What drives innovation in the upstream hydrocarbon industry?

Jeffrey B. Thurston and Robert R. Stewart

ABSTRACT

Anecdotal evidence suggests that the pace of technology development in the exploration and development (E&D) industry quickens in response to the necessity for cutting costs when commodity prices are low. Our review of the history of significant E&D technology advancements leads us to believe this model dos not adequately explain previous technology cycles. Rather, we suggest clusters of E&D innovations have been a response to demand pull and/or technology push. This perspective points to a current confluence of favorable drivers. Historically, alignments like this have fostered technological booms that have led to diffusion of some of the industry's most important technologies.

INTRODUCTION

"What laws govern the growth of man's mastery over nature?" asked the late economist Jacob Schmookler in his landmark 1966 book *Invention and Economic Growth.* Almost four decades after Schmookler stirred interest in the subject, understanding the link between economics and technology remains an important challenge. Michael Schrage, in MIT's December 2004 *Technology Review* asserts that "the dominant global issue of our time is the accelerating diffusion of innovation".

In the oil and gas industry, studies relating technology and economics often focus on the response of finding and development (F&D) costs to better exploration and development (E&D) methods (e.g. Fagin, 2000). There, the goal is not to reveal the mechanics of progress, as Schmookler sought to do, but rather to quantify its impact. Without doubt, understanding the behavior of costs is of critical importance. However, studying the origins and processes that bring about technological advancement is also useful; an understanding of them may help predict and enhance technological progress in the hydrocarbon sector.

This perspective leads us to identify two forces, summarized in Figure 1 that may advance E&D technology. One acts with increasing commodity prices giving rise to elevated expenditures on E&D services. This, in turn, leads to increased inventive and innovative activity. When market forces drive technological progress, it is called *demand pull*.

There appears to be a second, external route to progress. Sciences and technologies that originate outside of the petroleum sector can lead to progress within it. As an example of external sources, we evaluate how breakthroughs in Information Technology (IT) and their uptake by the upstream industry, correlate with upswings in technological progress in the hydrocarbon industry. When an advance finds its origin in expanded scientific capability it is called *technology push*.

These forces act in a cultural context. That is, the trajectory of innovation is influenced by factors such as entrepreneurial spirit, access to capital, and legal protection of intellectual property. These either cause friction and slow progress or provide a smooth route to prosperity (Figure 1). While the cultural smoothness of our pathway is important, we are using data primarily from US-based organizations (and are not comparing the effects of different cultures on innovation).

The following discussion describes some of the forces that may push and pull E&D technology, what this has meant to the upstream hydrocarbon industry in the past and possibly in the future.

PROGRESS BY DEMAND-PULL & TECHNOLOGY-PUSH

Up until the middle of the last century technology (and its underlying body of scientific and engineering knowledge) was thought to evolve independently of, not according to, economic forces. Schmookler (1966) countered this by proposing that inventors (and innovators) respond to investment activity.

He arrived at this controversial conclusion by comparing century-long records of patents and purchases in the railroad industry. Laying these time series beside one another revealed that peaks in annual patent counts consistently followed peaks in equipment purchases. The lag, Schmookler argued, indicates that variations in economic activity induce variations in inventive/innovative effort. That is, technology developers and their organizations perceive that an increasing market size signals increased profit potential for new technology, and they allocate resources accordingly.

The demand-pull theory does not suggest that scientific developments are irrelevant, just that people are motivated to make and incorporate them into new products and processes by the desire to exploit economic opportunities. Nonetheless, the demand-pull theory has been criticized for underestimating the importance of the state of scientific and engineering capability (e.g., Rosenberg, 1974). Usually, critics of the dominance of market demand draw from the work of Austrian economist Josef Schumpeter, who was the first to argue that advances are made by entrepreneurs seizing technological opportunities (an overview of Schumpeter's influential theories, from a geophysical perspective, can be found in Jarchow and Curá, 2000). In this view, advances are driven by the supply of science or technology.

Studies, from a range of industries, recognize that both market factors and new scientific and engineering advances are often engines of change. For example, a multi-industry study by Utterback (1974) attributed between 60 and 80 percent of advances to market pull and the remainder to science supply. Walsh (1984) describes polarization of the debate into opposing demand-pull and technology-push camps as "crude". One of the best known reviews (Mowery and Rosenberg, 1979) reveals no unambiguous evidence for either as the dominant driver. At the 2002 Canadian National Summit on Innovation and Learning it was recognized "that innovation is driven by market pull (global) and smart capital combined with technology push".

We have found only limited application of these theories to the energy industry. Yergin (1991) in *The Prize: The Epic Quest for Oil, Money and Power* notes that the dawn of the hydrocarbon industry, in the late 1840's, witnessed "entrepreneurial innovation" responding to market needs. Schmookler's original study, which included petroleum refining, is the only other published work we know of that that considers energy production and innovation. Regarding energy consumption, Popp (2002) analyzes patenting activity of energy-efficient innovations and concludes that energy prices (demand pull) and scientific advancements (technology push) both influence innovative activity.

Before continuing, we introduce a note about terminology. Schmookler differentiates an invention ("a prescription for a producible product or operable process so new as not to have been obvious to one skilled in the art at the time the idea was put forward") from an innovation ("the act of being the first to produce a new good or service or the first to use a new method or input"). His demand-pull theory applies equally to both. This characterization makes the processes of invention and innovation largely indistinguishable for many E&D technologies. We use terms such as technology "progress" and "advancement" somewhat synonymously with innovation and invention.

DEMAND FOR SERVICES

We first gather statistics related to oil and gas demand. Figure 2 shows a compendium of financial and operating parameters that are often used to capture the state of the upstream marketplace.

Hydrocarbon prices, service expenditures and activity are all broadly correlated. IHS Energy (Gochioco, 2005) has reported that, between 1994 and 2003 there was a correlation, with a time lag of 12 months, between higher oil prices and exploration activity. Studies covering previous periods document a similar relationship between the price of oil and availability of capital to find and produce it. One publication, covering the period between 1970 and 1990, notes that exploration activity in that era generally followed the rise and fall of oil prices (EIA, 1993).

A reliable indicator of marketplace conditions is the yearly account of E&D expenditures from the EIA. However, this record only goes as far back as 1974. To build a longer running time series (shown in Figure 2d), we extended it with seismic crew counts. Since the demand indicators are generally in good agreement, a similar picture would have emerged with any of the metrics from Figure 2b or c. Shaded blue rectangles on Figure 2d denote intervals featuring unusually high demand. These are periods when seismic crew counts (up until 1973) and E&D expenditures (after 1973) exceeded their long-run trend.

SUPPLY OF TECHNOLOGY

Supply-side influences signal their presence in different ways. Walsh (1984) identifies "radical innovations" that provide the basis for new fields of discovery and so spawn flurries of patenting activity. Leaps forward may also occur when there is a fertile body of knowledge from which researchers can draw. Popp (2002) presumes these times are reflected by numerous patent citations.

A key external technology for the upstream industry has long been information technology (IT). (e.g. Hopkins, 1998). We measure how loudly technological opportunity has knocked on the E&D sector's door by how quickly the upstream industry's spending on IT equipment has grown relative to the growth of its spending on other equipment and services.

Figure 3a shows the annual change of the hydrocarbon industry's IT spending to non-IT spending between 1960 and 2003. We consider IT supply abundant whenever this ratio exceeds the average. Major advances have occurred twice with the onset of new computing regimes (Van den Ende and Kemp, 1999). The first is the emergence of the digital computer around 1960. The second is introduction of minicomputers, used mainly for scientific applications and process control, around 1970.

Technology-push theory stipulates that supply sources remain external, so our measurement method assumes that the computing world has evolved largely independently of the oil and gas business. This is borne out by the fact that the hydrocarbon industry's share of all industrial IT purchases has generally been less than 1% (Figure 3b).

MEASURING PROGRESS

Moss (1993) compiled an annual count of onsets of widespread commercial use of new technologies in the E&D industry between 1947 and 1990. Technological advancements during the first part of this period (from 1947 to 1965) are covered by a 1968 study by the National Petroleum Council (NPC). E&D technologies documented in the NPC study typically evolved in three stages: experimental testing; gaining acceptance; and general acceptance. Moss recorded a technology as diffused when it entered the first year of the third stage. This record was prolonged to include the period from 1966 to 1990, primarily by surveying technical articles, interviews with industry experts and general reporting in the *Oil and Gas Journal* and *Petroleum Engineer*. This enabled documentation of an additional 116 new technologies, so that the period from 1947 to 1990 comprises the timing of the introduction of 205 technologies. This time series is shown in Figure 4.

More common measures for technological change are industry-wide patenting frequency (a metric we do not have) and industry-wide R&D spending (which we have but only covering the brief period also shown on Figure 4). Moss' diffusion counts are the longest running record available. Cuddington and Moss (2001) also argue these diffusion counts better measure progress than patenting activity or R&D expenditures. This record is most representative, they argue, because it is incremented only when a product or process becomes cost effective to deploy and so makes the jump from the prototypical to the typical.

We assume that Moss' diffusion count, shaped by customer preferences, and covering a long time span, captures the ebb and flow of E&D innovation. We use it as our primary progress metric. R&D spending appears to precede diffusions by roughly two years (although from only a single overlapping peak).

PUSHING AND PULLING E&D TECHNOLOGY

We analyze the influence of supply and demand on progress by comparing what happened in the E&D industry with what the demand-pull and technology-push models predict. Schmookler's theory indicates that after sales rise, industry-wide E&D and R&D spending should begin to grow. This, in turn, will be followed by a rise in the number of diffusions of improved processes and products. Alternatively, when progress happens according to the Schumpeterian view, the number of diffusions should rise along with the emergence of technological opportunities (Walsh, 1984).

In our analysis, we first scan for Schmooklerian lags. An inventive/innovative peak that is not preceded by rising demand initiates a search for evidence of the influence of supply. We have combined measures for demand, supply, and progress in Figure 5.

1956 is the middle of the first E&D innovation spike. The diffusion and crew counts provide evidence for demand pull. Our supply indicator is not reliable at this time, but it is well known that there were major breakthroughs in electronics. Examples are invention of the transistor in 1947 and recording on magnetic tape in the late 1940's. Our statistical data indicates this wave of E&D technology progress, which left in its wake an industry awash in technology still in use half a century later, has components of supply and marketplace influences.

The next apex was in 1962 and was immediately preceded by strong growth in IT spending in the oil and gas industry. It is interesting to note that the cycle centered on 1962 includes a second revolution in seismic technology featuring introduction of the first commercial digital field system and computers for seismic-data processing.

A prolific period for E&D technological progress reached a peak in 1972. The onset of this period coincides with prolonged IT spending growth, but weak economic demand. Although IT spending by the petroleum industry began to grow rapidly in 1966, E&D progress began rapid acceleration only in 1970 - the same time as the minicomputer regime began (Van den Ende and Kemp, 1999).

Finally, in 1984 there is an E&D technology pinnacle that occurred in when demand was high. This appears to have happened without an unusual technology supply. This period also conforms to the demand-pull sequence described by Walsh (1984). In this view, high R&D expenditures indicate an intensive R&D effort. This effort, driven by demand, enriches the marketplace with new processes and products (Figure 5).

To summarize then, the time series of Figure 6 suggests that the rate of diffusions of new technology appears to follow economic demand (1956, 1984) and/or technology push (1956, 1962, and 1972). It is interesting to note that new products have appeared more closely on the heels of abundant technology supply than on the strength of demand. There was, nonetheless, a speedier response to demand in the 1980's than in the 1950's. This observation is similar to that made in a recent article in *Business Week* by Engadine and Einhorn (2005) who report that "it now takes 60% less time to get a new concept to market".

One implication of this pattern of technology progress is that prolonged periods of depressed prices and low demand for services, (e.g. circa. 1975) are unlikely to witness rapid progress. Falling, or oscillating energy prices have been accompanied by significant progress, but this seems to stem from either technology supply (e.g. circa. 1962) or from a time delayed reaction to demand (e.g. circa. 1985). There has been some suggestion that depressed E&D spending alone motivates R&D efforts by forcing groups to differentiate themselves to attract what little business exists. We don't see evidence that this has been the case.

EMPLOYMENT AND TECHNOLOGY PROGRESS

In *The Color of Oil* Economides and Oligney (1990) assert the resource's primary colors are money, technology, and people. Identifying technology drivers, whether they originate from demand or supply, draws a link between the first two. Others have noted the influence of these on people in the industry. For instance, Kendell (1999) developed a multivariate model to describe employment numbers in the upstream oil and gas industry. He found the size of the E&D service-sector workforce to be largely dictated by the number of wells drilled (which in turn is determined by price, taxes, and technology).

Understanding the impact of technical advances on employment and vice-versa, already difficult to isolate from among the various influences, is further complicated by the fact that improved products and processes have the potential to exert both upward or downward pressure on the size of the workforce. Expansion can occur when new methods reduce costs and stimulate demand. Contraction can be a consequence of improved productivity reducing personnel requirements.

Nevertheless, significant technical supply with major market demand, in the late 1970s and '80s, seems attached to a marked increase in upstream employment (Figure 6). This crest is closely followed by undergraduate enrolments in geoscience (get a job!) and membership in professional societies. E&D innovations coincide with this personnel peak. However, innovation, in general, does not seem that closely connected with employment levels.

E&D TECHNOLOGY PROGRESS MODEL

We summarize these relationships with Figure 7. This model incorporates the correlations we have noted. We also extend it to include the relationship between improved financial performance and technology progress. This has been documented in Fagin (2000) and Cuddington and Moss (2001). These studies decouple the offsetting effects of depletion and technology progress to estimate the impact of advancements on F&D costs. Additionally, a 2000 study by the EIA notes improvements in drilling success due to rapid technology advances. Other benefits of R&D spending (and presumably attendant technology progress) have been documented by Anderson (2000), who conclude that a high R&D intensity ratio (ratio of R&D to E&P expenses) correlates with better corporate financial performance.

THE RECENT PAST TO NEAR FUTURE

We now try to understand E&D technology in the recent past (i.e. between the end of Moss' record in 1990 and the present). Figure 5 indicates that the period from 1985 to 2000 appears to lack major E&D technology drivers. Thus, this period may have been witness to lower rates of upstream innovation - as also suggested by steadily declining R&D expenditures. We should note though, that these expenditures are from petroleum-producing companies and may not fully capture the increasing R&D expenditures by the service companies and university consortia. Both of these groups have considerably increased their research efforts and are strongly driven to innovate technically.

The framework shown in Figure 7 also makes possible predictions regarding future progress. The modern landscape of technology supply to the E&D industry is a broadening panorama. Hopkins (1998) predicts the influx of additional sources by noting that "the industry has been looking outside of its traditional suppliers of technology to the 'far market' for technologies that might find application to petroleum exploration". This sentiment is echoed in Jarchow and Bahorich (2000) with the suggestion that "many key advances are being driven from outside the traditional energy industry". Further, indicators of recent (Figure 2) and future demand are also positive. The Smith Barney division of Citigroup Global Markets Inc. reports in their 2004 survey of worldwide E&D expenditures that respondents planned to increase 2004 spending by 4.4%. This follows a 9.4% increase in 2003, and a 24.8% increase (a twenty-year high) in 2001 (Kieburtz et al., 2004). Every major market pull and technology push episode has been accompanied by an innovation surge. Our current confluence of supply and demand factors should strongly favor a prolific period of investment in E&D research, to be rewarded with rapid advances in E&D technology, followed by improved F&D costs and higher corporate valuations.

CONCLUSION

We now return to Schmookler's provocative question about the processes of technical progress. History suggests that technological leaps and associated prosperity in the E&D sector will likely come from economic impetus and the scientific capability available to nimble innovators.

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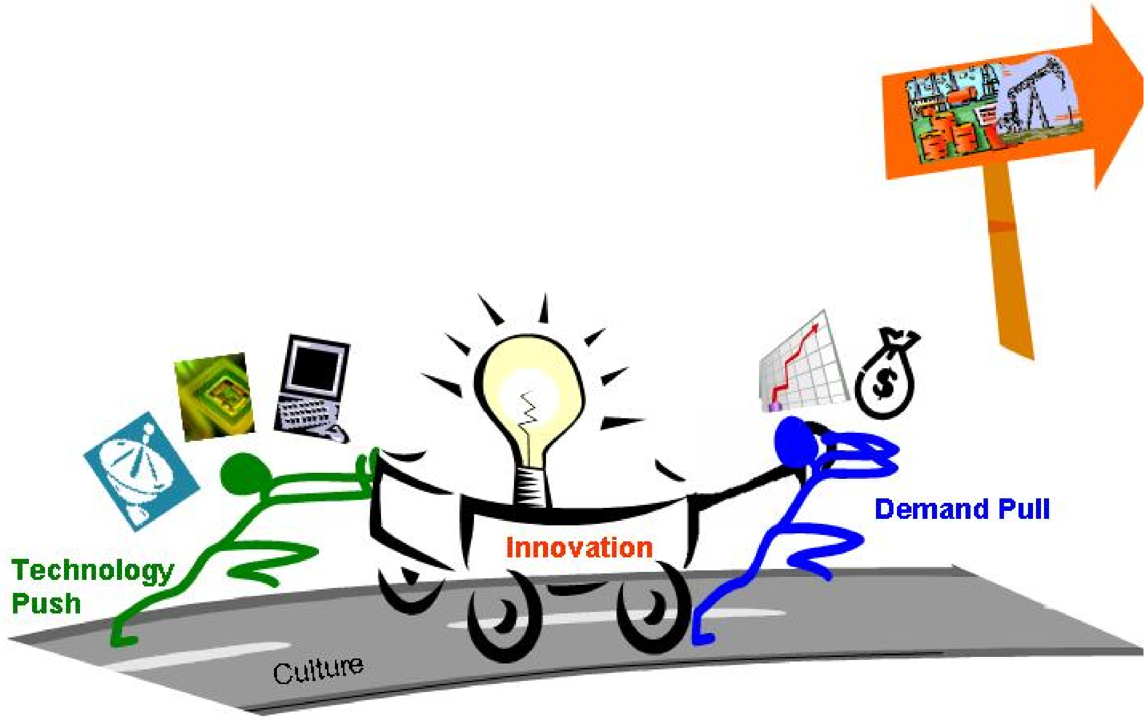

FIG. 1. Cartoon showing the sources of progress in the upstream petroleum industry.

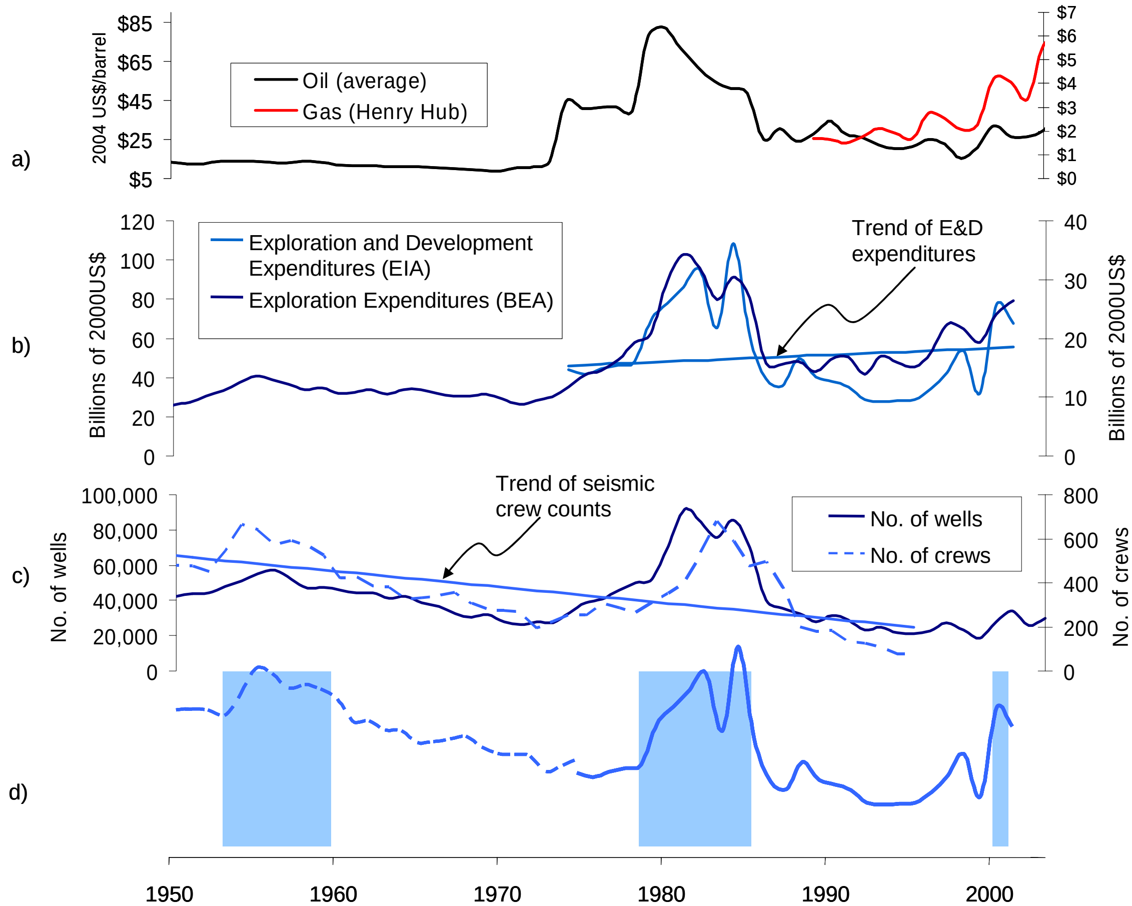

FIG. 2. Indicators of demand in the E&D industry. a) Oil and natural gas prices, b) Exploration and E&D expenditures, and c) Seismic and drilling activity, d) Composite record of demand with high-demand periods shaded blue. Sources: Crew counts are from the SEG, Exploration expenditures are from the Bureau of Economic Analysis. E&D expenditures are from the EIA (http://www.eia.doe.gov), Energy prices are from the BP Amoco Statistical Review of World Energy 2005.

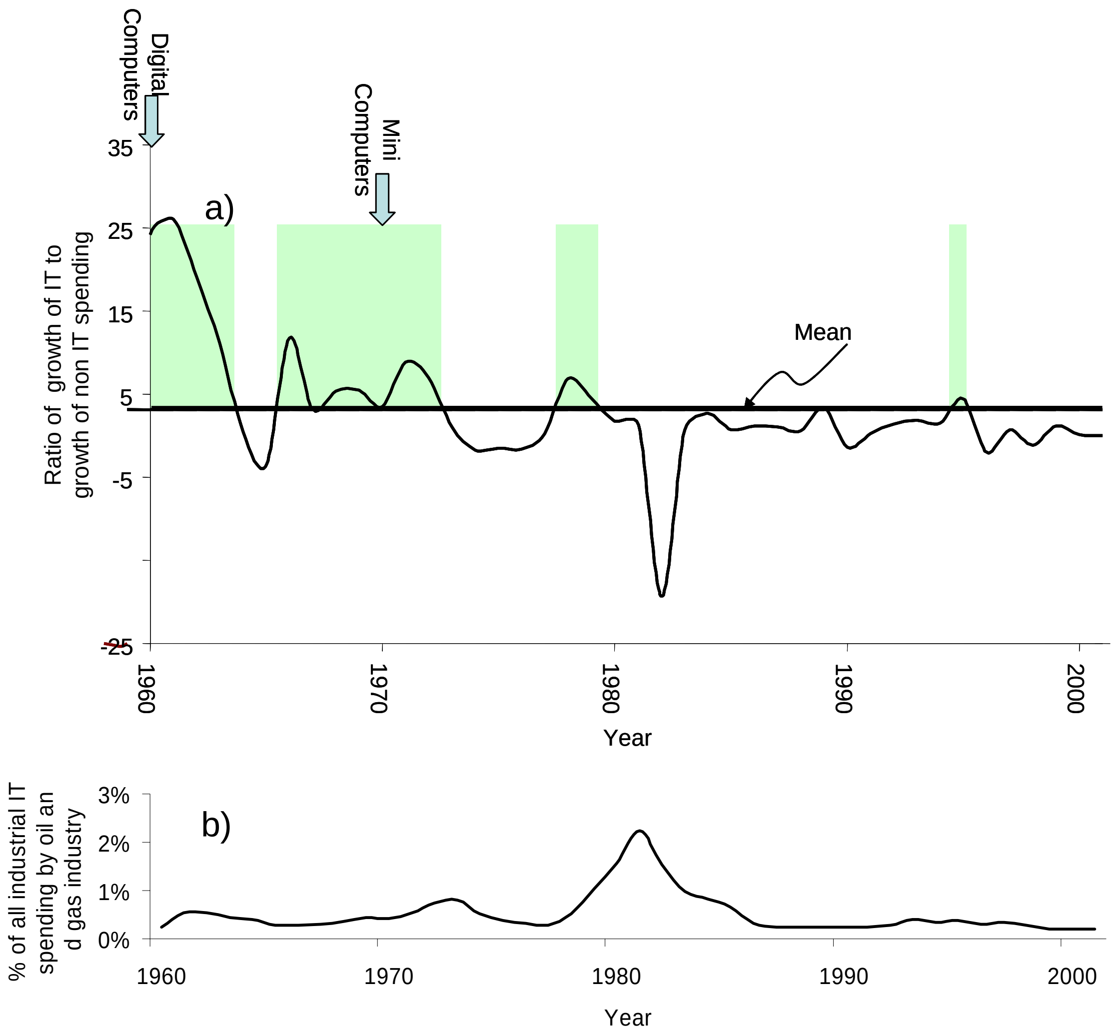

FIG 3. a) Ratio of year-on-year change in IT and non-IT purchases by US-based oil and gas companies. Periods shaded green correspond to years in which this ratio is above the long run average (between 1960 and 2000). These are taken as periods during which technology uptake was higher than usual. b) Percent of all industrial spending on IT that was accounted for by the oil and gas industry. Source: Bureau of Economic Analysis, Detailed Data for Fixed Assets and Consumer Durable Goods (http://www.bea.doc.gov/bea/dn/faweb/details/).

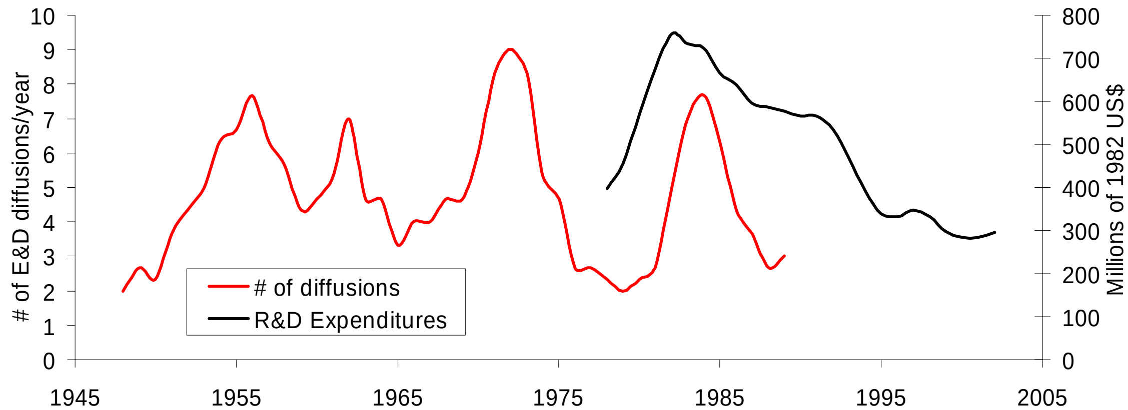

FIG. 4. Technology diffusions per year in the E&D industry for the period from 1947 to 1990 and upstream R&D spending (excluding extraction) for US energy companies. Both quantities have been smoothed with a 3-year running average filter prior to display. It is worthwhile noting that Graebner's (see e.g. http://www.spe.org/spe/jsp/basic/0,,1104_1714_1004089,00.html) four geophysical revolutions (occurring in 1955, 1962, 1972, and 1986) all took place amidst E&D industry-wide surges in technology progress. (Source: Technology diffusion counts are from Moss, 1993 R&D expenditures are from the EIA: http://www.eia.doe.gov/emeu/finance/frsdata.html).

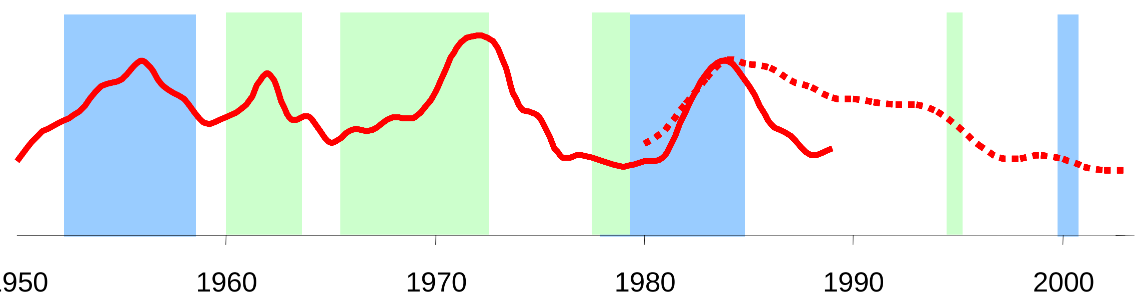

FIG. 5. Metrics for technology progress (from Figure 4) superimposed on demand peaks (shaded blue from Fig. 2d), and technology supply peaks (shaded green). R&D spending (dashed red line) has been shifted two years later so that it aligns with the record of diffusion counts (solid red line).

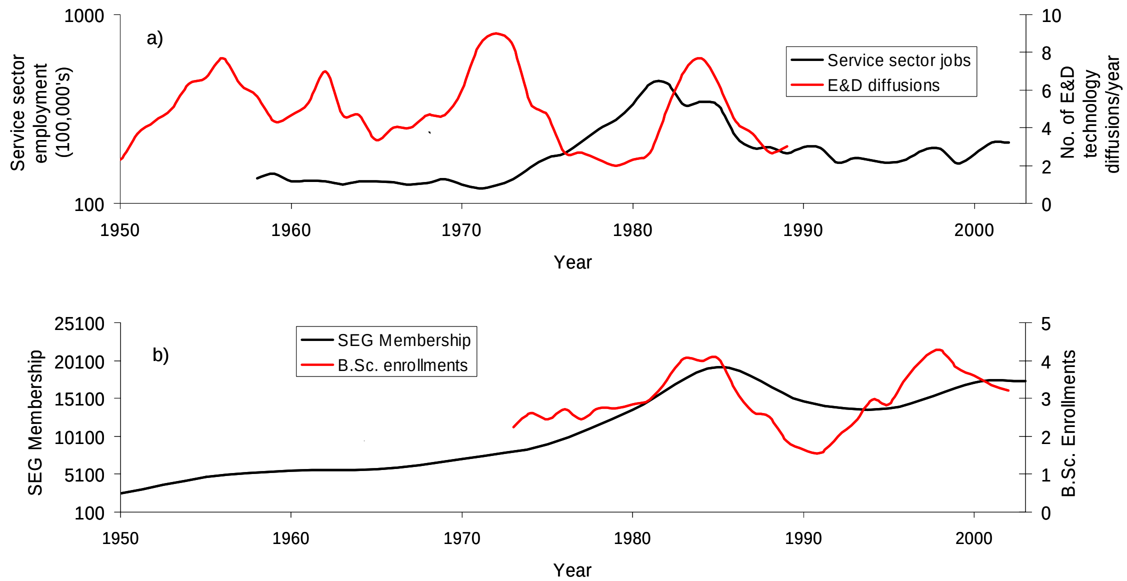

FIG. 6a). Oil and Gas service jobs overlain on diffusion counts from Figure 4. b) enrollments in B.Sc. Earth Science programs in Canadian Universities and SEG membership. Sources: Employment numbers from U.S. Department of Labor, Bureau of Labor Statistics, National Employment, Hours, and Earnings, oil and gas services, eeu10138001. Student numbers from Department of Earth Sciences, University of Western Ontario web site http://146.142.4.24/cgi-bin/srgate, (http://www.uwo.ca/earth/cddgc/fig1a.gif), SEG membership from: Society of Exploration Geophysicists (www.seg.org).

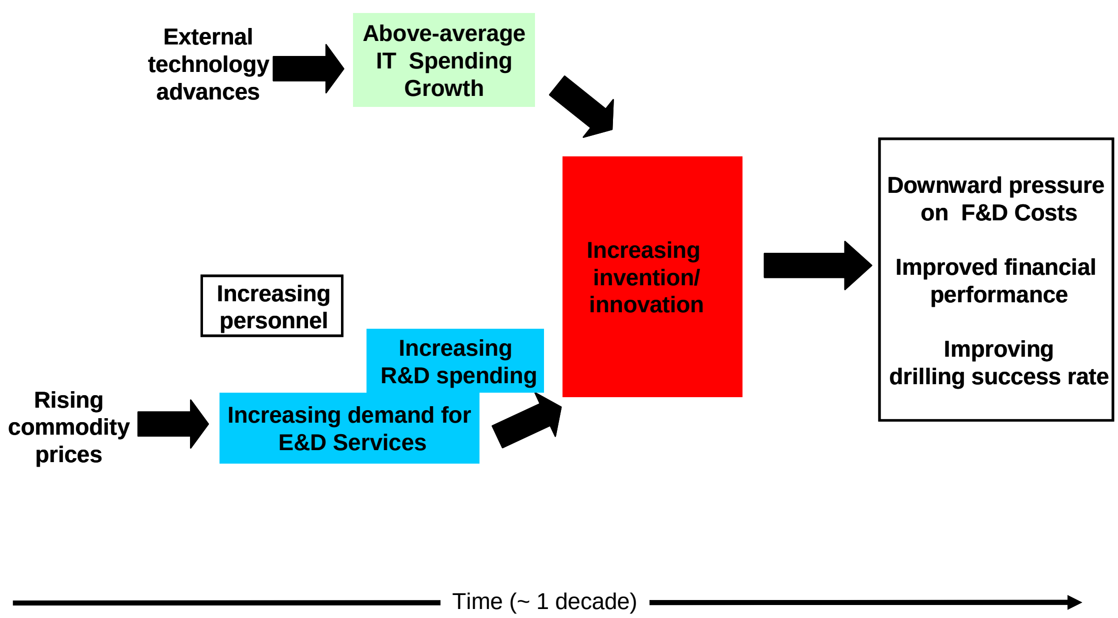

FIG. 7. Schematic diagram showing evolutionary cycle of E&D technology. We round out the cycle by adding the beginning (rising commodity prices spurring demand for services) and end (falling F&D costs and improved financial metrics) from published studies originating within the E&D industry (see e.g., Cuddington and Moss, 2001; Gochioco, 2005; Anderson, 2000; and Fagin, 2000).