Energy Policy ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Energy Policy

journal homepage: www.elsevier.com/locate/enpol

# There's nothing much new under the Sun: The challenges of exploiting and using energy and other resources through history

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HIGHLIGHTS

- Standard economic growth theory exemplified by R. Solow's work focuses on labour and capital, ignoring natural resources.
- The exploitation and use of natural resources, especially energy, over many thousands of years is examined.
- The claim that only labour and capital need be considered in standard economic theory is shown to be a travesty of reality.

article info

*Article history:*
Received 28 October 2014
Received in revised form
13 January 2015
Accepted 14 January 2015

*Keywords:*
Economic growth
Sun's role
Energy's role

abstract

The links between economic prosperity, or lack thereof, and the exploitation and use of energy and other natural resources go back to the earliest records of the human species – and in important respects even further back to when hunting and foraging characterised the earliest humanoid species. This paper surveys the challenges of resource exploitation and use, reflecting that as we exploit the most readily and cheapest resources, and extraction technology, available at the time, so the marginal returns of each tend to decline as the highest quality is depleted, costs rise, and alternatives are increasingly sought. There are few resources where this is truer than the various forms of energy which have been exploited down the ages. Many complex societies in the past have failed to make a successful transition, and the historic record demonstrates clearly the inadequacies of Solow-type growth theory. Scenarios of global energy prospects for the 21st Century need to consider the past and, in the light of it, ask whether the end of the Anthropocene Age is in sight or whether some kind of Promethean leap will come to the rescue.



## 1. Introduction

In January, 2014, this journal published a Special Issue on “Oil and Gas Perspectives in the 21st Century”. The Special Issue contained a paper by Robert Ayres and Vlasios Voudouris: “The economic growth enigma: Capital, labour and useful energy?” in which: they discussed the failure of neo-classical growth theory to take adequate account of energy and other natural resources; consideration of the concept of “useful energy”; and the inadequacies of the first law of thermodynamics (which some have interpreted as energy cannot be wasted or destroyed, but only converted). Robert Solow is principally associated with the standard neo-classical theory of economic growth, and here we consider his assumption that the growth theory need consider only two factors of production – labour and capital – against historic evidence and the realities of human existence. Admittedly, Solow in his famous paper on this subject began it by stating: “All theory depends on assumptions which are not quite true” (Solow, 1956). The weakness of his case lies principally in his ignoring of energy and other natural resources because they contributed little to national accounts in monetary terms. The reality is that human existence and material progress have been heavily dependent upon the exploitation of natural resources, and particularly of energy, from the earliest times – not just since the Industrial Revolution. Our ability to draw on larger and more concentrated supplies of useful energy (mainly from finite fossil fuel resources) has increasingly powered growth over the past 250 years, but the basic principles go back to the mists of time. A key question is: given the world's finite resources and limitations of renewable resources, how well is the human race positioned to cope with a human population anticipated to rise to nine billion by 2050, and possibly to over twelve billion by 2100?

## 2. A more comprehensive approach

A key element in Robert Solow's argument that energy “did not

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http://dx.doi.org/10.1016/j.enpol.2015.01.022
0301-4215/

matter" was his assumption that the increase in capital goods could offset any decline in the natural resource scarcity, so that a constant real income could be maintained. But underlying this assumption is a further one: that whereas in standard economics substitution is a fundamental component it does not apply comfortably to the exploitation of finite resources. Yet the tripartite role of labour, capital and energy can be understood better by regarding economic production (and distribution) as of necessity an energy requiring process; labour as high quality energy; and capital as mainly the means of utilising energy. Thus it does not make sense to substitute capital for the energy it is using.

The relevance of energy exploitation and use to almost every aspect of human life has been the over-arching theme of what has been termed "biophysical economics" in recent years. Following on the works of Howard Odum, the food and energy flows available to human individuals and societies from mankind's earliest days have been recognised as the most essential feature of basic human wellbeing. As Odum pointed out, the effective use of these flows enables social systems to adapt to overcrowding, fluctuations of yield, crises from competitors, and threats from internal disorder Odum (1971). Subsequently, Howard and Elisabeth Odum focussed particularly on what they believed was "the tightening grip of energy scarcity on the world's economy" arising mainly from population expansion Odum and Odum (1981). But they listed a number of other potential "hazards": epidemics, declining food production, famines, rapid urbanisation, and the enormous ongoing energy requirements arising from past investment in high-energy assets (highways, skyscrapers, power plants) and how best to reduce dependence upon them. Their hope was for "a Steady State" or, based upon continuing support for renewable energy sources, a shift to a manageable "Lower Steady State".

Much has been written about "a Steady State" in recent decades, from the early (1954) contribution by Harrison Brown on "The Challenge of Man's Future", through Barbara Ward and Rene Dubos's "Only One Earth" and the reports of the Club of Rome's "Limits to Growth", to the writings of Herman Daly and his stress on "ecological economics" (of which Juan Martinez-Allier's "Ecological Economics: Energy, Environment and Society", Blackwell, 1987, is an important and under-noticed example).

In parallel and since then a body of work has grown up focussed upon the need to consider energy, other natural resources, and economic systems as comprising a fundamental ecosystem which cannot be understood by considering any of its components in isolation. Thus in one of the earliest major successor works to those of Howard Odum: "Energy and Resource Quality: The Ecology of the Economic Process", Charles Hall, Cutler Cleveland, and Robert Kaufmann stated:

> "From this perspective, economics is defined as the study of how energy is used to transform natural resources into goods and services to meet society's material needs and how these goods and services are allocated. We use the concept of *return on energy investment* (their italics) as our principal conceptual tool, one that links together the often diverse phenomena that must constitute a comprehensive text on energy, society, and the environment (Hall et al., 1986, p. xiii)."

This approach encompassed consideration of the physical characteristics of the various forms of energy, the geological constraints, the quality of various natural resources, the availability of useful energy, and the patterns of energy use. There is now a substantial body of published work on what is termed the Energy Return On (Energy) Investment [EROI]. Estimates of EROI for the wide range of activities relevant to applying the concept in much earlier times, however, tend to be rough and ready.

Reflecting the realities behind these considerations in the past, Vaclav Smil in his important "Energy in World History" (1994), wrote of energy as "the only universal currency"

> "The evolution of human societies has been dependent upon the conversion of ever larger amounts of ever more concentrated and more versatile forms of energy. From the perspective of natural science, both prehistoric human evolution and the course of history may be seen fundamentally as the quest for controlling greater energy stores and flows. This endeavour has brought about the expansion of human populations and has allowed for increasingly complex social and productive arrangements. Neither the growth of technical capabilities and a deeper understanding of the surrounding world, nor the effort to secure a better quality of life, would have been successful without innovations in energy use (Smil, 1994, p. 1)."

Vaclav Smil has subsequently written "Energy in Nature and Society: General Energetics of Complex Systems" (2008), which provides further evidence to support his views.

Following Howard Odum, many biophysical economists have also critiqued aspects of the development of modern economic and social disciplines. Odum focussed upon the need to include "net energy" (gross energy available less the efforts required to provide it); a tendency to overstate remaining energy resources as these are defined in gross energy terms; the need to use energy for useful purposes, and not waste or use it to fuel excessive growth demands; and recognise the fact that subsidies frequently have some unintended adverse consequences. In one paper Howard Odum listed twenty areas which were of concern to him. Odum (1973)

## 3. Reasons for the collapse of earlier complex societies

These early conceptual studies have been enhanced by many historical and, increasingly, archaeological studies. Joseph Tainter, in his "The Collapse of Complex Societies", explained that his work flowed from a concern with the study of the collapse of earlier civilisations. This has been a subject of recurring concern, reflecting its significance for the human race, and its widening geographical significance as the linkages between different parts of the world become more frequent and generally stronger. Although modern societies may be less vulnerable to collapse than previous ones, and technological advances more obvious, there remains concern in many quarters. This arises in particular from our ongoing reliance upon finite resources-and recognition of the limitations of renewable resources-to meet the rising demands of population expansion and expectations of maintaining or achieving higher material standards of living for an increasing number.

For Joseph Tainter the understanding of why complex societies collapse lies in the shifting marginal productivity of socio-political change. Human societies are maintained by a continuous flow of energy. Each must evolve in harmony with available resources or human societies will be threatened. But the more complex societies become the more costly they are to maintain. Beginning with the investments required by the human species in overall nutrition, Tainter concludes that the historical record demonstrates that such investments reach a point where further investment gives a declining marginal payoff – in life expectancy in particular. Tainter's key conclusion is

> "Complex societies depend on production of other resources besides agricultural crops. Energy and minerals production, as the modern industrial world is well aware, follows the same productivity curve as subsistence agriculture, and for a similar reason. The fuel resources used first by a rationally-acting

Please cite this article as: Jefferson, M., There's nothing much new under the Sun: The challenges of exploiting and using energy and other resources through history. Energy Policy (2015), http://dx.doi.org/10.1016/j.enpol.2015.01.022

human population, and the mineral deposits mined first, are typically those that are most economically exploited, that is, most abundant, most accessible, and most easily converted to the needs at hand. When it subsequently becomes necessary to use less economical resources marginal returns automatically decline (Tainter, 1988)."

Lying behind this hypothesis exist a number of possible causes. Resource depletion; the inability of the exploitation of new resources to avoid eventually declining marginal returns as costs rise; catastrophes in the natural world; conflict; and insufficient responses to circumstances. Food and water availability have been recurring issues. The provision of useful energy has been an issue down the ages, but in richer societies increasingly satisfied by fossil fuel transformation and, latterly, nuclear and some forms of renewable energy. Among the major catastrophes in the natural world the greatest impact has been climatic change – mostly glaciation or more modest cooling rather than near surface warming. Since the Last Glacial Maximum of around 20–25,000 BC the Earth's near-surface temperature has been relatively stable, apart from a further one-thousand year cooling during the Younger Dryas from around 10,500 BC. There was a further period of cooling around 6000 BC, and during the Little Ice Age from around 1200 AD. Environmental conditions have generally been conducive to an increase in human population and agricultural output for at least the last 7000 years. This includes the 20th Century, with its mild warming (0.8 °C) fitting into the broad pattern favourable to human existence of the Holocene Period over the past 12000 years, if the impacts of the Little Ice Age and bubonic plague are set to one side. Other natural catastrophes – volcanic eruptions and tsunamis and other impacts of tectonic faults – have occurred over the centuries, but their impact has been relatively local and modest compared to the eruption of Mount Toba (Sumatra) around 70,000 BC, and the succession of eruptions at Santorini between 1700 BC and 1177 BC which caused Minoan civilisation to collapse.

However, one particularly interesting aspect of the five thousand or so years following the Younger Dryas was the sea level rise which impacted on littoral (sometimes termed eustatic) populations, although the rise was moderated by post-glacial rebound in more northerly latitudes (isostatic rebound). For example, much of modern Finland was formerly seabed or archipelago, and the height of hills from North Wales through Northern England to much of Scotland reflects the same phenomenon in the UK. This sea level rise both led to inundation of settlements and enforced migration on the one hand (Barker, 1985); and then, as sea level stabilised somewhat, formed the basis for supporting larger human populations and the development of complex societies on the other from about 7000 years ago. The reason for the latter was primarily the increased availability of fish and shell fish, which became more readily accessible, were available all the year round, and were beneficial for human health – not least because of their polyunsaturated omega-3 content. John Day and his co-authors have studied a dozen locations around the world in the past, and in their seminal 2102 paper considered six complex societies Day et al., (2012).

Coinciding with these developments more human settlements occurred around estuaries (where shell fish were most accessible and fish more readily attainable, thus reflecting relatively high coastal margin productivity), and alongside major rivers and their flood plains. Seagoing became more widespread, and the transportation of fish inland occurred from an early stage. In ancient Mesopotamia the Bau temple archives from Girsu reported a merchant's receipt of 13300 processed fish that had been transported over 200 km. Another archive entry mentions the private sale of Lagash fish and turtles 140 km. upstream at Nippur Adams (1974). Cotton was produced to make fishing nets at Caral, on the River Supe in Peru, before 2000 BC Solis et al., (2001). Whereas studies of prehistory have traditionally focussed on the central role played by hunting for certain mammals, the role of fishing and shell fish collecting has been underplayed. It would appear that from at least 7000 years ago the EROI of fishing and shell fish collection was relatively attractive for humans along coastal margins, and in some cases far inland.

The other major causes of collapse – conflict and inadequate responses to threats remain with us-as the frequent resort to the phrase: "The Law of Unintended Consequences" persistently reminds us. All these causes came into play in Joseph Tainter's study of eleven past complex societies which collapsed, but they only cover the period from about 2500 BC. In fact most of the basic principles behind the collapse of complex societies are mirrored in far earlier periods – stretching back hundreds of thousands of years – before complex societies emerged.

Earlier hunting, fishing and foraging frequently required communication, co-ordination, and the expenditure of energy. As Graeme Barker has put it in the context of optimal foraging theory:

> "The basis is the assumption that the economic actions of foragers will be sensible and effective in context, seeking to maximise rates of energy return and to minimise risk. Foragers are faced with a range of opportunities and constraints on a daily basis. Different resources provide different amounts of energy, but their acquisition also takes energy, and foraging time is finite. They therefore have to weigh up competing demands relating especially to the density and distribution of resource 'patches' and the time it will take to locate, pursue and process a resource and, if desired, get it back to camp (Barker, 2006)."

Graeme Barker also reminded us that the returns offered by various food sources with respect to the amount of energy invested in procuring them is an important determinant of subsistence scheduling by foragers today (Barker, 2006, p. 401). A more general implied warning for the human race is his point that when high-ranked resources are abundant, the "predator population" (for which nowadays read "the consumer") increases in number, leading to over-exploitation and declining rates of return. For foragers this meant a greater concentration on lower-ranked resources, a reduction in predation efficiency, and likely reduction in the predator population due to malnutrition and increased mortality. This allowed high-ranked resources to recover and the cycle to begin again (Barker, 2006, p. 411).

The Holocene period saw rising human populations and increased rainfall in many areas of the world, but not in all. An early casualty occurred across the Arabian Peninsula and Gulf, where the Natufian culture had once reigned supreme but where increasing numbers of people and over-exploitation of wild animals and edible plants led to its decline (Mithen, 2003, p. 47). In North Africa the Holocene had been characterised by heavy rainfall like the rest of the African continent, but before 5500 BC the human population was leaving the Sahara to its desertification (Mithen, 2003, pp. 497 ff. and 573).

More generally, however, population pressures increased-leading to the need to supplement or substitute hunting and foraging increasingly by farming; migrations over larger areas; or occupation and exploitation of land at higher altitudes up to and through the Iron Age. Although over forty reasons have been advanced for the transition from foraging to farming (some from "the lunatic fringe" (Barker, 2006, pp. 382–383)), authors from Mark Nathan Cohen (in "The Food Crisis in Prehistory: Overpopulation ad the Origins of Agriculture", 1977) to Jared Diamond (in "Guns, Germs and Steel: A Short History of Everybody for the Last 13,000

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Years", 1997; and "Collapse: How Societies Choose to Fail or Survive", 2005) have focussed on the sensitivity of farming to population pressures and vice-versa. These shifts sometimes also led to diminishing returns, and a reversion to earlier customs for a time.

It also led to an increase in trade over wider areas, a subject which exercised the attention of one of the great early prehistorians – Gordon Childe Childe (1942). Yet even as late as 1969 Colin Renfrew could observe that archaeologists had hitherto paid insufficient attention to trade in the context of economic growth (or to its energy supply and use implications from the earliest inputs of wood and other materials in the days of sailing or rowing, to the resources transported and finally used) (Renfrew, 1969, 1973). In the intervening years there has been much greater focus on trade both generally (Torrence, 1986; Curtin, 1984; Morley, 2007) and especially in relation to specific areas such as the Mediterranean Basin and around the Indian Ocean (Paine, 2014; Horden and Nicholas, 2000; Abulafia, 2011; Pearson, 2003). The overland Chinese Silk Routes have attracted attention and writers for a very long period, as have trade routes through such Middle Eastern centres such as Petra. Other areas where perhaps a surprising level of trade occurred remain relatively neglected – such as the appearance of flint implements made in different parts of England and Wales in places as far afield as Ireland and some locations in mainland Europe Edmonds (2004). It can hardly be denied that early trade in copper, tin, and iron ore was fundamental to human development and required the use of substantial quantities of energy. Bruce Trigger has provided a useful overview of trade in a wide range of resources in early complex societies (Trigger, 2003, pp. 342–358).

The chronological pattern of origin and spread of domesticated grains such as emmer, spelt and einkorn wheat, of barley, of some condiments, and then later of some fruit and vegetables, across whole continents in ancient times may not be known with great precision, but this process was clearly of the greatest importance for human existence and progress. Some items so diffused may still occasion some surprise. The opium poppy (*papaver somniferum*), for example, has been found at numerous Neolithic sites in Central and Northern Europe as described by Zohary and Hopf in: "Domestication of Plants in the Old World" Zohary and Hopf (2012). In the late 1980s the first evidence of opium poppy seeds from the Neolithic period being found in England was discovered at Redlands Farm, in Northamptonshire (Harding and Healy, 2007, pp. 24 and 36). This species originated in the Mediterranean area, and may have then been used as oil, a spice, or for medicinal purposes.

The whole history of the human race and its exploitation of natural resources is diametrically at odds with the fundamentals of Nobel Prize winner Robert Solow's theory of economic growth. Indeed it is curious that modern neo-classical economists appear to have ignored, for the most part at least, the work of David Ricardo two centuries ago with respect to the importance of resources, resource quality, and the tendency for increased exploitation to decrease mean quality.

Over the past few centuries energy has been expended and different forms of energy developed, together with advances in technology to process them, in ways which are familiar to us all. But what is the history behind the various fuels the human species has used in the past?

## 4. Fuel provision and use in history

The Sun, of course, has been fundamental to life on Earth, human survival and development, and energy provision. From the provision of heat and light, and its conversions through photosynthesis to food, animal feed, and wood, the Sun has exerted its sway over every aspect of human development in its earlier stages. Then, through the formation of peat and the fossil fuels, some of the aftermath of this photosynthesis fuelled energy provision for the Industrial Revolution and the availability of many services we now look for from energy. Once solar radiation alone began to make way for the controlled burning of wood, and subsequently charcoal, the human race began to exploit their many advantages. Recent advances in archaeological investigation techniques have tended to push back even further estimates of innovation in humanoid history. Only two or three decades ago it was estimated that humans first used controlled fire about 250,000 BC. In recent years this date has been pushed back – to at least 400,000 BC, and perhaps 800,000 BC. One body of opinion considers that evidence from Kenya and Ethiopia suggests that controlled fires were first exploited by *homo erectus* over one million years ago, although this hypothesis is disputed on the grounds that these represent the opportunistic use of natural fires (Twomey, 2013). Interest in the origins of the controlled use of fire has been expanded by the hypothesis that its control led to the advent of cooked meals. As Yuval Noah Harari has recently pointed out, the domestication of fire has been pivotal for human development, as "*homo erectus*, Neanderthals, and the forefathers of *homo sapiens* were using fire on a daily basis" (Harari, 2014; Gibbons, 2007; Wrangham, 2009). The use of wood and charcoal, and the deforestation which could have severe local consequences (including local climatic change as observed by some in Ancient Greece), goes far back in history as John Perlin described. According to Diogenes Laertius, Plato considered that wood made mining and civilisation possible. In Ancient Rome Pliny was not alone in believing that wood was "indispensable for carrying on of life" (Perlin, 2005, p. 29). It was the shortage of wood that caused the recycling of copper in order to save wood consumption. Acute shortages of wood eventually caused the manual removal of iron from copper slag, heralding the beginning of the Iron Age. Copper smelting required about 90 kg of wood per kilogram of metal. The Romans recovered about 60,000 t of copper from their Rio Tinto site, which would have required 400,000 ha of deciduous forest representing every tree within a radius of eleven kilometres (Smil, 1994, p. 155). The slag heap amassed at Rio Tinto (some 900,000 t) is modest compared to that on Cyprus (over 4 million tonnes) where smelting began around 2500 BC. The thick copper strips to be viewed nowadays in Crete's Heraklion Museum gives some idea of the energy required to extract, smelt, and transport copper. Bronze was produced by smelting copper and tin, the first with a melting point at 1083 °C, the second at 232 °C. Brass was also produced from early in the first century BC by combining it with zinc (melting point at 419 °C), though in small quantities under the Roman Republic and Empire, and not in large quantities until the late fifteenth century AD. Iron was to replace copper and bronze gradually.

Under the Roman Empire the use of bronze, copper and brass ("orichalcum") were used in coinage, as well as gold and silver for the highest denominations. The As was originally made of bronze, then of copper from 23 BC; the Dupondius of brass (though easily confused with the As in many cases); and the Sestertius of silver until about 23 BC, before being cast in brass until the 3rd Century AD-when it became a bronze coin with a smaller dimension before its minting ended around 260 AD. As time went on later Emperors were reduced to melting down older Sestertii, but this resulted in the zinc content being melted off as its melting point was so much lower than that of copper. Bronze, and even lead, were used to make up the shortfall. This history suggests that even "capital" is not entirely free from a material resource content and, although coinage debasement during the Roman Empire reflected inflation, and military and social conflict, it also reflected declining EROIs.

Iron had first been produced in Mesopotamia around 2600 BC, but it was not until around 1400 BC that its use began to become extensive, and after 1000 BC before it became substantial. Charcoal had long been used to smelt copper, and tin and zinc, in ancient pit hearths. But with a melting point of 1535 °C, and charcoal only capable of reaching 900 °C without further intervention, it required a forced air supply to drive the temperature of the furnace up to 2000 °C. Technology advanced slowly – copper smelting hardly advanced between the Roman Empire and 1400 AD – although furnaces developed significantly after the latter date. The European blast furnace, producing pig iron, originated around 1400 AD and in the succeeding two centuries improvements in bellows greatly improved productivity. But by 1700 AD deforestation was becoming a serious concern, exacerbated by shipbuilding requirements, with iron production in England consuming about 1100 square kilometres of forest annually. By 1810 the production of pig iron in the United States required about 2600 square kilometres of forest per year. (Smil, 1994, pp. 144–152)

Coal had first been exploited during China's Han Dynasty, about 2000 years ago, and the production of coke perhaps as early as the 4th Century AD and certainly by the 9th Century AD – reflecting a scarcity of wood. However, the first extraction of coal in Europe appears to have been not until the 12th Century AD. Shortages of wood increasingly caused the cost of charcoal and lumber to rise, resulting in the large-scale shift to coal from the 16th Century AD, led by England. Once outcropping coal seams had been exploited deeper mining was required, posing challenges of dealing with water incursion and ventilation as well as greater human labour. Meanwhile the preparation of coke by burning the outer layer of coal had first been described by Thomas Proctor and William Peterson in England in 1589 and was more clearly suggested by Sir Hugh Plat in 1603. After 1642 the practice of coking became more widespread, reflecting the English enthusiasm for drinking beer (uncoked coal could not be used because of the sulphur emitted).

From the late 16th Century in England various attempts were made to smelt iron from coal. In 1619 Dud Dudley wrote how wood shortages had induced him “to attempt, by new invention, the making of iron with coal”. However, it was not until 1709 that Abraham Darby successfully built a coke-fired blast furnace to produce cast iron. The resulting availability of inexpensive iron was a major contribution to the Industrial Revolution – and to the early steam railway locomotives. Outside Europe industrial scale development came later, with a faster switch from coal to oil and natural gas in North America, Japan, and Russia. China and India continue to be heavily dependent upon domestic coal extraction and use; and many of the developing countries of Africa, and much of South and East Asia, on imported oil as well as fuelwood and limited use of new forms of renewable energy.

From a very early stage of human existence simple tools began to be made (the ard plough, sickles and scythes, for instance) and by the Roman period more modern looking harrows. Increasing recourse was made to draft animals, which in turn required energy to provide for their food and water requirements. Water lifting devices came into use from around 1300 BC and in a multiple of forms. Early examples include the *shaduf* – a simple counter-poise lift – many of which the writer observed operating in the northern part of the island of Bahrain in the mid-1950s. The palm plantations which existed there have largely disappeared. In ancient Egypt use of the Archimedes screw to raise water was widespread. In ancient China they might be operated by two people treading on a spoked axle.

Canals were built using prodigious amounts of human energy to assist irrigation. *Qanats* (known under various other names in different locations, such as kariz in Farsi and galleria in Spanish) were built originally in Persia in the early part of the 1st millennium BC, from where they gradually spread westwards and eastwards. (It has been claimed that even in nearby Bahrain the first *qanats* were not built until the 4th Century AD in the reign of Anushirvan Belgrave (1953)). These were tunnels carved out at varying depths below ground level, with vertical shafts linking them roughly every 20–35 m, through which water could flow by gravitational force. This innovation meant reduced evaporation of water, and was particularly useful in arid climates. There are, or have been, *qanats* in many countries from Spain in the west to China in the east (in the latter case at the oasis of Turpan, in the Xinjiang desert, once on the northern part of the Chinese Silk Routes). They were also built in Greece, Italy, and Luxembourg (for a Roman villa), Peru and northern Chile.

Watermills for grinding grain were introduced in the first-century BC, and undershot wheels optimally turned by swift-flowing streams and mill-races began to appear in the 16th century. They were applied to many purposes, from ore crushing and iron making, to wood turning and oil pressing, and to metal burning and grinding, among others. But it was not until the late 18th Century that these water wheels became energy efficient – and within fifty years they were being supplanted by water turbines.

Windmills first began to appear around 950 AD in Iran, as did wind towers on houses (*barjeel*) which harnessed such wind as existed in the south of that country, in Bahrain and what we now term the Emirates, in Oman and – best known of all – Sana'a in Yemen. In some cases *barjeel* were linked to *qanats* to provide cooling in buildings. Windmills did not appear in Europe for another two centuries. These were originally post mills, as the whole structure was mounted on a single post supported by four diagonal quarter bars. Being unstable in higher winds, they were replaced over much of Western Europe by smock mills (which had wooden frames) and tower mills (where the tower was built of stone or brick) – both having a top cap which turned into the wind. Energy efficiency improvements included better blade design (the Dutch introduced slanted blades, which reduced drag, around 1600 AD to replace the earlier flat blades), and the English fantail, introduced around 1750 AD, which allowed the sails to turn automatically into the wind.

And so we reach the Industrial Revolution and modern times. As Robert Ayres and Vlasios Voudouris focussed upon the period since the beginning of the Industrial Revolution in the Special Issue paper previously mentioned, only some outline information will be provided here. Among the major advances were Thomas Newcomen's early (1712) engine to power pumps in coal mines, and James Watt's steam engine with the financial support of Matthew Boulton from 1775. At the latter point the average engine capacity was about five times that of contemporary water mills and nearly three times that of contemporary windmills. During the first half of the 19th Century the basics of solar photovoltaics and fuel cells were developed, and by 1909 the basics of nuclear power had been established (Marie Curie had discovered radium and Frederick Soddy's book: “Interpretation of Radium” had been published), and in 1912 the first Concentrating Solar Power facility was erected.

Over the previous 2500 years there had been a number of developments in using, or harnessing, the power of the Sun. Ken Butti and John Perlin have described this history well in “A Golden Thread: 2500 Years of Solar Architecture and Technology” Butti and Perlin (1980). In Ancient Greece deforestation had reached the point where many cities regulated the use of wood and charcoal by the late 5th Century BC. There was a generalised shift to the adoption of “passive solar”, designing and placing homes so that (in the Northern Hemisphere) they faced southwards, to capture as much sun as possible in winter as well as summer. The Romans made further advances, again motivated initially by the consequences of deforestation. These advances included using clear glass to raise the effectiveness of solar heating, expanding solar architecture to public buildings and greenhouses, and – as strongly promoted by Vitruvius in the first century BC – modifying the "south-facing" principle where local climatic conditions required this. Vitruvius also indicated that designs for Italy would be less appropriate for North Africa, where intense heat would make it desirable for buildings to face North, away from the Sun.

There was no early adoption of "active solar", which is somewhat surprising as Hero of Alexandria invented a solar "syphon" in the first century AD, which heated air inside a closed sphere and as the heated air expanded the pressure on the water forced it out. Apart from the occasional excursion into the potential for solar mirrors little happened to advance solar power until, in 1860, Augustin Mouchot called for reaping the rays of the Sun. Over the next two decades solar pumps and engines began to appear, and by 1884 John Ericsson had produced a parabolic-trough reflector. Further efforts over the next 25 years to advance solar engines and plants were made, but with modest results. Then in 1912 Frank Shuman opened the first Concentrating Solar Power plant – 572 collectors over a total area of 10276 square feet – in Meadi, some 25 km south of Cairo, Egypt. It was greeted with great public acclaim as far afield as Germany, England and the United States, but then the First World War intervened and the Age of Oil began to intrude.

Developments continued with other solar technologies, however. Solar water heaters made steady progress, and from the late 1930s solar photovoltaic systems on the roofs of houses began to be put in place. In recent years there have been further developments in the use of Concentrating Solar Power (CSP), with plants in the United States, Spain, Morocco, and Algeria. The potential for harnessing the enormous power of the Sun to provide energy services over a wide area, using Ultra High Voltage Direct Current (UHVDC) transmission, has been scouted – not least through the Desertec concept promoted originally by the German Aerospace Centre – but with only limited success. The Arab "Spring" is considered in many quarters to have undermined the feasibility of placing large CSP systems in the Sahara and bringing energy services to Europe and sub-Saharan Africa via UHVDC transmission. In October, 2014, it was announced that all but three of the original nineteen shareholders in the Desertec Industrial Initiative had withdrawn their support for the most ambitious project to date to harness and export solar power generated in the Middle East and North Africa, the remaining three (Saudi Arabia's ACWA Power, China's State Grid, and Germany's RWE) now only supporting "a service company" – reflecting current political uncertainties and social turbulence. The CEO of Desertec commented: "some companies said we're not interested in the Middle East and North Africa" (Anon, 2014). Solar PV meanwhile has taken off, generally as a result of substantial subsidies. But despite the many technological advances over the past century across the range of energy forms the question arises: where do we, or may we, go from here?

## 5. Energy-related scenarios for the 21st Century

Scenario development over forty years ago, as practised in The Royal Dutch/Shell Group, began by considering "building blocks", then what was in "the pipeline" – with some uncertainty as to what would ensue; and then other possibilities. It was fully recognised that the future was uncertain and that those who claimed otherwise were likely to suffer from some delusion. It should, perhaps, be mentioned that this writer was a member of this scenario team for much of the 1970s Jefferson (1983, 2012, and 2014a).

Among the "building blocks" must be considered factors mentioned earlier in this paper: global human population increase and the implications of migration; demands for food and water availability; the pressures of seeking to achieve or maintain material living standards of those in the so-called "developed" world; the risks of conflict and natural catastrophes; and the liability of inadequate responses to threats. Here we consider only those elements which may strictly be termed energy-related. However, there is one issue which strays beyond energy into the field of political science, especially in the light of the rapid urbanisation of the human population taking place. As Norman Yoffee has put it:

> "Stability in historic states and civilisations is maintained when those in the periphery consider that the resources they provide the centre also return the benefits to them… Although the political centre, for its own goals, may seek to control the extraction, production and/or distribution of key materials, the goods and services required by the state for its continued stability must be acquired from the traditionally organised groups that provide them in return for real and perceived benefits" (Yoffee, 2005, p. 139).

This lesson from past complex societies resonates with those who already consider there is a "Great Disconnect" between urban and rural communities in many industrialised countries which does not harbour well for future social stability and flow of natural resources to points of final consumption.

The Special Issue in the January, 2014, edition of this journal covered most of the building blocks. The emphasis on the importance of declining marginal rates of return, as exemplified by the concept of EROI – Energy Return on Energy Invested. The inherent weaknesses of Robert Solow's economic growth theory as it applied to the period of the Industrial Revolution (which here has been taken back hundreds of thousands of years in time) was highlighted. This was because of the theory's focus on labour and capital to the neglect of resources – especially useful energy. There was also coverage of the likely exaggeration of generally claimed proved reserves of conventional oil in particular, and the implied weaknesses of the general definition of proved and probable reserves of oil (and natural gas, excepting methane) in gross as opposed to net terms. The published work by Vaclav Smil on power densities, given the generally low power densities of renewable energy and non-conventional fossil fuels by comparison with conventional fossil fuels, also has relevance here when considering future energy possibilities and challenges. Power densities and the potential for new renewables have been addressed by this writer elsewhere Jefferson (2014b, 2013).

The basic concept of EROI remains of fundamental importance, as it has done in history. Due to the different qualities of the various fossil fuels and renewable forms of energy, the technologies employed in exploiting and converting them (including those for nuclear energy), and locational considerations (mean wind speeds, direct and indirect solar radiation, and precipitation levels vary) there may be some differences in EROI estimates, but there is a fair degree of agreement in the literature. Allowance should be made for the fact that the EROIs of the various fossil fuels have tended to decline in recent decades. The generally low power densities of renewable forms of energy have ongoing significance, bolstered by the need for back-up supplies to cope with the intermittency of wind and, to a degree, solar. For modern biomass and biofuels the enormous natural material feedstocks required to produce a significant impact, plus the implications for land and water availability for food production as well as habitat and species loss, are of profound concern.

Socio-political uncertainties continue to challenge the development of CSP with UHVDC transmission as mentioned earlier, as does opposition to nuclear fission due to fears of operational error, terrorism, and wastes. Hence the two most obvious technologies, in terms of large-scale contribution to bulk electricity supplies, remain fundamentally challenged.

Concerns with ongoing fossil fuel use in the light of rising atmospheric concentration of carbon dioxide in particular, plus the continued emissions of certain gases with much higher Global Warming Potentials than carbon dioxide, have intensified over the past 25 years despite only a modest rise in near-surface global temperature over the past 110 years and apparent stabilisation over the past 18 years. Although fossil fuel resources remain substantial, proponents of the Peak Oil issue are clearly correct in pointing out that official claims of proved conventional oil reserves do not bear close examination for three main reasons: first, because they include Venezuelan Heavy Oil and Canadian Tar Sands; secondly, because a number of OPEC-Member countries have increased their proved conventional oil reserves figures without having found additional reserves; and thirdly, following on from the previous point, have shifted from a 90% basis for confidence in the proof to a 50% basis. Ian Chapman covered this subject in the January, 2014, Special Issue of this journal. It should also be remembered that some 90% of the world's transport system is still dependent on oil products.

Meanwhile, despite the large subsidies provided (at electricity customers' expense) for promoting additional wind and solar supplies, and the obvious expansion of their contributions in recent years, the targets passed around by many in politics and NGOs remain largely fanciful.

Faced with the challenges of the needs and wants of a world population exceeding nine billion by 2050, and possibly 12 billion by 2100, future energy scenarios will need to recognise that some – possibly many – aims and targets will remain out of reach. Some have warned of the onset of a “Penumbral Age” resulting from “a fossil fuel frenzy”, market failure, and then a “Great Collapse” in which no inhabitants survive in Africa or Australia before steps are taken to bring about partial recovery (Oreskes and Conway, 2014). Others have warned of the twilight of the Anthropocene Age (Jefferson, 2014b, 2013), or an “intelligent design” which could herald the curtain dropping on Sapiens' history (Harari, 2014, p. 413). At what may seem to be a more humdrum level, Vaclav Smil has warned against: trusting in optimistic assessments of the adoption of new energy sources, and dismissing the persistence and adaptability of established resources and technologies. He has also stressed the need to remember that energy transitions are inherently prolonged affairs lasting decades. (Smil, 2010) These issues are fundamental, yet when it comes to natural resources in general – and energy resources in particular – Robert Solow apparently considered them irrelevant to economic growth theory.

## 6. Conclusions

This paper began by pointing out that Robert Solow's economic growth theory, by focussing solely on labour and capital and ignoring natural resources in general and energy in particular, was a travesty of the realities of human existence as well as economic growth. Useful energy, that is energy resources harnessed to provide needed energy services, has been the basis for economic growth since the start of the Industrial Revolution, as Robert Ayres and Vlasios Voudouris established in their contribution to this journal's Special Issue on Oil and Gas in the 21st century published in January, 2014. This paper has set out some of the evidence for claiming that useful energy has been the foundation not only of human existence from its outset but of humanoids before us. The historical evidence that complex societies have collapsed due to the challenges of exploiting resources – first drawing on those nearest, easiest and cheapest to exploit; then discovering that decreasing marginal returns followed, with associated rising costs and pressures to seek out both more costly resources and alternatives – as established by Joseph Tainter-was set out. But again the basic principles of seeking out the easiest and nearest resources and then discovering the associated decreasing marginal returns and raised costs were seen to be demonstrated even before complex societies emerged from around 2500 BC. Indeed they have been with *homo sapiens* and their ancestors since hunting and foraging began, and with the draft animals they coached and used as agriculture developed.

The effort required over hundreds of thousands of years has been vast. This led here to highlighting the importance of Energy Return on Energy Invested (EROI). Difficult though it is to estimate with precision the EROIs for the full range of energy resources, it is a fundamentally important concept. Interestingly, much of the work on the EROI concept has been done by those associated with biophysical economics – Howard Odum, Charles Hall, Cutler Cleveland, Robert Kaufmann, and those who have followed in their footsteps – particularly David Murphy.

Then this paper considered, albeit briefly, the fundamental questions raised by controversy over “proved” conventional oil reserves and the genuine “Peak Oil” issue, which leads to uncertainty over whether exploitable non-conventional oil and natural gas reserves will be sufficient to meet global requirements even fifty years from now. Once again the issue of EROIs, diminishing marginal returns, and rising costs will intrude. Along the way there will be a need to examine the realism of renewable energy targets, selecting the few that are large-scale and reliable in supply; testing the potential for relatively safe and secure nuclear power; and encouraging the most efficient end-uses in line with Planet Earth's capacity to meet them.

Rising human population numbers, the continuing exploitation of finite resources and, beyond an uncertain point, the limitations of renewable resources, which the world faces in the 21st Century pose enormous challenges. Scenarios of possible energy futures and of human existence more generally should not ignore the risks of drastic change and the lessons of human history.

For energy policy the lessons of history would appear to be

- The Sun has had a dominating influence throughout the Earth's history, particularly through photosynthesis. Actions which undermine the effectiveness of the Sun and the availability of plants and animals which help sustain the human race are in principle counter-productive. Harnessing the Sun's power to provide useful energy for life on Earth is one of the most powerful means for safeguarding the future of mankind, but due regard for where direct and indirect solar radiation levels are satisfactory is an important element in optimal decision-making.
- With human population projections indicating steady increases in the World total throughout the 21st Century, reduction in agricultural output arising from efforts to exploit modern biomass and biofuels should be avoided. Similarly, deforestation which hampers agricultural output and exacerbates water availability should be avoided.
- Wind and water have provided some useful energy over many centuries, and recent technological advances have advanced their potential. But to a much greater extent than solar power, wind energy in particular is hampered by its intermittency.
- Many of the World's resources are finite. The history of the World over thousands of years provides examples of major perturbations when shortages emerge. Even presumed “new” renewable energy technologies draw down scarce and/or “rare earth” metals, and thus may have a limited life span.
- The clearest thread running through the history of the production and use of useful energy is the tendency for the energy

returns on energy invested to decline, costs to rise in consequence, and the need to find alternatives to intensify.

– The historic record shows that climatic change and conflict have proved powerful influences on human society in the past. We ignore warning signs and the desirability of precautionary measures at our peril, even when conflicting views abound. Human history provides numerous examples of descent into conflict and violence. This tendency continues to overshadow the prospects for nuclear power.
– Successful responses need not only appropriate technologies but also sound policies and measures, yet so often responses have failed to meet requirements and have suffered from "the Law of Unintended Consequences". There is much that we can learn from past history which may help avert the increasing energy challenges of the 21st Century, as summarised in the title of David Archibald's recent book (Archibald, 2014).

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Please cite this article as: Jefferson, M., There's nothing much new under the Sun: The challenges of exploiting and using energy and other resources through history. Energy Policy (2015), http://dx.doi.org/10.1016/j.enpol.2015.01.022