The Nexus of Population, Energy, Innovation, and Complexity
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"Abstract. For the past 200 years, humans have benefited from the abundant, inexpensive, and easily obtained energy of fossil fuels. Energy surpluses such as this are unusual in human history. In systems with little surplus energy, population growth is low and complexity emerges slowly due to the energetic costs it carries. On the rare occasions when energy is readily available, societies respond by growing rapidly. They must become more complex in response to the social, economic, and resource challenges of dense population. More complex societies are more expensive, requiring greater energy per capita. The process of increasing complexity necessitates greater energy production, creating a positive feedback cycle. Past societies have collapsed under such pressures. Population and complexity grew rapidly when the Industrial Revolution replaced economies based on annual solar radiation with economies fueled by fossil energy. The Green Revolution of the 20th century is credited with preventing mass starvation, but it has made food production and sustaining population ever-more dependent on high-energy (low- entropy) inputs. Some believe innovation will overcome the limitations of resources and permit unchecked growth. However, increases in complexity, innovation, and fossil energy are all subject to diminishing returns, and cannot continue to support population at current levels."

-human population has tended to be seen as a function of food supply and subsistence of population pressure
-a growing related concern is how many humans can our planet support without irreparably harming its ecosystems
-this research has led to the formula that environmental impact is a function of population, affluence (i.e., consumption level), and technology
-this article builds on this by arguing population is linked to energy, societal complexity, energy gain, and innovation

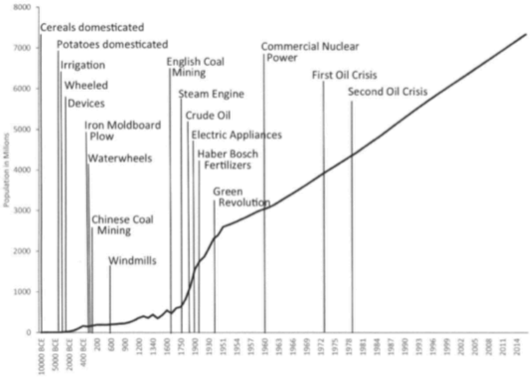
-increased population densities tend to increase societal stress and is addressed primarily through an increase in complexity (e.g., maintenance of order, security, and supply provisioning)
-complexity requires energy, and as a society increases in complexity more energy is required per capita
-this complexity can only be sustained when the net energy is high enough
-the non-renewable/finite energy our complex societies depend upon tend to have the easiest-to-access/least expensive sources used first with the net energy that supports our complexities declining over time
-while technology and innovation can help offset some of this loss early on these aspects of problem solving are subject to diminishing returns, becoming more costly and difficult in terms of resources, especially energy, as time passes
-"Exploring these factors in combination raises questions about whether population, affluence, and technology can be sustained at their current levels, let alone their current trajectories." (p. 1006)
-human societies (in fact, all living systems) are significantly influenced by energy inputs for their subsistence, organisation, and regulation
-adaptive systems also need energy for learning and problem solving
-complexity provides benefits but also has costs in its underpinning of societal systems (e.g., economic, political, and material)

-solar energy falling upon the planet sustained human subsistence (at a 2000-2500 calorie level) up until just a handful of centuries ago
-human energy use per capita appears to have peaked in the mid-1970s around 230,000 calories
-modern life's heat, power, and lighting are provided primarily via hydrocarbons; even our food production has come to depend upon them, with approximately 10 calories of hydrocarbons used for every 1 calorie of food production
-the current global population and its complex societies are sustained via hydrocarbons
-Malthus believed that food was human population's limiting factor and it is still central to societal stability, but his view of impending crisis due to food limitations has yet to materialise
-the tension that exists between Malthus's view and those who hold that technology and innovation allow us to forever overcome resource constraints can be resolved by viewing the issue through the nexus of energy, complexity, population, and innovation

Energy and Growth
-Lotka argued that evolutionary advantage went to human and ecological systems that captured and used the most energy
-Odum extended this idea and named it the Maximum Power Principle
-this principle explains "why surplus or inexpensive energy is quickly used, and why rapid growth and change occurs as a consequence." (p. 1008)
-such energy availability is very rare which explains why human societal change has been relatively slow/gradual for millennia
-when rare energy windfalls have occurred, they've led to major societal shifts termed 'revolutions'
-Home erectus's harnessing of fire may be the first example in controlling an exogenous energy source
-it provided heat, light, security, and the ability to cook food–and possibly led to an increase in brain size and the development of cooperative behaviour, language, and improved cognitive functioning
-the adoption of sedentary agriculture allowed for an increase in calorie output per unit of land compared to nomadic hunting and gathering
-the use of draught animals furnished more power to human societies as it allowed the use of calories from plant matter not edible by humans
-prior to the Industrial Revolution, agriculture occupied about 90% of human economic activity with most energy production feeding back into food production; thus growth of the population and economy were slow
-when New World, high-caloric foods were adopted globally, population growth increased dramatically
-changing practices (e.g., crop rotation, land drainage, new ploughs) also led to intensified food production and a doubling of population from 1571-1686, then again by 1831
-expanding transportation networks helped to support non-agricultural population and labour began shifting to cities
-coal energy powered these changes for the most part
-the size of the human system grew, as did the energy use per capita and material standard of living
-coal-powered machinery increased production per unit of labour
(See Figures 1-3 below)
-the additional work provided by hydrocarbons has been referred to as 'energy slaves'; it's been estimated that 16 energy slaves per person existed in 1940; in 2011, that estimate was 89 per person
-the labour savings has contributed to affluence and prosperity, and explains why human slavery mostly disappeared after the Industrial Revolution began
-as the IR proceeded, energy and population reinforced each other with an increasing population requiring more energy which in turn helped increase food distribution and general wealth

Figure 1

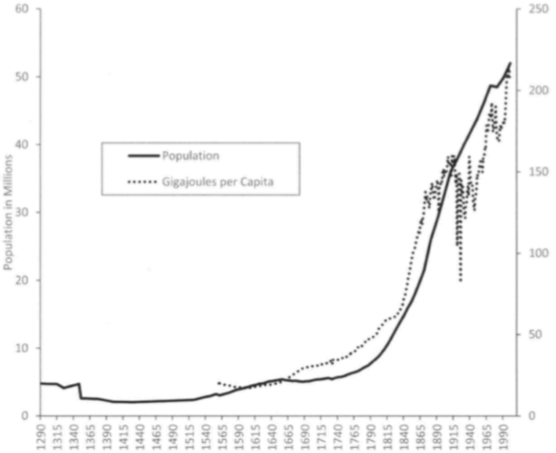
Landmark Events in the History of Population Growth and Energy Use



Sources: Smil (1994: 259–267); U.S. Census Bureau (2013).

Figure 2

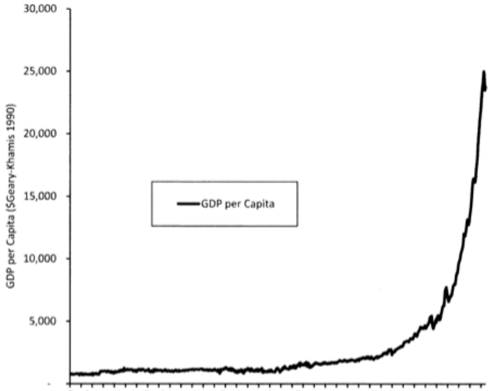
Population and Energy Consumption per Capita



Sources: General Register Office (1950: 22); Wrigley et al. (1997: 614–615); Warde (2007: 131–138); Office for National Statistics (2011); Broadberry et al. (2015: 20).

Figure 3

GDP per Capita



Sources: The Maddison Project (2013); Broadberry et al. (2015); Fouquet and Broadberry (2015).

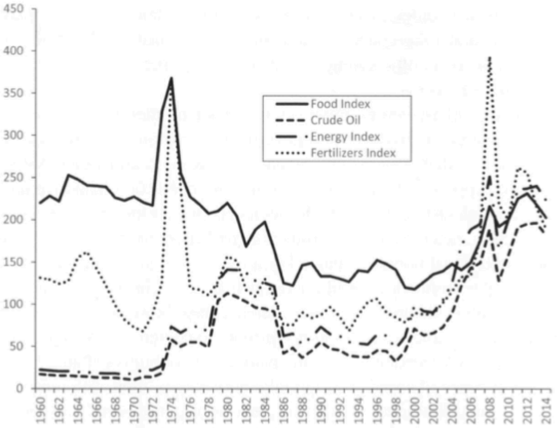
-productivity increased and the use of machines decreased the degree to which human/animal labour was required, allowing more food to go towards non-agricultural populations
-agricultural production was greatly intensified along with new practices and technology
-the limits of land became a focus prior to the IR when Malthus was concerned over how population increases could be supported
-hydrocarbons have for 150+ years reduced the pressures of population growth

Energy and Food
-population growth and food supply became a concern again during the early 20th century
-applied science, technology, and engineering helped humanity once again avoid a Malthusian crisis
-Borlaug tested and then introduced better crop varieties, hydrocarbon-based fertilisers and pesticides, and farm mechanisation but warned that population growth would inevitably undo any gains
-the food production gains were aided by the Haber-Bosch method of synthesising ammonia and converting it to fertiliser
-cash crop production soon replaced subsistence farming but this Green Revolution has been criticised for contributing to soil erosion, groundwater depletion, environmental contamination, and reduced biodiversity

-for this research, it is the chaining of food production with hydrocarbons that is of prime importance
-everything from fertilisers and pesticides to irrigation and planting and harvesting machinery to distribution of food is now dependent upon hydrocarbon inputs
-while innovative science helped avert a growing hunger crisis, it introduced a new energy addiction
-as with industrial production, food production is now reliant upon energy subsidies and has raised the risk of hunger for more people (see Figure 4)

Figure 4

Price Indices for Food, Oil, Energy, and Fertilizers



Source: World Bank Global Economic Monitor (2015).

-the energy crisis of the 1970s and financial crisis of 2008 both impacted energy and fertiliser prices, demonstrating the connection between the energy and food economies

Energy and Complexity in Society
-growth in population is one aspect of human societies, another is its complexity, and by this is meant more types of parts; that is, structural differentiation where specialised behaviour/roles grow
-the various systems' organisation can also grow, adding complexity via increased institutions and norms
-our modern societies are defined by high complexity with a lot of specialisation
-large human societies often respond to problems/stressors by adding complexity be it more complex technology or establishing new institutions/bureaucracies with diverse structure and function
-complexity carries costs, that are currently subsidised by hydrocarbons
-in subsistence economies, complexity was funded via small, irregular agricultural surpluses
-greater complexity required more work, but such intermittent surpluses restricted growth in complexity
-modern society funds complexity via various energy proxies (e.g., time, money, materials), but as hydrocarbon limits are being encountered thai funding is becoming strained

Thermodynamics and Resource Limits
-the extraction, refining, and recycling of material generates entropy–a dissipation of usable energy
-there exists limits as to what energy can do; some material is always lost in recycling and that produced cannot provide the same quality as the virgin stock due to degradation
-there are no substitutes for some resources and some critical ones are already nearing the end of their recoverable reserves
-phosphorous is one such mineral; although abundant, there is no known substitute and little recycling
-it is essential to all living cells and could be a bottleneck for food production given its importance to fertiliser

Energy Gain and the Energy-Complexity Spiral
-resources (especially energy) are required to obtain resources
-it is the ‘net’ gain that is of importance to humans and has impacts upon population, land use, and resource consumption
-high-gain systems have a high output compared to input with a steep thermodynamic gradient, high initial organisation (low entropy), and with high resource change with use
-systemic organisation requires little effort due to the steep thermodynamic gradient; resource capture is high, simpler, and less costly making benefits high and allowing population to grow and become dense and concentrated (see Figure 5)

Figure 5

Social Consequences of High-Gain (Low-Entropy) and Low-Gain (High-Entropy) Systems

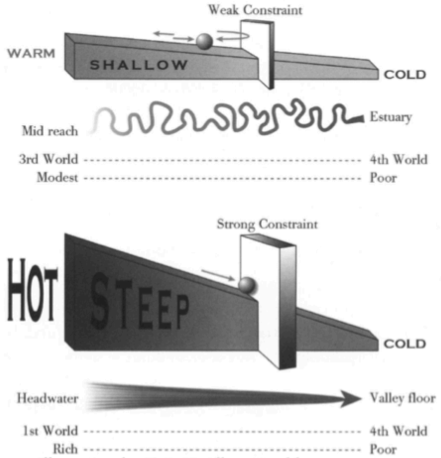
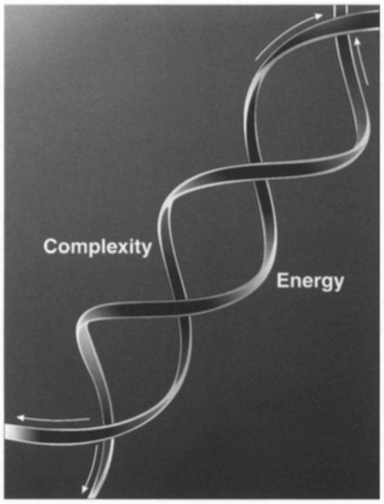


Illustration by T. F. H. Allen. Used by permission.

-a low-gain system may have more resources available but they tend to be widely dispersed making them more costly leading to very slow population growth
-gain, however, decreases over time with the easiest-to-exploit resources used up first; technological innovation that aids exploitation demonstrates their greatest impact initially with subsequent increases being adaptive to help maintain flow as stock dwindles
-shifting into a high-gain phase results in rapid growth with positive feedback where populations can grow and innovation speeds up
-energy is the key input for all resource acquisition, including energy itself
-an important concept concerns the energy-return-on-energy-invested (EROEI) and reflects the net energy gained
-gaining more energy requires increasing complexity and vice versa (see Figure 6)
-as complexity grows, more energy is required and when abundant energy exists, complexity increases and producers increases in scale (e.g., population size and density)
-over time, however, diminishing returns are encountered and despite additional inputs, fewer outputs occur
-there is a propensity to use the easiest-to-obtain and best quality resources first–known as the best first principle
-as these resources diminish in quantity and quality, the system shifts from a high-gain one to a low-gain one
-for oil, this means deeper wells, offshore platforms, tar sands, etc.
-solutions to problems begin with the least expensive and most easily implemented; the result is increased complexity and costs

Figure 6

Symbiosis of High Complexity System and High Energy Inputs

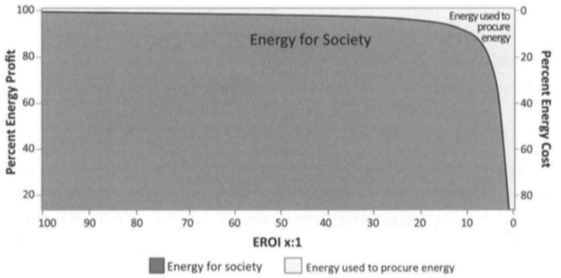


-"As the most efficient solutions are employed, complexity begins to yield smaller returns on investment. If complexity grows faster than the resources available to support it or to make it worthwhile, societies can no longer sustain themselves. When a society enters a phase of diminishing returns to complexity in problem solving, it becomes increasingly vulnerable to collapse." (p. 1023)
-societies thru history have had to confront the energy-complexity challenge
-Rome, for example, expanded exponentially for several centuries appropriating resources and labour creating a high-gain situation in which conquered lands and people subsidised the Empire; eventually, however, such conquests became unprofitable and difficult/impossible to continue
-by about 100 AD expansion ceased and funding had to rely upon annual solar energy with little to no surplus per capita; it had become a low-gain system; when crises arose in the 3rd century AD, Rome responded by increasing complexity and thus costs funded via increased taxes leading to decreased living standards and land abandonment
-Mayan civilisation similarly encountered diminishing returns and addressed them via increased complexity; complex hydraulic engineering attempted to counter drought; alongside this were increasingly complex rituals but both became more costly over time and eventually experienced a significant demographic collapse
-modern society is similarly attempting to deal with energy resource decline and negative consequences via increased complexity using ever-increasing amount of our finite, high-gain resources

Diminishing Returns and Minimum EROI
-the energy returns from hydrocarbons was high in the past but has been steadily falling
-in the US, the EROI for oil was about 100:1 in the 1940s, 20:1 in the 1970s, and about 15:1 at the time of the writing of this paper
-hydropower has been gauged at about 100:1 but all the best sites have been developed
-electrical generation via wind is about 18:1, solar photovoltaic about 6.8:1, nuclear provides a range of 5-8:1, and sugar ethanol near 10:1 while corn ethanol is close to 0:1
-industrial society has been estimated to require at least 3:1 to function and the lower EROI of an energy source, the less available to society (see Figure 7)
-any energy source below about 8:1 is an issue for society and its problem solving via complexity

Figure 7

The "Energy Cliff": Rapid Fall in Usable Energy as Energy Return on Invested Energy (EROI) Drops Below 8



IPAT

-Ehrlich and Holdren developed the formula impact = population x affluence x technology (IPAT) to help determine the causes of the environmental impacts of human activity
-the formula has been criticised for its oversimplification, particularly the focus on the environment to the detriment of other factors of importance (especially complexity)
-Ehrlich and Holdren believed population was the primary factor with it, therefore, holding the most potential for mitigating consequences upon the environment–controlling this is a very divisive topic
-affluence is unlikely to be willingly decreased; in fact, most argue for its general level to be increased
-this leaves technology, yet it is viewed as the silver bullet to 'solve' our resource issues
-while it can mitigate somewhat via improved efficiency, these gains (due to increased affluence and/or population) have not been able to offset consumption gains

-most technology has been created to conserve labour, not energy and/or materials
-some efficiencies shift consumption from the end-user to earlier in the production process
-there is also Jevons Paradox where more efficient products lead to more of them being consumed (Jevons first noticed this with coal use)
-cornucopians believe that the successes of the past century or so in countering resource concerns can continue forever

-Simon Kuznet's world is often cited as proof of this
-he argued that as economies develop, inequality and environmental impacts increase at first but then fall once income reaches a certain level; he did not believe unlimited growth was possible but that a self-correcting mechanism would bring a balance that was indefinitely supportable
-he believed industrialisation (especially of food production) was necessary for this
-it is a theoretical curve that depends greatly upon hydrocarbons

-Julian Simon is also a technological optimist who argued limiting population was morally reprehensible
-he acknowledged energy was the master resource but that human ingenuity and adaptability was the ultimate resource and that scarcity would result in higher costs that would lead to conservation, recycling, resource discovery and substitution; thus, population growth and resource limits were nonsensical concerns
-he held that human progress was a constant, particularly via technological breakthroughs; he ignored instances of growth/sustainability being thwarted by resource constraints laying the blame for failing societies for their lack of ingenuity

Diminishing Returns of Innovation and Education

-science began via observations of nature and home-grown experiments by scholars, philosophers, and laymen but as the questions became more challenging, the research became more complex and costly (e.g., research facilities with expensive equipment, administrative bureaucracy and more staff, lengthy education and interdisciplinary teams)

-innovation is subject to the same increasing complexity and diminishing returns of other activities

-the easiest and least costly discoveries occur early in a field with subsequent breakthroughs being more difficult, taking longer, and costing more

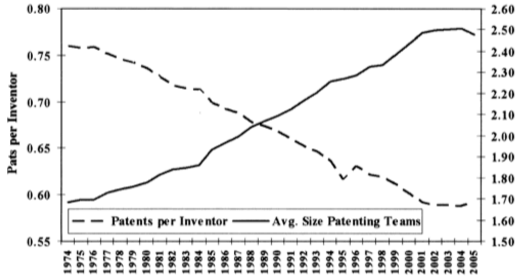
-a proxy for determining if increasing complexity and costs yield proportionate returns in research in patenting and it has shown falling patent numbers per inventor for the last few decades

-data suggests innovation peaked in the 19th century and has been declining since (measured by technological developments per capita)

-innovation has encountered diminishing returns, yet the rate of investment has escalated, increasing more than 10-fold between 1950 and 2000 in the US, reaching its highest level in terms of GDP share in 2016 alongside class for significant increases in the number of STEM graduates (see Figure 8)

Figure 8

Declining Productivity of Innovation as Measured by Patents per Inventor (after Strumsky et al. 2010: 502)

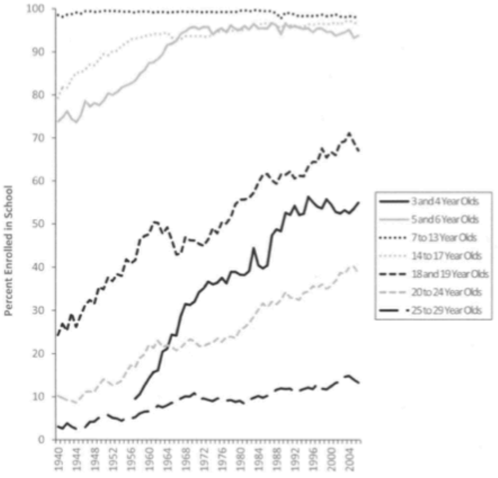


-education plays a critical role in support of innovation and mastery of important topics/fields requires increasing time given knowledge growth and/or much greater specialisation

-educational attainment has never been higher with a concomitant increase in the costs for this (see Figure 9)

Figure 9

Percent of Children in the United States by Age Group Enrolled in School (1940–2013)



Source: U.S. Department of Education (2015).

-these costs continue to increase as the returns to knowledge production decrease

-"there is not sufficient support for technological optimism and the idea that technology will forever overcome resource limits. Whether technology is seen as a positive or negative influence in the IPAT formulation, it will not fulfil its expected role in reducing the effects of population and consumption." (pp. 1032-1033)

Population and a Lower-Gain Future

-hydrocarbons have created a levee effect (i.e., flood protection projects tend to result in more damages due to overconfidence and development in vulnerable areas placing more people and structures in harm's way)
-society has been buffered from natural limits and led to a sense of security where population has expanded significantly placing more at risk
-as a finite resource, this security can only be temporary
-the planet's carrying capacity is a function of biogeophysical reality as well as one of society influenced by our expectations and choices
-biogeophysical aspects cannot be controlled due to thermodynamic and biological principles
-societal aspects consist of our problem-solving strategy of increased complexity but is impacted by diminishing returns
-"Innovation can relieve some pressure on the environment and resources, but it is also subject to diminishing returns. Even if technology could compensate for reduced energy gain and population growth, complexity and its costs would continue to rise. As the amount of energy dedicated to complexity increases, the share of energy available per person dwindles." (p. 1033)
-we have the most influence over population of the energy, complexity, population, and innovation nexus
-how many people can be supported depends upon a number of variables such as resource distribution, risk, equity, and environmental impact
-it's estimated that ecosystems could remain functional were we to use 10% of current energy consumption
-much lower population numbers of the past relied upon biomass to provide low per capita energy needs
-sustaining 7+ billion with natural biomass is impossible and likely challenging for 'renewables', and as resources become more scarce the use and allocation of them will need to be much more purposeful
-without our high-gain hydrocarbon system far fewer humans can be supported
-a future of lower energy gain is inevitable given declining EROI and may increase the need for problem-solving complexity while the capacity to support it fades (especially with increasing amounts of energy required to supply energy)
-we will need to collect energy from dispersal sources and have more of our economy directed at this task
-this may require a reversal of urbanisation
-energy transitions are difficult, take time, and there are no high-gain alternatives to hydrocarbons on the horizon
-the success we've had in feeding an exploding population is due to hydrocarbons and their impact on fertilisers, agricultural intensification, and distribution
-"Diminishing returns of net energy and innovation make it doubtful whether we can produce sufficient food to support the current population or projected population growth over the long term." (p. 1034)
-past populations and economies were not able to approach our current sizes and growth rates using daily solar energy
-the potential carrying capacity of our planet may continue to be somewhat elevated given the knowledge and innovations we've developed but without a high-gain energy system our standards of living and population cannot be sustained

Conclusions

-population issues have tended to be viewed from the perspective of food supply, and occasionally energy
-the authors suggest progress can be furthered by viewing them via the nexus of innovation, energy, complexity, and population
-the high-gain energy provided by hydrocarbons has helped our population to explode the last two centuries
-this has resulted in stress (e.g., social, economic, resource depletion) that is addressed via increased complexity that requires increasing amounts of energy (referred to as the energy-complexity spiral)
-the resource depletion that results has been offset by innovation
-the easiest and least costly 'solutions' are arrived at first but over time innovation encounters diminishing returns leaving harder, more costly problem solving that takes longer and is increasingly inefficient
-excess energy is a rare occurrence for biological systems but when it does occur, the system in question grows
-humanity's past has only a few such instances, the Industrial Revolution being one that began with the use of coal but then shifted to oil and gas that witnessed an exploding population, rapid growth in complexity and high rates of innovation
-the resulting change is anomalous in human history
-most of human societal changes have occurred gradually as a result of our problem-solving strategy of increasing complexity in a world of limited energy to support shifts
-with inexpensive and abundant energy, quickly increasing complexity is not a burden; however, as inexpensive solutions dwindle in the capacity to address new problems, complexity takes on increasing costs due to diminishing returns
-in the past, when a complex society's problems exceeded the ability of a solar energy-based economy to support them, the society 'collapsed'
-modern societies and their complexities have grown and been sustained by hydrocarbon subsidies with energy shortages being mostly avoided due to innovations
-while efficiencies are helpful they cannot counter growing consumption, populations, diminishing returns, and falling EROI
-"Innovation is not a sufficient strategy for the long term, and the growth of population works against efforts to reduce fossil fuel dependency." (p. 1036)
-there existed around 600 million humans at the start of the IR with none living anywhere close to the energy-intensive lives of today's advanced economy citizens
-in Malthus's time, the limit was food supply; in modern times, the limit is hydrocarbons
-a spiralling energy-complexity system experiences increasing costs as accessible energy resources dwindle and the production of energy takes an increasing slice resulting in falling EROI and net energy
-this challenge is compounded by other emerging problems such as: disease, climate change adaptation, war, poverty, inequality, etc.
-the world's population is vulnerable to the diminishing returns impacting our complexity, innovation, and energy
-if we can reduce our population, we must also live below the limits of energy supply
-we are, unfortunately, driven to exploit energy when it is available making any 'solution' exceedingly complex