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The Allocation of Energy Resources in the Very Long Run[1]

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May 2015

Abstract

This paper investigates the Nordhaus (1973) model developed to understand how markets allocate energy resources. In particular, the model proposes that royalties earned by non-renewable energy producers are closely related to the cost of the backstop energy source, the interest rate and the switching date to the backstop energy source. Here, the paper presents the prices of the main and backstop energy sources, extraction costs and royalties, as well as transport costs, taxes and interest rates, over more than five hundred years in Britain to test the model's ability to explain very long run market behavior. While the model needs a more rigorous analysis, the very long run data and this crude test suggests that certain episodes might be explained by the model and that others do not appear to be. Also, each of the three explanatory variables do appear to be relevant in these explained episodes. In general, though, energy markets appear to be myopic, unaware of the limits of the non-renewable resource being traded, and only in moments of crisis do they consider the finiteness of the resource and, then, perhaps too dramatically, triggering major new technological, infrastructure and R&D investments.

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1. Introduction

A central concern to energy economists in the 1970s was the threat of energy resource limits to economic growth. William Nordhaus' (1973) article on The Allocation of Energy Resources was one of the finest and grandest examples of this effort to understand how an economy can continue to grow despite limited fossil fuel resources.

Strongly influenced by his supervisor Robert Solow (1974), William Nordhaus became highly proficient at developing "small models applied to real problems, blending real-world observation and a little mathematics to cut through to the core of an issue." (Krugman 2014). Shortly after he completed his PhD in 1967, energy economics began to benefit from the skills and imagination of this innovative researcher coming out of the golden age of MIT's PhD programme.

This is particularly interesting, since he had identified the crucial role energy played in the economy before the oil price hike of 1973. Naturally, other scholars had already alerted economists and the world of this role – particularly Mori Adelmann (1972) at MIT, Sam Schurr and his colleagues (Schurr and Netschert 1960) at Resources for the Future, and, of course, the 'Limits to Growth' team (Meadows et al. 1972). Yet, just as he pre-empted the importance of the economics of climate change and of technological development (Nordhaus 1977, 1991, 1997), he was at the right place, at the right time.

As his research assistant on the project, Paul Krugman offered some insight into the evolution of the paper. "The first summer I worked for him, Nordhaus began with only a vague sense of how to think about the problem of appropriate pricing of energy. I was able to watch the process by which he crystallized that vague sense into a model, and then was able to see the way in which that model transformed everyone's perception of the issue." (Krugman 2014).

Nordhaus (1973) was interested in identifying how energy resources would be allocated, both positively and normatively. In other words, first, how do markets allocate energy resources? As he said "[i]t takes an act of faith to believe that "the market" can somehow see the proper allocation through this tangle of complexity, uncertainty, and politics" (Nordhaus 1973 p.538). And, second, how energy resources should be allocated? Always the pragmatist, he tried to provide "a middle ground between .. summon[ing] … all current and future citizens … into Yankee Stadium" (Nordhaus 1973 p.538) to decide on how to allocate resources and developing a model that forecasts all present and future prices. Indeed, his model offered a very long run perspective, looking 200 years into the future.

Given his very long run perspective, this special issue offers an opportunity to examine the Nordhaus' (1973) framework and comment on how energy markets have allocated resources in the very long run. Therefore, the focus in this paper is to look at backstop energy resources, extraction costs and royalties, as well as transport costs, taxes and interest rates, over more than five hundred years in Britain. The focus is on coal markets from the thirteenth century until the mid-twentieth century, because they provide a case study in which governments had limited influence over prices, and markets dominated the allocation of energy resources. This data analysis provides a crude test of his model.

This brief historical analysis builds on and greatly extends a discussion in Fouquet (2011a) on long run energy prices. For those interested in the sources of the data presented in this paper, the extensive data collection exercise by Thorold Rogers (1865–86) on agricultural prices in market towns across England provided indicators of the cost of fuels as far back as the eleventh century. William Beveridge (1894) then gathered reliable data from the sixteenth century onwards, creating long run series reflecting the price of energy faced by individual institutions. The institutions included some of the Oxford and Cambridge colleges, the Eton and Westminster Colleges and the Navy, as well as long-standing hospitals. They have been combined to get an average price of individual fuels in Southern England, where most of the institutions were based. Gregory Clark (2010) has recently added to the data sets. All the costs and prices are converted into values in the year 2000 using the price index data from Allen (2007).

2. Backstop and Non-Renewable Energy Sources

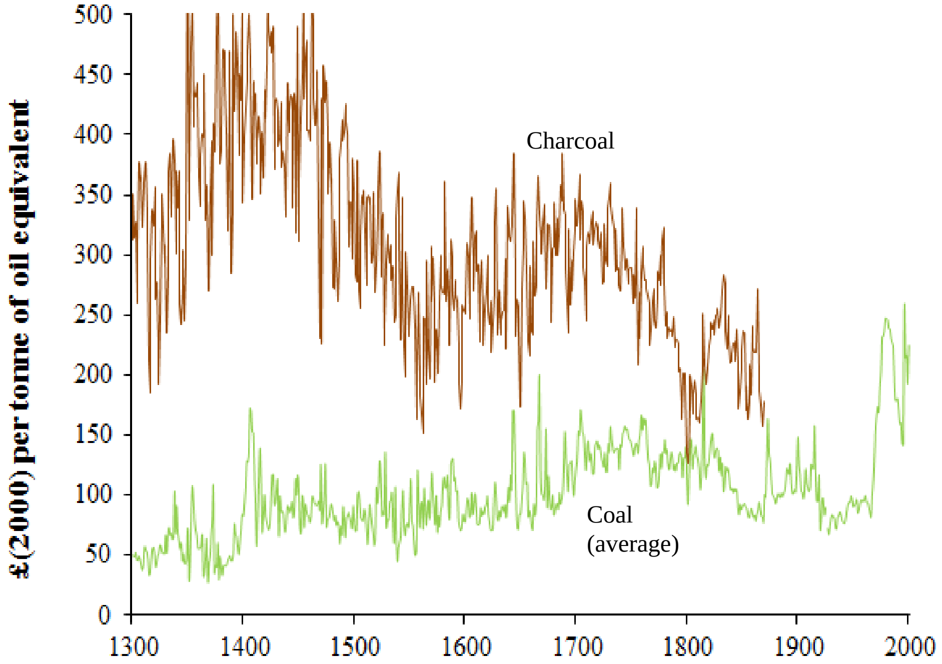
Nordhaus (1973) presented a model of a relatively cheap non-renewable resource and an abundant but expensive backstop technology – he proposed either a fast breeder or fusion nuclear power source[2]. For much of its history, the backstop energy source in Britain was woodfuel. Although limited in England and, to a lesser extent, in Wales and Scotland, it could also be imported from overseas. It effectively was between 1650 and 1800, since England and Wales imported two-thirds of its bar iron from Sweden and Russia (King 2006). At the height of imports, in the 1780s, the 50,000 tonnes of bar iron imported into England and Wales would have required 170,000 tonnes of charcoal and coppiced woods equivalent to 3% of England's surface area (Fouquet 2008 p.60).

Naturally, there was a limit to the abundance of this backstop energy source, especially when considering the demands of a global economy. However, until the

[2] The former is still seen as very expensive forty years later, while the latter cannot realistically be considered one, due to current scientific and engineering limitations.

twentieth century, Britain could have considered woodfuel a genuine backstop energy source. Between 1700 and 1900, total energy consumption increased sixteen-fold (from 1.4 to 22.2 million tonnes of oil equivalent), which could have been supplied to a large extent by imports of fuelwood, charcoal or the goods produced from these fuels. After all, Sweden was 9 times larger than England, and Russia was 340 times larger. Clearly, the rising prices from using woodfuels would have greatly reduced energy consumption and impeded economic growth and development, but it was a more realistic backstop energy source then than nuclear fusion or even probably fast breeder reactors are today (Hatcher 1993).

Nordhaus (1973 p.533) explains that, for a non-renewable resource, "[t]here are three important elements in determining current royalty …: the cost of the backstop technology, the interest rate, and the switch date." Figure 1 presents the prices of both the backstop, charcoal, and the non-renewable energy source, coal. In the fourteenth century, the dominant source was the backstop energy source, because coal markets and technologies had not yet been fully developed. The rising population placed significant pressures on woodfuel and charcoal prices. After the Black Death, and the near halving of the population, woodfuel prices dropped. Prices began to rise again as population grew once more in the sixteenth century.



Source: Fouquet (2011a).

Figure 1. Average Charcoal and Coal Prices in England, 1300-2000

In sixteenth century England, the introduction of grates for burning coal and chimneys to externalize emissions enabled households in urban areas to switch from woodfuels to coal. The experience of the 1300s suggests that woodfuel prices would have increased a great deal further in the sixteenth century (above £(2000)300) without the slow transition towards coal for residential heating demands (Fouquet 2010). Similarly, in a number of industries, methods were developed to use coal rather than charcoal – although it took until the eighteenth century for adequate and affordable techniques to be developed in the large iron industry.

The transition from woofuels and other biomass sources to coal took roughly three hundred years. In 1700, coal already provided 73% of all primary (non-agricultural) energy consumption. By 1800, its share had reached 95%. King Coal was at the heart of British economic growth (Flinn 1984).

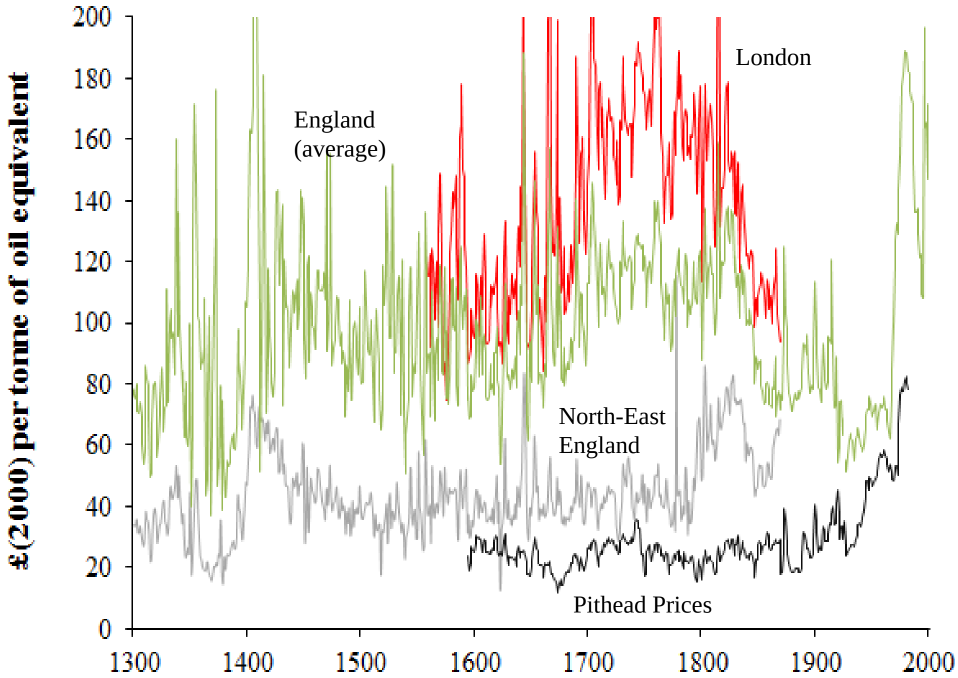
Reflecting this transition, the prices of charcoal and of coal varied considerably. In the seventeenth century, the differential between the two prices was certainly increasing, with the former triple the latter. But, in the eighteenth century, the gap was closing; by 1800, there was less than 50% difference in prices. According to Nordhaus (1973) model, this should have been captured in higher royalties for the producers (see below).

3. Long Run Trend in Taxes and Transport Costs

In the Introduction, it was proposed that governments had little influence over coal markets. While this is broadly true, the government did alter the course of price trends by introducing and varying the tax facing many consumers in Britain. Certainly, average coal prices appear to have risen between 1600 and 1800, and the main explanation for this rise in coal prices to the consumer from the late 1600s (see Figure 1 and 2) was the introduction of taxes on coal to pay for wars. The tax stood at an average of 12% between 1691 and 1697, and then increased to 33% in 1698, peaking at 38% from 1714 to 1758, varying between 29% and 34% throughout the second half of the eighteenth century, and then dropping to 15% in 1816, after the Battle of Waterloo. In 1831, national duties on coal were removed, although modest local taxes of about 5% remained until 1903 (Hausman 1987 p.592). Therefore, average consumer coal prices increased as consumption grew, reflecting the government´s ability to capture some of the consumer surplus associated with a relatively inelastic demand.

Figure 2 presents more detailed trends in coal prices over seven hundred years in England. It shows prices in London, in England (on average) and in the North-East (without the tax). From 1500, coal prices in the North of England stayed close to £40 (in 2000 values) per tonne for three hundred years. Removing the taxes from the average England and London series creates three parallel trends, indicating the cost of distributing coal around the country. The average English transport costs of coal were 60% of the untaxed value from the 1300 until about 1700. In other words, transport costs (and middlemen) were a large component of the price faced by the consumer.

From the beginning of the eighteenth century, transport costs fell to about 45%. They dropped substantially as a result of the expansion of canals, especially in certain regions (such as South Wales, East Midlands and Lancashire (Turnbull 1987 p.549)). Others benefitted from improving coastal trade (Ville 1986). London prices were consistently about 10% higher than the average and, there, reductions in distribution costs only occurred from the 1790s. Then, from the 1840s, and the advent of the railways, coal prices across England fell towards the price paid in the North East – though, more slowly for London prices.



Source: Fouquet (2011a).

Figure 2. Pithead and Regional Coal Prices in England, 1300-2000

4. Long Run Trends in Extraction Costs

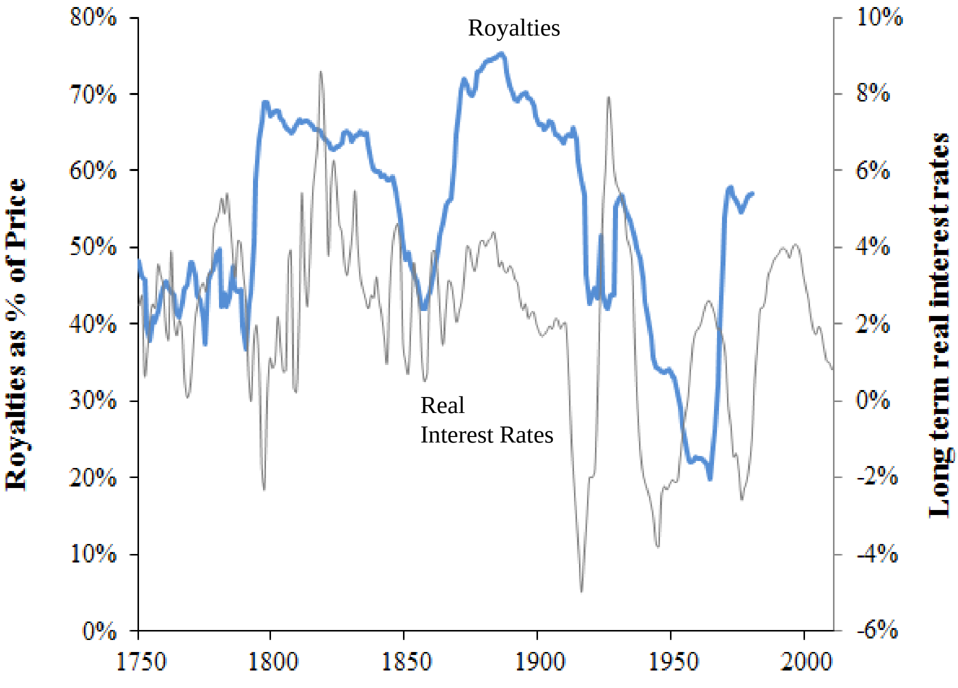
In analyzing non-renewable resource prices, Nordhaus (1973 p.531) "distinguish[ed] between extraction costs, the vector z(t), or the marginal cost per unit of output excluding rents and royalties; and royalties, the vector y(t), which are a reflection of the presumed scarcity of a particular resource.". From 1600, there was data on pithead prices, which acts as an indicator of the extraction costs (see Figure 2). The trend was generally flat (in the $20-$30 per tonne of oil equivalent range) from the seventeenth to the end of the nineteenth century, which is impressive given that coal mines had to be dug deeper to meet rapidly growing demands. In fact, there were declines in extraction costs in the second half of the seventeenth and of the eighteenth centuries – although prices gravitated back to the $20-$30 range. The latter period probably reflected the ability to use early steam engines to pump water out of the deeper mines. Thus, for three hundred years, the greater difficulties of extraction were balanced-out by improvements in technical ingenuity.

It also indicated that until the end of the nineteenth century, there was an elastic supply of labor. In 1913, the peak year of coal production in Britain, there were one million coal miners – 7% of the male work force was extracting coal. However, from the 1870s until the 1920s, miners' strikes signalled the demands for higher wages and better working conditions – there were more than 2,200 coal-mining related deaths in 1913 (Fouquet 2011b). British mines became more mechanized, but overall production costs rose substantially, because coal mines still needed many workers and could never be completely mechanized (see Figure 1). More generally, one can can expect that where substitutability between capital and labor is limited for technical reasons, as in coal mines, the trend in extraction costs will tend to increase, as the economy develops (Ayres and Warr 2009). In other words, if energy is fuelling economic growth and development, then, wages will rise, thus, so will labor costs and, ultimately, energy prices.

5. Long Run Trends in Royalties

Having a proxy for extraction costs (i.e., pithead prices) and prices near the mines (e.g., the North East of England) in Figure 2, it is possible to estimate a crude indicator of royalties. As mentioned, between 1500 and 1800, coal prices in North East England stabilized around $40 per tonne of oil equivalent. Thus, given that extraction costs were in the $20-$30 range, the royalties were roughly one quarter to one half of the costs – though this does ignore (presumably modest) local supply costs. Then, from just before 1800, they increased dramatically.

Nordhaus (1973 p.534) explains "… if the interest rate is high, then the royalty on energy resources is relatively low. Conversely, if these conditions are reversed, the royalty on energy resources is high". Looking at the last 250 years, for which real interest rates exist, Figure 3 suggests that this relationship seems to hold in a few historical periods, but is far from the norm. For instance, in the late eighteenth century, 10-year average real interest rates fell from 4% to 0% and royalties jumped from 40% to almost 70%. Then, around 1800, real interest rates rose again and royalties declined. However, for much of the nineteenth century, there is little correlation. And, then, from 1880, the opposite occurs, and the two variables appear to be positively correlated – real interest rates drop from 4% to 2% and then fall into negative values during the First World War, and royalties on coal seem to follow. Then, from 1950, the negative relationship seems to return. Real interest rates jumped from -2% to 2%, and royalties fell to 20%. In 1965, real interest rates drop back down to -2% and royalties bounce back to 60%. However, this was also a period of heavy government intervention, and institutional factors might have played a stronger role than interest rates in determining royalties. Overall, the historical evidence is inconclusive, and a more thorough econometric analysis would be required to discern the influence of interest rates on royalties and, thus, on trends in coal prices.



Source: Royalties: see Figure 2; Interest Rates: Officer (2012); Allen (2007) – 10-year average.

Figure 3. Royalties on Coal Prices and Real Interest Rates in England, 1750-2010

More importantly, as Nordhaus (1973) emphasized, royalties reflected resource scarcity. He proposed that the "switch date" - that is, the year in which the economy has to make the transition to the abundant, but expensive backstop energy source - imposes upward pressure on royalties and, therefore, prices. The sooner the date at which the economy needs to begin the transition to the backstop energy source, the higher will be the price.

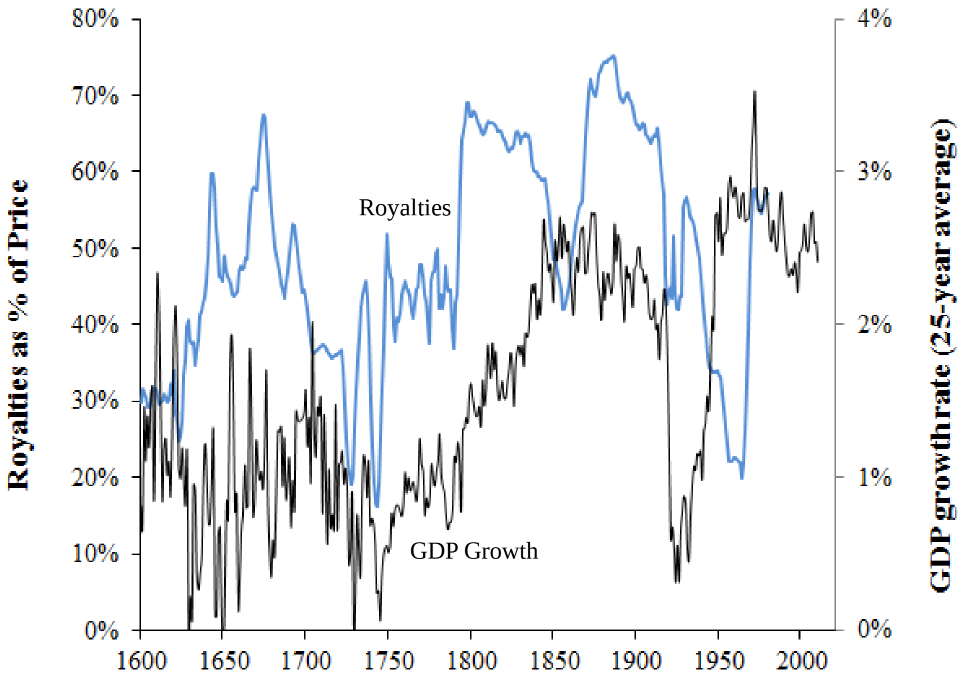
So, when was the perceived switch date? As a young economist, William Stanley Jevons (1865) made his name by effectively asking this question. He famously proposed the paradox that efficiency improvements would lead to an increase in coal consumption, rather than a decrease, because of what is now known as the 'rebound effect' (Madureira 2012). He combined this idea with long run projections of British population and economic growth to forecast coal consumption over the next one hundred years – which he proposed would grow by 3.5% per year, reaching 2.6 billion tons in 1961 (Jevons 1865 XII.23) – equivalent to 1.6 billion tonnes of oil[3]. Jevons estimated that, at this growth rate, the country would consume roughly 100 billion tons of coal between 1860 and 1960. However, he also used geological estimates of coal reserves to indicate that, at that rate, Britain's main fuel would disappear in 80 years (Madureira 2012 p.410).

Two years before, an industrialist, William George Armstrong, had already made a forecast, using more simple linear assumptions about consumption patterns, that Britain's coal reserves would last 212 years (Madureira 2012 p.410). Two years before that, in 1861, the geologist Edward Hull "had estimated the recoverable resources as assessed by the Geological Survey for England, Wales and Scotland amounted to about 80,000 million tons of coal, which, at the rate of production in the late 1850s, would last for 1,100 years." (Madureira 2012 p.403). Thus, the markets might have believed that the switch date to a backstop energy source had fallen from 1,100 years (in the future) in 1861 to 80 years in 1865. It may be a coincidence, but royalties increased from around 40% of the pre-tax price in 1857 to 70% in 1872.

Certainty, just as the US has been concerned about oil supplies since the 1970s, British industrialists and politicians were fearful about dwindling coal reserves in the mid-nineteenth century. As Figure 4 shows, the (25-year average) growth rate

[3] Out of interest, United Kingdom's peak year of coal consumption was 1913, reaching 160 million tonnes of oil equivalent, which was 50% of the Jevons' forecast for 1913 and 10% of the Jevons' peak (i.e. 1961) forecast. Nevertheless, he was partially correct about the impact of rebound effects on energy consumption, although only for a few decades in the second half of the nineteenth century (Fouquet 2014).

of British GDP, which had been fuelled by deeper and longer coal mines, had been accelerating since the 1750s. “British leaders viewed the linkage between coal and the empire as the mainstay of their strategic clout, which was then consolidated through trade networks, industrial advantage, shipbuilding industries and naval power. More than a commodity, what was at stake was a string of economic interdependencies with repercussions for the British way of life. There was such anxiety about coal’s interlocking effects that the slightest sign of disturbance could escalate into sweeping policy issues. Irrespective of the different political positions of economists and geologists, they both shared the view that industrial ascendancy and world supremacy was closely bound up with coal.” Madureira (2012 p.419).



Source: Royalties: see Figure 2; GDP: Broadberry et al. (2015).

Figure 4. Royalties on Coal Prices and GDP Growth Rates (25-year average) in England/Britain/United Kingdom, 1600-2010

Royalties peaked in the mid-1880s at 75% of the pre-tax price, which coincided with the peak of British long-run average GDP growth rate (see Figure 4). Both, the growth rate and royalties fell a little over the next thirty years. Then, as economic growth rates collapsed, royalties fell from 65% in 1913 to 42% in 1919. Afterwards, the British economy was no longer as fundamentally tied to coal, and royalties fell to 20%. Coal was no longer king in Britain, and was no longer scarce (Church 1987).

6. Conclusion

Given the growing concern about the ability for economies to continue to grow despite limited fossil fuel reserves, William Nordhaus (1973) sought to ask 'how do markets allocate energy resources?' and 'how can energy resources be allocated efficiently?' The purpose of this paper was to offer a crude test of the model he developed to answer the first question. The model is tested by using energy prices over more than five hundred years.

The model is based on the relationship between royalties associated with the production of a non-renewable energy resource and (i) the cost of the backstop energy source, (ii) the interest rate and (iii) the switching date to the backstop energy source. Although elegant and simple, a general weakness of the model is that, both to the market and to the analyst, a backstop technology may not be clearly identified. As a result, the cost and the switching date may be highly uncertain.

Despite this general limitation, for the history of Britain, it was possible to identify a backstop energy source, woodfuel (i.e., firewood and charcoal), which could have been an expensive alternative to coal. For most of the period, there is little evidence of concern for the switching date to the backstop. However, a fear of running-out of coal did take hold of Britain in the mid-nineteenth century. This was a remarkable period of one hundred years of accelerating economic growth rates and popular fears of resource scarcity developed. In turn, the markets translated this fear into a dramatic increase in royalties, though with more ambiguous effects on national average coal prices. Nevertheless, this led to the discovery of new coal reserves, new methods of extraction, more efficient ways of consuming energy and, ultimately, substitutes for coal, in the form of new energy sources (such oil, gas and electricity) rather than the backstop technology. It ultimately led to the gradual decline of coal use in Britain, perhaps like the energy crisis in the 1970s was a signal of the beginning of a gradual decline of oil use in industrialised economies.

This paper only offered a crude attempt to test the Nordhaus (1973) model of resource allocation – and the model needs and deserves a more rigorous analysis. The general impression the very long run data and this crude test provided was that energy markets tend to be myopic, unaware of the limits of the non-renewable resource being traded and of a backstop technology. Only in moments of crisis does it consider the finiteness of the resource and, then, perhaps too dramatically, triggering major new technological, infrastructure and R&D investments. Yet, these create the new landscape of future energy markets.

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