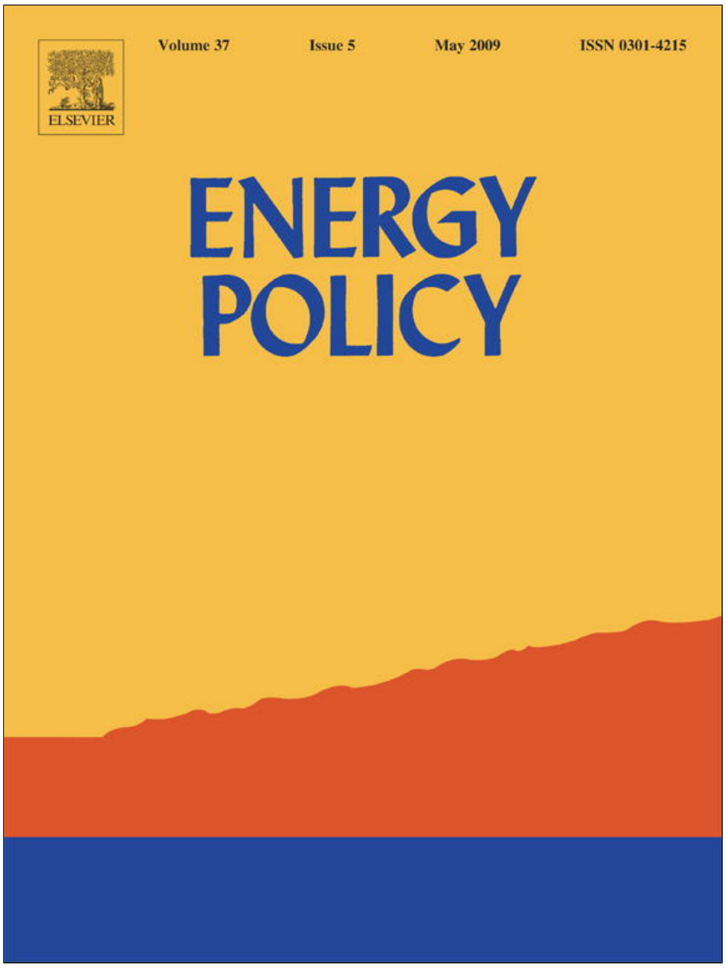
Volume 37
Issue 5
May 2009
ISSN 0301-4215
ELSEVIER
ENERGY
POLICY

Energy Policy 37 (2009) 1767–1781

Contents lists available at ScienceDirect

Energy Policy

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

Technology S-curves in renewable energy alternatives: Analysis and implications for industry and government

Melissa A. Schilling *, Melissa Esmundo

Stern School of Business, New York University, 40 West 4th Street, New York, NY 10012, USA

ARTICLE INFO

Article history:
Received 11 November 2008
Accepted 6 January 2009
Available online 23 February 2009

Keywords:
Renewable energy
Technological innovation

ABSTRACT

Plotting the performance of a technology against the money or effort invested in it most often yields an S-shaped curve: slow initial improvement, then accelerated improvement, then diminishing improvement. These S-curves can be used to gain insight into the relative payoff of investment in competing technologies, as well as providing some insight into when and why some technologies overtake others in the race for dominance. Analyzing renewable energies from such a technology S-curve perspective reveals some surprising and important implications for both government and industry. Using data on government R&D investment and technological improvement (in the form of cost reductions), we show that both wind energy and geothermal energy are poised to become more economical than fossil fuels within a relatively short time frame. The evidence further suggests that R&D for wind and geothermal technologies has been under-funded by national governments relative to funding for solar technologies, and government funding of fossil fuel technologies might be excessive given the diminishing performance of those technologies.

0. Introduction

Almost 85% of the energy used in the United States in 2007 was generated from fossil fuels, with approximately 40% of total energy coming from petroleum, 23% coming from natural gas and 22% coming from coal. Nuclear energy provided approximately 8% of the energy used in the United States, and renewable energy sources (including hydroelectric, geothermal, biomass, solar energy, and wind energy) collectively provided just over 6% (US Department of Energy, Annual Energy Review, 2007). This, of course, has alarming consequences, including (but not limited to) the emission of greenhouse gasses that results from the use of fossil fuels, and the price volatility and political instability that can result from reliance on fuels that are finite in quantity and unequally distributed around the world.

Renewable energies are at a disadvantage in comparison to fossil fuels in at least two respects: (1) current production capacity and (2) costs. However, we will show here that some of the assumptions that are typically made about the attractiveness of renewable energies overall, and the comparative advantage of individual renewable energies vis-à-vis the others may be misguided. In particular, examining renewable energies through the lens of technology improvement S-curves yields some enlightening – and important – surprises that ought to be taken into consideration in future investment by both government and industry. In particular, we will provide evidence that suggests (a) both wind energy and geothermal energy are poised to become more economical than fossil fuels within a relatively short time frame, (b) R&D for both wind energy and geothermal energy has been underfunded by national governments relative to funding for solar technologies, and (c) government funding of fossil fuel technologies may be excessive given the diminishing performance of those technologies.

We will begin by reviewing the literature on technology S-curves and technology cycles to provide insight into how investment can be expected to affect performance improvement in different energy technologies. In the next section, we will provide brief overviews of some prominent renewable energy sources, including their key advantages and disadvantages. We will then present data on the historical consumption of energy from renewable sources, the evolution of their costs, and government investment in R&D for renewable energy technologies. We will then utilize a technology S-curve perspective to analyze the rates at which the performance of renewable energy technologies have improved, revealing key differences in their performance trajectories. Analyzing renewable energy alternatives from a technology S-curve perspective builds on the tradition of using experience curves to analyze "learning by doing" in renewables (e.g., Neij, 1997), but emphasizes instead the "learning by searching" accomplished through R&D expenditure (Huber, 1992; Kobos et al., 2006), which can provide an especially

* Corresponding author. Tel.: +1 212 998 0249; fax: +1 212 995 4235.
E-mail addresses: mschilli@stern.nyu.edu (M.A. Schilling), Melissa.Esmundo@stern.nyu.edu (M. Esmundo).

0301-4215/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.enpol.2009.01.004

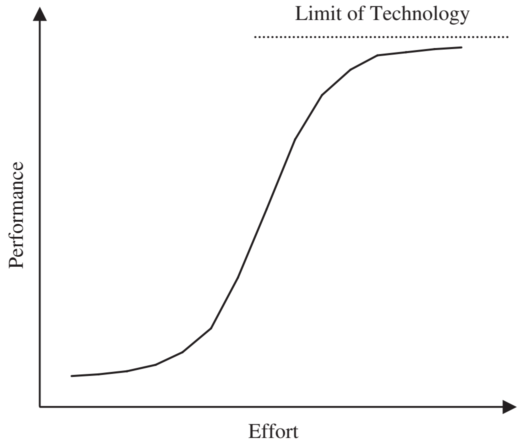

Fig. 1. S-curve of technology performance.

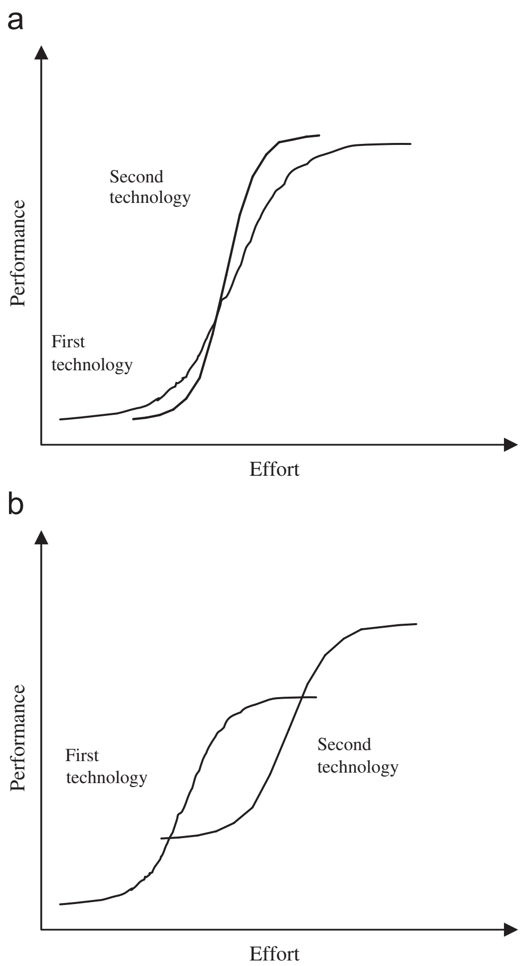

Fig. 2. Technology S-curves—introduction of discontinuous technology. (a) New technology has steeper S-curve and (b) New technology has higher S-curve.

valuable lens to view the improvement of relatively immature technologies. In the final section, we will discuss the implications and limitations of our research.

1. S-curves in technological improvement

Many technologies exhibit an S-curve in their performance improvement over their lifetimes (Ayres, 1994; Christensen, 1993, 1994; Foster, 1986; Twiss, 1992). When the performance of a technology is plotted against the amount of effort and money invested, it typically shows slow initial improvement, then accelerated improvement, then diminishing improvement (Fig. 1). Performance improvement in the early stages of a technology is slow because the fundamentals of the technology are poorly understood. Great effort may be spent exploring different paths of improvement or in exploring different drivers of the technology's improvement. However, as scientists or firms gain a deeper understanding of the technology, improvement begins to accelerate. Developers of the technology target their attention towards those activities that reap the greatest improvement per unit of effort, enabling performance to increase rapidly. However, at some point, diminishing returns to effort begin to set in. As the technology begins to reach its inherent limits, the cost of each marginal improvement increases, and the S-curve flattens out.[1] S-curves of technological improvement have been well documented in a wide range of technologies, including disk drives, automobiles, sailing ships, semiconductors, vacuum tubes, steam engines, and more (see Foster, 1986 or Ayres, 1994, for a range of interesting examples).

Often a technology's S-curve is plotted with performance (e.g., speed, capacity, power, etc.) against time, but this must be approached with care. If the effort invested is not constant over time, the resulting S-curve can obscure the true relationship. If effort is relatively constant over time, plotting performance against time will result in the same characteristic curve as plotting performance against effort. However, if the amount of effort invested in a technology decreases or increases over time, the resulting curve could appear to flatten out much more quickly, or not to flatten out at all.

Technologies are not always given the opportunity to reach their limits—they may be rendered obsolete by new, *discontinuous technologies*. A new innovation is discontinuous when it fulfills a similar market need, but does so by building on an entirely new knowledge base (Anderson and Tushman, 1990; Christensen, 1999; Foster, 1986). Initially, the technological discontinuity may have lower performance than the incumbent technology and effort invested in the new technology may reap lower returns than effort invested in the current technology. This causes firms to be reluctant to switch to investment in the new technology. However, if the disruptive technology has a steeper S-curve (Fig. 2, panel a) or an S-curve that increases to a higher performance limit (Fig. 2, panel b), there may come a time when the returns to effort invested in the new technology are much higher than effort invested in the incumbent technology. New firms entering the industry are likely to choose the disruptive technology, and incumbent firms face the difficult choice of trying

[1] Technology S-curves are closely related to the more broadly defined "experience curves." Whereas experience curves refer collectively to many sources of efficiency gained through production and use of a product, technology S-curves refer specifically to technological improvements that are embodied in product or process design (as opposed to workers becoming more dexterous, or improvements in relations with suppliers, for example). Because the improvements are embodied in codified artifacts, they are treated as cumulative and non-deteriorating (i.e., if R&D investment is halted, the state of performance that has been thus far achieved is maintained). R&D investments are also typically treated as a fixed cost rather than a variable cost, meaning that all units of output benefit from the efficiency achieved through the R&D investment. Furthermore, it is common to assume that such technological improvements are fairly transparent and readily transferable across different producers. Thus, late entrants to a technology benefit by the R&D efforts of those who have gone before them, and can acquire knowledge about how to produce state-of-the-art technology within a reasonable amount of time rather than beginning at the bottom of the S-curve. Though this may be a heroic assumption in some industries, it is probably a reasonable assumption for the energy technologies surveyed here.

to extend the life of their current technology, or investing in switching to the new technology. If the disruptive technology has much greater performance potential for a given amount of effort, in the long run it is likely to displace the incumbent technology, but the rate at which it does so can vary significantly.

There are a number of limitations of using the S-curve model as a prescriptive tool. First, it is rare that the true limits of a technology are known in advance, and there is often considerable disagreement among firms about what the limits of a technology will be. Second, the shape of a technology's S-curve is not set in stone. Unexpected changes in the market, component technologies, or complementary technologies can shorten or extend the lifecycle of a technology. Furthermore, firms can actively influence the shape of the S-curve through the nature of their development activities. For example, firms can sometimes overcome barriers that appear to create a limit to a technology's performance improvement (Ayres, 1994), or stretch the S-curve of a technology via new development approaches or revamping the architectural design of the technology. Christensen provides an illustrative example of this from the disk drive industry. A disk drive's capacity is determined by its size multiplied by its *areal recording density*, thus density has become the most pervasive measure of disk drive performance. In 1979, IBM had reached what it perceived as a density limit of ferrite-oxide-based disk drives. It abandoned its ferrite-oxide-based disk drives and moved to developing thin-film technology that had greater potential for increasing density. Hitachi and Fujitsu, however, continued to ride the ferrite-oxide S-curve, and ultimately achieved densities that were eight times greater than the density that IBM had perceived to be a limit.

Finally, whether switching to a new technology will benefit a firm depends on a number of factors, including, but not limited to, (a) the advantages offered by the new technology, (b) the new technology's fit with the firm's current abilities (and thus the amount of effort that would be required to switch, and the time it would take to develop new competencies), (c) the new technology's fit with the firm's position in complementary resources (e.g., a firm may lack key complementary resources, or may earn a significant portion of its revenues from selling products compatible with the incumbent technology), and (d) the expected rate of diffusion of the new technology. Thus a firm that follows an S-curve model too closely can end up switching technologies earlier or later than it should.

1.1. Technology cycles

The S-curve model above suggests that technological change is cyclical: each new S-curve ushers in an initial period of turbulence, followed by rapid improvement, then diminishing returns, and ultimately is displaced by a new technological discontinuity (Anderson and Tushman, 1990; Utterback and Abernathy, 1975). The emergence of a new technological discontinuity can overturn the existing competitive structure of an industry, creating new leaders and new losers. Schumpeter (1942) called this process "creative destruction," and argued that it was the key driver of progress in a capitalist of society.

Several studies have tried to identify characteristics of the technology cycle to understand better why some technologies succeed and others fail, and whether established firms or new firms are more likely to be successful in introducing or adopting a new technology (e.g., Anderson and Tushman, 1990; Chandy and Tellis, 2000; King and Tucci, 2002; Robinson and Sungwook, 2002; Sahal, 1981; Suarez and Utterback, 1995; Utterback and Abernathy, 1975; Utterback and Suarez, 1993). One model of technology evolution that rose to early prominence was proposed by Utterback and Abernathy. They observed that a technology passed through distinct phases. In the first phase (what they termed the *fluid phase*) there was considerable uncertainty about both the technology and its market. Products or services based on the technology might be crude, unreliable, or expensive, but might suit the needs of some market niches. In this phase, firms experiment with different form factors or product features to assess the market response. Eventually, however, producers and customers begin to arrive at some consensus about the desired product attributes, and a dominant design emerges. The dominant design establishes a stable architecture for the technology, and enables firms to focus their efforts on process innovations that make production of the design more effective and efficient, or incremental innovations to improve components within the architecture. Utterback and Abernathy termed this the "*specific phase*" because innovation during this period is specific to a particular technology.

Building on the Utterback and Abernathy model, Anderson and Tushman studied the history of the US minicomputer, cement, and glass industries through several cycles of technological change. Like Utterback and Abernathy, Anderson and Tushman found that each technological discontinuity inaugurated a period of turbulence and uncertainty (which they termed the "*era of ferment*"). The new technology might offer breakthrough capabilities, but there is little agreement about what the major subsystems of the technology should be or how they should be configured together. Thus, while the new technology displaces the old (*substitution*), there is considerable design competition as firms experiment with different forms of the technology. Just as in the Utterback and Abernathy model, Anderson and Tushman found that a dominant design always arose to command the majority of the market share unless the next discontinuity arrived too soon and disrupted the cycle, or several producers patented their own proprietary technologies and refused to license to each other. Anderson and Tushman also found that the dominant design was never in the same form as the original discontinuity, but it was also never on the leading edge of the technology. Rather than maximizing performance on any individual dimension of the technology, the dominant design tended to bundle together a combination of features that best fulfilled the demands of the majority of the market.

In the words of Anderson and Tushman, the rise of a dominant design signals the transition from the "era of ferment" to the "era of incremental change." In this era, firms focus on efficiency and market penetration. Firms may attempt to achieve greater market segmentation through offering different models and price points. They may also attempt to lower production costs by simplifying the design or improving the production process. It is typically during this period that the cost of a technology is brought down most dramatically as cumulative output of the technology increases and firms reap learning curve and scale advantages. This period of accumulating small improvements may account for the bulk of the technological progress in an industry, and continues until the next technological discontinuity.

Understanding the knowledge that firms acquire during different eras lends insight into why successful firms often resist the transition to a new technology, even if it provides significant advantages. During the era of incremental change, many firms cease to invest in learning about alternative design architectures, and instead invest in refining their competencies related to the dominant architecture. Most competition focuses on improving components rather than altering the architecture, thus companies focus their efforts on developing component knowledge and knowledge related to the dominant architecture. As firms' routines and capabilities become more and more wedded to the dominant architecture, the firms become less able to identify and respond to a major architectural innovation (Henderson and Clark, 1990; Leonard-Barton, 1992). For example, the firm may establish divisions devoted to the primary components of the architecture, and structure the communication channels between divisions on the way those components interact. In the firm's effort to absorb and process the vast amount of information available to it, it is likely to establish filters that enable it to identify the information most crucial to its understanding of the existing technology design (Henderson and Clark, 1990; Linton and Walsh, 2004). As the firm's expertise, structure, communication channels and filters all become oriented to maximization of its ability to compete in the existing dominant design, they become barriers to recognition and reaction to a new technological architecture.

Application of these concepts to energy technology is fairly straightforward. In the United States the vast majority of energy production is based on the use of fossil fuels (e.g., oil, coal). The methods of producing energy from these fuels are well established, and there are many firms whose fortunes are tied to efficient fossil fuel production and/or utilization. On the other hand, technologies that produce energy from renewable resources (e.g., solar, wind, geothermal, hydrogen) are still in the "fluid phase," or "era of ferment." It is unclear whether or when any one (or combination) of these technologies will rise to become a new dominant design. As a result, there is relatively little investment in renewable energy technologies compared to fossil fuel energy technologies, and that investment is fragmented among several contending alternatives (Jacobsson and Johnson, 2000). National governments regularly contribute some funding to development of alternative energies, and organizations such as Royal Dutch Shell, General Electric, and Ballard Power are all experimenting with various forms of solar photo cell technologies, wind turbine technologies, and fuel cells. However, the dollar figures of these efforts pale in comparison to the industry funds that are currently being invested to extend the life of fossil fuels. Furthermore, all of the prominent renewable energy alternatives are currently more expensive than fossil fuels, slowing both consumer and industrial demand for these energy technologies despite their environmental benefits. However, as we will show, from a technology S-curve perspective, most of the prominent renewable energy alternatives are yielding much greater gains in performance improvement per R&D dollar spent when compared to performance improvements in fossil fuel technologies. Furthermore, S-curve analysis suggests that some of the renewable energy technologies that are best positioned to eclipse fossil fuel technologies in cost efficiency in the near term have been relatively underfunded compared to other renewable energy technologies, yielding implications for both government and industrial policy for rethinking renewable energy investment. We turn now to profiling some of the more noteworthy renewable energy technologies, offering some limited insight into their key advantages and disadvantages, and then analyzing their S-curves of technology improvement with respect to R&D investment.

2. Prominent renewable energy alternatives

In this section, we will provide a brief introduction to five prominent renewable energy alternatives (hydroelectric power, geothermal power, solar power, wind power, and biomass energy), focusing on (a) the key fundamentals of how they work, (b) their current production capacities,[2] and (c) their key advantages and disadvantages. We will then discuss transmission, intermittency and fuel-cost issues that pertain to several of the technologies and, finally, provide a summary comparison of costs in cents per kWh over the time period 1980–2005.

2.1. Hydroelectric power

Hydroelectric power refers to the energy that can be captured from flowing water. Most typically this energy is captured using dams on major rivers, but it can also be captured from water level differentials created by tides, or from the flow of water in the form of waves. In terms of total electricity production, hydroelectric power is the leading renewable energy resource in the United States, providing 10% of the electricity used, and accounting for just under 3% of total energy used in 2005. Hydroelectric power is even more important in particular regions such as the Rocky Mountain states (where it accounted for 14% of the electricity used in 2006) and the Pacific coast (where it accounted for 63% of the electricity used in 2006). Worldwide, hydroelectric power provided one-fifth of the total electricity used, making it second only to fossil fuels as a source of energy (ORNL, 2006).

Hydroelectric power's key advantages are that it is clean (it releases no air emissions nor does it produce solid or liquid wastes), and it is one of the least-expensive sources of electricity in the United States. In 2006, a hydroelectric power plant required only 0.6 cents per kWh to finance its operation and maintenance; by comparison the costs at nuclear and coal plants equaled 2.2 and 2.1 cents per kWh respectively. The downside of hydroelectric power plants is that they are often physically disruptive to the local environment as dams replace river ecosystems by lakes, altering or destroying habitats and disrupting fish migrations. Hydroelectric dams are primarily responsible, for example, for reducing the Pacific Northwest salmon population from about 16 million to 300,000 by blocking the upstream migration of spawning fish and by killing young fish that must pass through turbines as they travel downstream (ORNL, 2006). Hydroelectric dams also affect the water quality of both downstream and upstream waterways through such mechanisms such as increased soil erosion, supersaturation of water with gases from the air, and water stratification which deprives deep water (and the fish that live in it) of oxygen (ORNL, 2006). As a result, hydroelectric power dams have come under heavy fire from environmental protection groups for their direct and deleterious impact on a number of aquatic species.

2.2. Geothermal power

Geothermal energy is heat captured from the earth. Most of the geothermal energy used as of 2006 came from hydrothermal sources (i.e., hot water or steam sources). However, there is potential in the long run to also utilize the geothermal energy available in the heat of hot, dry rock formations deeper within the Earth's crust. The amount of geothermal energy is enormous; scientists estimate that United States hot dry rock resources could supply all of the United States primary energy needs for at least 30,000 years (EERE, 2007a). However, the technology for tapping geothermal energy is still at a relatively early state of development, and has drastically limited the amount of geothermal energy that is commercially available. According to the Geothermal Energy Association, the United States installed capacity of geothermal energy was approximately 2800 MW electric in 2006, putting it at just under 3% of the production capacity of hydroelectric power, and under 0.3% of total electricity production capacity in the United States. Regionally, however, geothermal power is much more important, accounting for approximately 6% of the energy produced in California, 10% for northern Nevada, and 25% for the Island of Hawaii.

[2] For ease of comparison, we will focus on electricity production capacity in kilowatts.

Geothermal's key advantages are that there is a large amount of potentially tappable energy, it is mostly clean (steam plants release small amounts of carbon and other emissions into the atmosphere with electricity production; binary plants that utilize lower temperature water release no emissions), and it is reasonably inexpensive. Estimates by the Energy Efficiency and Renewable Energy division of the US Department of Energy put the cost of electricity production costs for geothermal steam plants at four to 6 cents per kWh in 2006, and 5 to 8 cents per kWh for binary plants. Estimates by the National Renewables Energy Laboratory that use a composite measure of flash steam and binary plant geothermal energy production posit an even lower cost, ranging from 3.1 to 4.3 cents per kWh in 2005. Either set of estimates suggests that geothermal energy is more expensive than fossil fuels or hydroelectric power, but less expensive than wind, solar power, or biomass. Geothermal's key disadvantage is that given the state of technology, it is currently very geographically constrained with only limited areas enabling cost-efficient use of geothermal energy. There is also some risk of releasing sulfur or other hazardous gases into the air.

2.3. Solar power

Solar power is divided into two main technologies: thermal solar (whereby the heat of the sun is captured either passively or through concentrating mechanisms such as curved mirrors), and photovoltaic (also called solar cells), which convert sunlight (photons) directly into electricity via semiconductive materials. Solar power has very large potential capacity (estimates suggest that the solar energy resources in a 100 square mile area of Nevada could supply the United States with all of its electricity – about 800 GW – using modestly efficient commercial photovoltaic modules) (DOE–EERE, 2008). However, its commercial capacity is currently very limited. According to the US Department of Energy's Renewable Energy Annual Report, in 2006, the electricity generation capacity of solar sources in the United States was just 411 MW, or .04% of the total electricity production capacity of the United States.

Solar power's key advantages are that it is clean (it results in no emissions and does not require physical disruption of the environment), and it has a large potential capacity. Its key disadvantage is its cost, which also greatly limits commercially available capacity. The National Renewable Energy Laboratory estimates put the cost of solar energy in 2005 at between 11 and 15 cents per kWh for concentrating solar and 18–31 cents per kWh for photovoltaic solar. A big part of the cost of photovoltaics stems from the relatively low efficiency of current photovoltaic technology and the high materials costs for producing photovoltaic cells.

2.4. Wind power

Wind power is typically captured through the use of turbines. The total wind energy resource in the United States is very large, with nearly 88 quadrillion BTU (roughly the amount of fossil fuel energy used yearly in the United States) available from sites with average wind speeds over 5.6 m/s at a 10 m height (EERE, 2007b). Though wind is available virtually anywhere, power available from wind increases as the cube of wind speed, making high wind areas much more attractive for energy production. As with many of the renewable energy technologies, commercial capacity is a very small fraction of the potential resource. In 2005, United States electricity production capacity from wind was over 8000 MW, putting it at just under 1% of total US electricity production capacity (DOE, Annual Energy Review, 2007). Wind energy production is rapidly growing, however, and estimates by the National Renewable Energy Laboratory for 2006 suggest that electricity production capacity was over 10,000 MW, enough to power 2.5 million average American homes.

The key advantages of wind energy are that it is clean (it produces no emissions and physical disruption of the environment can be minimized), it is reasonably inexpensive, and technological advance is yielding rapid efficiency gains, causing its price to fall quickly. Estimates by the National Renewable Energy Laboratory put wind at between 4.3 and 5.5 cents per kWh in 2005, roughly one-tenth its price in 1980, and slightly more expensive than geothermal energy. The key disadvantage of wind energy is that wind farms are often considered unsightly, and can pose a potential threat to migratory birds. Other often cited disadvantages are wind's intermittency, and that the most attractive wind sites in terms of production capacity are often not near urban areas, requiring investment in transmission lines. Transmission and intermittency issues are discussed in greater detail later in the section.

2.5. Biomass energy

Biomass energy is derived from material produced by living things such as plants, animal waste, or bacteria. Plant material (e.g., wood) is often burned; animal waste can provide gases that are burned to release energy; some plant materials are fermented to produce alcohol. One of these alcohols, ethanol, is widely used in blends with gasoline to reduce auto emissions and decrease fossil fuel consumption. In terms of installed US electricity production capacity, biomass accounted for approximately 10 GW in 2006, just over 1% of total US electricity production capacity. Including ethanol in these figures (which is not typically used to generate electricity but serves as a direct liquid fuel source for automobiles) raises biomass' contribution to roughly 3% of total energy consumption (EERE, 2007c, d).

The key advantages of biomass are that it provides a renewable alternative for liquid transportation fuels, the technologies are relatively simple and available, and biomass faces few geographic constraints. The key disadvantages of biomass are that its use releases greenhouse gasses into the atmosphere, it is land intensive, and the agricultural production of many biomass sources results in increased use of water, fertilizers, herbicides, and insecticides. Furthermore, the amount of land required to produce biomass inputs implies that it faces significant long-term production capacity constraints. Analysis by the National Renewable Energy Laboratory puts the cost of biomass energy at between 6.6 and 8.0 cents per kWh, depending on the technology used. This makes biomass energy more expensive than hydroelectric, geothermal, and wind energy.

2.6. Transmission issues, intermittency, and fuel costs

One commonly voiced obstacle to some of the renewable alternatives (particularly wind) is the current lack of transmission capacity to move energy from high potential sites (such as the Dakotas) to population centers. Building transmission lines is very costly, and because many power producers usually share major transmission lines, there is a classic public goods problem: no individual company wants to pay. However, studies by the National Renewable Energy Laboratory suggest that transmission obstacles are often overstated. First, both wind and solar power are well-suited to a distributed energy model (e.g., solar panels on homes, wind turbines in farmers' fields) that enables power to be transmitted to the grid via existing transmission lines. NREL studies indicate that the wind energy resources that are located within a short distance (e.g., 10 miles) of existing transmission lines are substantial. Second, the transmission capacity problem is often a function more of historic methods of evaluating and allocating the power capability of lines rather than the actual capability; changes in evaluation and allocation rules are expected to allow power-generation expansion without requiring additional wires (DeMeo and Parsons, 2003). Third, while it is often assumed that large, utility-grade wind turbines cannot be installed on the distribution grid without expensive upgrades, case studies indicate that in many cases wind generation can be connected to the distribution system in amounts up to about the rating of the nearest substation transformer without upgrading. For example, in a study to determine the feasibility of interconnecting large wind turbines to a typical distribution system in northeastern Colorado, analysts determined that up to 94.5 MW (63 GE 1.5 MW wind turbines) could be added to the 17 existing substation distribution grids that makeup the Highline Electric Association grid without upgrading the substations, and without causing quality or safety problems (DOE–EERE, 2005).

There are some losses of economies of scale from a highly distributed model. For example, according to the (American Wind Energy Association), a large wind farm (e.g., 51 MW) can deliver electricity at a lower cost, roughly $0.036 per kWh, compared to $0.059 per kWh for a small (e.g., 3 MW) wind farm. Often, however, the bigger obstacle is the monopoly granted to a regional energy wholesaler, restricting the use of locally generated electricity. This problem is already being addressed gradually through regulatory reform.

There are also challenges associated with management of the electricity load from intermittent resources like wind and solar, to meet fluctuating energy demands. Whereas energy from fossil fuels, biomass, hydropower and geothermal can be turned on and off, wind and solar energy are reliant upon environmental conditions. However, it is important to note that utility operators also cannot control electricity demand, and thus utilities are already designed to accommodate fluctuating loads through distributed capacity. Wind and solar increase the amount of variability that must be accommodated by the utility system, but NREL estimates suggest that the incremental costs of accommodating this variability are relatively small. Energy producers in California have found that wind and solar power are very complementary because peak solar production is during the middle of the day, and peak wind production is in the morning and evening.

Finally, a key advantage commonly overlooked with respect to energy alternatives such as wind, solar, and geothermal power is that there are no fuel costs, now or in the future, which removes one major component of price instability (though it is important to note that there will still be price risk related to the cost of construction materials such as steel, silicon, etc.). US utility companies traditionally have not worried much about long- or short-term price risk because most are regulated monopolies and can pass their costs on to consumers. However, as utilities are become increasingly deregulated, price stability will become a crucial competitive dimension.

Table 1
Cost of energy (COE) for alternative energy sources, expressed in cents per kWh.

Year	Renewables[a]								Fossil fuels[b]			
	Geothermal		Concentrating solar		Photovoltaics		Wind		Coal	Natural gas	Petroleum	Fossil fuel composite[c]
	Upper	Lower	Upper	Lower	Upper	Lower	Upper	Lower				
1980	13.8	11.3	84.0	69.5	125.0	106.3	51.3	43.0				
1981	13.1	10.6	74.0	57.0	119.0	100.0	47.5	40.0				
1982	12.5	10.0	66.0	46.8	112.5	93.0	43.3	36.3				
1983	11.9	9.4	56.0	38.3	105.0	84.5	38.8	32.5				
1984	11.3	8.8	46.8	27.5	99.0	78.0	36.0	29.0				
1985	10.6	8.1	36.0	24.0	93.0	72.0	31.3	25.3				
1986	10.0	7.5	30.3	21.3	87.5	68.8	28.8	22.5				
1987	9.7	7.2	27.0	19.0	82.0	63.0	25.3	18.8				
1988	9.4	6.9	25.0	17.0	77.0	59.5	22.5	16.8				
1989	8.8	6.3	23.5	16.0	72.0	55.5	20.0	14.8				
1990	8.4	6.3	22.0	15.0	68.8	52.0	17.6	12.5	1.6	2.1	2.6	1.7
1991	8.1	5.9	21.5	14.0	66.0	49.0	15.0	11.3	1.5	1.9	2.1	1.6
1992	7.5	5.6	21.3	14.0	62.5	45.0	13.8	10.0	1.5	1.9	2.0	1.5
1993	6.6	5.3	21.0	13.8	59.0	43.3	12.0	8.8	1.4	2.0	1.9	1.5
1994	6.4	5.1	20.8	13.5	56.3	40.5	11.3	7.6	1.3	1.7	1.8	1.4
1995	6.3	4.9	20.0	13.3	53.0	37.5	9.8	6.9	1.3	1.6	1.8	1.3
1996	6.2	4.8	19.3	13.0	51.0	34.0	8.8	6.3	1.2	1.8	1.9	1.3
1997	5.9	4.4	18.5	12.9	48.0	31.3	8.4	5.9	1.1	1.8	1.7	1.2
1998	5.6	4.0	18.0	12.8	46.0	29.0	7.8	5.3	1.1	1.5	1.4	1.2
1999	5.3	3.8	17.5	12.8	43.8	27.0	7.5	5.0	1.1	1.6	1.5	1.1
2000	5.1	3.8	17.3	12.8	42.5	26.0	7.3	4.9	1.0	2.3	2.2	1.3
2001	5.0	3.7	17.1	12.8	40.5	24.0	6.7	4.7	1.1	2.3	2.0	1.2
2002	4.9	3.6	17.0	12.7	38.0	23.0	6.4	4.6	1.1	1.9	1.8	1.1
2003	4.7	3.4	16.7	12.7	36.0	21.0	6.3	4.5	1.0	2.6	2.2	1.4
2004	4.4	3.2	16.0	12.0	33.0	20.0	6.0	4.4	1.1	2.8	2.2	1.5
2005	4.3	3.1	15.0	11.0	31.0	18.8	5.5	4.3	1.2	3.5	2.9	1.8

[a] Cost estimates constructed by the National Renewables Energy Laboratory based on data compiled from multiple sources including National Labs, Department of Energy, EPRI, PERI; GPRA 2003; and OPT Data book. Costs include capital, operating and maintenance costs. Values in constant $2005. Upper and lower values differences in costs due to facility types and scale.

[b] From the Energy Information Agency's Electric Power Annual, in constant $2005. Costs include fuel, operations, and maintenance. Capital costs are not typically included for calculating costs for fossil fuel plants as the average plant age is roughly 40 years. Data were unavailable prior to 1990.

[c] Derived by multiplying the price per BTU of each fossil fuel by the total BTU content of the production of each fossil fuel and dividing this accumulated value of total fossil fuel production by the accumulated BTU content of total fossil fuel production, and then converting to cents per kWh.

2.7. Summary of comparison of costs

Table 1 shows a comparison of cost estimates for the various renewable energy alternatives (with the exception of hydro-electric power and biomass energy, for which yearly cost data were unavailable) and the most important fossil fuel energy sources, as well as a fossil fuel composite price created by the US Department of Energy based on proportional use of each. For comparability, all values have been converted to cents per kWh. As shown, fossil fuels are still less expensive on average than renewable energies, but wind power and geothermal power are getting close to fossil fuel prices, particularly since wind and geothermal are still on sharply decreasing cost trajectories whereas fossil fuels are now increasing in price due to the combination of having exhausted nearly all of the options for technological improvement and encountering the diseconomies of scale inherent in reliance upon finite inventories of natural resources.

In the next section, we show that evaluation of these technologies using a technology-improvement S-curve approach that incorporates the rate of investment in the technologies proves even more illuminating about the future of these technologies.

3. R&D investment and cost improvement in energy technologies

US energy consumption grew by 312% from 1949 to 2005, and the vast majority of that energy was supplied by fossil fuels (see Fig. 3). Of the energy provided by fossil fuels, roughly 27% came from coal, 26% from natural gas, and 47% from petroleum. Over

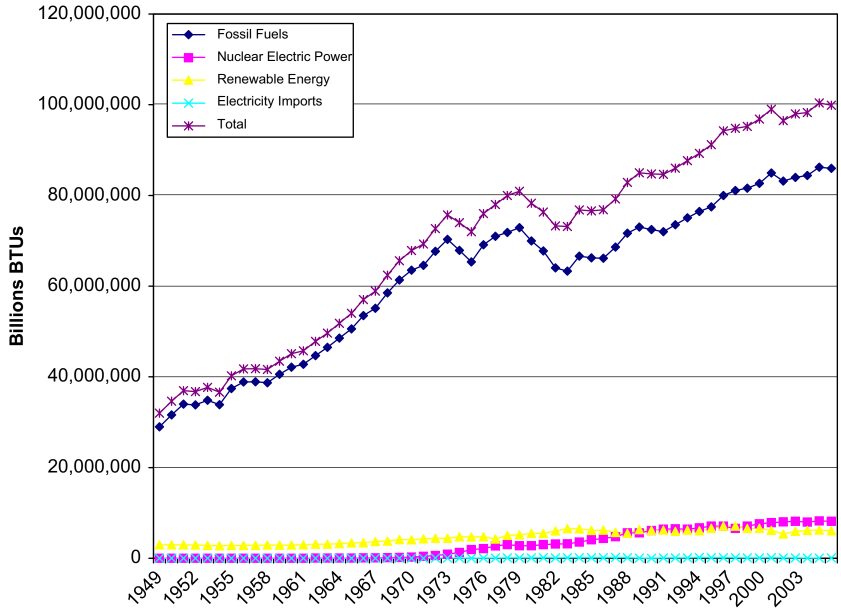

Fig. 3. US Energy Consumption by Source, 1949–2005.

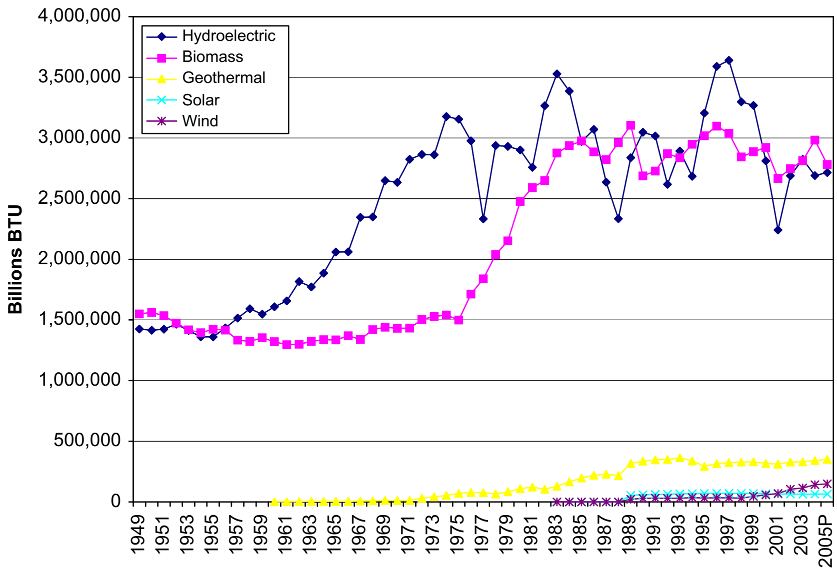

Fig. 4. US Renewable Energy Consumption (detailed), 1949–2005.

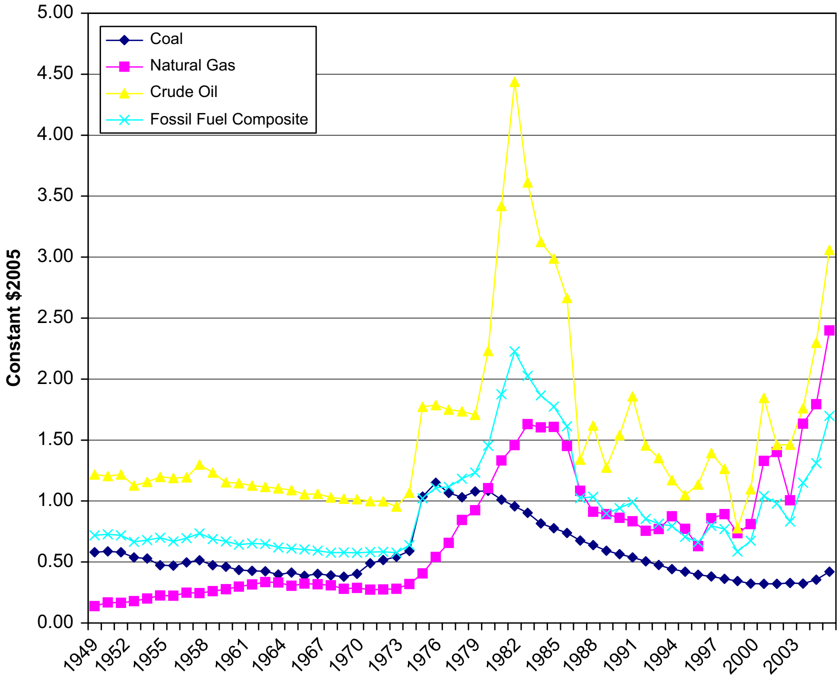

Fig. 5. US historical cost of receipts ("Cost of receipts" refers to the price paid for fuel purchases only and does not include operating or maintenance costs.) at electric generating plants, from US Department of Energy, January 7th, 2007 monthly energy review, cents per kWh, nominal dollars.

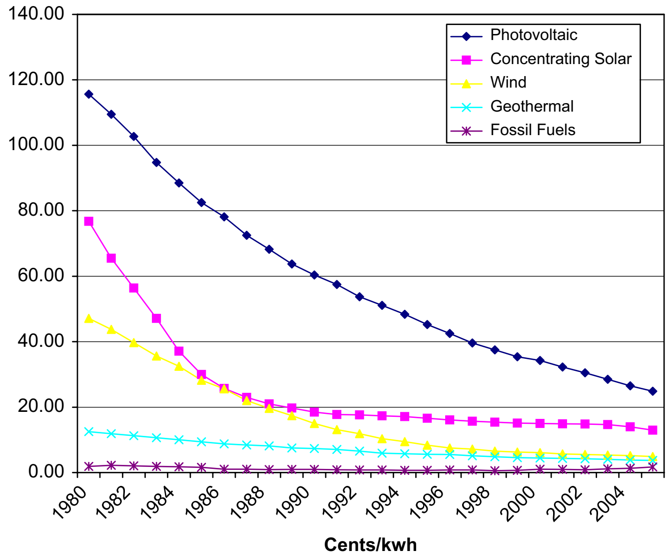

Fig. 6. US historical cost of renewable energies vs. fossil fuels, per estimates from the National Renewable Energy Laboratory, US Department of Energy, cents per kWh, constant $2005. (The cost data for renewable energies include capital, operating and maintenance costs. The cost data for fossil fuels in this graph include only fuel costs because operating and maintenance cost data are unavailable prior to 1990. However, in the later graphs plotting technology performance against R&D investment, we constrain ourselves to the post 1990 period for fossil fuels so that operating and maintenance costs can be considered).

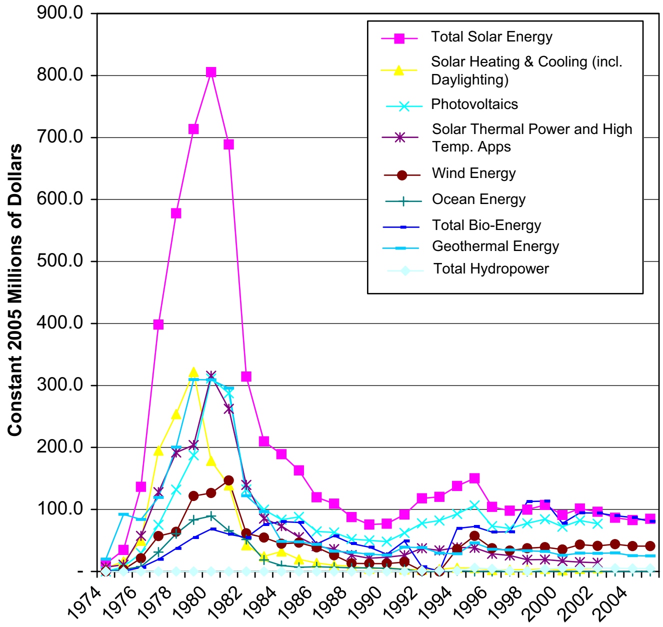

Fig. 7. Historical yearly R&D funding of renewable energies by US government.

the same time period, nuclear electric power grew to account for just over 8% of US energy consumption, and renewable energy sources collectively accounted for just over 6%. The vast majority of renewable energy consumed in the US was provided by hydroelectric power and biomass energy (see Fig. 4). Geothermal, solar, and wind energy sources provided less than one-tenth of a percent of the US energy needs in 2005.

However, as discussed previously, the costs of several renewable energy alternatives are approaching that of fossil fuels, which should, in the long run, dramatically change this balance of energy consumption sources. This convergence in costs is both a function of dramatically decreasing costs of producing renewable energy, with a coincident rise in the costs of fossil fuels. As shown in Figs. 5 and 6, the costs of many of the major fossil fuels have been on the rise for the last decade, while the costs of generating energy from renewable sources have been in steep decline.

In order to foster the development of renewable energy alternatives, the US government and many other governments of

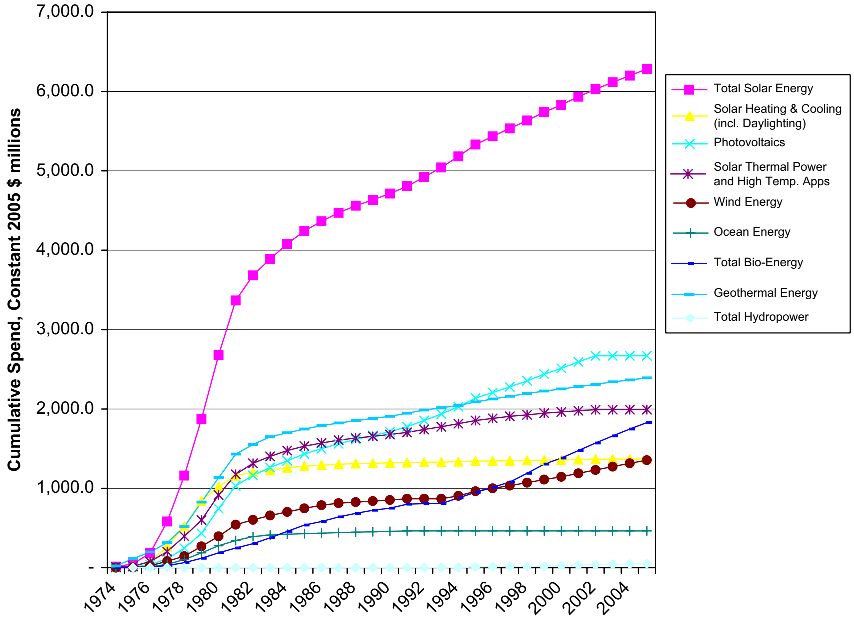

Fig. 8. Cumulative historical R&D funding of renewable energies by US government.

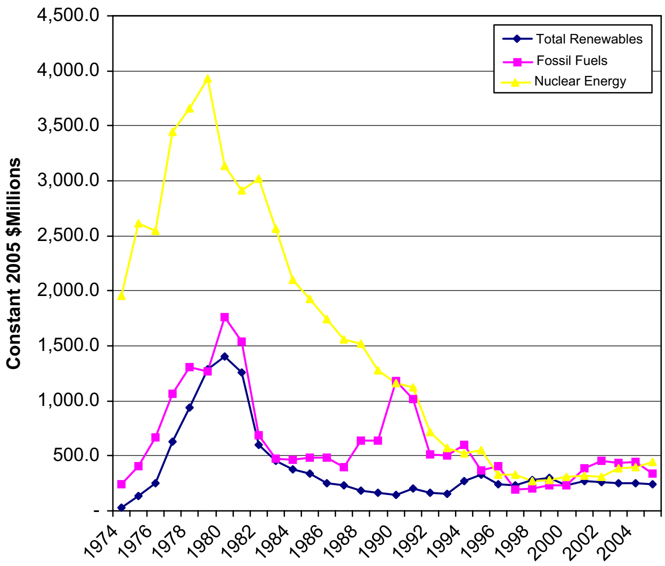

Fig. 9. Historical yearly R&D funding of renewable energies, fossil fuel technologies and nuclear energies.

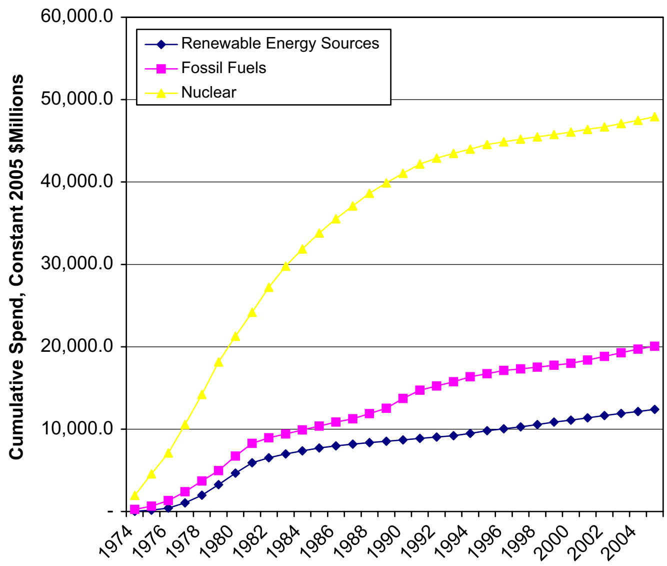

Fig. 10. Cumulative historical R&D funding of renewable energies, fossil fuel technologies, and nuclear energy by US government.

the world have funded research and development in a number of renewable energy technologies. The International Energy Agency, an agency initially established during the oil crisis of 1973–1974 to coordinate measures in times of oil supply emergencies, tracks the R&D spending on energy technologies of its 26 member countries. Of these 26, data are most reliably available over the period 1974–2005 for nine countries: Canada, Japan, the Netherlands, Norway, Spain, Sweden, Switzerland, United Kingdom, and the United States. Since we will use only the data available from these countries, we employ these data only to observe patterns and draw inferences; we cannot state conclusively that the patterns observed among these countries hold for all countries of the world. It is also important to note that because we do not have data on investment by industry, these figures dramatically understate investment in those technologies that have well-established commercial bases (most notably fossil fuels, but also to lesser extents hydropower, biomass, and photovoltaics). Fig. 7 shows the investment of the US government in various renewable energy technologies, in constant 2005 millions of dollars. As shown, investment shot up dramatically following the oil crisis in the 1970s, most notably in solar technologies. Fig. 8 shows the cumulative amount that the US government has invested in each technology, revealing again that vastly more dollars have been spent on solar technologies than the other renewable alternatives (Fig. 9).

During the same time period, the US government spent somewhat more on fossil fuel technologies than all renewable energy alternatives combined, and spent dramatically more on the development of nuclear energy technologies, though investment in nuclear energy tapered off rapidly in the late 1980s and 1990s. The cumulative investment in those technologies is provided in Fig. 10.

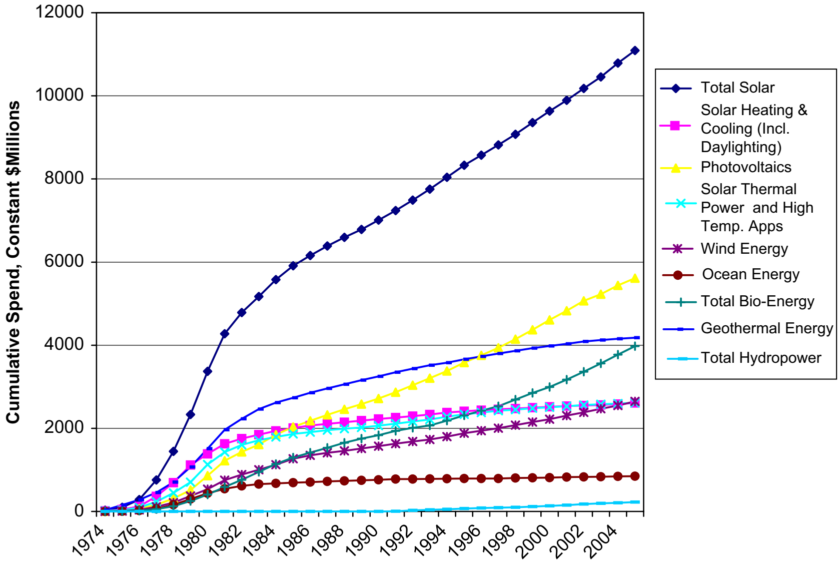

Fig. 11. Cumulative historical R&D funding of renewable energies by governments of Canada, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, UK and US.

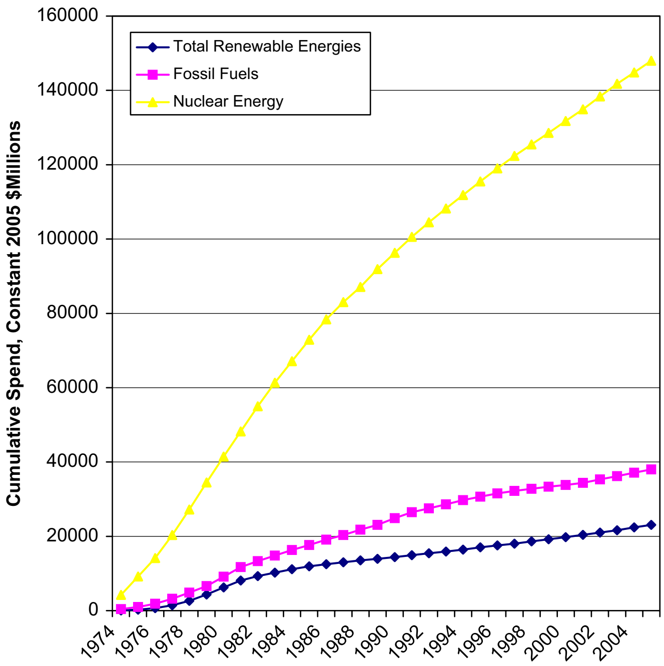

Fig. 12. Cumulative historical R&D funding of renewable energies, fossil fuel technologies, and nuclear energy by governments of Canada, Japan, Netherlands, Norway, Spain, Sweden, Switzerland, UK and US.

These patterns do not change very much when the R&D spending data are aggregated across the nine countries for which we have data (see Figs. 11 and 12). As shown in Fig. 13, most of the countries increased their spending on renewable energy alternatives during the period following the oil crisis, and US R&D spending on renewable energy alternatives was greater than that in the other nine countries for all but the last 2 years, when Japan's government spending on renewable energy spending eclipsed that of the US. Almost half of Japan's R&D funding for renewable energy alternatives was for photovoltaics, likely reflecting the importance of photovoltaics to Japan's large consumer electronics (and in particular liquid crystal display) commercial sectors. Another key difference in energy technology R&D worth pointing out is Japan's investment in nuclear energy. While investment in nuclear energy has fallen dramatically since the early 1980s in nearly all of the International Energy Agency member countries, it has stayed remarkably high in Japan (see Fig. 14). In fact, Japan's 2005 R&D budget for nuclear energy is almost twice that of the spending by the 25 other member countries *combined*.

It is also important to note that these figures dramatically understate the amount of R&D invested in fossil fuel technology as the majority of investment in fossil fuel technologies comes from industry. Over the period 1974–2005, the nine national governments included here spent a total cumulative amount of just under $38 billion on fossil fuel R&D, whereas the world's 10 largest publicly held oil and gas companies collectively spent over $70 billion on R&D.

3.1. Technology S-curves in energy technology

As noted previously, to examine a technology S-curve of performance improvement, it is necessary to plot the performance improvement against cumulative investment; plotting performance against time can be seriously misleading since investment may not be consistent over time. To accomplish this, we first transform the renewable energy data from cents per kWh to kWh per dollar (so that increasing performance is expressed as an upward-sloping trend), using an average of the upper and lower values provided by the (National Renewable Energy Laboratories). We then plot these kWh per dollar against the cumulative R&D spending of the nine countries for which data were obtained from the International Energy Agency. The results (shown in Fig. 15) are illuminating. The first important observation is that both wind energy and geothermal energy have exhibited much more improvement per dollar invested than concentrating solar (thermal solar captured through concentrating mechanisms such as curved mirrors) or photovoltaics. The concentrating solar technology curve appears to have already gone through one complete S-shaped cycle, and is perhaps entering another. Bearing in mind that all of the cost data points are yearly data between 1980 and 2005, the compression in the points for concentrating solar in the right side of the curve reflects the fact that R&D investment in concentrating solar has slowed

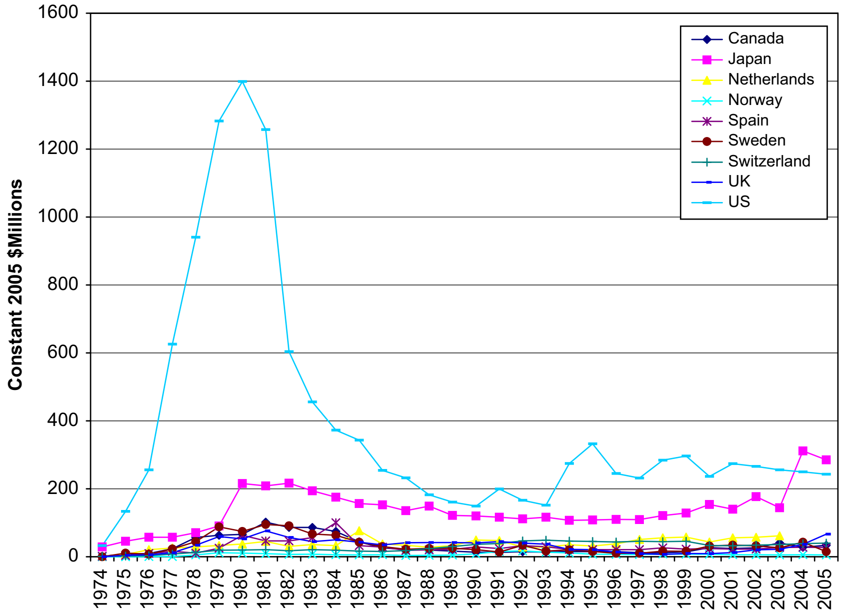

Fig. 13. R&D spending on renewable energies by country.

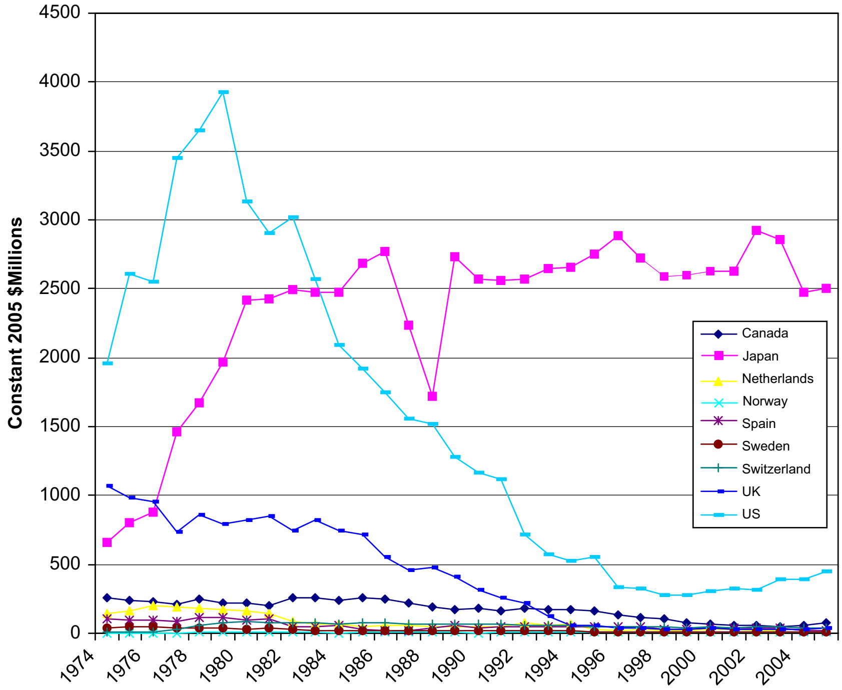

Fig. 14. R&D spending on nuclear energy by country.

significantly, consistent with the previous data shown on R&D investment. The photovoltaics curve appears to be at the very beginning of an S-curve with a much slower performance improvement rate than the other technologies. Significantly more has been spent on photovoltaics than on the other renewables, yet it has thus far achieved a much lower performance, at least in terms of kWh per dollar.

Both wind energy and geothermal energy, on the other hand, show very sharply increasing performance curves. Wind energy shows the archetypal s-shape, suggesting that it may already be entering a period of slowing performance improvement (though, as noted previously, changes in technological trajectories are not uncommon and S-curves are by no means deterministic). Geothermal energy shows exponential growth, achieving more kWh per dollar than the other three technologies and showing no indication of slowing performance improvement.

To analyze these curves further, we begin with the assumption that performance improvement in renewable energy technologies will approximate the Pearl curve most commonly used in technology studies

$$y = L/(1 + ae^{-bi})$$

where y refers to performance, L refers to the expected limit of performance, and i refers to cumulative investment. Then a is a

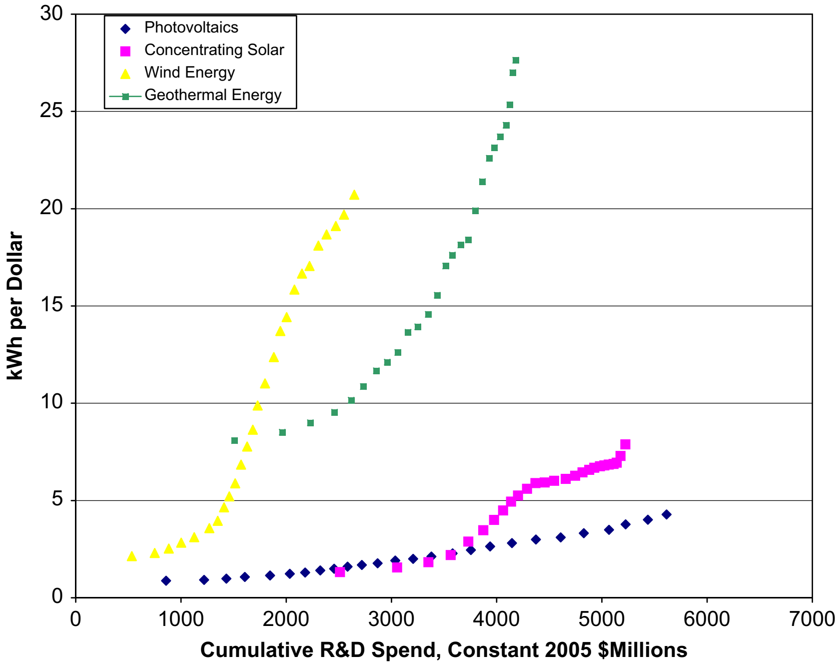

Fig. 15. Technology S-curves: kWh per dollar vs. cumulative government R&D funding for photovoltaics, total solar, wind energy, and geothermal energy, 1980–2005. (Investment dollars are cumulative over the period 1974–2005 but performance is shown only from 1980 forward as this is when the earliest cost data is available from the National Renewable Energy Laboratory).

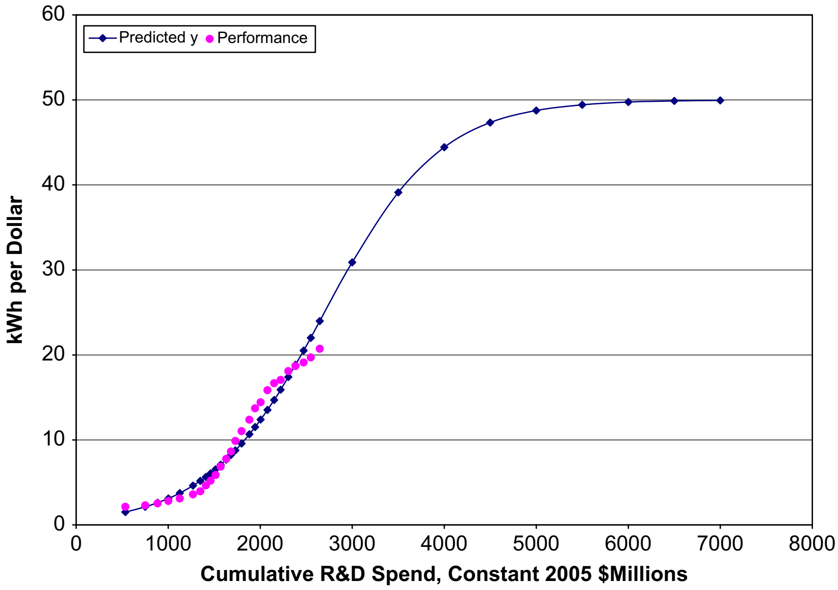

Fig. 16. Predicted vs. actual performance for wind energy, by cumulative R&D investment.

coefficient that determines the height of the curve and b determines its slope.

We can reformulate the relationship as

$$\log_e((L/y)-1)=\log_e a - bi$$

By defining

$$Y=\log_e((L/y)-1)$$
$$\alpha=\log_e a$$
$$\beta=-b$$

we obtain the linear formula

$$Y=\alpha+\beta i$$

which enables us to use linear regression to assess the fit of the curve and the coefficients a and b. A range of values can be used iteratively for the limit (L) to examine its impact on the fit of the curve.

For the wind energy data, a very good fit (Adjusted R squared of 0.96; sum of squared errors 50.11) was achieved with a limit of 50 (about 2.5 times the highest observed value), an intercept of 1.87, and a slope of 0.00069 (see Fig. 16). The sum of squared errors for the regression decreases as the limit decreases, which may suggest that we are in the “dominant design” or “era of incremental change” state, though as noted before, S-curves are not deterministic and there may be reasons to expect another upturn in the performance improvement rate given the

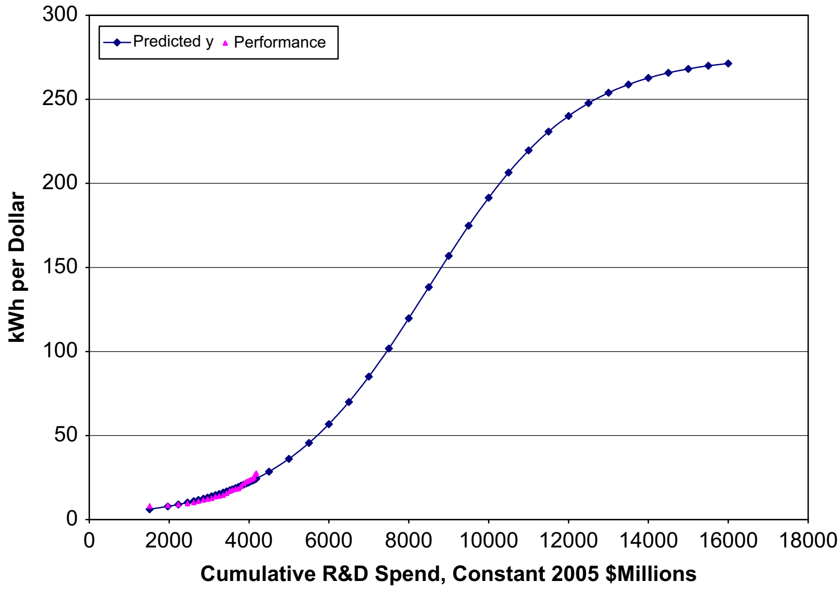

Fig. 17. Predicted vs. actual performance for wind energy, by cumulative R&D investment.

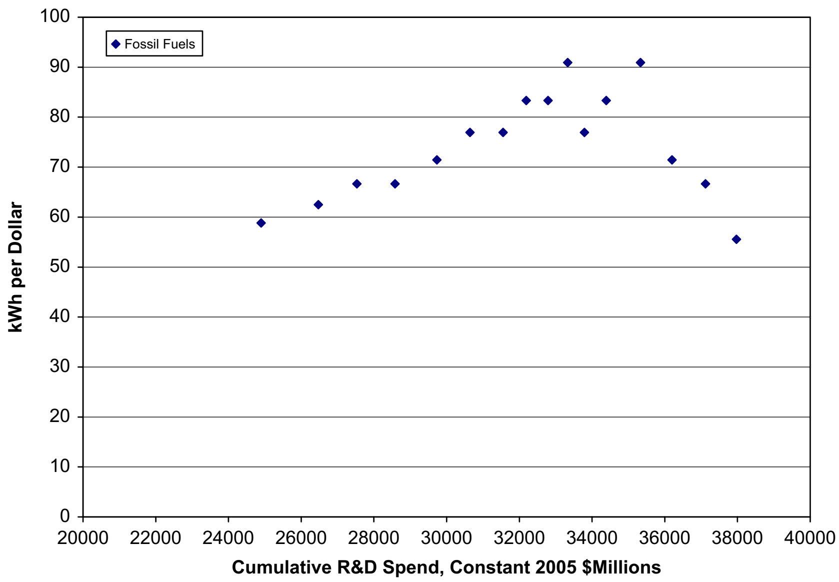

Fig. 18. Technology S-curves: kWh per dollar vs. cumulative government R&D funding for fossil fuels, 1990–2005.

rather minimal investment that has thus far gone into wind energy.[3] If 50 kWh per dollar is an appropriate limit for wind energy, the regression coefficients suggest that this limit should be reached by the time cumulative investment reaches 6 billion dollars.

For the geothermal energy data, a very good fit (Adjusted R squared of 0.95; sum of squared errors 44.57) was achieved with a limit of 276 (about 10 times the highest observed value), an intercept of 2.00, and a slope of 0.00024 (see Fig. 17). For these data the sum of squared errors decreases as the limit increases, suggesting that geothermal may still be in a very early ("fluid") state of development. If 276 kWh per dollar is an appropriate limit for wind energy, the regression coefficients suggest that this limit should be reached by the time cumulative investment reaches 16 billion dollars. Perhaps more important, the regression coefficients suggest that geothermal energy should become less expensive than the current composite fossil fuel price at a cumulative R&D investment of less than $7.5 billion. Even if we lower the expected limit for geothermal energy radically, to 100 kWh per dollar for example, the results suggest that geothermal energy will become less than expensive than the current composite fossil fuel price at a cumulative investment of less than $9.8 billion. Needless to say, if fossil fuels continue their upward price trends, both wind energy and geothermal energy

[3] It is also important to note that the appearance of a slowing performance improvement in wind for the last couple of years may be due to data inaccuracies in figures available from the National Renewable Energy Laboratory as their aggregations include more estimated data points for very recent years than in the older data.

will become more economical than fossil fuels before these cumulative investment amounts are reached.[4]

The S-curve for technology improvement for the fossil fuel composite is shown in Fig. 18 (because the scale of R&D investment in fossil fuels has been so much greater than that for renewables, it was impractical to plot the fossil fuels S-curve in the same figure). As with renewables, the cost data are plotted against cumulative R&D investment data. The result, however, does not look much like an S-curve, and in recent years performance has deteriorated rapidly. To understand this result it is important to note that fossil fuel technologies were already long mature by the 1990s. Coal's biggest advances in both performance and use occurred between 1875 and 1925; petroleum and natural gas experienced their biggest advances between 1920 and 1970. Thus, in the case of fossil fuels, we are viewing only the portion of the S-curve that would be expected to be flat, well after the big gains have already been achieved. As technology improvements slowed in fossil fuels, its performance curve became much more heavily influenced by volatility in fuel prices than by investments in R&D. This illustrates a key point about technology S-curves: scarcity in the inputs required for a technology can lead to diseconomies of scale, causing the S-curve to ultimately turn downward—not because of R&D investment, but despite it.

4. Conclusion

In the preceding discussion we utilized a technology S-curve approach to analyze performance trajectories in several prominent renewable energy technologies, and compared them with the performance trajectories of fossil fuel technologies.

There are a number of limitations of this analysis. First, it is notoriously difficult to estimate the average costs of energy production since these costs vary depending on a myriad of factors, including facility scale and age, the type of technology employed, the quality of the energy input, etc. Energy cost estimates are thus almost inevitably plagued with a degree of imprecision. Furthermore, to draw inferences about the relationship between investment and cost we were reliant upon data from nine countries when it would have been preferable to have data from all government and industry sources.

Despite these limitations, however, we believe this analysis offers several important insights. First, the technology S-curves created by plotting performance against investment suggest that R&D investments in fossil fuel technologies by government is probably excessive: fossil fuel technologies do not appear to be reaping performance improvements from R&D investment, and in fact are experiencing declining performance despite the significant investment. On the other hand, the cost data indicate that fossil fuels are still, despite their deteriorating performance, less expensive than the renewable alternatives considered here, so it should not be surprising that they account for the bulk of commercial energy production and consumption.

Second, the results suggest that renewable energy sources (particularly wind and geothermal) have been significantly underfunded relative to their potential payoffs. The technology S-curves for both wind energy and geothermal energy show major performance gains as a function of R&D investment, and both appear to be poised to become economically comparable, if not superior, to fossil fuels with modest investment. However, government R&D investment in these technologies has been diminutive. The collective government R&D investment in wind energy and geothermal energy by the nine countries considered here totaled just over \$2.6 billion and \$4.1 billion, respectively, over the 1974–2005 period. Over that same period, the same governments spent almost \$38 billion on fossil fuel technologies. Of the countries examined here, the United States, Norway, Japan, and Canada still invest more government dollars yearly on R&D for fossil fuel technologies than for all of the renewable energies *combined*. By contrast, Spain, Sweden, Switzerland, and the United Kingdom spend more R&D on renewable energies than fossil fuel technologies.

Third, the technology cycles perspective offered here suggests that investment in fossil fuel technologies by *incumbent firms* may still be rational as most of these firms are likely to have considerable asset positions and strategic commitments in fossil fuel energies that make it currently more profitable to focus on fossil fuel energy sources than renewable energy sources. However, the data suggest that *new entrants* into the energy industry are likely to benefit more from investment in wind or geothermal energy alternatives than fossil fuel, biomass, or solar technologies. Furthermore, the rates of performance improvement in renewable energies (and performance erosion in fossil fuels) suggest that incumbent firms should begin (if they have not done so already) to develop strategies for transition to renewable energy options lest they become victims of disruptive technological change. While it can sometimes be shareholder-wealth maximizing for a firm to practice a harvest strategy of sticking to an obsolescing technology until the firm's demise, the complementary asset positions of oil and gas companies in energy production infrastructure and distribution probably make transitioning to renewable energies a more attractive option from both shareholder and social welfare perspectives.

Acknowledgements

The authors wish to gratefully acknowledge the suggestions and assistance of Jorn Aabakken (National Renewable Energy Laboratory), William Baumol, Henry C. Co, Alyssa A Frederick, and Paul Hesse (US Department of Energy).

References

American Wind Energy Association. 〈www.awea.org〉.
Anderson, Philip, Tushman, Michael, 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. Administrative Science Quarterly 35, 604–634.
Ayres, R.U., 1994. Toward a non-linear dynamics of technological progress. Journal of Economic Behavior and Organization 24, 35–69.
Chandy, Rajesh K., Tellis, Gerard, 2000. The incumbent's curse? Incumbency, size, and radical product innovation. Journal of Marketing 64 (3), 1–18.
Christensen, Clayton M., 1993. The rigid disk drive industry: a history of commercial and technological turbulence. Business History Review 67, 531–588.
Christensen, Clayton M., 1994. Exploring the limits of the technology s-curve. Production and Operations Management 1 (4), 334–366.
Christensen, Clayton, 1999. Innovation and the General Manager. Irwin McGraw Hill, New York.
DeMeo, Ed., Parsons, Brian., 2003. Some common misconceptions about wind power. Presented at the All States Wind Summit, Austin, Texas. May 22.
Foster, Richard N., 1986. Innovation: The Attacker's Advantage. Summit Books, NY.
Henderson, Rebecca, Clark, Kim, 1990. Architectural innovation: the reconfiguration of existing product technologies and the failure of established firms. Administrative Science Quarterly 35, 9–30.
Huber, G.P., 1992. Organizational learning: the contributing processes and the literatures. Organization Science 2, 88–115.
Jacobsson, S., Johnson, A., 2000. The diffusion of renewable energy technology: an analytical framework and key issues for research. Energy Policy 28, 625–640.
King, Andrew, Tucci, Christopher, 2002. Incumbent entry into new market niches: the role of experience and managerial choice in the creation of dynamic capabilities. Management Science 48, 171–186.

[4] This conclusion is based on an assumption of relatively stable market prices for construction materials for wind power and geothermal power facilities. Significant increases (or decreases) in such prices would influence both the likelihood and the timing of wind and geothermal energies becoming more economical than fossil fuels.

Kobos, P.H., Erickson, J.D., Drennen, T.E., 2006. Technological learning and renewable energy costs: implications for US renewable energy policy. Energy Policy 34, 1645–1658.
Leonard-Barton, Dorothy, 1992. Core capabilities and core rigidities: a paradox in managing new product development. Strategic Management Journal 13, 111–125.
Linton, J.D., Walsh, S.T., 2004. Integrating innovation and learning curve theory: an enabler for moving nanotechnologies and other emerging process technologies into production. R&D Management 34, 517–526.
National Renewable Energy Laboratories. 〈www.nrel.gov〉.
Neij, L., 1997. Use of experience curves to analyse the prospects for diffusion and adoption of renewable energy technology. Energy Policy 23, 1099–1107.
Oak Ridge National Laboratory (ORNL). 2006. Hydropower: Licensed to protect the environment. Interview retrieved from 〈http://www.ornl.gov/info/ornlreview/rev26-34/text/hydmain.html〉 in January, 2007.
Robinson, William T, Sungwook, Min, 2002. Is the first to market the first to fail? Empirical evidence for industrial goods businesses. Journal of Marketing Research 39, 120–128.
Sahal, Devendra, 1981. Patterns of Technological Innovation. Addison-Wesley Publishing Co., Reading, MA.
Schumpeter, Joseph A., 1942. Capitalism, Socialism, and Democracy. Harper & Brothers Publishers, New York.
Suarez, Fernando F., Utterback, James M., 1995. Dominant designs and the survival of firms. Strategic Management Journal 16, 415–430.
Twiss, B.C., 1992. Forecasting for technologists and engineers: a practical guide for better decisions. IEE Management of Technology Series 15. Peter Peregrinus, London.
United States Department of Energy (DOE), Annual Energy Review. 2007. Retrieved from 〈www.eia.doe.gov〉 in March, 2007.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2005. Distributed Wind Generation Study for Northeast Colorado. December, 1. Retrieved from 〈www1.eere.energy.gov〉 in January, 2009.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2007a. Overview of Geothermal Technologies. Retrieved from 〈www1.eere.energy.gov〉 in March, 2007.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2007b. Overview of Wind Technologies. Retrieved from 〈www1.eere.energy.gov〉 in March, 2007.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2007c. Overview of Biomass Technologies. Retrieved from 〈www1.eere.energy.gov〉 in March, 2007.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2007d. Biomass Program. Retrieved from 〈www1.eere.energy.gov〉 in February, 2007.
United States Department of Energy, Energy Efficiency and Renewable Energy (EERE). 2008. Learning about PV: the Myths of Solar Electricity. Retrieved from 〈www1.eere.energy.gov/solar/myths.html〉 in January, 2009.
Utterback, James M., Abernathy, William J., 1975. A dynamic model of process and product innovation. Omega: The International Journal of Management Science 3, 639–656.
Utterback, James M., Suarez, Fernando F., 1993. Innovation, competition and industry structure. Research Policy 22, 1–21.