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Understanding Radical Technology Innovation and its Application to CO2 Capture R&D: Interim Report, Volume One—Literature Review

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Summary

In recent years there has been growing interest in pursuing “radical” innovations in energy and environmental technologies to ameliorate the problems of global climate change and to ensure a more sustainable energy future. In the public realm, R&D managers and policymakers have proposed a range of new programs, funds and government agencies to pursue this idea. This report reviews the published literature on radical innovation to establish a baseline of current understanding of this concept and means of achieving such goals. The results of this review indicate that there has been little research directed toward understanding how a public R&D program could systematically achieve radical or breakthrough technologies, and that defining radical innovation remains challenging and elusive. This review also finds that radical innovation in large technological systems such as electricity supply is difficult to achieve; that it often requires clusters of complementary innovations; and that it tends to occur over long periods of time—often on the order of 6-8 decades. Success also often depends upon significant and sustained government policy support. The literature further indicates that little if any research on radical innovation has specifically addressed environmental control technologies for fossil-energy systems. In this context, further research is needed to more fully characterize what types of changes are implied by terms such as “radical,” “breakthrough” or “revolutionary” when applied to innovations in fossil energy environmental control technologies.

1. Introduction

Government organizations whose central mission is technology research and development (R&D)—such as the U.S. Department of Energy’s National Energy Technology Laboratory (DOE/NETL),—are increasingly looking for “radical” or “breakthrough” technologies that can fundamentally change the game (Orbach 2006; DOE 2006). Along a similar line, the National Research Council recommended that a new energy R&D agency should be created to sponsor “creative, out-of-the-box, transformational, generic energy research…as opposed to incremental research on ideas that have already been developed” (NRC 2006). Outside the energy domain, public R&D funding agencies such as the National Science Foundation (NSF) also have been considering how to increase support of "transformative" research—research that holds the potential to radically change our understanding of current science or engineering concepts (NSB 2007).

This report presents the results from the first phase of a research program whose long-term objective is to better understand the nature and foundations of radical technological innovation, specifically in the domain of environmental control technologies for fossil-energy systems. From this, we hope to draw lessons for the management of R&D in government programs such as the U.S. DOE's carbon dioxide (CO_2) capture R&D program (Figure 1). The starting point for this research is a broad literature review of radical technological innovation, with a focus on energy and environmental technologies. The findings from this literature review will be used to inform subsequent phases of this research project (Figure 1). These findings will also be examined with respect to possible implications for other public R&D programs designed to achieve "radical" change among environmental-control technologies.

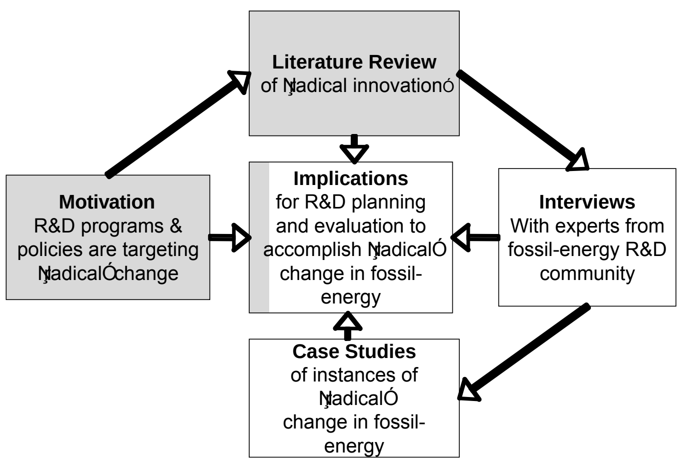

Figure1: The research described in this summary report (shaded areas) fits into a larger research project that aims to better understand "radical" innovation in fossil-energy technologies and from this, to attempt to draw implications for managing research programs in this domain.

To provide greater context and motivation for this research, Section 2 of this report discusses current R&D programs and recent policy recommendations related to radical innovation. Section 3 characterizes the literature on radical innovation (and related terms such as "discontinuities" and "breakthroughs") using publication and citation counts, while Section 4 summarizes results from an in-depth literature review. The final section summarizes findings, discusses implications for government-supported R&D programs and suggests directions for further work.

2. Background Discussion

R&D managers and policymakers have become increasingly interested in supporting "high-risk research" and developing "out-of-the-box, transformational" technologies (Council on Competitiveness 2004; NRC 2006; NSB 2004; NIH 2006).[1] These discussions often involve establishing a new program, fund, or even agency, dedicated to supporting this type of research. Such proposals have been motivated, in part, by a perception among researchers that a peer-review system for funding R&D is overly risk-averse (Chubin and Hackett 1990).[2]

In 2004 the Council on Competitiveness recommended high-risk research be stimulated through "Innovation Acceleration" grants that reallocate 3 percent of U.S. federal R&D budgets. The National Academies' Committee on Prospering in a Global Economy released a report in 2006 entitled *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic* Future. The report called on Congress to strengthen U.S. commitment to long-term basic research. Specifically, they recommended setting aside at least 8 percent of budgets of federal research agencies for discretionary funding managed by technical program managers, to catalyze high-risk, high payoff research.

However, currently there is no way to determine how many research dollars the U.S. government spends on so-called "high-risk, high payoff" research. While public R&D statistics are collected, analyzed and published by several organizations—for example, the biennial Science & Engineering Indicators (NSB 2006) and the American Association for the Advancement of

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1 While this review was largely limited to the U.S., technology and R&D leaders outside the U.S. also perceive there is a need to support bold, high-risk research; the European Commission created a special program--New and Emerging Science and Technology--under its Sixth Framework Program for funding "unconventional and visionary research."

2 Chubin and Hackett (1990) surveyed a group of researchers from the National Cancer Institute regarding views of the peer review system for obtaining research grants. About 61 percent of those surveyed agreed with the statement "Reviewers are reluctant to support unorthodox or high-risk research" (p. 66). This risk aversion embedded within the system is believed to have several roots: scientists, constrained by the terms of their employment (i.e., the need to acquire tenure), are discouraged from pursing unconventional ideas; reviewers, are unable to effectively evaluate unconventional ideas (e.g., their inherent bias to preserve the status quo of an area of research on which they have spent their career).

Science annual report analyzing the President's budget request for R&D (AAAS 2008)—expenditures are not broken down into categories such as "radical" or "incremental." A precursor to developing metrics to characterize R&D spending will be establishing a common operational definition for these types of research.

With regard to energy technologies, the National Academies' Committee on Prospering in a Global Economy recommended (pg. 5) creating an Advanced Research Project Agency for Energy (ARPA-E) modeled after the Department of Defense's Defense Advanced Research Project Agency (DARPA) to fund "creative 'out-of-the-box' transformational generic energy research that industry by itself cannot or will not support." This research is characterized as high-risk but with a potentially high payoff for the nation. This report notes (pg. 137) that ARPA-E's investments in foundational research are "needed to invent transforming technology that in the past were supplied by our great industrial laboratories." Along a similar line, the current DOE research program on carbon capture includes a program that aims to support breakthrough concepts dedicated to "revolutionary and transformative approaches" to carbon capture and storage (DOE 2008).

Several other federal R&D funding agencies, including the National Institutes of Health (NIH) and the National Science Foundation (NSF) have been focused on improving their ability to fund "highly innovative" or "transformative" research. The NIH Director's Pioneer Award program began in 2004 and supports individual scientists of exceptional creativity who propose highly innovative approaches with the potential to produce significant impact, to major challenges in biomedical research (NIH 2006). In 2004 the National Science Board (NSB)—the governing and policymaking body of NSF—established a Task Force on Transformative Research. This task force was charged to "consider new policies that would enhance the ability of the National Science Foundation to identify, evaluate, and fund innovative, 'transformative' research defined as research that has the potential to revolutionize an existing discipline through a paradigm shift or create a new one" (NSB 2004).

The current and proposed R&D programs discussed here have several commonalities. All involve establishing a separate program, fund, or even agency, for funding research characterized as "high risk," "transformative," or "highly innovative." It is also implicitly assumed transformative changes can be achieved through highly novel, or out-of-the-box research.

The basic designs of these programs, however, do differ. In particular, the various programs have very different approaches for evaluating and deciding what (or who) to fund. While the proposed APRA-E would take a form similar to the DARPA model, where program managers exercise substantial autonomy and freedom, the NIH Director's Pioneer Award program instead selects exceptionally creative individuals (similar to the McArthur Genius Grant), in effect, evaluating the *person* instead of the *idea*. The NSB (2007) has recommended that NSF create an agency-wide "Transformative Research Initiative", although implementation details for this proposed program are still under development.

3. Overview of the Literature on Radical Innovation

This section provides a broad, quantitative assessment of the literature on radical innovation and related terms. Publication counts related to radical innovation were analyzed using the ISI Web of Science database. Additionally, Google Scholar was used to collect and analyze the most highly cited works on this topic.

First, an ISI database topic search was performed for articles that included at least one of the following terms: radical innovation, breakthrough technology, disruptive technology, and revolutionary technology.[3] The original search generated 601 records. When the results were refined to include only articles (i.e. reviews, editorials, letters, etc. were removed), the group was narrowed to 440 . The ISI database allows search results to be analyzed by topic area. The majority (just over 50 percent) of the articles on radical innovation fell into the ISI topic area: "Business and Economics." Search results were also analyzed by journal name. The journal titles shown in Table 1 demonstrate the concentration of research in areas such as product innovation, technology management, and R&D management and policy. It is worth noting that the ten journals containing the most articles on radical innovation, account for only about 27 percent of articles in this literature. For example the *Journal of Product Innovation Management*, which contains the most references, accounts for only about 5 percent of the articles on radical

[3] Specific entries for this search included:
TOPIC=("radical innovation*" OR "breakthrough technolog*" OR "disruptive technolog*" OR "revolutionary technolog*"); Timespan=All Years; All Databases.
On March 31, 2008, this research returned 601 results. This result was further refined to include only articles, for which there were 440 results.

innovation. This supports the prior observations (e.g., Garcia and Calantone 2002), that radical innovation has been researched across a relatively broad cross-section of scholarly communities.

Table 1. Top journals in the literature on radical innovation

Rank		Number of Articles	Percent of Total Articles
1	Journal of Product Innovation Management	21	5%
2	Technological Forecasting and Social Change	19	4%
3	Research Policy	14	3%
4	R&D Management	13	3%
5	Research-Technology Management	11	3%
6	BT Technology Journal	10	2%
7	International Journal of Technology Management	10	2%
8	IEEE Transactions on Engineering Management	8	2%
9	Harvard Business Review	6	1%
10	Journal of Cleaner Production	6	1%
	Sub-Total: Top 10 Journals	***118***	***27%***
	Total	***440***	***100%***

The **ISI** dataset was also used to examine how interest in radical innovation as a research topic has changed over time. Figure 2 shows a time-series trend of articles published between 1970 and 2007. The number of articles published between 1970 and 1990 was negligible, ranging from zero to 3 publications per year). Then in the early 1990s articles rapidly became more common reaching a peak of 50 in 2007. While it is not readily apparent what factors stimulated this growth in publications, the data in Table 1 suggests a growing interest in the idea of radical innovation.

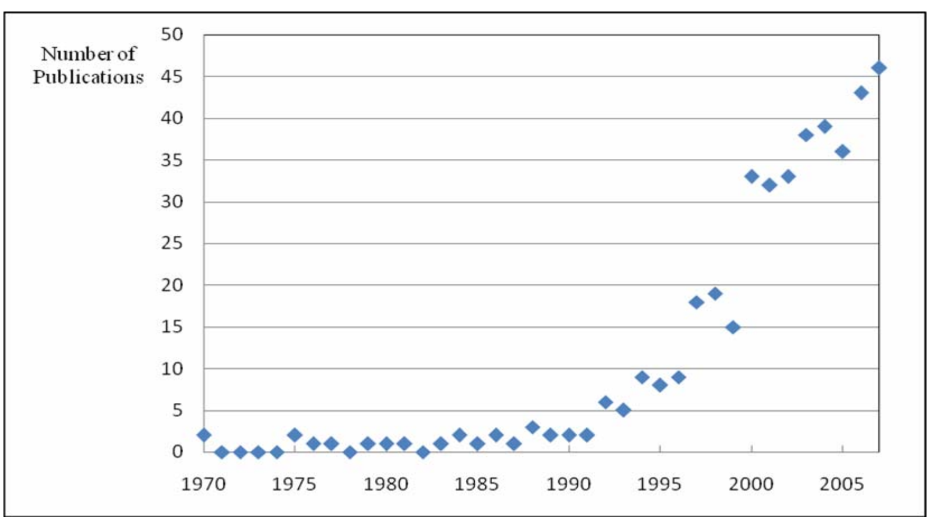

Figure 2. Articles published on radical innovation: 1970–2007.

The results of the citation analysis in Google Scholar are illustrated in Table 2 which lists the five most highly cited publications focused on either radical innovation or breakthrough technology.[4] The studies summarized in Table 2 help illustrate several findings from this literature review and are detailed more extensively in the next section. First, while studies on radical innovation have been carried out in a diversity of industries ranging from biotechnology to footwear, research has generally not focused on environmental technologies for fossil-energy—for which there are no "natural" markets in the absence of governmental requirements. Rather, the focus has been on technologies sought in a free market economy. Further, all of the studies in Table 2 have examined radical or breakthrough technologies in the context of their relationship to firms or industries, and the definitions and metrics for identifying radical innovation have been developed accordingly. Researchers have not developed definitions or metrics applicable to managing public R&D activities that seek these types of changes. Finally, Table 2 also helps demonstrate that researchers have used a variety of different, but overlapping definitions to characterize radical and breakthrough innovations. At times, these terms are not well defined.

[4] The following terms were used to search Google Scholar: "radical innovation" [yielded about 10,800 hits] and then both "breakthrough technology" [yielded about 2,200 hits] and "technological breakthrough [yielded about 6,710 hits]. The most highly-cited publications were chosen from the first 10 pages (100 entries) of Google Scholar, subject to the following selection rules:
(1) The publication focused on studying the innovation process (as opposed to for example, a science or engineering research paper that characterized a finding as a "breakthrough");
(2) The publication focused on *technological* innovation (as opposed to, for example, organizational innovation);
(3) The publication had a relatively major focus on radical innovation or at least on types of technological innovation (judged based on articles abstract or previews available through Google Books Search);
(4) The publication was not a review article; and
(5) Only one publication per lead author was included.
The results presented in Table 2 are slightly biased towards older publications, which have had more time to be cited.

Table 2: Most high-cited publications on "radical innovation" and "breakthrough technology."

Author & Year	Publication Title	Term(s) and Definition/Description	Other Metrics	Industry(s) Studied
RADICAL INNOVATION				
Henderson & Clark (1990)	Architectural Innovation: The Reconfiguration of Existing Product Technologies and the Failure of Established Firms	**Radical Innovation** "…based on a different set of engineering and scientific principles and opens up whole new markets and potential applications." (p.9)	Radical innovation often creates great difficulties for established firms; It can be the basis for the successful entry of new firms; It can redefine an industry; It establishes a new dominant design: involves components with a new set of core design concepts, which are linked together in a new architecture	semiconductor photolithographic alignment equipment
Utterback (1994)	Mastering the Dynamics of Innovation	**Radical Innovation/Discontinuous Change** "…change that sweeps away much of a firm's existing investment in technical skills and knowledge, designs, production technique, plant, and equipment."(p. 200)	Radical innovation renders one or more existing technologies obsolete	typewriters; lighting; plate glassmaking; ice & refrigeration; imaging
Dewar & Dutton (1986)	The Adoption of Radical and Incremental Innovations: An Empirical Analysis	**Radical Innovation** "…fundamental changes that represent revolutionary changes in technology…they represent clear departures from existing practice." (p.1422)	The major difference between incremental and radical is degree of novel technological knowledge embedded	footwear
Ettlie, Bridges & O'Keefe (1984)	Organizational Strategy and Structural Differences for Radical versus Incremental Innovation	**Radical Innovation** "One aspect of the dimension appears to whether or not the innovation incorporates technology that is a clear, risky departure from existing practice." (p. 683)	Radical if a technology is new to the adopting unit and new to the referent group of organizations; Radical if it requires both throughput (process) as well as output (production or service) change	food processing
Leifer, McDermott et al. (2000)	Radical Innovation: How Mature Companies Outsmart Startups	**Radical Innovation** "…a product, process, or service with either unprecedented performance features or familiar features that offer potential for significant improvements in performance or cost." (p. 5)	Radical innovation creates such dramatic change in products, processes, or services that they transform existing markets or industries, or create new ones	12 projects in large established firms across a variety of industries
BREAKTHROUGH TECHNOLOGY				
Anderson & Tushman (1990)	Technological Discontinuities and Dominant Designs: A Cyclical Model of Technological Change	**Technological Discontinuity/Breakthrough, Revolutionary Innovation** "…innovations that dramatically advance an industry's price vs. performance frontier." (p. 604)	Identified as a discontinuity when the innovation: pushes performance frontier by a significant amount by changing product or process design	minicomputer; glass; cement
Ahuja & Lampert (2001)	Entrepreneurship in the large corporation: a longitudinal study of how established firms create technological breakthroughs	**Breakthrough Inventions** "Those foundational inventions that serve as the basis for many subsequent technological developments." (p. 523)	Uses the most influential patents (the top 1% of patents applied for in a year on the basis of their citation weights) as an indicator of breakthrough invention	chemicals
Zucker & Darby (1996)	Star Scientists and Institutional Transformation: Patterns of Invention and Innovation in the Formation of the Biotechnology Industry	**Scientific Breakthroughs** [not defined]	"Scientific breakthrough are created by and embodied in, and applied commercially by particular individuals…." (p. 12709); Focuses on the role of "star" bioscientists (identified by their research productivity) and their collaborators	biotechnology
Chandy & Tellis (1998)	Organizing for Radical Product Innovation: The Overlooked Role of Willingness to Cannibalize	**Radical Innovation** "…(1) incorporate substantially different technology from existing products and (2) can fulfill customer needs better than existing products" (p. 475)	Separately defines a technological breakthrough as ones that "adopt a substantially different technology than previous products but do not provide superior customer benefits per dollar"	computer hardware; photonics; telecommunications
Florida & Kenney (1990)	The Breakthrough Illusion Corporate America's Failure to Move from Innovation to Mass Production	**Breakthrough Technology** [not defined]	[none offered]	high-tech industries

4. Results from the Literature Review

This section details findings from a broad literature review of research on radical innovation and related terms, which are often used interchangeably in the literature (e.g., "breakthrough," "disruptive," "discontinuous," etc.). The literature review was guided by three sets of questions:

(1) What is radical innovation? What attributes are commonly ascribed to radical innovation? How is it defined? What are some examples of radical innovation?

(2) What are the major topics areas in the literature on radical innovation? What does the research say regarding public R&D management for achieving radical innovation?

(3) How are these terms used among energy and environmental technologies? What are some examples of radical innovation in these domains?

As was discussed in the last section, the literature on radical innovation is broad in scope. This is, in part, because many different scholarly communities have addressed the topic. This literature review is based on research from the following areas: economics of innovation and industrial organization, organizational learning, R&D and technology policy and management, environmental technological innovation and policy, corporate strategy, new product development, marketing, and the history of technological change. Several articles that have been reviewed and/or critiqued in the literature (Ehrnberg 1995; Garcia and Calantone 2002; Danneels 2004; Dahlin and Behrens 2005) served as useful starting points for identifying major focus areas within the literature, and also pointed to further sources of information.

4.1 What is radical innovation?

Technological innovation can be defined as the process by which new or improved products or processes are created and introduced into the market.[5] While the general distinction between radical and incremental innovation has been recognized at least since Joseph Schumpeter's work in the first half of the twentieth century, researchers have tended to draw upon

[5] It has become common for innovation to be defined more narrowly and viewed as a distinct process from invention or diffusion. In this sense, technological change is usually represented as a trilogy of stages - Invention is defined as the generation of new ideas, technological innovation, the development of new ideas into marketable products and processes, and diffusion, the spread of new products and processes across potential markets (Stoneman 1998).

a wide range of terminology to describe this point (e.g., revolutionary, macro-invention, breakthrough, discontinuity, and disruptive). This next section summarizes how researchers have characterized, defined, and measured these concepts and discusses examples of technologies that have been perceived as radical.

4.1.1 Attributes of radical innovation

Radical innovation has generally been characterized in two distinct ways. First, as rare events (Tushman and Anderson 1990) that result from a stroke of individual genius or luck (Mokyr 1990). These innovations can be unpredictable, incorporating a dimension of "surprise" (Criqui, Martin et al. 2000). The historian Joel Mokyr (1990: 13) referred to macro-inventions as those that require one to step outside accepted practice and design "an act of technological rebellion and heresy."

Second, radical innovation has also been described, in contrast, as a long and difficult process. Technological innovation is a risky undertaking and the development of a radical technological innovation is, in particular, often characterized as a lengthy, complex, and highly uncertain process, fraught with barriers and difficulties (Freeman and Soete 1997). These innovations have been associated both with high technical uncertainty (will it work, and at what cost?) as well as a high degree of market uncertainty (Freeman and Soete 1997). For example, Ettlie (1982) conducted of study of 40 federally supported innovation projects from five government agencies, and found projects were more likely to be commercially successful when the project involved incremental, as opposed to radical, technology. Radical innovation can take a long time—typically 10 years or longer—to bring to fruition (McDermott and O'Connor 2002).

Generally speaking, radical innovations, in their earliest incarnations, are usually quite crude. Their ultimate success nearly always depends upon gradual improvements, refinements, and modifications; the development of complementary technologies; as well as organizational change and social learning. In this sense, radical innovation is viewed as a process, rather than as a discrete event.

4.1.2 Definitions of radical innovation

Researchers have used a variety of different, often overlapping, definitions to characterize radical innovation and there is currently no broadly accepted definition for in the literature (Green, Gavin et al. 1995, Chandy and Tellis 2000; Garcia and Calantone 2002; Dahlin and Behrens 2005). Garcia and Calantone (2002) attributed the lack of a stable definition to the fact that this topic has been researched from many scholarly communities. Moreover, "radical" appears to be a complex and multidimensional construct. Dewar and Dutton (1986: 1423) expressed a similar sentiment: "The distinction between radical and incremental is easier to intuit than to define or measure." As a result, studies tend to define radical innovation differently, and sometimes not at all (Dahlin and Behrens 2005). In general, the definitions and descriptions of radical innovation tend to characterize "radicalness" either in a technological sense or in an economic sense.

In a technological sense, radical innovations have been commonly defined as innovations that could not have evolved through improvements to, and modifications of, the existing technology (Helpman 1998; Lipsey, Carlaw et al. 2005). Radical innovations are based on a different set of science and engineering principles (Henderson and Clark 1990), and incorporate substantially different core technology (Chandy and Tellis 2000). Incremental innovations in contrast, improve upon and extend existing technology. Radical innovations are also commonly described as innovations that serve as the basis for many subsequent technological developments (Ahuja and Lampert 2001).

Radical innovations have also been characterized as representing a significant leap forward in the technological frontier or adding significant new value to the marketplace. For example, Tushman and Anderson (1986) defined a technological discontinuity as an order-of-magnitude improvement in the maximum achievable price-versus-performance frontier of an industry. Radical innovations have also been defined as innovations that offer unprecedented performance features or familiar features that hold potential for significant performance or cost improvements (Leifer, McDermott et al. 2000).

Finally, radical innovations have been commonly defined or described in terms of the profound impacts they have on firms, industries and markets. Schumpeter (1942) argued "creative gales of destruction" destroy the foundation of large, established firms' competitive advantage by rendering their technology and past investments obsolete. Similarly, Utterback (1994: 200) defined radical innovations or discontinuous change as "change that sweeps away much of a firm's existing investment in technical skills and knowledge, designs, production technique, plant and equipment," and Henderson (1993) described an innovation as being radical when it renders a firm's information filters and organizational procedures partially obsolete.

Despite the strong research focus on understanding the implications of major innovation on a firm's capital and knowledge investments, defining a technology or innovation as "radical" based on the impact it has in the market or more broadly, in society, can be problematic because of the circularity embedded in this definition. Sood and Tellis (2005) for example, explicitly avoided using terms such as breakthrough or discontinuous, stating that these types of terms "are intrinsically problematic because they define an innovation in terms of its effects rather than its attributes."[6] Similarly, Behrens and Dahlin (2005) argued that a technology's impact on a particular firm would depend on how that firm deals with this type of change, which is in turn, a function of that firm's prior knowledge. Basing a definition of a particular technology on its impact is incorrect because it will depend on a particular firm's characteristics—i.e., a technology might be radical to one firm, but not be to another.

4.1.3 Classifying innovations

Describing an innovation as "radical" is essentially a comparative description; a new technology or product are typically considered radical with respect to current technology or way of thinking. There are a number of ways to classify innovations (e.g., product vs. process). The category of "radical innovation" is commonly evoked within typologies that attempt to characterize a product's or process' degree of innovativeness. Additionally, beginning with the work of the economist Joseph Schumpeter (1939; 1942), studies of technological innovation often have distinguished between incremental and radical innovation, although sometimes using different terminology (e.g., Henderson and Clark 1990; Henderson 1993; Green, Gavin et al. 1995; Leifer, McDermott et al. 2000; Sood and Tellis 2005).

Given the variety of definitions for radical innovation, it is not surprising that an abundance of typologies have been developed to categorize the innovativeness of new technologies. Garcia and Calantone (2002) reviewed the new product development literature to analyze technological innovation typology and innovativeness terminology. They found the majority of studies (20 out of

[6] Instead, Sood and Tellis (2005) classify types of technological change based on the intrinsic characteristics of the technology. They identify and define three types of technological change: platform innovations, component innovations, and design innovations. A platform innovation is the emergence of a new technology based on scientific principles distinctly different from those of existing technologies, while a component innovation is one that uses new parts/materials within the same technological platform. A design innovation is a reconfiguration of the linkages and layout of the components within the same technological platform.

29) have used a dichotomous categorization (e.g., radical/incremental, radical/routine, really new/incremental, discontinuous/continuous). Triadic categorizations (e.g., low/medium/high innovativeness) were used in two of the 29 studies, and tetra-categorizations (e.g., architectural/niche/regular/revolutionary) were used in five of the 29.

Freeman (1992) proposed a taxonomy for technological innovation involving four levels of change: incremental innovation, radical innovation, changes of technical systems, and changes of techno-economic paradigms. Radical innovations, according to Freeman, were discontinuous events, where the discontinuity occurs in the production system. In contrast, he described incremental innovation as the type of innovation that occurs continually in industries, often stimulated by the need to lower costs or improve quality, design, performance and adaptability. Changes of technical systems involve far-reaching changes in technology and affect different parts of the economy, ultimately leading to entirely new sectors. These can involve clusters of radical innovation. Examples of technical systems include railways, semiconductors , synthetic materials and petrochemicals. Freeman compared changes of techno-economic paradigms to Schumpeter's "creative gales of destruction." These new technological systems have pervasive effects on the economy as a whole, changing production and management systems. Examples include electric power and steam power. Changes in techno-economic systems involve clusters of both radical and incremental innovations.

In addition to the different ways of defining innovation, *who* is doing the classifying is also a key consideration when considering classification systems--perspective is important. Abernathy and Clark (1985: 4) made this point, stating:

> *The first step in developing a categorization of innovation is to get straight the question of perspective. Technological innovation may influence a variety of economic actors in a variety of ways, and it is this variety that gives rise to differing views of the significance of changes in technology. What may be a startling breakthrough to the engineer may be completely unremarkable as far as the user of the product is concerned.*

Innovations have been commonly categorized in the literature by researchers (most often, social scientists), using an economic perspective, and by considering the competitive implications of a given innovation for large or incumbent firms in an industry.

Perspective will be influenced not only by *who* is classifying the innovation, but also by *when* the classification occurs. Some technologies perceived as radical in retrospect—for example, the automobile—often appear less "radical" when they are first introduced because they borrow or leverage certain characteristics of the prevailing technological system (Kemp 1997). For example, Kemp (1997: 285) drew upon the early automobile to illustrate this point:

> *Photographs of the first automobiles clearly showed that the automobile originally was nothing else than a carriage powered by an engine instead of being drawn by a horse (the early express on a 'horseless-carriage' thus described the first automobiles rather well.) Only in a few respects did radically new products constitute a radical break with the past, which suggests that the term 'radical' is somewhat misleading. Radical innovations often combine the new with the old (or even combined older technologies) and often rightly so because this helped the product to service the initial harsh market selection and establish itself in the marketplace.*

4.1.4 Examples of radical innovations

While many of these various definitions are complementary, the lack of a stable definition with specific criteria for identifying exactly *what* constitutes a radical innovation, has led to a broad spectrum of technologies have been labeled "radical" (Table 3).

Table 3. Examples of radical innovations from the literature

Study	Terminology & Definition	Select Examples
Tushman & Anderson (1986)	**Technological discontinuity:** Offers sharp price-performance improvements over existing technologies.	jet engines; xerography; transistors; float glass method in making glass; thermal cracking of oil; Dundee kiln in cement making;
Henderson & Clark (1990)	**Radical innovation:** Based on a different set of engineering and scientific principles, can open up whole new markets and potential applications.	Transition from electric powered ceiling fans to central air conditioning
Rosenberg (1994)	**Major Innovation:** Provides framework for many subsequent innovations, each dependent upon or complementary to, the original one.	Electric power plant, transistor, computer
Helpman (1998)	**Radical innovation:** If it could have could not have evolved through incremental improvements in the technology that it challenges for some particular use.	Bronze, printing press, electricity; X-rays, radio astronomy, penicillin
Chandy & Tellis (2000)	**Radical product innovation:** Incorporates a substantially different core technology and provides substantially higher benefits relative to previous products	Quartz watch, fluorescent lamps, personal computer
Leifer, McDermott et a. (2000)	**Radical innovation:** Offer unprecedented performance features or familiar features that offer potential for significant improvements in performance or cost.	Computerized tomography (CT); magnetic resonance imaging (MRI), personal computer, cell phones
Dahlin and Behrens (2005)	**Radical invention:** Criteria for determining a radical invention include: (1) novel; (2) unique; (3) has an impact on future technology	Oversized tennis racquet, wide-body tennis racquet

No studies were found where environmental control technologies, or more specifically, environmental control technologies for fossil-energy systems, were characterized as "radical." Electricity however, in addition to being selected by the National Academy of Engineering as the top engineering achievement of the 20th century (NAE 2003), was not surprisingly characterized in several studies as an example of a radical innovation.

4.1.5 Toward better metrics

Researchers have acknowledged that current definitions and methods for identifying and measuring radical innovation are insufficient (e.g., Ehreberg 1995; Dahlin and Behrens 2005) and have made several attempts to develop better metrics. Green, Gavin et al. (1995) developed and validated a measure that captures four separate dimensions of radicalness (technological uncertainty, technical inexperience, business inexperience, and technology cost). In this work, they focused on measuring radicalness from the perspective of a firm. Innovations can be more radical on some dimensions, less radical on others. Furthermore, they treat radicalness as a continuous variable, allowing innovations to have varying degrees of radicalness. Along a similar line, Chandy and Tellis (2000) develop multiple dimensions of radicalness, each of which is measured using a 9-point scale. They define two-dimensions, based on if the product (1) uses substantially different core technology, and (2) provides substantial customer benefit relative to the prior product generation.

Through a different line of research, a number of studies have used patent measures to identify radical, highly novel, or valuable inventions (e.g., Ahuja and Lampert 2001; Shane 2001; Dahlin and Behrens 2005). Tratjenberg (1990) for example, found the economic value of a patent was positively correlated with the number of times a patent is cited, weighted by the number of possible citations. Similarly, Albert et al. (1991) established an empirical relationship between how many times a patent is cited by later patents, and it's impact. Backwards citations—i.e., the prior patents and other documents cited by the focal patent, have also been used to measure the radicalness of a particular invention. For example, Carpenter et al. (1981) used backward citations to scientific literature as a proxy for measuring novelty. Similarly, Ahuja and Lampert (2001: 533) assumed that if a patent has zero backwards citations the technology has "no discernable technological antecedents."

4.2 What are the major topic areas in this literature?

The next section reviews several of the main areas of research within the literature on radical innovation. The first part of this section reviews research that has been motivated by an interest in understanding the competitive implications different types of innovations have on firms and industries. The second part describes major conceptual models related to the incremental-radical dichotomy that have been used to describe technological progress.

This review has also sought to better understand what the research has to say regarding public R&D management for achieving radical innovation. To the best of our knowledge, this topic has not been directly addressed in the literature. However, a growing line of research has focused on better understanding management practices for radical innovation in large, established firms. These research findings are discussed in the last section.

4.2.1 Types of innovation & their competitive implications

As noted earlier, the origin of the radical-incremental dichotomy (also sometimes referred to as revolutionary-evolutionary) in the innovation literature is most commonly traced to the economist Joseph Schumpeter (Freeman 1992; Dahlin and Behrens 2005). Schumpeter (1939; 1942) viewed technological change as central to continual capitalist growth and placed particular emphasis on technological progress as constituting a series of major breaks with the past. He emphasized that "perennial gales of creative destruction" could undermine the position of large monopolies, sweeping away entire industries. As an example, he once stated: "Add as many mail-coaches as you please, you will never get a railroad by doing so" (Schumpeter 1935: 4).

Schumpeter's work placed far greater emphasis on the discontinuous nature of technological change than on smaller more gradual improvements and has been highly influential in shaping how economists and scholars have approached studying technological change (Rosenberg 1982).[7] In particular, researchers have tended to differentiate between different *types* of innovation with respect to the competitive implications they have for firms and industries.[8]

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[7] While Schumpeter strongly emphasized the discontinuous nature of technological change, other scholars such as Marx, A. P. Usher, and S. C. Gilfillan, have been more impressed with the continuity of technological change (Rosenberg 1982).[7] For example, Enos (1958) studied the five major technological changes in petroleum refining industry and found the subsequent improvements contributed more to technological progress than the original development. Freeman (1992) has stressed the value of both perspectives, suggesting that studies of incremental improvements should be complemented by studies that focus on more radical discontinuities.

[8] In particular, types of technologies often refer to the impact they have on the knowledge and competencies of established firms. Tushman and Anderson (1986), for example, classify major technological shifts as either competence-enhancing discontinuities or competence-destroying discontinuities. Competence-enhancing discontinuities build on the existing know-how within a product class. Competence-destroying discontinuities in contrast require new skills, abilities and knowledge to develop and produce the new product.

Since the 1970s, a persistent theme within the innovation literature has been the decline of large, incumbent firms when "radical" technologies are introduced into the market, pioneered by new entrants who then rise to dominate the market.[9] Cooper and Schendel (1976: 61) described what has become a classic story in the literature, of the established firm confronted by a radical innovation:

> *A typical sequence of events involving the traditional firm's responses to a technological threat begins with the origination of a technological innovation outside the industry, often pioneered by a new firm. Initially crude and expensive, it expands through successive sub-markets, with overall growth following an S-shaped curve. Sales of the old technology may continue to expand for a few years, but then usually decline, the new technology passing the old in sales within five to fourteen years of its introduction.*
>
> *The traditional firms fight back in two ways. The old technology is improved and major commitments are made to develop products utilizing the new technology. Although competitive positions are usually maintained in the old technology, the new field proves to be difficult. In addition to the major traditional competitors (who are also fighting for market share in the new field), a host of new competitors much be confronted. Despite substantial commitments, the traditional firm is usually not successful in building a long-run competitive position in the new technology. Unless other divisions or successful diversifications take up the slack, the firm may never again enjoy its former success.*

Henderson (1993) examined two theories for why large incumbent firms fail to create radical innovations: (1) lack of motivation (the economic perspective), and (2) lack of ability (the organizational perspective). Her analysis, using data from the semiconductor photolithography equipment industry, showed support for both theories. In other words, large firms are more likely to invest in incremental innovation than radical innovation, and large firms are also less successful that new entrants, in exploiting radical innovation. For new entrants on the other hand, often the only way to gain a foothold in a well-established market is by doing something totally different, which creates for these organizations an incentive to pioneer radically new technology (Hill and Rothaermel 2003). Furthermore, smaller firms can leverage their flexibility and nimbleness, making them more well suited to exploit radical innovation.

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[9] Despite the persistency of the theme of the incumbents curse throughout much of the innovation literature, some more recent empirical evidence seems to suggest it may be overstated (Danneels 2004, Chandy and Tellis 2000, Ahuja and Lambert 2001).

Chandy and Tellis (2000) empirically analyzed a large cross-section of radical innovations from the office product and consumer durables areas. Their research results showed over the last 150-years, small firms and new entrants introduced slightly more radical product innovations than large firms and incumbents. However, since World War II, large firms and incumbents have introduced a majority of radical product innovations. Chandy and Tellis (2000: 14) concluded "incumbents or large firms are not necessary doomed to obsoleteness by nimble outsiders." Danneels (2004), also more recently suggested the innovative inertia of incumbent firms might be overstated.

In the 1980s and 1990s, researchers expanded on the radical-incremental dichotomy. Tushman and Anderson (1986) classified major technological shifts as either *competence-enhancing* or *competence-destroying*, depending on if they either reinforced or destroyed an established firms' existing competencies, skills, and knowledge. Henderson and Clark (1990) introduced the idea of an *architectural innovation* in which core concepts remain unchanged but are linked together differently, in a new architecture (Figure 3). Radical innovations, according to this classification, are those where not only the concepts are linked together differently but the core concepts themselves are overturned.

		Core Concepts	
		Reinforced	Overturned
Linkages between Core Concepts and Components	Unchanged	**Incremental Innovation**	**Modular Innovation**
	Changed	**Architectural Innovation**	**Radical Innovation**

Figure 3. A framework for classifying innovations along two dimensions (based on a figure from Henderson and Clark 1990).

They illustrate this framework using the ceiling-mounted room fan as an example. Improvements would be those that improve blade design or the design of the motor would be considered incremental, while the introduction of a portable fan would be an architectural innovation, because it takes the same core concepts remain the same but they are linked together in a different way. The transition to central air conditioning, in contrast, would represent a radical innovation.

Architectural innovations can involve seemingly minor technological change but they can have disastrous consequences for established firms. While much of what the established firm knows is useful and needs to be applied to a product, some of what it knows can actually handicap the firm's ability to create an architectural innovation. Henderson and Clark suggested this is is a consequence of the way knowledge is organized and managed—i.e., a firm's communication channels, information filters, and problem-solving strategies—tend to reflect the design and linkages of a particular technology. Organizations are not naturally structured to learn about changes in architecture.

In the book *The Innovator's Dilemma,* Christensen (1997) focuses on *disruptive technologies* and *sustaining technologies* and their implications for established firms in an industry. A sustaining technology retains the industries rate of product performance improvement (e.g., total capacity and recording density in the disk drive industry), along a dimension of performance that mainstream customers have historically valued. These sustaining technologies can be radical or incremental. In contrast, disruptive technologies bring a very different value to the market. A disruptive technology will initially under-perform established technologies in a mainstream market, and will have features that only a fringe market segment will value, but because of increasing demand for these new features, a disruptive technology redefines the performance trajectories (e.g., in the case of the disk drive industry, shrinking the size of disks).

These disruptive technologies need not be radical in nature, in fact, Christensen (1997: 15) writes "generally disruptive innovations were technologically straightforward, consisting of off-the-shelf components put together in a product architecture that was often simpler than prior approaches." While disruptive is sometimes used interchangeably with "radical" in the literature, the distinction between disruptive and sustaining is quite distinct from the radical-incremental dichotomy. Christensen's theory of disruptive technologies focuses on the *value* a technology brings to the market and whether or not it is a dimension customers have traditionally valued.

4.2.2 Models of technological progress

A number of descriptive constructs have been developed that relay both the incremental and radical nature of technological change. *Cyclical models* of technological change describe how periods of gradual, cumulative innovation are disrupted by radical innovations (Abernathy and Utterback 1978; Tusham and Anderson 1986; Anderson and Tushman 1990; Utterback 1994). Tushman and Anderson (1986: 441) summarized this cyclical pattern:

> *Technological change is a bit-by-bit, cumulative process until it is punctuated by a major advance. Such discontinuities offer sharp price-performance improvements over existing technologies.*

Utterback (1994) profiled a number of industries including typewriters, electric lighting, plate glassmaking, ice and refrigeration, and photography where radical innovations have emerged, successfully invaded, and then eventually overwhelmed the established technology (Table 4).

Table 4. A series of technological discontinuities in five industries (based a table from Utterback 1994).

Industry	Technological Discontinuities
Typewriters	Manual to electric; to dedicated word processors; to personal computers
Ice and refrigeration	Harvested natural ice to mechanically made ice; to refrigeration; to asceptic packaging
Lighting	Oil lamps to gas; to incandescent lamps; to fluorescent lamps
Plate glassmaking	Crown glass to cast glass through many changes in process architecture; to float process glass
Imaging	Daguerreotype to tintype; to wet plate photography; to dry plate; to roll film; to electronic imaging; to digital electronic imaging

Often, the incumbent technologies often do not exit without a last fight. This phenomenon is sometimes referred to as the "sailing ship effect," following the observation that when steam-powered ships became competitive in the mid-19th century, the performance of sailing vessels improved significantly (Grubler, Nakicenovic et al. 1999).

Graphically, the lifecycle of a technology can also be depicted as an *S-shaped curve* (Figure 4). These curves are often used to visually depict the relative advantage of one or more competing technologies, along some performance dimension.[10]

[10] The S-curve has also been applied in technology forecasting to describe the general pattern of technology adoption and substitution (*e.g.,* Grubler et al. 1999).

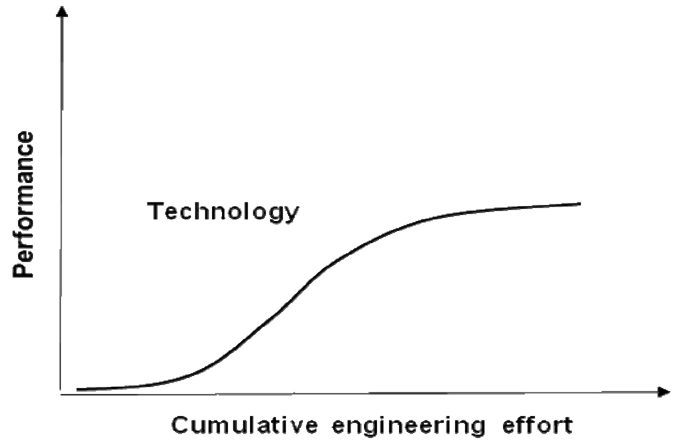

Figure 4: Plotting a particular dimension of a technology's performance against a measure of cumulative experience yields an S-shaped curve, extending from a technologies' early conceptual beginnings to maturity.

The notion of a *technological paradigm* introduced by Constant (1973) and Dosi (1982; 1988) is related to the concepts of technology cycles and S-curves. Technological paradigms are an extension of Thomas Kuhn's work on scientific paradigms, from the literature on the philosophy of science (Kuhn 1962). Technological paradigms have been used to explain the path-dependent pattern of technological progress. Constant (1973: 554) in his study of the turbojet, offered the following definition:

> *We define a technological paradigm as an accepted model of technical operation, the usual means of accomplishing a technical task. It is the conventional system as defined and accepted by a relevant community of technological practitioners. A technological paradigm is not just a device or process, but, like a scientific paradigm, is also rationale, practice, procedure, method, instrumentation, and a particular way of perceiving a set of technology.*

A radical innovation marks the emergence of a new technological paradigm. These major technological shifts might arise as a result of new scientific insights that can lead to new technological or economic opportunities; when a pressing technological need can't be met with current technologies; or when existing technological trajectories reach real (or perceived) technological limits (Kemp 1994).

Dosi (1988) referred to the technological progress along the economic and technical trade-offs curve defined by a paradigm as a *technological trajectory*. Well-known examples of technological trajectories in microelectronics are the exponential improvement in the number of transistors that can fit on one chip, computational speed, and cost per unit of information (Kemp 1994). In the energy domain, an example is the increase in the maximum capacity of steam turbine generators. Technological trajectories are similar to S-shaped curves in the sense that they can be used to track the evolution of a technology's performance over time. The beginning of a new trajectory marks a radical innovation, while the path of the trajectory represents a series of incremental innovations.

While concepts such as technology cycles, S-shaped curves, and technological paradigms are quite rich in theory, they unfortunately offer little guidance regarding how to actually identify a radical innovation (Dahlin & Behrens 2005).

4.2.3 Radical innovation in large established firms

The observation that incumbent firms often have a difficult time introducing more radical innovations has created a line of research aimed at improving the management practices associated with radical innovation in large established firms (e.g., Tushman and O'Reilly 1996; McDermott and O'Connor 2002). Likewise, Tushman and O'Reilly (1996) argued organizations must become ambidextrous: skilled at pursing both incremental and discontinuous innovation.

Researchers studying innovation processes in firms have acknowledged that management practices aimed at more incremental types of innovation can be detrimental to radical innovation, where the uncertainty, risk, and the potential payback are all much higher (Leifer, McDermott et al. 2000; McDermott and O'Connor 2002). One major research effort to understand the management practices in large established firms for radical innovation was launched in 1994 by the Radical Innovation Research Group from the Rensselaer Polytechnic Institute, with support from the Industrial Research Institute. This effort involved a longitudinal study of the management practices associated with twelve radical innovation projects in ten large established firms. One aspect of this study focused on the "people-side" of radical innovation. McDermott and O'Connor (2002) found it was important to have a "sponsor" (someone willing and in a high enough position within the firm to identify and promote these types of projects). They also found the individuals who operated most successfully on radical innovation project teams tend to have been with the firm for an extended period of time (>15 years), and had rotated through a number of positions.

McDermott and O'Connor (2002) also noted a tension between the need to incubate these projects and the need to integrate them with the rest of the organization's activities. Isolation can offer a certain degree of protection from the shorter-term objectives of the organization, but on the other hand, it can cut off project from an important source of learning, competencies and resources. Furthermore, too much detachment from the parent organization can make it difficult for the project to gain legitimacy in the organization. McDermott and O'Connor stressed the importance of managing this balance, although the appropriate balance is likely to be highly context specific (e.g., the characteristics of the project, organization, industry, and market).

In addition to these insights that focus on *managing* radical innovation projects, some research findings relate to how firms can *create* radical innovation. Increasing experimentation and learning from failure is a strategy organizations have used to increase the opportunity to create a radical innovation. Edmonson and Cannon (2005: 309), for example, focused on deliberate experimentation:

> *[Organizations] recognize failure as a necessary by-product of true experimentation, that is, experiments carried out for the express purpose of learning and innovating. By devoting some portion of their energy to trying new things to find out what might work and what will not, firms certainly run the risk of increasing the frequency of failure. But they also open up the possibility of generating novel solutions to problems and new ideas for products, services and innovation.*

Similarly, Fleming (2001) found experimenting with new combinations of old components can help organizations create technological breakthroughs, but also increases, on average, the number of "failures" or less useful innovations. Hence, this finding suggests that in order for an organization to successfully experiment, it will also need to maintain an organizational culture that accepts, and even welcomes, failures. Furthermore, a culture that promotes experimentation and embraces some risk, should not only exist in a formal research and development (R&D) laboratory, but should permeate throughout an organization, right down to the production line (e.g., see Leonard-Burton 1992, on Chaparral Steel's activity of continuous experimentation and its positive acceptance of risk). In order to overcome the barriers embedded in technical systems that tend to inhibit experimentation, organizations should ensure they have staff with expertise in experimental design to advise pilot projects and other experiments (Cannon and Edmonson 2005). Firms should also align incentives to promote the goal of experimentation in order to circumvent barriers embedded in social systems of an organization (Cannon and Edmonson 2005).

In addition to improving their capacity to manage and increase opportunities for creating radical innovation, large established companies must also improve their capacity to *exploit* radical innovation developed outside their organizations. One step that organizations can take to increase the likelihood that it will be able to respond to a technological discontinuity pioneered by a competitor is to continuously scan for unmet consumer needs and/or unexploited technological opportunities. An organization's ability to assimilate and exploit external knowledge was described by Cohen and Levinthal (1990) as an organizations "absorptive capacity," defined as "the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends." Thus, the ease with which an organization is able to assimilate new information depends upon the extent of its pre-existing knowledge structure. The diversity of knowledge within an organization is important because it provides a more robust base, and increases the likelihood that new information will relate to what is already known (Cohen and Levinthal 1990).

4.3 How are these terms applied to energy & environmental technologies?

The third and final set of questions guiding this literature review focuses specifically on understanding what research has been carried out on radical innovation in the energy and environmental domain. In particular, how have these terms been applied to energy and environmental technologies? Are there any examples of radical innovation in this domain that could be used to provide insights for a public sector R&D program?

4.3.1 Radical innovation in the electricity industry

Terms such as radical/incremental or revolutionary/evolutionary have not been commonly applied to describe technological change in the electricity industry. When they are used, technical progress in the electricity sector is generally characterized as incremental (Hirsch1989; MacKerron 1993; Tester et al. 2005). Researchers have tended to emphasize the stream of gradual, evolutionary innovations to boilers and steam turbines—e.g., enlarging the size of components, making them more efficient—that has created the supply of cheap and abundant electricity in the U.S. (Hirsch 1989; Victor 2002).

The evolutionary nature of the electricity industry is not surprising, given that innovation processes tend to be more incremental than radical in large technical systems, which exhibit strong path-dependencies (Markard and Truffer 2006). The electricity supply system can be characterized by its capital-intensive infrastructure, broad range of technical components and technologies, and variety of actors and institutions. Most system components are closely interrelated and are associated with various kinds of technical norms, organizational practices, and institutional procedures. As a result, radical innovation in the electricity industry faces considerable barriers. Radical change often requires clusters of complementary innovations, and tends to occur over long periods of time—i.e., on the order of 6-8 decades (Grubler, Nakicenovic et al. 1999). Technological change of this magnitude tends to occur quite slowly depending upon the relative advantage of the new technology, scale, infrastructure requirements, and technological interdependence.

Markard and Truffer (2006) developed case studies of nuclear, wind turbines, and gas turbines, as examples of radical innovation in the electricity sector. They identify four sets of factors that can lead to radical innovation in the electricity sector (Table 5). Markard and Truffer (2006) found the development of civilian nuclear power and wind turbines were driven by a combination of external stimuli (public debates regarding energy security and concern over pollution) and government action. In addition, the foundations for civilian nuclear power had been laid in the early twentieth century through scientific advances and the U.S. nuclear bomb-making program (Victor 2002). In the case of gas turbines, significant innovation impulses have been traced to the advances in gas turbine technology in the aircraft industry (Islas 1997; Markard and Truffer 2006).

Table 5. Five factors that can lead to radical innovation in the electricity industry

Factor	Example
Developments external to the system	Oil crisis; increasing environmental awareness
Developments internal to the system	System expansion that places greater importance on security of supply
Reverse salients	Power plants with high air pollution emissions; a large share of oil-fired power plants
Government policies	R&D programs; production incentives

Through these case studies, Markard and Truffer found the three radical innovations became established in the electricity industry through processes driven by a combination of internal and external developments, which caused frictions within the system and then motivated policy interventions designed to support new, promising technological options. Incumbent organizations, including the electric utilities, put up considerable resistance to this change. These incumbents used powerful associations to both lobby policy makers and coordinate innovation processes focused on incremental improvements to existing technical systems. Markard and

Truffer (2006: 623) concluded that as a result, radical innovations in the electricity industry depend upon "strong and enduring support by government policies in order to penetrate the sector."

Loiter and Norberg-Bohm (1999) also studied the role of government policy with regard to wind turbine development. In this work they distinguished between radical and incremental innovation, but provided no explanation as to how they drew this distinction. They found the majority of radical innovations in this specific technology area were adapted from another industry or application (e.g., soft-start electronics and variable speed constant frequency electronics were adapted from AC motor control technology). They identify a second group of radical innovations that were developed by public research programs in response to specific design problems. The development of special purpose airfoils, developed in the 1980s through a joint project between a private company and the federally-funded Solar Energy Research Institute, is one such example.

In another piece of work focused on wind power, Garud and Karnoe (2003) compared the successful development of Denmark's wind turbine industry with that of the U.S., where, despite significant technological and financial resources, a viable technological path was not created. They credit Denmark's success to its *bricolage* approach, which began with a relatively low-tech design that was improved over time as different actors sought modest yet steady outcomes. In contrast, they label the U.S. path as *breakthrough*, one that is more high-tech, and focused on generating dramatic outcomes. From this comparative study, Garud and Karnoe found the high-tech breakthrough approach may possess inherent disadvantages because it stifles the learning processes that allow emerging technological paths to be shaped by multiple actors. They conclude (p. 296): "...Actors in the U.S. may have failed, not despite, but *because* of their pursuit of a breakthrough."

Terminology such as "radical" or "breakthrough" has also been used in the energy domain to describe emerging technologies. For example, Grubler, Nakicenovic et al. (1999) have characterized mature, incremental, and radical technologies based on the difference in cost, market share, and stage of technological development. They labeled solar thermal, solar PV, and geothermal "radical" because these technologies have higher and more uncertain costs, a low market share, but with high potential for further cost and performance improvements. Using this framework, a radical technology 20 years ago might be a considered an incremental technology today—i.e., the way in which technologies are characterized can evolve over time.

Finally, another area of research that has studied radical innovation in the domain of sustainable energy technologies has focused on commercialization and deployment. Radical innovations are often initially launched in niche or submarkets, where they are able to offer a certain price/performance advantage over incumbent technologies. When these new technologies are sold on a commercial basis in niche markets, the experience gained can lower costs and allow the technology to become more competitive in more mainstream markets. Policymakers, particularly in European countries, have even attempted to replicate the conditions of these niche markets, a technique referred to as "Strategic Niche Management" (van der Laak 2007).

4.3.2 Radical innovation among environmental technologies

A sub-set of the literature on technological innovation has focused on how policy—and in particular, regulation—affects technological innovation among environmental technologies. These studies usually don't differentiate between different types of innovation. This might be at least in part, because environmental regulations often depend on the existence of technological solutions (Kemp 1997).

The work by Ashford, Ayers et al. (1985) was one of the only studies that differentiated between radical and incremental innovation in this domain, although they did not describe the method or criteria by which they did so. They found that the stringency of regulation is an important factor in the degree of innovation that occurs. They considered a regulation to be stringent either (1) because it requires significant reduction in exposure, (2) because compliance using existing technology is costly, or (3) because it requires a significant technological change. In this study the authors found that the environmental regulation had induced radical innovation in three of the ten cases considered. These three cases are shown in Table 6. Kemp (1997) later discussed this study and pointed out that it is difficult to tell whether or not a response is "radical."

Table 6. Examples of "radical innovation" in response to environmental regulation

Regulation	"Radical" Industry Response
Product ban of Polychlorinated Biphenyls (PCBs)	Development of substitutes for PCBs
Product ban of Chlorinated Fluorocarbons (CFCs)	Development of a new pumping system not dependent upon CFC
Occupational Lead Hazard	Development of direct smelting process to replace sinter machine and blast furnace

5. Conclusions

This literature review marks the first phase of a research project designed to better understand the nature and foundations of radical technological innovation—specifically, in the domain of environmental control technologies for fossil-energy systems—and from this, to draw lessons for the management of R&D in government programs such as the U.S. DOE's CO_2 capture R&D program.

There is growing interest in understanding radical innovation, as evidenced by the dramatic increase in publications on the topic, beginning in the early 1990s. As far back as the first half of the twentieth century, researchers have focused on understanding the competitive implications of different types of technologies, for firms or industries. Thus, the incremental vs. radical dichotomy has become a widely recognized distinction in the innovation literature. One of the most persistent themes in this literature has been the decline of large, incumbent firms when so-called radical technologies are introduced into the market, pioneered by new entrants who then rise to dominate the market. In turn, this observation has helped stimulate a more recent line of research aimed at understanding the management practices associated with radical innovation in large established firms. Within the innovation literature, descriptive concepts such as technology cycles, s-shaped curves, and technological paradigms have been developed to describe the innovation patterns that have occurred throughout different industries.

In the public realm, R&D managers and policymakers have focused on supporting "high-risk research" and developing "out-of-the-box, transformational" technologies (Council on Competitiveness 2004; NRC 2006; NSB 2004; NIH 2006; DOE 2008), and have proposed a range of new programs, funds and even agencies. While radical innovation has become a central topic in the literature on innovation, there has been little research directed towards understanding how a public R&D program could achieve the "radical" or "breakthrough" technologies often sought. However, the findings discussed throughout this paper do allow some preliminary observations that might be useful to R&D policymakers and planners. In particular, radical innovations tends to pioneered by smaller firms, or new entrants to a market, and are often characterized as very difficult, lengthy, and risky processes. Further, radical innovations in their earliest incarnations, are quite crude and usually require complementary innovations to reach fruition.

Radical or revolutionary change in large technical systems such as electricity supply is difficult to achieve, often requires clusters of complementary innovations, and tends to occur over long periods of time. This type of change is perhaps better categorized as what Freeman (1992) called "changes in technical systems." Markard and Truffer (2006) found that developing radical innovations in this sector depended upon "strong and enduring support by government policies in order to penetrate the [electricity] sector." In the case of the wind turbine industry, research has shown that radical innovation has tended to be either imported from other industries or developed by public research programs in response to specific design problems (Loiter and Norberg-Bohm 1999). In general, research has not addressed how to structure or manage public R&D activities to achieve "radical" innovation.

This literature review has also established that despite growing interest in the topic of radical innovation, studies still tend to define radical innovation (and related terms) differently, and sometimes not at all. While the general distinction between radical and incremental innovation has been commonly made in the literature, radical innovation remains a rather fuzzy concept "easier to intuit than define or measure" (Dewar and Dutton 1986: 1423). In general radical innovations are commonly defined using one or more of the following attributes:

- based on totally different science or engineering principles;
- represent a major price-performance improvement over existing technologies; and
- create a major disruption in the marketplace, rendering established firms' knowledge, technologies, and production techniques, obsolete.

The lack of a common definition has been problematic for the innovation research community because it tends to prevent comparisons between findings from different studies (Behrens and Dahlin 2005). The lack of a stable definition could also impede public R&D policymakers and managers seeking to achieve radically new technologies.[11] Moreover, the majority of research has examined radical innovation or breakthrough technologies in the context of their relationships to firms or industries, and the definitions and metrics for identifying radical innovation have been developed accordingly. Researchers have not discussed nor developed

[11] The NSF Advisory Committee for Government Performance and Results Act (AC/GPA) recognized in their latest report the absence of a formal definition can create confusion when trying to judge what research is or has the potential to be "transformative" (Rogers & Spencer 2007). As an example, NSF program officers were asked to identify among the performance highlights provided to the NSF AC/GPA for review, those they considered "transformative" and to write a brief explanation of why those were chosen. Without a common definition to work from, program officers designated 40% of the performance highlights as "transformative" and the Committee in their report noted a wide variability in the nature of what was denoted as "transformative" (Rogers & Spencer 2007: 9).

definitions or metrics specifically for managing public R&D activities that seek these types of changes.

Finally, research on radical innovation has not specifically looked at environmental control technologies for fossil-energy systems—for which there are no "natural" markets in the absence of governmental requirements. Rather, the focus has been on technologies sought in a free market economy. Only a relatively small sub-set of the literature has focused on energy and/or environmental technologies. In such studies, terminology such as "radical" or "revolutionary" is often not defined (e.g., Loiter and Norberg-Bohm 1999) and tends to be applied in different contexts when describing energy and environmental technologies. These findings imply one area for further research would be to more fully characterize what types of change are implied by terms such as "radical" and "revolutionary" when used to describe innovation among environmental control technologies in fossil-energy systems.

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