militarism and resulted in World War II. It is to be devoutly hoped that nothing like that occurs in the coming decades.

5. Looking further ahead: is there a light at the end of the tunnel?

Nature has cycles, and so does the economy. In 1926, the Russian economist Kondratieff first called attention to a long cycle, of about 50 years, which has attracted much attention over the years [29–33]. In recent years the subject has emerged again from obscurity. Based on historical coincidence, long-waves have coincided with shifts in major energy sources, starting with the age of coal, followed by petroleum and gas – and, if that pattern were to continue – by 'something else', most likely nuclear energy technology e.g. [34].

According to one of the most popular timing schemes, a new cycle of growth, triggered by a cluster of nuclear energy-related innovations, should have started in the 1970s. The timing of the shift seems to have been confirmed by the peaking of US domestic petroleum output in 1969–70 and the global energy crisis of the early 1970s. The new upswing should have peaked 25 years later, around the year 2000. In that case, the subsequent period of decline would be well under way by now (2006). However, the 'age of oil' clearly did not end in the 1970s, and the widely expected rise of nuclear energy was aborted by reactor accidents in the 1980s [35]. The question might be raised as to whether the apparent linkage of long-waves to energy technologies in the 19th and early twentieth centuries was accidental and misleading, or whether the linkage was real but the K-wave became globalized after 1970, with a considerably longer cycle. In fact I am now inclined to lean towards the latter notion.

In short, the factors noted in the first part of this essay would seem to fit into a long-wave scheme, shifted in time, with an economic decline beginning soon and an upswing sometime after that, perhaps starting in the '30s. The upswing would presumably be driven by a cluster of energy-related innovations, induced by current trends and needs. It would be fun to discuss the possibilities individually, but it is extremely difficult to forecast the timing of specific breakthroughs, precisely because they depend upon discoveries not yet made. For that reason it seems more appropriate to look further ahead and consider the possibilities from a different perspective, namely sustainability.

6. Prerequisites of a sustainable world: c. 2100

First of all, to be sustainable the world must be peaceful and secure, under the rule of law. US power is declining and world peace will not be achieved by a 'Pax Americana'. Nor can it be imposed and enforced by any other single country (such as China). It will require some form of world government, and global law and police power, which means an end to the present age of "absolute national sovereignty" currently being cited in defense of their policies by North Korea and Iran. How that might be achieved in the course of the next century is not obvious, nor is it the subject of this essay. (The creation of the European Union offers a possible model, however.)

Sustainability by 2100 also implies an end to further environmental degradation. But that does not mean that today's environmental resources – notably climate, forests, soils and bio-diversity – can be preserved, any more than population growth can be stopped overnight. The degradation trend has quite a bit of momentum. It cannot be stopped suddenly. However, one very positive factor is that global population may peak and begin to fall as early as the middle of the present century, provided human life-spans are not dramatically increased meanwhile [36]. AIDS, declining male fertility and easy contraception are factors. But the basic reason is that, in an urbanized society with rising living standards, children are a luxury, requiring housing, food and education, whereas in poor rural societies they are free labor and a substitute for social security in old age.

But the conditions, including rural poverty and corruption, that encourage rapid deforestation in the tropics today will undoubtedly continue in Africa, Indonesia, Malaysia and South America for many years if not decades. Most of the remaining tropical forests will have been destroyed by 2050, resulting in the spread of deserts in Africa and a significant increase in temperatures (and fire hazards) in the Amazon basin. Much the same can be said of ocean fisheries, many of which – like cod – are already approaching, or have passed, the point of no return. Most coral reefs and mangrove swamps, nature's fish hatcheries, will have been destroyed by unwise coastal development, rising ocean water levels and rising temperatures.

Reforestation is fairly easy (even automatic) in some climatic conditions, especially in northern Canada, Alaska and Siberia where rising temperatures and nitrogen fertilization will both help. But it is far more difficult where forests have long ago been replaced by deserts, and topsoil has been lost to erosion, as in North Africa and the Middle East. Similarly, without the coral reefs and mangrove swamps, restocking the oceans with fish will be very difficult, even after competitive high-tech fishing is stopped, as must happen sooner or later. In short, environmental degradation cannot realistically be halted overnight. The era of sustainability, if it is to be achieved at all, will necessarily start after 2050 from a much more degraded base than we presently enjoy, worldwide.

Environmental problems in 2100 will certainly be far more severe and obvious than is the case today. Deforestation will have added more carbon dioxide to the atmosphere, and exposed more of the soil surface to direct heating by the sun's rays, especially in the tropics. Global warming will have raised average global temperatures by several (3–6) degrees Celsius, and more in the far north (although the Gulf Stream may no longer keep northwestern Europe mild). Nevertheless much of the permafrost in Alaska, northern Canada and Siberia will have melted, releasing methane to the atmosphere that will accelerate the global warming process. The Arctic ocean will have lost its ice cover, resulting in a further reduction in global albedo and a further acceleration of the warming process. Much of the Antarctic ice (e.g. the Ross Ice Shelf) that is currently resting on the sea bottom will have floated away and broken up. Depending on how fast this happens the sea level will have risen by at least half a meter and possibly 2 or 3 m rendering many slow-lying islands and coastal regions uninhabitable. Hurricanes and typhoons will continue to be ever more frequent and powerful as ocean surface temperatures rise.

By 2100 huge numbers of people will have been displaced from low-lying areas, by rising sea levels and natural disasters. This will happen especially in South Asia and East Asia, but also in other fertile estuaries, such as the Nile, the Amazon and the Mississippi Deltas. Northwest Europe will be hard put to protect itself from the rising seas, and much of Florida, the Gulf Coast and the barrier islands off the East coast of the US (including Long Island) will be flooded unless vast dike building projects are initiated almost immediately. Only the Dutch seem to have grasped the enormity of the problem. Those who survive the disasters will have become refugees. The problem of resettlement for environmental refugees will be a major challenge, especially in Asia.

Since much arable land in low-lying regions will be flooded, or subject to flooding during frequent storms, and most of the remaining good farmland is already occupied, there are only two possible destinations for the refugees. Most of them will end up in Asian cities. But the other possibility is large scale reclamation and resettlement of deserts. There are plenty of deserts in the world that were formerly fertile and could be fertile again. However reclamation will require large quantities of fresh water, and fresh water is already scarce. Moreover, several areas are currently being irrigated by pumping "fossil" water from the ground, that was left over from the melting of the glaciers. The Ogallala aquifer in the western US is an example. It was created by the melting of a glacier that formerly covered Wyoming and the northern Rockies. The Great Salt Lake of Utah is all that remains on the surface. Now the underground water is being pumped and used to irrigate areas in west Texas, Oklahoma, Colorado, and Nebraska that do not have enough natural rainfall to support agriculture. But the Ogallala underground water is not being replaced and it will be mostly used up by 2100. What then?

In short, one of the conditions for sustainability by 2100 is that a great deal of fresh water will have to be transported by canal or pipeline from areas with excess rainfall – such as southern China, southern India, Bangla Desh or northern Australia – to areas with too little rain, such as northern China, Rajasthan, the Indus valley and central Australia. To irrigate bigger areas, like the Sahara and the Gobi, will be a much more difficult task. Water from Siberian rivers, diverted to the south, might make the Gobi fertile, but the engineering involved would be daunting. Irrigating the Sahara will require either pipelines from the Niger River, or very large desalination plants located on Mediterranean coast, or the Atlantic coast. The interior of Australia could be irrigated by a combination of canals (from the north) and desalination plants. Indeed, a global water distribution system will have to be built, eventually. All of these solutions will require steel for pipes, and energy for pumping, in large amounts. This will also require international cooperation.

Iron is not scarce, and steel will not be scarce by 2100. Today the global steel industry faces over-capacity. It needs markets. Luckily, there is also a potential solution to the energy problem. Empty landscapes such as the world's deserts are ideal locations for wind turbines and photovoltaic (PV) cells. Later, PV technology may be established on the moon, where solar energy is available in large quantities. The photovoltaic (PV) cells can be manufactured on the moon itself from lunar materials, by robotic factories remotely tele-operated from the Earth [37,38]. Moreover, the standard problem for both wind and PV, namely that the energy output depends on an irregular input (of wind and sun) is not a problem for a desalination plant. Desalination need not be continuous.

Moreover, well before the year 2100, the vexing problem of medium-to large scale energy storage, for which rechargeable batteries are the only current (and unsatisfactory) answer, can probably be solved. There are at least two possible technical solutions. The first is by means of magnetically levitated high-speed flywheels, buried for safety in reinforced concrete underground vaults (for which obsolete missile silos would be appropriate). The other solution, better suited to small scale and local users, would be in superconducting magnetic fields, using newly developed quaternary ceramic or even organic superconductors, cooled by liquid nitrogen. Superconducting magnet storage would be well-suited to store energy from wind turbines located (for instance) on remote mines, farms or pipelines.

An international electric power grid is also part of the solution. Power will have to be transported from areas with surplus generating capacity, such as the Andean headwaters of the Amazon and the Himalayas, to the big cities on the plain where most consumers (and industries) are located.

Adaptation and mitigation (such as dam and dike construction) will require major investments, probably comparable in magnitude to those currently devoted to military power. Moreover, the projects involved will not only be costly, they will require international cooperation. Virtually all of the major investments needed will not generate high financial returns, at least in the early years, and will require public sector financing.

7. Sustainability at the household level

A sustainable world in the year 2000 will certainly require much more per capita energy (exergy) consumption globally than today. But exergy consumption in the US and Western Europe must also be significantly decreased [39,40]. It will require even more draconian cuts in the consumption of liquid hydrocarbon (or alcohol) fuels. This precludes any vision of a private jet or several large SUV's in every garage. In fact, travel will be much more expensive (and less pleasant) than it is today. On the other hand, electric power will be plentiful and affordable. Most energy consuming activities will utilize electricity, some of which will be transmitted by microwaves from the surface of the moon, or from orbiting solar satellites. Nuclear power will have a significant role, but so will hydroelectric power, wind power, tidal power, terrestrial PV on roofs, coal gasification (for hydrogen) and alcohol fuels obtained by genetically engineered enzymes from waste biomass, especially lignin wastes.

Apart from transportation, urban lifestyles will not differ dramatically from current patterns in upper middle class areas. Population density will almost certainly decrease, even in South Asia, as birth rates continue to fall. But the decrease will be much more dramatic in Western Europe, North America, Japan and China. Only a few adults will choose to be parents, because of the high cost of education and upkeep. Children will constitute a much smaller segment of the population, whereas older people – healthier than today – will constitute a much larger fraction of the population. Children, being scarce, will be supervised and cared for better than they are today. Street crime by gangs of neglected youths will gradually disappear.

A declining global population will be reasonably well fed, though on a much less animal-based diet than the rich countries enjoy today. Obesity will gradually decline. This shift towards vegetarianism will occur spontaneously, thanks to health concerns and environmental factors. Most agriculture will be devoted to food for humans and not for animals. Grain fed beef, in particular, will become much more expensive, followed by pork. Non-farmed fish will also be an expensive luxury, as ocean fishing rights are privatized, regulated and closely monitored by satellites. Fish farming will expand to fill the gap, however, and the environmental impact will be better controlled than it is today. Much of the land that has been cleared for cattle in recent decades will have been abandoned, reforested and used for lumber, paper pulp and bio-fuel.

Living quarters in central cities will, on average, be considerably larger than today (per capita), and they will be well furnished, but kitchens and bathrooms will not be very different from those now seen in upper class suburban homes. Robotic servants for cleaning and cooking will be available, but otherwise life in Western Europe, North America and Japan will not be very different from current patterns. Single family homes in distant suburbs will, however, be much more expensive to own and maintain, as a fraction of total personal income, than today. Only the very rich will be able to live far from public transportation. Life in Chinese and South Asian cities will resemble life in prosperous parts of Hong Kong and Singapore today, but housing will necessarily be concentrated primarily in high rise multi-family structures.

Agriculture will be mostly corporate-owned and mechanized, for production of major grain and other staple crops such as rice, wheat, corn and soya beans. Managers will live in towns, often as much as 100 km from their fields, and their tilling and machines will be tele-operated. Services such as fertilizing, pesticide spraying and grain harvesting will be mostly carried out by specialized subcontractors. Only fruits, vegetables, dairy products and highly specialized niche-products will be grown by owner-operators using (some) human labor. However sophisticated robots will be able to do some – but not all things – things better than humans.

Manufacturing will be largely robotic or automated and almost totally controlled by computers. Construction will also be largely robotic, using prefabricated components. Design, marketing, maintenance, repairs, renovation, recycling and waste disposal will employ some human workers. Food production will also be highly mechanized, except for specialties. Education, entertainment, the arts, health care, environmental protection and security services will be by far the largest employers.

Coal mining will continue in 2100, albeit mainly carried out by robots and highly automated machines. Conventional oil and gas production will have largely disappeared, but there will be some extraction of bitumens, tar sands and oil shale. Iron ore will still be mined in a few places. Bauxite and phosphate rock will still be mined, but a significant share of aluminum production will be based on other minerals like clay. Most other non-ferrous metals (copper, zinc, nickel, lead, etc.) will no longer be readily obtainable from terrestrial mines. However, undersea mining of the so-called manganese nodules will be carried out by robotic submarine dredges.

Fresh potable water will be a much more costly commodity than it is today. It will not be free or unmetered in most places. But new technology will enable cities to treat and recycle sewage water to a level of quality higher than natural springs or ground water offer today. (It will take many decades before the public is willing to accept recycled water on tap, even though astronauts do it routinely. However the current fad for bottled 'natural' spring water is likely to peak and decline before 2100.)

Urban trash will necessarily be collected, separated and recycled much more completely than today. The collection systems – like Germany's 'Green Dot' – that have been put in place in northern Europe already provide the basis for future evolutionary development. Metals will be recycled much more intensively than today. Iron and steel, aluminum and copper will approach a 90% recycle rate (especially after the technology for removing trace contaminants, such as copper, from recycled steel is finally developed). Electronic goods (TVs, PCs, cell phones, batteries, etc.) and electrical goods will be collected and recycled much more intensively, to recover the scarce metals, especially platinum, gold, copper and rare earths, that are embodied in them. Deposit fees will create significant incentives for returning used goods for recycle to the place of purchase.

Transportation is the area where the most radical changes will be necessary. Private automobiles will be smaller and more fuel efficient than today – partly because families will be smaller – but the average private vehicle of 2100 will not be radically different in appearance or performance from the best that can be envisioned today. Light metals (possibly even magnesium), fiberglass and composites will largely replace iron and steel in the body and chassis. Electric motors in the wheels will provide the motive power, and fuel cells will (most probably) provide the energy. Hydrogen production (by micro-organisms or electrolysis) and storage (probably in hydrides or carbon nano-tubes) will replace the present system of hydrocarbon-based propulsion power for vehicles (like taxis or buses) operating strictly within densely populated urban areas.

Given other needs for food and housing, there is not enough surplus land in South Asia, or China to create a highway system (with parking) devoted to privately owned vehicles comparable to those enjoyed now in Europe and North America. Bus service can be improved by allocating special lanes to such vehicles. Conventional trams and underground rail systems are gradually expanding in the biggest cities, but they are extremely expensive to build. Large scale car-sharing is another and cheaper alternative. The technology and organizations already exist and they can be significantly improved. All that is needed is strong support from local governments, primarily by providing preferential parking.

For longer intermediate distances, high speed rail is proving to be a very attractive alternative to both private cars and air travel, in both Europe and Japan. However the present steel-wheel on steel rail systems should eventually be replaced by mag-lev systems, based on aluminum guide-ways and external electric propulsion. Such systems could transport large numbers of people at 300–500 kph with electric power consumption around 10% of present day electrified railways.

Will a low-energy, low growth future mean "freezing in the dark" as nuclear power advocates 30 years ago accused anti-nuclear activists of proposing? The answer is clearly 'no'. The GDP per capita of North America, Western Europe and Japan in 2100 might only be two or three times what it is today. Industrial output will be sufficient, but there is no conceivable need for enormous increase in materials processing or energy consumption in the industrialized countries. Buildings do not need to be replaced every 10 years or even every 30 years. Infrastructure lasts much longer. Many current jobs will disappear. Energy services will be much more expensive than presently (as a fraction of income) but many other services will be cheaper. Many fewer workers, working fewer hours and years, will earn enough money to live quite well, even by current standards.

Economic growth will continue to be much faster in the non-OECD countries, as they gradually catch up to western levels. But the pattern of that growth will necessarily be different, and the materials and energy intensity of that growth will necessarily be significantly lower than we see today.

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