The Sustainability of `Sustainable´ Energy Use: Historical Evidence on the Relationship between Economic Growth and Renewable Energy

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July 2010

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2010-09

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Understandably, focus on a transition to a low carbon economy has overshadowed what happens when the transition has been completed. This paper tries to offer lessons about the very long run aspects of a future economy reliant predominantly on renewable energy sources. The evidence is based on past economies and civilizations and their experiences of economic expansion driven by renewable energy resources. The paper proposes that economies around the world, since antiquity, have managed to survive, and even develop and grow driven by renewable energy sources. Successful long run economic growth depended on sound management of demand, supply and trade of woodfuel. Where governments failed to develop appropriate policies, growth and development was severely constrained. Despite the uncertainty about the future, this paper proposes that researchers start to consider the nature of long run economic growth and appropriate policies within renewable energy systems.

Keywords: renewable energy; economic growth; low carbon economy; economic history

JEL Classification: N53, N54, O33, Q21, Q32, Q40, Q55, R41

Cite as: Fouquet, R. (2010) The Sustainability of `Sustainable´ Energy Use: Historical Evidence on the Relationship between Economic Growth and Renewable Energy. BC3 Working Paper Series 2010-09. Basque Centre for Climate Change (BC3). Bilbao, Spain.

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[2] A version of this paper will appear as: Fouquet, R. (2011, forthcoming) "The Sustainability of `Sustainable´ Energy Use: Historical Evidence on the Relationship between Economic Growth and Renewable Energy" in I. Galarraga, M. González-Eguino and A. Markandya (eds.) Handbook of Sustainable Use of Energy. Edward Elgar Publications. Cheltenham, UK, and Northampton, MA, USA..

1. Introduction

Throughout history, energy resources have played an important role in influencing the rate of economic growth and development. It has been seen as a boost to long term growth when new energy sources and technologies were deployed and created abundance (Rosenberg 1998, Crafts 2004, Ayres and Warr 2009). They have also been responsible for slowing down economies in times of perceived scarcity (Nordhaus 1980).

Given the interest in a transition to a low carbon economy, it is appropriate to ask about the role energy might play in this new context. At present, one can only speculate about the relationship between economic growth and development and low carbon energy resources. A transition to low carbon energy sources may provide a boost to the economy. Alternatively, an increasing dependence on renewable energy will imply different levels of resource availability and may create new limits on economic growth. Or, meeting the economy´s energy needs through renewable resources may impose substantially higher costs.

Many of the models of long run energy use have presented a cheap, non-renewable energy and an expensive renewable energy as the backstop technology (Nordhaus 1973, Dasgupta and Heal 1974, Stiglitz 1974, Heal 1976, Chakravorty et al. 1997). A transition to the more expensive renewable energy source means that firms would have to charge more for their products and customers budgets would not stretch as far. Thus, it would effectively act as a break upon economic growth.

These models present the transition to a backstop technology as the result of a severe depletion of the non-renewable energy source, leading to high prices and a need to find substitutes. Empirical studies (Barnettt and Morse 1963, Berck and Roberts 1996, Fouquet and Pearson 2003, Fouquet 2010a) and, recently, theoretical models (Tahvonen and Salo 2001) question whether the non-renewable resource will face long run scarcity issues and rising prices. These studies imply that if a transition to renewable energy sources were to take place, it would not be the result of dwindling fossil fuel reserves, but the result of either a preference for renewable energy or that it became cheaper than fossil fuels.

Based on historical experiences, Fouquet (2010b) argues that, although preferences are important, a transition to low carbon energy sources is unlikely without renewable energy providing energy services more cheaply than fossil fuels. This implies that a complete transition will only occur if the combined output of renewable energy and its associated technology is cheap. Thus, the transition to renewable energy sources is unlikely to impose higher prices – at least, not initially.

Yet, perhaps more in the long term, after the transition and the economy becomes dependent on renewable energy sources, it may face resource limits. Over the last three hundred years, modern economies have managed to grow spectacularly and have had an almost insatiable demand for energy resources (Fouquet 2008). So, even though supplies of renewable energy resources are potentially very large (compared with the size of the global economy), limits may indeed eventually be faced.

Traditional models of long run energy use do not address the situation once the backstop technology is the dominant energy source – that was not their purpose. While a transition to renewable resources is certainly decades away, at the earliest, there is now a clear demand for a better understanding of the relationship between long run economic growth and renewable energy use. In order to begin our understanding of the relationship, this paper gathers some evidence on how past economies have managed within the confines of renewable energy system. Given space limitations, this paper only seeks to present snapshots about a variety of different cases – focussing on woodfuels. These cases relate to the Roman Empire, Early Modern Europe and the Far East. They investigate the 'sustainability' of the use of this 'sustainable' energy - that is, how the renewable resource was used over very long periods. This involves considering the availability of resources, the rate of use, the existence of energy crises and the various governments´ attempts to manage demand and supply.

2. Woodfuel Consumption during the Roman Empire

Roman daily life was highly dependent on woodfuels. In addition to the consumption for cooking, hot baths, preparation of lime for construction and cremations of bodies were major users of fuelwood. Heating may have consumed as much as 90 percent of the timber used. Estimates suggest that, at its peak, with 1.5 million inhabitants, Rome would have consumed 2.25 million m^3 (equivalent to 0.7 million tonnes of oil equivalent (mtoe)) and required more than $30km^2$ of forest per year (Williams 2003 p.93).

There is evidence that forests were coppiced or felled in rotation to be able to meet the demands of Roman energy requirements. And yet, inevitably, Rome´s success and expansion imposed increasing pressures on forests, and the trade in wood spread ever further – by the third century, the largest beams were shipped to the city from the Black Sea. Although the cost of cooking, bathing, building and cremating (until the practice was abandoned with Christianity, possibly encouraged by the price of fuelwood) must have increased, no claims of a Roman energy crisis exist (Williams 2003 p.93).

The Empire also required large amounts of fuelwood to meet its demands for metal smelting. For instance, Populonia (level with the isle of Elba in present Italy) produced an estimated 500,000 tons of copper, needing 2.2 million tons of charcoal (equivalent to 1.6 mtoe)) from 36.1 million tons of wood, over a period of 500 years. This would have needed a forest of 1,875 km^2 if it had been stripped of its trees. However, given that the annual consumption was relatively modest by modern consumption, land requirements could have been closer to 10 to 15 km^2 if properly coppiced (Williams 2003 p.94).

In classical times, many industrial sites dependent on charcoal managed to produce for hundreds and even thousands of years. Examples currently in Greece, Cyprus, Italy and Spain show that very large total quantities of silver, copper or bronze (fusion of copper and tin) were produced over long periods of time. For instance, copper smelting in Cyprus left 4 million tons of slag residues. This equates to 200,000 tons of copper, requiring 60 million tons of charcoal (equivalent to 43 mtoe) from 960 million tons of wood on roughly 60,000 square km of forest. A forest about five times the size of the island. While Cyprus did suffer from deforestation, this was caused more from agricultural expansion than from industrial activities. And, they managed to produce copper for 3,000 years. Such large quantities of production over a very long period could only have been achieved if the use of wood for fuel had been managed in a relatively sustainable way (Williams 2003 p.94).

Thus, there is clear evidence that already in Classical times, energy requirements were often met in a sustainable manner. Modest growth could be met by managing a slightly larger area provided the source was easily accessible by land or by water.

3. Early Modern European Energy Concerns

The trend for much of human history has been of encroachment on woodlands. Although in specific cases, the growing use of wood for energy and timber was responsible, deforestation has been mostly due to agricultural expansion (Williams 2003). Nevertheless, it implies a declining stock of resources for meeting woodfuel needs and an increasing distance between the source and many of the users.

Between 1700 and 1850, temperate forest cover across the world declined substantially – by 1.8 million km^2. In Europe, 250,000 km^2 disappeared; in Russia, 710,000 km^2; in North America, 450,000 km^2; and in China 390,000 km^2. Between 1850 and 1920, the rate slowed a little – 1.29 million km^2 disappearing. Russia lost 800,000 km^2, North America 270,000 km^2 and China 170,000 km^2. Over that period, Europe only lost 50,000 km^2, but this reflects more than anything a lack of forests to clear (Williams 2003 p.277).

Around 1700, England and Wales was about 8 percent woodland and the Netherlands had virtually no forests; Northern France was about 16 percent covered, while Eastern Germany was about 40 percent woodland (Williams 2003 p.168). By 1850, much of Europe was deforested. One-quarter of Germany was covered in forests. France was 12 percent woodland. Most other countries, apart from Scandinavia and Russia, had very little forest left (Williams 2003 p.279).

Most European cities used woodfuels for heating. Comparing European cities in the fifteenth and eighteenth centuries, the real price of energy did depend on the proximity to forests. Austria, Germany and Poland had the cheapest energy. Interestingly, even in the fifteenth century, when still dependent heavily on woodfuel, the real price of energy was only a little higher in London. Later, when London, Antwerp and Amsterdam were dependent on coal or peat, their prices were in the middle range. This suggests that, where supplies were sufficient, coal use was not necessarily cheaper than being dependent on woodfuel. Spain, which had limited forest cover and little coal or peat, had the highest energy prices (Allen 2003 p.473).

The trend in real energy prices over four hundred years of major economic growth is also revealing. For a number of cities across Europe, there was no evidence of an energy crisis and only a few instances of rising real energy prices between 1400 and 1800. For this period and out of fourteen cities, only Paris, Strasbourg and Florence showed signs of rising prices in the eighteenth century. Otherwise, the trends in real energy prices were stable or declining (Allen 2003 p.479).

The general held view today is that the term energy crisis is an exaggeration. There were woodfuel shortages (Sieferle 2001, Allen 2003), but they tended to be local problems, rather than national ones affecting the whole economy. Much of the problem was associated with distribution networks. And, most likely, shortages hit different localities at different times. Overall, between the early fifteenth and nineteenth centuries, the European economy managed to grow successfully and with little constraints while being mostly dependent on woodfuel for heating (Allen 2003).

As mentioned above, in England and Belgium, by the seventeenth century, the predominant energy source in cities was coal. This does not suggest a woodfuel shortage but only that the cost of heating using coal was cheaper than with wood in these cities (Fouquet 2008 p.75).

The main commonality amongst all economies was that once agricultural production increased or efficiency improved population grew, putting pressure on woodfuel resources, both because of the changing land-use from forest to agriculture and the rising demand for wood products. Thus, consistently, economic growth eventually expanded to reach its resource limits. Faced with greater constraints, the reaction was either economic contraction, stagnation or even decline, better management of forest resources or a switch to another fuel. The next section considers government policies to balance the demand and supply of this renewable energy.

4. Forest Management in Germany

The multitude of local German economies benefitted from large forests close to rivers. Woodfuel provided their main source of heating for households and industries for centuries, with episodic tensions and adaptation. Evidence suggests that consumers were reluctant to switch – reflecting preferences for woodfuel and perhaps insufficient price differential to make substitution attractive and overcome the negative aspects of coal burning. When tensions did arise, woodfuel supply adapted to rising demands, either by felling more local trees or importing them along the river networks. In many cases, when economic growth led to pressures on resources, governments in German states did tend to intervene to assist the markets (Warde 2003).

For example, in Northern Germany, salt production depended on large quantities of wood to evaporate seawater. The industry managed to expand substantially (more than quadrupling) from the beginning of the fourteenth to the end of the sixteenth century without suffering from higher energy costs or fuel shortages. It did depend partially on importing fuelwood, and transport networks were crucial. In fact, the promotion of road building and development of navigable rivers were promoted for the purpose of supplying the region. And, this industry´s eventual decline was in no way a result of energy restrictions (Witthöft 2003 p.301).

The consensus about woodfuel shortages in Germany was that they were localised problems more associated with distribution of resources rather than a generalised lack of energy resources. The main problem was the lack of satisfactory transport routes to distribute. In the seventeenth and eighteenth centuries, this problem was alleviated in some regions by the expansion of rafting of timber and fuelwood to wooded uplands that had previously been undervalued (Warde 2003 p.594). Another cause of shortages was the political boundaries. Many of the German states believed in energy self-sufficiency and in preserving resources for domestic use (and not exporting wood). So, in some cases, industries needed to carry wood long distances (up to 30 km) within political boundaries when nearby sources existed but were outside the state limits (Warde 2003 p.592).

German energy and woodfuel consumption until the nineteenth century was dominated by household needs for cooking and heating. Crude estimates indicate that woodfuel consumption was around 11 million m^3 (equal to 5.5 mtoe) in 1500 and about 20 million m^3 (9.8 mtoe) in the seventeenth and early eighteenth century. In comparison, around 1600, iron production use would have been 1.5 million m^3 (about 0.8 mtoe) and, by 1700, silver, lead and salt production would have required less than 4 million m^3 (about 2 mtoe) of wood. Industrial activity grew substantially in the second half of the eighteenth century, and iron production would have needed about 10 million m^3 (equal to 1.t mtoe) by 1800 (Warde 2003 p.590).

This indicates that general forest management policies were driven by a need to meet household needs. Nevertheless, many of the early German states responsible for introducing policies were reflecting the repercussions of concentrated demands for local industries.

Forest management in Germany began in the late medieval and early modern period. In 1368, pines were replanted in the municipal forests of Nürnberg. It initiated a series of policies of managing woodlands across German states and urban centres, especially between 1470 and 1550. This trend reflected in part a growing awareness of the need for a security of energy supply (either because of the welfare implications to the population or because of the legal tensions that developed over scarce resources) and for the management of stable fiscal revenue - by avoiding volatile prices associated with the changing scarcity of resources (Warde 2003 p.585).

On communal land, households had been granted rights by local authorities to extract wood. However, over time, the rate of extraction was increasingly specified – as a means avoiding a tragedy of the commons. This was generally seen as an amount suitable to meet ‘subsistence’ needs – creating problems for families who sought to produce goods for markets. In noble forests, peasants were generally also allowed to collect deadwood and cut small pieces, and, similarly, this practice became increasing controlled by officials (Warde 2003 pp.588-9).

Until the nineteenth century, woodland management was based on practices developed in the fifteenth century, and was not particularly innovative. It focussed on felling trees by area, in relatively short succession, coppicing, and protecting (by, for instance, banning grazing around saplings) and promoting rapid regrowth. Although their control and power grew, forest officials´ role was to assess the stocks and parry poaching.

When faced with demand pressures on resources, policies generally sought to minimise resource use, by encouraging fuel efficiency, rather than increasing supply, such as reafforestation and trying new tree species. This reflected the more immediate returns from improving fuel efficiency (especially to industries) than investing in programmes to increase supply (Warde 2003 pp.593-5).

Institutional structure played an important role in the successful balancing of supply and demand. For instance, from the fifteenth century, regulations in Siegerland in Germany defined the nature and the rate of smelting and forging activities (including the number of working days), and banned the exports of iron ore, raw iron or charcoal. Despite being an important mining, smelting and forging region, and needing to important some charcoal, it appears that its dependency on renewable energy supplies did not limit economic activities until the nineteenth century (Witthöft 2003 p.296).

German state governments also promoted a switch to coal, which was reluctantly adopted in the nineteenth century, when industrial demands did severely outstrip supplies. By then, growing concerns of losing lumber led to scientifically managed forests and government policies (Sieferle 2001). Also, although the concept was vague and differed for each state, there was a general view that, in addition to the need to meet on-going demands, resources should be maintained for future generations (Warde 2003 p.595).

Before the nineteenth century, there were, no doubt, plenty of examples of areas where growth did lead to energy restrictions. Yet, in early modern Germany the existence and dependence on large wood reserves led to relatively successful policies of managing energy supplies and demand. This more involved energy policy no doubt reduced the tensions, but ironically delayed the transition to fossil fuels and the potential for greater economic growth.

5. The Japanese Experience

The early modern Japanese economy followed a similar course. It depended heavily on woodfuel for heating purposes. Facing the risk of shortages resulting from economic growth, local policies aimed at reducing consumption, improving efficiency, increasing supply and attempting a switch to coal. Like Germany, before the nineteenth century, coal substitution was the least successful of these policies. Its experience showed that, through regulation, governments could help boost renewable energy supplies, and balance it with demand.

During the sixteenth century, large-scale military conflict had used large quantities of timber. As discussed before, from the seventeenth century onwards, the country was at peace and population rose. Along with the encroachment of agriculture onto once wooded land, demand for timber for construction, shipbuilding and fuel led to severe deforestation. Soil erosion, floods, landslides, and barren lands were common occurrences in the seventeenth and eighteenth century (Totman 1989).

In the second-half of the seventeenth century, feudal lords, who owned most of the forests, began efforts to reduce deforestation. The first policy was to ban wood removal from except with direct authorisation from the feudal lord. Other measures included seedling protection, selective cutting and more patrols. These measures reduced production substantially, but also feudal lord revenue. Swiftly, production increased again to make back the losses and deforestation resumed (Totman 1989 p.246).

In Japan, at the end of the seventeenth century, the rising price of woodfuel drove a few industrial activities, such as for salt and sugar, to start shifting towards coal use, where the fuel could be found and extracted easily. But, in this densely populated country, the external costs of coal production and consumption were felt and created conflicts. Mining generated considerable pollution in nearby rivers, and coal burning emitted noxious fumes and sticky residue. Downstream rice field suffered. Given the highly organized nature of society, protests, litigation, compensation and regulation followed. Eventually, in the 1780s, mines were closed due to their damaging effects on society and the environment and wood burning was encouraged. But, inevitably, and despite more complaints, the high price of woodfuel forced growing industries in the nineteenth century to use coal (Totman 1995 pp.271-2).

Before this transition, however, in the eighteenth century, efforts to halt deforestation resumed and were more successful. Wood use was rationed, specifying the amount of wood that could be consumed according to social status. Timber for construction was used more sparingly. More efficient stoves were promoted for the use in homes. And, at the end of the century, an active policy of planting new trees was introduced. Along with these new measures came a scientific approach to forest management. The story of Japanese forest management and broader energy policies has often been told as a story of sustainable management, but it took nearly two centuries of deforestation and attempts to achieve a growth in wooded lands (Totman 1989).

6. The First Transition to Coal

The Chinese experience was very different. It was a story of poorly managed woodfuel supplies and substitution to coal, but ‘in the wrong order’.

China was probably the first location where coal was used to address the problem of insufficient woodfuel. Since the Han period (25-220CE) and perhaps as early as the fourth century BC, anthracite coal was used for a number of industrial activities. However, the potential for substitution was limited by technological developments, and the methods for using coal remained relatively crude (Wagner 2001, Thomson 2003 p.8).

During the Song Dynasty (960-1270CE), far more sophisticated techniques were developed. In that period, political stability and economic prosperity had generated a rapid growth in the demand for metals and iron, in particular. In 1078, Chinese iron production was about 125,000 tons – similar to iron production in England and Wales in 1790 (Hartwell 1966 p.34).

Despite use of coal for some industrial activities, iron had traditionally been smelted with charcoal. However, the expansion of iron production in the tenth century had led to deforestation problems. Alternative sources of fuels and technologies were sought. Much of the Chinese coal was found in the North, near the centres of iron work. Coke, derived from bituminous coal, was used for large scale iron smelting in the North from the eleventh century, and possibly earlier. Compared with other regions, that could hardly have expanded due to a lack of solutions and access to resources, the Northern Chinese iron production increased to meet much of the growing demand. From the ninth century, coal also appears to have been used in domestic activities, such as cooking (Hartwell 1966 p.5-56)

During the thirteenth century, however, the Chinese empire suffered from a number adverse events, most notably the Mongol invasions, which led to economic decline. When the Chinese economy re-developed in the seventeenth century, the economic base was in Southern regions with very little access to coal, and perhaps without the methods needed to turn coal into coke and to use coke for smelting. Northern China became an ‘economic backwater’ with little influence over the thriving economic South. And, the cost of shipping coal South was too high to make it commercially viable (Pommeranz 2000 p.62).

The modest Chinese expansion of the eighteenth century was dependent on woodfuel for iron production. As production grew and deforestation increased, authorities failed to develop successful policies to manage and balance demand and supply, placing a break on the potential for growth. ‘Medieval’ China found major technological solutions to the woodfuel problem, allowing its economy to expand. Yet, because of a period of economic decline, China lost the knowledge or ability to grow in a long term way. Upon its return to woodfuel dependence, it failed to realise that strong energy policies were necessary to grow within a renewable energy system.

7. A Future Economy Driven by Renewable Energy

The previous sections have presented histories of economies dependent on renewable energy. Being able to sustain growth depended on sound management of demand, supply and trade of woodfuel. Where governments failed to develop appropriate policies, growth and development was limited. Inevitably, the vast demands of full industrialization, coupled with inefficient energy technologies and primitive transport networks, implied that a transition to fossil fuels was critical for higher levels of economic growth and development, as seen during the nineteenth century in Britain, Germany and even Japan.

At the beginning of the nineteenth century, 95 percent of global primary energy use came from renewable resources. By the beginning of the twentieth century, it fell to 38 percent. And, at the beginning of this century, it was down to 16 percent (Fouquet 2009 p.15). Clearly, for many years still, the proportion of renewable energy in primary energy consumed at a global level will continue to decline, as the quantity of fossil fuels used increases (especially from contributions in developing economies) more than those of renewable.

Nevertheless, the tide may be changing. In a number of industrialised countries the proportion of renewable is rising. Indeed, as Tahvonen and Salo (2001) propose in their model, it is possible that, in the process of economic development, an agrarian economy uses renewable energy resources, moves to fossil fuels for a phase associated with industrialisation and, then, reaching a higher level of technological and economic capability, returns to renewable energy sources.

The important drivers for energy transitions of the past were the opportunity to produce cheaper and better energy services (Fouquet 2010b). They may well be the drivers for a transition to low carbon energy sources. Internalisation processes, such as carbon taxes or tradable permit schemes, can improve their competitiveness. But, it is likely that, for a transition to occur, low carbon energy sources and technologies will have to provide cheaper energy services.

If renewables manage to out-compete fossil fuels, then economies (industrialised or developing ones) will, in time, become dependent on these low carbon sources. Fossil fuels may, in the future, be seen as the ‘necessary evil’ - that is, a cheap and dirty energy source – that allowed economies of the past to reach a higher level of economic well-being. This fits with the concepts underlying the Environmental Kuznets Curve that environmental pollution needs to get worse before getting better.

But, will individual economies and the global economy be able to grow in the very long run within the confines of a renewable energy system? Although huge uncertainties about the future prevail, an exercise that considers the currently estimated global energy resources can help indicate the distance between the current global economy and notional limits.

For instance, one estimate of oil reserves of all types (nearly 2 million mtoe) suggests that they are currently 12 times the amount of oil that has been consumed in the industry´s 160 year history (157,000 mtoe) - or, 486 times the 2009 global consumption of petroleum (Farrell and Brandt 2006, BP 2010). In 2009, the current global primary (modern) energy consumption was a little over 11,000 mtoe (BP 2010), and the global primary energy consumption, including biomass, is likely to be around 12,000 mtoe (Fouquet 2009). One estimate of global fossil fuel reserves is close to 30 million mtoe (Rogner 2000 p.168). This is nearly 2,500 times the current annual global primary energy consumption. Unconventional natural gas reserves are especially large – roughly 80% of the total. But, as indicated above, even for oil reserves, the estimate is more than 450 times the current annual global oil consumption. Thus, even allowing for economic and population growth, fossil fuels are abundant. Thus, dwindling fossil fuel reserves is unlikely for a very long time. Without full carbon capture, atmospheric limits (to assimilate greenhouse gases) will have been reached far before resource limits.

An estimate of the technical potential for global renewable energy resources is over 180,000 mtoe (Rogner 2000 p.168). Two-thirds of this potential would be generated by geothermal sources; one-fifth from solar; one-twelfth from wind; one-twentieth from biomass. So, for example, the potential for wind energy is estimated to be 25% greater than the current global energy consumption. And, the total technical limit is 15 times the global economy´s primary energy requirements.

Just as a reference, the current global primary energy consumption is 15 times its level in 1900. Thus, it took around one hundred years to grow 15-fold. Although, we may not expect similar growth rates or a full dependence on renewable energy sources at the beginning of twenty-second century, these renewable energy limits could be threatened in the twenty-second century.

This is not an exercise in showing that a transition to renewable energy sources is dangerous for the economy. After all, an estimate of the 'theoretical' limits of renewable energy resources was nearly 3.5 billion mtoe – almost 300,000 times the current global primary energy requirement (Rogner 2000). These are potentially meaningless numbers, given the developments in energy technology we can expect over the next hundred years and more. Presumably, the limit is somewhere between 15 and 300,000 times current consumption. However, they do help to think about magnitudes.

Some have argued that increases in resource discoveries and improvements in energy technology were an important source of economic growth in the past (Ayres and Warr 2009). The ability to exploit new energy reserves, such as Colonel Drake´s oil discovery in Pennsylvania or the extraction of oil in the Middle East, were also boosts to economic growth. It is possible that within the limits of a renewable energy system, there will be less potential for new discoveries to be made. Some might argue that the location of these resources is known with greater certainty for most renewable than for fossil fuels. So, the potential for great new discoveries in the future is less likely. Effectively, the limits are known and the global economy will work its way towards them.

However, it is clear that renewable energy technologies of the future will be heavily dependent on research and development to improve their ability to harness natural forces. Technological developments will enable the economy to increase the limits of commercially viable renewable energy resources (from 15 times current global primary energy requirements towards 300,000 times). Thus, a crucial process within the renewable energy system will be the quality of signals that indicate existing (commercially viable) limits are being reached and technological improvements will be needed to avoid serious constraints on economic growth.

Probably more important than the limits will be the governments´ energy policies. Historically, sound policies towards energy demand, supply and trade were critical to extending the ability to use renewable. This may offend certain ideologies but, based on historical evidence, a return to renewable energy sources would be more successful if properly managed, instead of laissez-faire approach. Policies will probably need to address short and long term demand, supply and distribution issues. Yet, it is possible, and hopeful (from an economist´s perspective), that the policies will be 'light-handed' and using incentives, rather than heavy regulation.

8. Final Remarks

This paper considers economic growth in a renewable energy system. Previous sections in this paper tried to show that economies of the past survived, evolved and even grew within a renewable energy system. Indeed, the first key observation is that, in particular locations, industries were operative and dependent on renewable energy sources for centuries and even millennia. Second, growth in demands does clearly put pressure on resources. For instance, the expansion of the European and Far East Asian population and economy between 900 and 1350 and 1400 and 1800 led to a growth in demand for energy resources.

Third, in many localities, woodfuel supplies were able to meet the growing demand. This was, in cases considered, the result of government intervention and the promotion of better resource management. Often, they were coupled with efforts to reduce demand and improve efficiency of consumption. Based on the historical evidence, balancing demand and supply was crucial to achieving growth within a renewable energy system. Fourth, in many circumstances, trade was the solution, importing the necessary resources. Where local energy shortages were a problem, the main cause was due to the high cost of transporting resources, rather than an overall energy crisis.

Fifth, another solution was a substitution towards other fuels, such as coal. However, often, this was undesirable due the harmful and external effects of coal mining and combustion. Finally, the Chinese experience showed that solutions can be forgotten or may no longer be appropriate. Thus, economies can, first, make the transition from traditional energy sources to fossil fuels and, later, return to renewable energy sources.

One possible fear associated with a transition to a low carbon economy is the limits to economic growth that renewable energy sources might impose due to the availability of resources. After all, the standard narrative about the Industrial Revolution is that woodfuel could not have met the high energy demands associated with industrialisation (Cipolla 1962, Landes 1969, Wrigley 1987). That version of history is, no doubt, correct; but this paper turns this argument on its head. It gathers evidence on past economies that managed within the confines of renewable energy systems. Focussing on woodfuels, it shows how in the Roman Empire, Early Modern Europe and the Far East renewable energy resources were the drivers of economic activity for very long periods.

These were admittedly at slow growth rates by modern standards. But, they were also at times when technologies were very inefficient and transport networks poorly formed compared with the twenty-first century. For instance, with current technologies, transport infrastructures and institutional arrangements, the energy service demands of the Industrial Revolution would probably have been met quite easily with renewable energy sources.

This paper does not argue that resources were always managed properly, or that resource limits did not hinder economic growth. Instead, it argues simply that renewable energy systems (have not and) will not be necessarily doomed to stagnation and collapse. Indeed, to be successful, economies (needed and) will need to balance their demands with their supplies and be 'sustainable'. But, if correctly managed, it may be possible to make a transition to a low carbon economy and grow within a renewable energy system for a very long time.

A great emphasis has been placed on a transition to a low carbon economy. This is appropriate given the threat of climate change, and the difficulties and uncertainties of a transition. However, less research has gone into investigating what happens once we reach a low carbon economy.

This paper begins this investigation by considering how economies in the past grew within the confines of a renewable energy system. It proposes two gaps in our knowledge. First, traditional models of long run energy use have not addressed the situation once the backstop technology, such as a renewable energy source, becomes the dominant energy source again. Although a transition to a low carbon economy is a long way off, if it ever occurs, it is now time to improve our understanding of the relationship between long run economic growth and renewable energy use. Second, we need to identify effective new policies that would be relevant for managing 'sustainably' (i.e. in the long run) 'sustainable' energy sources. This would need to develop incentives that would meet energy service demands within technically and commercially viable renewable energy supply limits that will be distributed effectively. Careful investigation of renewable energy systems may be crucial to determining whether a transition to a low carbon economy becomes a new golden age in economic history or another dark age.

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