Depletion and Valuation of Energy Resources

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Glossary

backstop A substitute supply that is expected to become active when current supplies are exhausted. This is taken as a "renewable" supply available indefinitely at a constant unit cost. The "price of the backstop" would be this "high" unit cost. Commercially viable fusion reactors have been taken as the backstop energy source.

hotelling rent The rent per unit extracted that exists because of the finiteness (exhaustibility) of the stock being extracted from.

marginal cost of extraction Given an equilibrium, the cost of extracting one more unit

Nordhaus (Herfindahl) model A linked sequence of "Hotelling models," each with a higher unit cost of extraction. The demand schedule is unchanging in the Herfindahl version.

rent The positive gap between market price per unit and marginal cost for supplying an additional unit.

Ricardian rent The rent per unit that exists because of a quality advantage of the unit in question.

royalty A payment to the owner of a deposit by the extractor, who in effect is renting or borrowing the deposit.

In the early years of the 21st century, industrialized nations exist in a world of cheap energy. Direct outlays by households for electricity, household heating, and fuel for transportation occupy small fractions of almost all family budgets. Canada and the United States, with 5% of the world's population, consume 25% of global energy. In per capita terms, the United States consumes 354 million Btu/year, Western Europe consumes 170 million Btu/year, and India consumes 12 million Btu/year. A Btu is the amount of heat required to raise the temperature of 1 lb of water 1°F. Energy use in North America grew 31% between 1972 and 1997. Is an era of high energy costs just around the corner? Is there a signal of a higher priced era to be read out there today? In the period following oil price hikes in 1973–1974, the U.S. Department of Energy predicted $150 a barrel for oil in the year 2000 in year 2000 prices. Exxon predicted a price of $100. What has abundant energy accomplished for us? Since approximately 1800, the four most revolutionary changes in a person's life in industrialized countries are (1) the substitution of machine power for animal and manpower, (2) the more than doubling of life expectancy, (3) the arrival of relatively low-cost transportation for persons and commodities, and (4) the arrival of global and low-cost communication. Clearly (1) and (3) are outcomes of new forms of energy use. The dramatic increase in longevity is probably mostly a consequence of improvements in the processing of water, food, and wastes—that is, improvements in the public health milieu, broadly conceived rather than a result of low-cost power, directly. But the impact of reduced demands on humans and animals for power on a person's life expectancy should not be dismissed. Improved, low-cost communication is related to the arrival of electricity and electronics, not power per se. The words labor, from Latin, and work, from Greek, both capture the idea of an expenditure of painful physical or mental effort, of energy expenditure. People who do no labor or work then are those expending little energy. Revolutionary in human history is the substitution of machine power for human and animal power. Hoists (pulleys) and levers were early simple machines that magnified human and animal power considerably. Watermills and windmills arrived and showed what could be accomplished with new energy sources captured by machines and new types of power output—namely, steady and continuous rather than episodic. But it was the arrival of steam engines (heat machines) that revolutionized the concept of usable power. The concept of transporting goods and people changed dramatically and powering a factory was freed from ties to watermills and windmills.

1. DEPLETION PRESSURE

It is easy to make the case that depletion pressures induced invention and innovation in energy use. Since at least the time of Great Britain's Elizabeth I, say 1600, conservation of forests for future fuel and timber supply was prominent on the public agenda. In the early 1700s, English iron production was using up approximately 1100 km^2 of forest annually. The notion that forest depletion drove the development of British coal fields is a popular one. But causality is tricky here — did the arrival of cheap coal lead to a liquidation of remaining forests or did the depletion of forests induce innovation in coal supply? This really has no ready answer. Fuel scarcity apparently led to the importation of iron by England in the mid-18th century. Around 1775, coal became viable in smelting iron and England's importing ceased. Coinciding with the coalification of the British economy was the development of the steam engine, first as a water pump and later as a source of power in factories, such as cotton mills. Jevons (1865, p. 113) opined that "there can be no doubt that an urgent need was felt at the beginning of the 17th century for a more powerful means of draining mines." Savery's steam pump was operating in 1698 and Smeaton made Newcomen's engine, with a piston, sufficiently efficient to be commercially viable. In 1775, the new steam engine of James Watt was developed.

Given the documented concern in Great Britain about timber supply, say, before 1700, one should observe a rise in the price of wood for fuel, house-building, and ship-building at some point. The year 1700 seems like a reasonable year to select as having recorded an increase in wood price. Firewood prices grew three times faster than the general price level in England between 1500 and 1630 and the 17th century was one of "energy crisis." Over one-half of the total tonnage entering British ports in the 1750s was timber, and fir imports grew 700% from 1752 to 1792. France also experienced rapid increases in fuel wood prices over this latter period. The prevailing "high" price in 1700 should, of course, spur the search for substitute energy sources. Importation is one form of substitution and coal development would be another. Given flooding problems with new coal deposits, an investment in reasonable-quality pumps was a low-risk strategy. The deposits were known to exist and the demand for coal seemed certain. The Saverys and Newcomens rose to the occasion. This is a possible explanation for the invention and introduction of steam pumps after 1700. It shifts the emphasis from spontaneous invention to profit-driven invention and innovation. A wood supply crisis is the ultimate impetus in this scenario. Current or anticipated fuel scarcity raises fuel costs and induces a search for substitutes. Coal is the obvious substitute but mine-draining looms up as a serious constraint on coal production—hence, the pressure to invent and to make use of steam pumps. Cheap coal transformed the British economy. In 1969, Landes estimated coal consumption in Great Britain at 11 million tons in 1800, 22 million tons in 1830, and 100 million tons in 1870. The British appear to have been sensitive to energy use over the long run. The Domesday Book, published in 1086, records over 5000 water-wheels in use in England—one mill for every 50 households.

Attractive in this scenario is the low-risk nature of investment in pumping activity. The coal was there, the demand was there, and one simply had to keep the water level in the mines low. Recall that a Newcomen engine was part of a multistory structure and thus represented a serious outlay. However, the technology had been proven in small-scale engines and the minerals were there for the taking. The second watershed moment in the history of steam power, associated with James Watt, was its development for powering whole factories. It can be argued that it was the depletion of good watermill sites, well documented for the Birmingham region by Pelham in 1963, that spurred invention. Richard Arkwright's invention of the cotton-spinning machine and mill and James Watt's invention of the improved steam engine compete in the literature on the industrial revolution for the label, "the key events." Spinning mills required a power source and water-wheels were the standard at the time. But convenient sites for water-wheels had mostly been taken up by the 1770s. The price of those sites would have exhibited a significant rise in, say, 1775, the year Watt was granted his special patent for his engine with a separate condenser, an engine vastly more efficient than the Newcomen type. The climate was right for invention in the power supply field. Depletion of good water-wheel sites drove up their prices and the resulting umbrella of profitability made invention in this area attractive. At approximately this time, serious research of water-wheels was undertaken by Smeaton with a view, of course, to obtain more power from the waterflow. Obviously, a profit-driven view of events is not the only plausible one, but there is no doubt that profits accrued to Watt and his partner, Boulton.

Coal and oil compete as bulk fuels in many parts of the world for powering electricity-generating plants but steam engines for motive power have been displaced by gasoline, diesel, and electric engines in most areas of the world. Steam locomotives were common in industrialized countries as late as the 1950s. This is the classic case of a low-cost, clean energy source (e.g., a diesel engine for a locomotive) being substituted for a dirtier and, presumably, higher cost source. The conspicuous aspect of energy use is the capital goods that come with the energy flow. For example, wind is the energy source and the mill transforms the energy flow into usable power in, for example, grinding wheat. Similarly, the rushing stream is the energy source and the wheel and mount are the capital goods that allow for the production of usable power. What Savery, Newcomen, Watt, and others did was to invent a capital good that turned a heat flow into usable power. The role of the inventor is to envisage a capital good, a machine, that allows for the transformation of an energy flow into a power flow. From this perspective, it is difficult to conceive of an energy supply crisis. One looks forward to larger and better machines harnessing old energy flows better and new flows well. An oil supply crisis in the early years of the 21st century would translate into a transportation cost crisis but not an end-of-civilization crisis. Approximately one-fifth of electricity in the United States was generated with petroleum in 1970. In 2002, that figure is one one-hundredth. Coal burning produces approximately one-third more carbon dioxide than oil burning and approximately twice as much as the burning of natural gas, per unit of heat. Transportation fuel can be synthesized from coal and methane, but only at relatively high costs, given today's technology. The Germans used the Fischer-Tropsch process to produce gasoline from coal during World War II and the search for a catalyst to produce gasoline from methane is under way.

The appropriate aggregate production function to consider for an economy takes the form of output flow, $Q = F[N, K, E(K^E, R)]$, where $E(\cdot)$ is power derived from an energy flow R, say, oil, and capital equipment, K^E, K is other capital, and N is labor services. Before 1800, K^E was windmills and water-wheels for the most part and R was wind and water flow. In the 21st century, food is cooked in and on electric stoves rather than in hearths, light is provided by electric units rather than candles or lanterns, and heat is provided by furnaces and distribution devices rather than by fires, fireplaces, and stoves. $E(K^E, R)$ is dramatically different even though basic houses are similar in concept and shape and eating styles and habits are not hugely different. What would the world be like with steam power but no electricity? There was an interval of approximately 75 years during which this state existed. Steam power was decisive in liberating people from much heavy labor. Steam power could drive hoists, diggers, and pumps. It could also power tractors, locomotives, and even automobiles. Factories could be well mechanized with steam engines. In 1969, Landes suggested that the 4 million hp of installed steam engines in Britain in 1870 was equivalent to 80 million men, allowing for rest, or 12 million horses. A worker with steam power was like a boss with, say, 16 healthy workers at his bidding. In 1994, Smil estimated that a worker can put out 800 kJ net per hour. From this, he inferred that the Roman empire's 85,000 km of trunk roads required 20,000 workers, full time, working 600 years for construction and maintenance. The gain in bulk power production from the use of electric motors rather than steam motors seems marginal when history is viewed on a large time-scale. Electricity rather created new activities such as listening to the radio, watching television, and talking on the telephone. These are large gains in the range of consumer goods, essentially new attractive commodities, but they are on a different order from innovations relieving humans of great and steady physical exertion. Electric stoves and washers have undeniably made housework easier, and air-conditioning (room cooling) has the lessened the discomfort of labor for many as well as altered the geographical distribution of settlement.

With regard to personal travel, steam power might have been revolutionary enough. Steamships were quite different from sailing ships and trains were quite different from stagecoaches. Steam-powered automobiles and trucks are technically feasible. The internal combustion engine, drawing on gasoline and diesel fuel, is not a crucial technology, though steam power for vehicles was quickly displaced. Steam power revolutionized the concept of daily work and of personal travel. Huge numbers of people ceased to be beasts of burden. Huge numbers of people were able to visit relatively distant places quite rapidly. Diets changed significantly when new foods could be transported from distant growing places. Crucial to modernization, however, was the substitution of machine power for human and animal power, which steam engines effected, and the spread of reasonable living standards to low-income families. Steam power brought about this latter effect only indirectly, by making mass production techniques widespread. Mechanization brought down the prices of many goods (e.g., cotton) but displaced workers in the handicraft, labor-intensive sectors. Wages rose in Great Britain some 50 years after the industrial revolution was well rooted. Machine-intensive production relieves workers of much grinding physical exertion but usually eliminates many traditional jobs as well. A large virtue of market-oriented (capitalistic) development is that entrepreneurs create and often invent new jobs for the workers displaced by mechanization. Wages and living standards have risen, particularly with a decline in family size.

2. DEPLETION ECONOMICS

Though in 1914 Gray first formalized the idea that impending natural stock (say, oil) scarcity would show up in current price as a rent, a "surplus" above extraction cost, Hotelling presented the idea most clearly in 1931. A royalty charged by an owner of a deposit to a user of the deposit is, in fact, "Hotelling rent." Thus, the idea of "depletion" being a component of current mineral price is ancient. Competing, however, with the Gray–Hotelling theory is a theory that has current oil price rising up the market demand schedule because each subsequent ton is becoming more expensive to extract. Deeper is more costly. This approach was adopted by the great W. S. Jevons in his monograph on coal use in Great Britain: "...the growing difficulties of management and extraction of coal in a very deep mine must greatly enhance its price. It is by this rise of price that gradual exhaustion will be manifested ..." (Jevons, 1865, p. 8) Jevons' son, also a professor of economics, reflected on his father's work, pointing out that the price of coal had indeed risen over the 50 years since his father's book was written, by, however, just 12% relative to an index of prices. And reflecting on his father's analogy of high energy prices being like a tax, Jevons recommended accumulating alternative forms of capital to compensate future generations for their shrunken coal capital. A standard modern view has the current rent in oil price, a reflection of the profit or rent derivable from currently discovered new deposits. Hotelling theory sees current oil price as a reflection of (1) how long current stocks will carry society until users are forced to switch to substitute sources and (2) what price those substitute sources will "come in at." It was then the value of remaining stocks that held current price up, rather than pressure from currently steadily worsening qualities. As Nordhaus has made clear, in Hotelling's theory of depletion or "resource rent," current price turns crucially on the cost of supply from the future substitute source (the backstop) and on the interval that current stock will continue to provide for demand. See Fig. 1 for an illustration of Hotelling theory.

r is the interest rate in the market and Hotelling's approach is often referred to as the r percent theory of resource rent because profit-maximizing extraction by competitive suppliers implies that rent rises over time at r percent. Hence, the quantity sequence in an equilibrium extraction program is the one displaying rent rising at r percent per period. Current rent (price minus current unit extraction cost) turns out to be simply discounted terminal rent, with this latter term being defined by the unit cost of energy from the backstop or substitute source. To say that the price of oil is high today could mean that remaining stock is not abundant and substitutes will

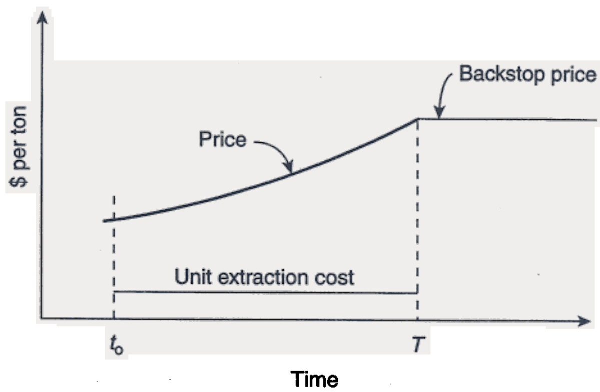

FIGURE 1 Hotelling model. In this competitive case, rent (price less unit extraction cost) rises r% until the stock is exhausted, at date T. Price "fed into" a market demand schedule yields current quantity supplied at each date. Unit cost, backstop price, stock size, and the demand schedule are parameters. Interval (t_0, T) is endogenous.

be available at high prices (Hotelling theory) or that future supplies will come from lower quality, high-cost deposits (Jevons theory). These two theories have been brought together in one model in a simple version by Herfindahl (see Fig. 2) and in a more complicated version in 1977 by Levhari and Leviatan and many others. The Herfindahl version has scarcity or depletion rent rising at r percent and, although unit extraction costs are constant, then jumping down as the next deposit or source is switched to. For the case of many deposits, Fig. 2 depicts a combination of intervals with rising rent linked by jumps down in rent. Quality decline causes rent to jump down. The Hotelling or depletion effect moves counter to the quality-decline effect. Thus, even in this simple world of no uncertainty or oligopoly in supply, one cannot be accurate in saying that exhaustibility is showing up in current price movement as an increasing rent or depletion effect (Fig. 2).

Hotelling provided a systematic theory of how depletion would show up in current price and how finiteness of the stock would show up in the pace of stock drawdown. In the simplest terms, exhaustibility is represented by a wedge between current unit cost and price. Thus, if world oil stocks were dwindling rapidly, one would expect oil prices to be high, well above unit extraction costs. And in fact, episodes of high world oil prices have been observed in recent decades, times when average world oil prices were well above unit extraction costs. Such wedges are labeled "rents" in standard economics and, with something like oil, the wedge might be referred to as scarcity rent or Hotelling rent. The world demand schedule does not shift in these episodes but current extracted output does shift back

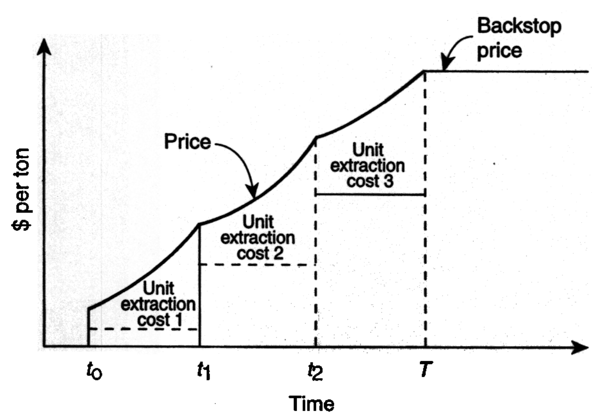

FIGURE 2 Nordhaus (Herfindahl) model. A three-source, linked Hotelling model. Low-cost supplies are exhausted first. Rent rises r% except at source switch. Rent jumps down across source switch. Intervals of source use are endogenous.

for some reason. It is these fairly sudden contractions in current production that cause current prices to jump up and "create" extra rent. The first large jump was in the fall of 1973. Another occurred in 1979, with the collapse of the Palhevi monarchy in Iran, and a large drop in price occurred over mid-1985 to mid-1986. Here the argument is that discipline among a cartel of oil suppliers broke down and world supply increased fairly quickly.

Price changes are largely driven by changes in current production flow or supply and current production is a complicated function of parameters, including estimated remaining stock or cumulative supply. Hotelling theory is an intertemporal theory of discounted profit maximization by competitive producers that links current production to remaining stock, extraction costs, demand conditions, and backstop price. It makes precise the exhaustibility effect or depletion in current resource price. Hotelling theory obtains a "depletion effect" in current price relatively simply in part because it makes use of the traditional assumption of perfect foresight by profit-maximizing agents. Economic theory relies on this assumption because it becomes an essential component of intertemporal profit maximization. The real world is, of course, replete with events that are very difficult to anticipate, such as wars, government regime switches, and technical changes. For example, research suggests that oil may be generated deep in the earth by unexpected geothermal processes. Uncertainty makes simple calculation of a depletion effect in current price a dubious course.

In its original form, Hotelling theory abstracted from uncertainty completely. And Hotelling did not take up quality variation in current deposits or stocks. This has, fact, led many observers to argue that Hotelling theory is fundamentally flawed as an explanation of rent or price paths for, say, oil. Also, Hotelling did not address oligopoly in supply and such market structures have been considered to be crucial in explaining oil price movements in recent decades. In the face of those well-known difficulties in arriving at a theory of oil price determination, in 1985 Miller and Upton tested "Hotelling's valuation principle" for a sample of oil-producing companies whose shares were being traded on the New York Stock Exchange. Employing heroic simplifying assumptions, they derived an equation to estimate in a sequence of straightforward steps and fitted their equation to the data, with positive results. It seems undeniable that extraction to maximize discounted profit is the reasonable maintained hypothesis and in a sense Miller and Upton confirm this position. But profit maximization by an extractive firm in an oligopoly setting, for instance, yields a quite different extraction program than that for a firm in a competitive setting. Miller and Upton provide weak evidence in favor of competitive extractive behavior by oil extraction companies. Implicit in their work is an argument that Hotelling rent is positive and present in the price of oil. However, the plausible "crowding" of such rent by stock quality decline cannot be evaluated from their analysis. In 1990, Adelman argued that current oil rent reflects the marginal cost of discovering new supply and most rent earned by producers is a Ricardian rent, one attributable to a quality advantage possessed by current suppliers lucky enough to be currently working a low-cost deposit.

Consider the reality of a backstop source of energy. Suppose the world does have a 20-year supply of "cheap" oil available, as Deffeyes suggested in 2001. (The Edison Electric Institute estimates that proven reserves of oil will last 37 years, those of natural gas will last 61 years, and those of coal will last 211 years.) In 2001, Kaufmann and Cleveland presented a careful, empirically based critique of Hubbert's bell-shaped supply schedule. Why is a foreseeable energy supply crisis not showing up in markets today? The answer appears to be that backstop supplies are fairly abundant, in the form of large deposits of coal, natural gas, tar sands oil, shale oil, and uranium. None of these supplies is as attractive and as low-cost as oil but it would not be complicated to power a modern economy with a combination of these energy feedstocks. Directly difficult would be fuel for transportation, given current engine technology and driving habits. Whatever transpires with long-term oil supplies, the era of low-cost individualistic transportation will likely end. The century 1920–2020 may well go down in history as the curious low-cost, automobile period, an era of individuals dashing about the surface of continents in big cocoons of steel on expensive roadways, while seriously polluting the atmosphere.

In 1974, Nordhaus brought his combination of Hotelling and backstop economics together in an ingenious empirical exercise. Given a backstop supply price and a sequence of world demands for energy into the distant future, and given world stocks of oil, coal, and uranium and unit extraction costs, he let his computer solve for the Hotelling transition path from his base period, 1973, to the era of constant cost fusion power. Naturally, stocks with lower unit extraction costs provide energy early on. See Fig. 2. Thus, one observes an oil supply era of endogenous length, a coal era, a uranium era, and then the fusion power era with constant unit cost into the indefinite future. A critic can easily dismiss this investigation as computer-aided, crystal-ball gazing. However, the Nordhaus model was subjected to sensitivity testing at low cost, and the empirical output appeared to be fairly robust. Central to this is, of course, discounting. Events beyond 30 years register little today, given discounting. Hence, fusion power costs largely fade out in the current price of energy, as do many other parameters of the model. It remains, nonetheless, a very good framework for organizing one's thinking about the future of energy. When the oil runs out, modern life does not end, just the curious era of abundant, low-cost energy, especially for personal transportation.

Nordhaus's "simulation" yielded a current price (1973) of energy somewhat below the observed market price. He inferred that this occurred because his model was "competitive," *a priori*, whereas the real world contained much oligopoly in energy production—hence, an obvious need to refine the computer formulation. However, the introduction of oligopoly to extraction models is tricky, if only for reasons of incorporating the dynamic consistency of agents' strategies. There must be no obvious possibilities for profit-taking simply by reneging on one's "original" strategy selected at time zero. To rule out such possibilities for profits, problems must be analyzed and solved backward, from tail to head, and this turns out to be much more complicated than, for example, Nordhaus's essentially competitive formulation. There is an important lesson here. If one believes that current energy prices reflect noncompetitive behavior among suppliers, which seems most reasonable, then quantifying such capitalizations is known to be difficult. One can rule out simple explanations for current energy price levels. The combination of Hotelling theory and backstop theory indicates that traditional supply and demand analysis is an inadequate way to think about current energy price formation. The addition of oligopoly considerations complicates an already complicated process of current price determination.

In the simplest case of current price shift, as for, say, October 1973, suppliers revise estimates of remaining stock downward and current price jumps up. "Mediating" this price shift is a process of agents discounting back from "the terminal date" to the present, discounting along a Hotelling extraction path. Current quantity extracted jumps down and current price jumps up. If demand is inelastic in the region, aggregate revenue will jump up. Thus, the motivation to raise current price could be for reasons of revenue. With some coordination of quantities in, say, a cartel, the current price jump may be an oligopoly or cartel phenomenon rather than an outcome of stock size revision. Somewhat analogous is a revision by suppliers of the anticipated backstop supply price. A revision of expectations upward would lead to a current price jump upward and vice versa. A price drop occurred briefly when University of Utah researchers announced "cold fusion." And the popular interpretation of the large drop in world oil prices during 1985–1986 is that cartel discipline broke down Organization of Petroleum Exporting Countries (OPEC) and key members raised their outputs above their quota levels.

It is undeniable that the current interaction of the world supply curve for oil and the world demand curve yield the current price. At issue is how depletion rent and oligopoly rent are capitalized in the current costs of production, costs that determine the characteristics of the effective supply schedule. In the mid-1970s, reasonable observers debated whether the 1973 jump in world oil price was the result of production restraint by OPEC, an oligopoly effect, or a reckoning that future oil stocks would be rather smaller than had been anticipated. In any case, current production was cut back and world prices leapt up. A popular view of the poor performance of the U.S. economy in the later 1970s was that it had to accommodate unanticipated supply-side shocks in the energy sector. The notion of cost-push inflation became popular and an extensive literature emerged on this issue.

Since impending exhaustibility is predicted to manifest itself in currently high price, which is reflecting a large scarcity rent, a standard view is that the current and anticipated high prices should induce a search for substitute supply. How tight is this link between, say, rising current oil price and a spurt of invention to develop an alternative supply? It was argued above that this link is relevant for explaining two of the most significant events in human history—the effect of timber scarcity in Great Britain on the timing and intensity of the invention of mine-draining machinery (the steam engine) and the effect of watermill site scarcity on the timing and intensity of invention in steam engine efficiency (Watt's separate condenser). It may be the anticipated high price rather than the current actual high price per se that induces inventors to perform, to come up with substitute supply. Simply anticipating that, say, oil will be exhausted soon while current price is not yet high may be sufficient to get invention going. Inventors can have foresight. They need a process or invention that brings in a competitive supply of energy when the oil runs out. In 2003, Mann argued that recent low oil prices have slowed innovation in the alternative energy sector.

Interesting models in which the substitute supply is, in fact, invented or perfected today in the public sector in order to force current oil suppliers to lower current prices have been developed. The invention is annouced and mothballed until the oil is exhausted. In such a scenario, it is not high prices today that speed up invention, rather it is the anticipation of the high prices in the future that induces inventors to perfect the substitute today.

3. *THE SCARCITY OF CLEAN ENERGY SUPPLIES*

Attention has shifted from energy sources with low cost, per se, to sources that can provide energy cleanly, at low costs. Smog in Los Angeles seems to have spurred policymakers to move toward designs for a future with cleaner air and with low-emission vehicles, homes, and factories. Eighty-five percent of world energy supply is currently derived from fossil fuels and 1% is renewable (excluding hydropower). The recent DICE model of global warming of Nordhaus and Boyer has unlimited energy produced at constant unit extraction cost from hydrocarbons but energy production contributes directly to an atmospheric temperature increase, via carbon dioxide emissions. The temperature increase shows up in explicit current economic damage. This is a large departure from the Hotelling view because Nordhaus and Boyer have no stock size limitation for, say, oil. Price, inclusive of an atmospheric degradation charge (a Pigovian tax on energy use), rises along the industry demand schedules because, essentially, of the increasing scarcity of moderate atmospheric temperatures. It is "moderate temperature" that is being "depleted" in this view and a "depletion charge" in the form of a marginal damage term (a carbon tax) is required for full cost pricing of energy. A world without carbon taxes is, of course, one of "low" energy prices, one in which the atmosphere is a carbon sink, with carbon dioxide dumped in at zero charge. User fees for dumping? "If U.S. consumers pay $1 billion a year, would that be enough to cover the problem? How about $10 billion? The level of economic damage that might be inflicted by greenhouse gas abatement is so uncertain that even the Kyoto treaty on global warming ... says not a word about what the "right" level of emissions should be." (Mann, 2002, p. 38) In 2002, Sarmiento and Gruber reported that atmospheric carbon dioxide levels have increased by more than 30% since the industrial revolution (the mid-18th century).

A formal statement of the world energy industry along Nordhaus–Boyer lines looks much like the Hotelling variant of Levhari and Leviatan amended to incorporate a continuous quality decline of the oil stock. Aggregate benefits (the area under the industry demand schedule) from current energy use, q, are $B(q)$. Temperature interval, T, above "normal," increases with q in $dT/dt = \alpha q$. Energy users (everyone) suffer current economic damage, $D(T)$. Thus, the only way to stop the full cost price of energy from rising is to switch to a source that does not drive up global temperatures. Here, the current price is $[dB(q)]/(dt)$ and the carbon tax in price is the discounted sum of marginal damages from temperature increments. (A constant unit extraction cost changes the formulation very little.) This price needs the right Pigovian tax on carbon emissions, a dumping fee, to be the full market price for energy.

Will the current, dirty, energy-generating technologies be invented around? Would they be invented around if current energy prices were higher? Mann thinks so. How abundant will fuel cells, solar generation installations, "pebble bed" nuclear reactors, windmill farms, synthetic fuels, and more sophisticated electric power transmission grids be 20 years from now? Are carbon taxes and attendant high current energy prices the best prescription for a cleaner energy future? Many policymakers have not espoused this approach, particularly in the United States and Canada.

4. SUMMARY

Depletion theory is the attempt to explain price formation for commodities such as oil, those with current flows being drawn from finite stocks. Price rises above unit extraction cost because of a depletion effect and one analyzes the nature of this effect in order to try to predict future price paths. Until recently, attention was focused on how the progressive scarcity of an oil stock was translating into the current high price for oil in use. In the past decade, attention has shifted from how the limitation on future supply is showing up in, say, oil price to how the effects of pollution from fossil fuel burning should be incorporated into current price. The depletion effect on the clean environment becomes a component (a pollution tax) in current full price. The hope is that full pricing of energy will signal to users how best to use energy currently and will signal to suppliers the potential profitability of innovating in the energy supply process.

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