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# Technological capabilities and late shakeouts: industrial dynamics in the advanced gas turbine industry, 1987–2002

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This article focuses on technological discontinuities and late shakeouts in mature industries. The empirical case is combined cycle gas turbine technology in the power generation industry, where two of four main incumbents (GE, ABB, Siemens, and Westinghouse) exited the industry after several years of competition. We show that the vast differences in firm performance are strongly related to variation in technological capabilities, such as sourcing and integration of knowledge from related industries and after-launch problem solving. The findings from this case may also be of general interest for studies of dynamics in other mature, complex industries.

## 1. Introduction

Students of strategy and business history have suggested that many important industries as they mature become increasingly oligopolistic (Chandler, 1977, 1990; Lazonick, 1991). Such findings are paralleled in the industry life cycle literature, where initial phases of competition among many (small) firms are followed by “shakeouts” after which a few surviving firms compete mainly on cost and focus shifts from radical product innovation to incremental product changes and process development (Cooper and Schendel, 1976; Abernathy and Utterback, 1978; Tushman and Anderson, 1986; Klepper, 1996).

The main interest in this literature is to understand early phases in industrial evolution and the determinants of which firms that will survive into more “mature” phases. The *ex post* situation following shakeout has been much less researched. However, there are important cases where mature industries, after a period of incremental technical change and cost-based competition, enter a late phase of technological discontinuities and “late shakeouts.” According to Davies (1997), this new phase of technological competition is characterized by a rapid launch of new

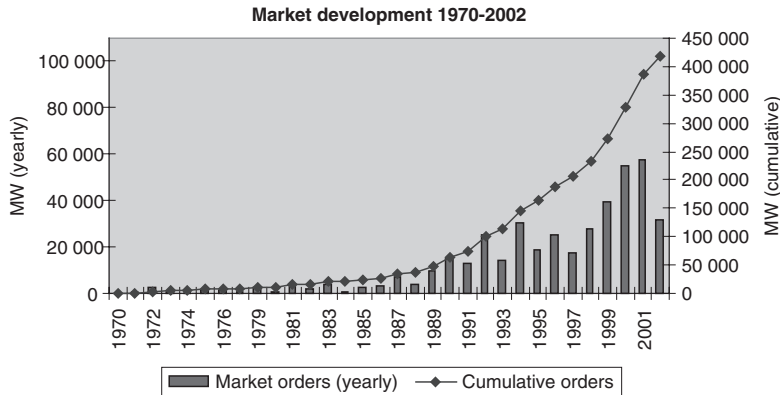
product generations and technologies by incumbent firms rather than new entrants. As noted by Klepper (1997), however, we know much less about these dynamics of mature industries.

On a more general level, it has been pointed out that in spite of similar contingencies there may be room for a variety of corporate strategies within such industries (Bonaccorsi *et al.*, 1996). Further, differences in firm capabilities are likely to play a decisive role for competitive outcomes (Dosi and Malerba, 1996; Jacobides and Winter, 2005). A key suggestion in this article is that late dynamics and shakeouts in mature industries to significant degree can be explained by differences in technological capabilities.

To investigate this hypothesis, the article presents a comparative study of four firms in a mature, important, old, complex, and technologically advanced capital goods industry: the power generation segment of the heavy electrical engineering industry. After a period of transformation and restructuring in the 1980s, this industry—previously characterized by national champions—consolidated around a few internationally operating corporations. In North America, General Electric was the industry leader, with Westinghouse as a distant second. In Europe, a cross-border merger between Swiss BBC and Swedish ASEA created ABB that aspired to be an electro-technical world leader and threatened the traditionally dominant position of Siemens (Belanger *et al.*, 1999; Tell, 2000). Other important firms in the heavy electro-technical industry, such as Anglo-French GEC Alsthom and Japanese Mitsubishi, licensed key generation technologies from the American leaders. It was generally assumed that after this sweeping restructuring and consolidation, competition between the survivors would enter a more stable and predictable period. Actual developments, however, turned out to be very different.

The electro-technical giants faced a dual challenge: severe price competition in newly deregulated and privatized markets combined with a sudden increase of technological change in a core business, power generation. Whereas investments in nuclear energy had virtually ceased and coal-fired boilers long ago had reached their limits of thermal efficiency and economy of scale, another technology suddenly took off: advanced gas turbines in combined cycle configurations (Figure 1). In a slowly growing total market for electricity generation equipment in the late 1980s and early 1990s, combined cycle gas turbine technology (CCGT) gained an increasing share of the annual installed capacity, from just over 10% in 1987 to over 35% in 1993. From the mid-1990s and onwards, the entire power generation field experienced a rapid expansion, where CCGT remained at around 30% of annual installed base until the turn of the century.

The leading electro-technical firms clearly recognized the importance of the new technology: all of the four incumbents invested heavily at the start of this market expansion. Their fortunes differed dramatically, though, and the previous round of heavy consolidation notwithstanding, there was a new industry shakeout and consolidation before demand leveled off. At the end of the 1990s, GE was winning



**Figure 1** CCGT market development 1970–2002 (total market orders in MW).

and Siemens came out as a strong number two, whereas both ABB and Westinghouse exited the industry by selling their power generation businesses (to Alstom and Siemens, respectively).

This article analyzes the competitive outcomes in mature, complex systems-oriented industries facing technological change. The empirical focus is on explaining the dramatically different outcome of the “CCGT-race” for the incumbents at the starting line. Why did only two (GE and Siemens) of the original quartet survive, and why these two? More specifically, the aim of this article is to analyze the role of technological capabilities in explaining “late shakeouts.”

In the next section, we discuss theories on industry life cycles and present an operationalization of the concept of technological capabilities, followed by a methodology section describing our data sources. In Section 4, we describe the dynamics of the CCGT industry, including product launches and competitive outcomes, with a focus on the period of 1987–2002. In Section 5, we describe the technological capabilities of four incumbent firms. Section 6 provides an analysis of these capabilities in relation to competitive outcomes. Finally, Section 7 discusses the findings and relates them to previous literature.

## 2. Shakeout in mature capital goods industries: successive discontinuities and technological capabilities

### 2.1 Industry life cycles and early stage shakeouts

In a Schumpeterian vein, it has been hypothesized in the industry life cycle literature that innovation creates discontinuous change, altering the conditions under which firms compete, changing relative positions among firms and causing entry as well as exit (cf. Abernathy and Utterback, 1978; Cooper and Smith, 1992; Utterback and

Suárez, 1993; Christensen, 1997), before the rate of change of market shares declines and the leadership pattern stabilizes, leaving the industry with an oligopolistic structure (Klepper, 1996, 2002).<sup>1</sup>

Particular attention has been given to the causes of so-called shakeouts, i.e., short time periods where a large number of the competing firms exit the industry, leaving a few remaining industrial leaders.<sup>2</sup> Shakeouts occurring in early phases of the industry life cycle have been quite well described, and several alternative explanations have been put forward: (i) the emergence of a dominant design (Abernathy and Utterback, 1978; Tushman and Anderson, 1986; Utterback and Suárez, 1993), (ii) successive “technology shocks” (Jovanovic and MacDonald, 1994) or “secondary discontinuities” (Olleros, 1986), and (iii) dynamic returns to R&D (favoring old and large firms) (Klepper 1996; Klepper and Simons, 2005). However, as noted by Klepper (1997) we know much less about the dynamics of mature industry life cycle stages:

“The PLC (product life cycle) does a good job of describing the stages of industry evolution through the formative eras of many industries. But after the number of firms stabilizes and firm market shares settle down, there appear to be fairly regular developments that are not captured by the PLC... [An] unpredicted facet of the mature phase is that many products appear to experience a sharp rise in innovation in this stage. This was reflected in the list of product and process innovations in autos and more generally in the patent counts by Gort and Klepper.” (Klepper, 1997, pp. 174–175)

In particular, we have noted the lack of studies describing mature industries characterized by continued technological dynamics, not only in terms of process innovation (as suggested by Abernathy and Utterback (1978)) but also of successive product discontinuities, and subjected to shakeouts in later phases, i.e., a long time after initial shakeouts have occurred. In this study, we will investigate such a mature sector: the electro-technical industry.

## *2.2 Late phase industry dynamics: complex product systems and successive technological discontinuities*

Traditionally, industries have been defined on the basis of their main product, i.e., an industry consists of firms producing close substitutes (Porter, 1980). However, firms

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<sup>1</sup>This pattern has been shown to hold for industries such as automotives, typewriters, tires, televisions, and penicillin (cf. Klepper, 1997; Klepper and Simons, 2005).

<sup>2</sup>Klepper (1997) provides the following definition of a shakeout: “[...] for a product to be deemed as experiencing a shakeout, the fall in the number of firms had to be pronounced (at least 30% from the peak) and sustained (not rising subsequently to 90% of the peak)” (p. 165). Not all industries experience such shakeouts in an early phase. Exceptions include diapers (Elzinga and Mills, 1996), petrochemicals (Arora, 1997), and turboprop aircraft engines (Bonaccorsi and Giuri, 2000).

in the electro-technical industry tend to be highly diversified. We have, therefore, opted to focus our analysis on one particular product within the broader electro-technical industry: advanced CCGT. This product is complex and not perfectly standardized. Previous research has indicated that the generic model of industry-technology evolution seems to be less useful in understanding the life cycle of such *complex product systems* (CoPS), in comparison to mass produced consumer goods (Davies, 1997; Hobday, 1998).<sup>3</sup>

CoPS may be characterized as products with high unit costs and degree of customization, several alternative architectures and deep systems (Hobday, 1998; Magnusson *et al.*, 2005). In CoPS industries, successive innovations play an important part in industry evolution: as the overall architecture—or dominant design—of a CoPS is settled, several new product generations occur *within* the architecture through the continuous introduction of changes in system components and subsystems (Teece, 1986; Davies, 1997). As noted by Hobday (1998): “In some cases, innovation proceeds long after the delivery of the product, as new features are added and systems are upgraded and modified” (p. 700).<sup>4</sup> Thus, in contrast to some generic models, the emergence of a dominant design or standard does not signal a decrease in the rate of technical development.<sup>5</sup>

As pointed out by Davies (1997), CoPS industries such as the electro-technical one normally exhibit a relatively stable firm structure, with few exits and entries, partly due to high entry barriers such as installed base, network externalities, and technological interdependencies. Competition in the mature stage of such industries is not necessarily characterized by cost-based fights over market shares until new entrants challenge, and eventually defeat, incumbent firms by introducing technological discontinuities. It may, instead be a matter of technological competition between industry incumbents, resulting in the success of some and the relative failure of others, and thus to a new industry consolidation based on technological capabilities. Here, the CoPS literature has emphasized that the development, manufacturing, and sales of CoPS require both breadth and depth in underlying knowledge bases (Prencipe, 2000; Wang and von Tunzelmann, 2000; Magnusson *et al.*, 2005). It has also highlighted the importance of system integration capabilities, i.e., the ability to integrate the product system and the subsystems and components it entails (Henderson and Clark, 1990; Prencipe *et al.*, 2003).

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<sup>3</sup>Other examples of CoPS include telecommunication exchanges, aircraft engines, high-speed trains, and flight simulators.

<sup>4</sup>This corresponds to the abovementioned observations of “secondary discontinuities” (Olleros, 1986), or “sub-discontinuities” (Ehrnberg, 1995) throughout the product life cycle (cf. also Cooper and Smith, 1992).

<sup>5</sup>Sustained rapid technological change after the emergence of a dominant design is not restricted to CoPS, but has also been a feature in industries such as cardiac pacemakers (Hedefjäll, 1997) and wind turbines (Bergek and Jacobsson, 2003).

Thus, similar to the analyses provided by Klepper and his colleagues, survival rates in industry evolution are here perceived as determined by the technological capabilities of firms. However, although Klepper's conclusion that old and large firms have better chances of survival than new and small entrants may be helpful in the study of early life cycle phases, it cannot help us to understand the outcome of competition between a small number of industry incumbents who are *all* old and large. The case of advanced gas turbines and CCGT, thus, provides an interesting opportunity to better understand the role of technological capabilities for competition in a mature cohort of a few well-established firms. Rather than studying "the making of an oligopoly" (Klepper and Simons, 2000), we examine "the industrial dynamics of an oligopoly," with particular focus on differences between industry incumbents in terms of their technological capabilities.

While the literature on dynamics in CoPS industries does provide an alternative view of industry evolution than traditionally envisaged in product life cycle models, it is complemented by this study in two main ways. First, hardly any CoPS studies systematically investigate competitive outcomes on industry level relating to the impact of secondary discontinuities. For instance, in his series of articles using in-depth studies of the aircraft jet engine industry, Andrea Prencipe has primarily focused on the evolution of the CoPS in itself (i.e., the aircraft engine) and the implications for firm capabilities, systems integration, and the boundaries of the firm (Prencipe, 1997, 2000; Brusoni *et al.*, 2001; Lazonick and Prencipe, 2005), rather than the continuous battle for market shares between the main competitors GE, Pratt & Whitney, and Rolls Royce. By incorporating time-series data on market shares and exit and relating this to the introduction of new product generations, this article seeks to remedy this shortcoming in the extant CoPS literature.

Second, with respect to system integration the CoPS literature has mainly focused the vertical organization of CoPS industries, distinguishing between vertically integrated firms, loosely coupled networks of suppliers orchestrated by a systems integrator, and market contracting (Brusoni *et al.*, 2001; Dosi *et al.*, 2003; Prencipe, 2003).<sup>6</sup> In contrast to this approach, we focus the underlying knowledge needed to develop CoPS—in this case the CCGT and the advanced gas turbine—and investigate how firms source and integrate this knowledge. This implies a broader perspective, since we neither predefine whether knowledge is sourced from external or internal sources, nor whether external knowledge sources are found within the vertical supply chain or in related industries.

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<sup>6</sup>In general, it has been argued that the more modular the underlying technology, the more scope for outsourcing, using "market for technologies" (Sanchez and Mahoney, 1996; Arora *et al.*, 2001). Brusoni *et al.* (2001) extend this argument by arguing that whether systems integration is decoupled (market exchange), loosely coupled (networks), or tightly coupled (vertical integration) depends on the predictability of product interdependencies and the rate of change in component technologies.

### 2.3 *Technological capabilities in large industrial enterprises*

#### 2.3.1 Organizational capabilities: strategic and operational aspects

Organizational capability has emerged as a concept to denote the ability of firms to do or make things, “to have a reliable capacity to bring that thing about as intended action” (Dosi *et al.*, 2000, p. 2; cf. also Helfat and Peteraf, 2003). The concept is a higher-order concept, in the sense that it does not primarily refer to the operative routines of a firm, but rather to the larger assemblage of productive knowledge accumulated in such routines (Nelson and Winter, 1982). Organizational capabilities are essentially a product of learning (Nelson, 1991; Eisenhardt and Martin, 2000) or even a “system of learning” themselves (Helfat and Raubitschek, 2000).

We perceive the capabilities of a firm as constituted both by strategies and operational activities. In a stylized way, the former are cognitive representations that are public and deliberate as top management tries to communicate its intentions to both internal and external stakeholders, whereas the latter are embedded in the day-to-day routines of the firm (cf. Fransman, 1994; Witt, 1998; Zollo and Winter, 2002; Gavetti, 2005; Winter, 2006). The emphasis of this article is on *technological* capabilities, which are a particular subset of organizational capabilities that distinguish firms operating in science-based industries from large manufacturing enterprises in general (cf. Tell, 2000).

#### 2.3.2 Technological capabilities: Technology strategy and technology activities

In line with the discussion on general organizational capabilities, we view technological capabilities as consisting of both strategy and activities. *Technology strategy* involves top-management intentions and de facto actions regarding what technological resources to develop and how these resources should be utilized in the market (Collins *et al.*, 1996). In periods of discontinuous technological change, an overall strategic problem is to make choices about which particular technologies to adopt and which development ventures to pursue (Porter, 1985; Nelson, 1991; Teece *et al.*, 1997; Helfat and Raubitschek, 2000). We will not elaborate on this decision in detail, since the focus in this article is the post adoption fate of four companies that did decide to enter the CCGT field.

However, the choice to participate in a new technology implies further strategic decisions concerning, e.g., the magnitude of commitments to the new technology, the timing of those commitments, the source of technology (internal versus external) and the degree of technological specialization and scope (cf. Cooper and Schendel, 1976; Maidique and Patch, 1982; Zahra *et al.*, 1999; Torrisi and Granstrand, 2004). We assume that differences in dimensions such as these have an influence on firm performance. In this study, we focus on four variables, derived from previous literature (Porter, 1983, 1985; Collins *et al.*, 1996):

- *Technology leadership*: whether companies aspire to have the most advanced technology and be first to market with new products and product generations.

In literature, it is often assumed that a technological leadership position in terms of product performance is advantageous in high-tech industries. The advantages and disadvantages of being first to market with new products have been more debated, however (cf. Ollerros, 1986; Lieberman and Montgomery, 1988, 1998).

- *Technology scope*: the degree of diversification in selecting target technologies (narrow or broad scope). Large firms may be described in terms of capabilities profiles, signifying varying levels of commitment in a range of technologies (Patel and Pavitt, 1997). Here, firms differ in terms of the number of technology fields that they are actively involved in, i.e., in the degree of technological diversification. According to the literature on technology diversification, diversification reduces dependency on outside actors and increases the flexibility of a company (cf. Patel and Pavitt, 1997; Granstrand, 1998), which supposedly increases its competitiveness and chances for long-term survival. On the other hand, the cost of technological diversification may be substantial (cf. Gambardella and Torrisi, 1998), in particular with respect to integration and coordination.
- *Technology sourcing*: how companies acquire strategic technologies—internal sourcing (in-house R&D within the corporate group) or external sourcing (through e.g., alliances, joint ventures, licenses, or acquisitions). The capabilities literature stresses the importance of possessing unique capabilities (cf. Cockburn *et al.*, 2000) and emphasizes the ability to integrate internal and external sources of technology (cf. Eisenhardt and Martin, 2000; Helfat and Raubitschek, 2000; Teece *et al.*, 1997), but does not clearly state whether internal or external sources are to be preferred.<sup>7</sup>
- *Cost leadership*: whether companies have the ambition to have (among) the lowest costs in the industry. This is not traditionally included in discussions on technology strategy. However, it has been recognized that a key capability of firms is the ability to take advantage of new technologies in a cost effective way (cf. Cockburn *et al.*, 2000); further there is usually a close correlation between a firm's overall competitive strategy and the direction of its technology development efforts (Porter, 1985). We may, thus, see this variable as an indicator of the extent to which a firm's technology strategy is aimed at creating cost advantages rather than product differentiation.

In this article, we focus on the “strategic intent” of managers with respect to these variables. In other words, we try to measure the “espoused” strategies. The implementation of these strategies is assumed to be captured by the concept of technological activities.

*Technological activities* refer to what kind of operations firms perform with regard to the exploration and exploitation of technology (cf. Granstrand and

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<sup>7</sup>Helfat and Raubitschek (2000) indicate, however, that coordination of tacit knowledge may require tightly coupled organizational mechanisms.

Sjölander, 1990; Tell, 2000). In particular, we are interested in search-oriented activities undertaken by the firm in order to obtain new technological knowledge. These include, but are not restricted to, the day-to-day activities of engineers in research labs as well as the activities by production engineers involved in making a new product ready for manufacture. Indeed, as shown by Kline and Rosenberg (1986), technological activities may take place in various parts of the company's value chain including the interfaces between the company and external actors (e.g., suppliers and customers).

In particular, the literature highlights the ability to develop and/or introduce new products and processes (cf. Teece *et al.*, 1997; Cockburn *et al.*, 2000; Eisenhardt and Martin, 2000). In addition, Helfat and Raubitschek (2000) emphasize the ability to learn from previous mistakes. We interpret this as an ability to identify and solve problems experienced by the firm and the users of its products. In line with this discussion, we operationalize the concept of technology activities in terms of three variables: R&D activity, product launching, and problem-solving activity.

### 3. Measurements and data

#### 3.1 Performance/outcome

The performance of the four companies in our study in the CCGT field was measured primarily in terms of market share.<sup>8</sup> We used a database containing orders for CCGT plants, including data on order year and total power capacity of each CCGT plant measured in MW. The database covers the period of 1970–2003, but for this study we primarily used data for the period of 1987–2002. All orders in the database have been confirmed as delivered and, thus, represent actual purchases of products. The database was compiled by staff at SPRU using a multitude of different sources, including annual reports, technical specifications, new product announcements, trade press, and interviews with key people in the industry (Appendix B). Interviews were conducted using a “snowballing approach,” which was to ask early contacts for further contacts until the same names kept being mentioned. As far as possible, both marketing and engineering people were interviewed.

#### 3.2 Espoused technology strategy

As described earlier, the strategy variables chosen were technology leadership, technology scope, technology sourcing, and cost leadership. To identify and “measure” these variables, we analyzed the corporate annual reports of the four

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<sup>8</sup>This is not optimal—a company may for example have a large market share but low profitability, or it may be focused on a narrow market niche, being extremely profitable. However, we found it very difficult to find comparative financial data on a segment level.

**Table 1** Variables, measurements, and key words

Strategic variable	Measurements	Examples of typical references
Technology leadership	Explicit references to the strategy References to the launch of “breakthrough” technologies, efficiency records, etc.	Technology leadership, pioneering technology, technology pacesetter, breakthrough/record-breaking technology
Broad technology scope	Explicit references to the strategy Number of technologies pursued. We formed 13 technology categories <sup>a</sup> based on an assessment of technological relatedness of the technologies mentioned in the annual reports and counted how many of these each company pursued each year	Broad scope, full range, full assortment
Technology sourcing	Explicit references to the strategy in annual reports Reports on alliances and other cooperative arrangements in trade press, etc.	Cooperation, alliance, partnership
Cost leadership	Explicit references to the strategy	Cost leadership, lowest cost, low-cost position

*Notes:* <sup>a</sup>(1) Gas turbines/CCGT; (2) steam turbines/“conventional” power plants; (3) combustion/combined heat and power/district heating; (4) advanced coal (IGCC, PFBC, etc.); (5) nuclear power; (6) hydro power; (7) distributed power (micro turbines, jet engines, etc.); (8) wind energy; (9) solar energy; (10) fuel cells; (11) control systems; (12) environmental technology; (13) other.

companies in the studied period (1987–2002).<sup>9</sup> For the technology sourcing variable, we also used other published material, such as reports about joint ventures and alliances in trade press journals. In line with the aim of the article, we focused on references to the business segment denoted power generation (or similar).

We compiled direct references to the four variables as well as other types of statements that were related to the variables (Table 1). Predefined search terms were

<sup>9</sup>ABB annual reports were available for 1988–1998. Westinghouse annual reports were available for 1989–1997.

not used. Instead, we generated conceptual categories related to the variables based on a close reading of text sections. Examples of typical references are given in Table 1. We not only relied on a grounded theory methodology (Strauss and Corbin, 1990; Dougherty, 2002), but added iterations between theory and empirical finding to qualify these variables. For example, when we searched the annual reports for statement concerning scope, we saw that hardly any references were made to narrow technology scope. We, therefore, decided to focus on statements referring to broad technology scope (or the absence of such statements).

The data were collected and coded in three steps. First, two researchers analyzed the annual reports using a one-researcher-to-one-company research strategy. Second, to check for consistency in the analytical approach, each researcher also analyzed a sample of reports from the companies analyzed by the other researcher and compared the results (cf. Whittington *et al.*, 1999). Third, two master students made an independent coding of the reports (Alstermark and Hegefjård, 2006), which was compared with the coding made by the two researchers. The intercoder reliability between these analyses varied between 50 and 94%, depending on the variable.<sup>10</sup>

One of the main benefits of annual reports as a data source is that they were written in the time period of interest. Previous research has shown that annual reports provide a fairly comparable set of data for a broad sample of corporations (Bettman and Weitz, 1983) and can be a rich source of information concerning company strategies (Bowman, 1978). On the other hand, annual reports contain a somewhat arbitrary mix of items that corporate management wants to highlight, e.g., business results and key orders received during the reported year; technological investments and product launches in selected areas; assessment of market trends for regions and/or technologies; and sometimes (but seldom) explicit strategies defining the positioning of the company. A comparison of companies for 1 year often yields a confusing picture, but when similar business areas are compared over an extended period, it is possible to see a systematic pattern emerging.

### 3.3 Technology activities

As described earlier, technology activities were operationalized into three main variables: R&D activity, product launching, and problem solving.

#### 3.3.1 R&D activity

R&D activity was measured through patent data. We used two patent databases: (i) Thomson Derwent's Derwent World Patent Index<sup>®</sup>, which contains 1.5 million patent documents added into the database each year from 40 patent-issuing

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<sup>10</sup>The main difference was related to the variable "cost leadership." For this variable, the master students took any mentioning of cost to imply a cost leadership strategy, whereas the researchers required explicit mentioning of the strategy. In this article, the latter coding has been used.

authorities,<sup>11</sup> and (ii) a database, compiled at Linköping University from information supplied by the web site of the US Patent and Trademark Office (USPTO). This contains all granted patents applied for by GE, ABB, Siemens, and Westinghouse and their subsidiaries in 1986–2000 in a selection of patent classes.

The general advantages and disadvantages of patent data have been discussed extensively elsewhere (Patel and Pavitt, 1991; Holmén and Jacobsson, 1997; Le Bas and Sierra, 2002; Hagedoorn and Cloudt, 2003). Here, we will focus on the particular characteristics and methodological problems of this study.

A first methodological problem concerns the well-known variation in the propensity to patent between (i) technological fields and (ii) different firms (Patel and Pavitt, 1991). Since this is an intra-sector study, the main question with regards to (i) is whether the propensity to patent in the CCGT industry is high enough for patents to be a good indicator of R&D activity. Although empirical studies of the propensity to patent in the CCGT industry is lacking, several studies have shown that the propensity to patent is high in the broader electrical equipment industry of which power generation and CCGT are part. For example, in a study by Scherer (1983) it had the highest propensity to patent of all industries in the sample, and Mansfield (1986) found that over 80% of the patentable inventions in this industry were indeed patented. When we consider that CCGT is a science-based industry, which generally tends to imply that patents are an important means of appropriation (Pavitt, 1984), it seems reasonable to assume that the propensity to patent in the CCGT field is as high as in the rest of the electrical equipment industry. We, therefore, conclude that patents are a relevant indicator of R&D activity in this industry.<sup>12</sup>

With regards to (ii), differences in the propensity to patent are usually assumed to be especially large between firms with different countries of origin. In particular, it may be argued that our use of US patent data may result in an over-estimation of the patenting activities of GE and Westinghouse in comparison with ABB and Siemens. This concerns primarily the use of the Linköping University database, since the Derwent World Patent Index<sup>®</sup> covers many different patent offices all over the world. However, in a previous study we concluded that there was no substantial US bias in our dataset.<sup>13</sup>

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<sup>11</sup>The patents obtained from this database were applied for in the period of 1973–2002. In the analysis, we primarily use patents applied for in the period of 1987–2002. For more information about Thomson Derwent's Derwent World Patent Index<sup>®</sup>, please visit <http://www.thomsonderwent.com/products/patentresearch/dwpi/>.

<sup>12</sup>Of course, some inventions may not be patentable. In the case of CCGT, control and safety systems may have some non-patentable features.

<sup>13</sup>In that study, we calculated the “GE-to-ABB ratio” of our dataset and compared it to ratios derived from searches on company names in the European Patent Office (EPO) database, Patent abstracts Japan and the USPTO 1988–1998. The ratio of our dataset was lower than the ratios of

A second problem concerns the identification of relevant patents/patent classes related to CCGT. Patent class titles are often difficult to interpret and, above all, are not clearly related to products. In addition, CCGT comprises many different technological areas, which makes it even more difficult to identify relevant patents. We have used five different search strategies in order to capture the four companies' patenting activity in the CCGT field:

1. First, we used the search term "combined cycle" in the Thomson Derwent database, in order to capture the architectural or systemic aspects of CCGT.<sup>14</sup> This search resulted in 92 patent records. A scrutiny of these patents showed that they concerned relevant technological fields.<sup>15</sup>
2. As a second step, we identified the main USPTO patent classes that the patents from the first search were assigned to and searched our own database for patents in these classes. We identified four important subclasses of USPTO class 60 (Power plants) (Appendix A) and found 118 patents in these classes.
3. For the third search, we used the Derwent manual code "gas turbine engine," which according to industry experts contained CCGT-relevant patents. This search resulted in 151 patent records.
4. Fourth, we identified the main USPTO patent classes related to the patents identified in step 3 (Appendix A) and made a search in our database for patents in these classes, resulting in 1938 patents.
5. Fifth, we searched our database for patents in a selection of classes that according to industry experts are related to gas turbines (Appendix A).<sup>16</sup> This search resulted in 1745 patents.

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USPTO and Patent abstracts Japan and, in fact, showed the closest correspondence to the EPO ratio, where we would expect an ABB bias (Bergek *et al.*, forthcoming).

<sup>14</sup>Since we assumed that there is not natural correspondence between the patent class structure and system integration aspects, we attempted to capture these aspects through a key word search.

<sup>15</sup>Some of the patents were related to other combined cycle technologies, such as IGCC and PFBC, but since these include some common components, e.g., gas turbines, we have nevertheless included them in our dataset.

<sup>16</sup>Industry specialists at ABB aided us in the identification of patent classes related to CCGT. We provided three specialists—the current patent manager of ABB Corporate Research, a gas turbine specialist and the former patent manager of one of ABB's subsidiaries—with descriptions of patent classes and patent data (including inventor names) and asked them to identify relevant patents and/or classes. Based primarily on inventor names, these experts were able to pinpoint patents and patent classes related to gas turbine technology and other CCGT-relevant technologies. We then selected those that matched the classes identified in the Thomson searches.

We then created three patent categories containing patents related to the same USPTO classes. When duplicate records had been removed, roughly 3700 patents remained.

### 3.3.2 Product launching

Product launching refers to the introduction of new product generations. We used a database containing all announcements of new products in the CCGT area, compiled by staff at SPRU using a number of different sources (see above). The data include date of announcement and main technical specifications concerning the new product, such as rated power and thermal efficiency. It should be noted that all new turbines launched by the four firms were received successfully in the market in the period studied, except for GE's 9H turbine, which had only received a few orders in 2002.

### 3.3.3 Problem solving

Problem solving refers to how companies handled failed products. It is difficult to measure since little public data are available. Available information include announcements—in annual reports and trade press—of problems, reports of costs associated with those problems, descriptions of problem-solving activities, and announcements of the final solution of problems. Interviews with industry representatives provided additional information. These “fragments” were used to illustrate differences in terms of openness about problems (whether it was announced publicly or not) and time between first problem and problem solved, but strict comparisons were not possible.

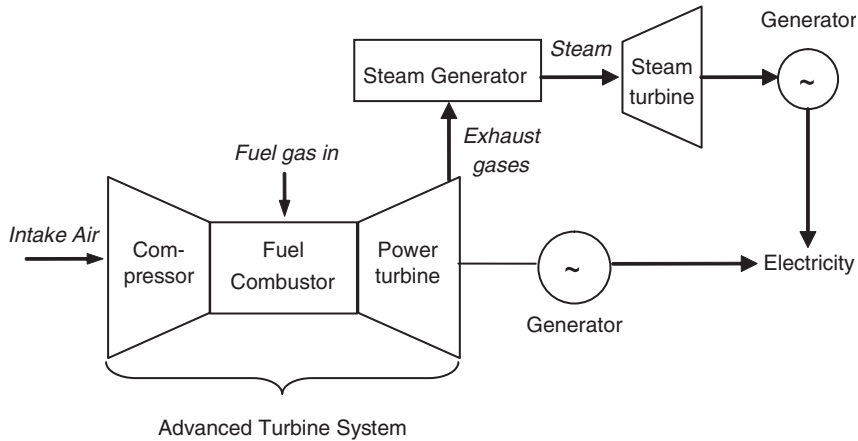
## 3.4 Limitations

We identify a number of limitations of the study:

1. Due primarily to space limitations, we have not included an analysis of different geographical markets. It should, however, be noted that no company had privileged access to certain geographical markets. All companies received orders from all main geographical markets, except for Westinghouse that only competed in the European market through its licensee Mitsubishi.<sup>17</sup>
2. Since, we only use patents as an indicator of technological activity, we have not estimated the relative economic value of different patents. In accordance with Le Bas and Sierra (2002), we consider an uneven economic value of patents to be an inevitable feature of technological activities characterized by uncertainty and learning, and expect similar variations in the distribution of value of patenting across firms and countries.

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<sup>17</sup>We have also searched the market order database for differences with regards to product-market segments, but have not found any relevant basis for segmentation.



**Figure 2** Schematic model of a single-shaft CCGT system. Source: Curtis, 2003.

3. This study has been conducted on the segment and product level, since we believe this is where most competition takes place. There is also a shortage of studies on these levels in the literature. Inevitably, there is a risk that such a study fails to capture corporate effects on segment capabilities and performance. For instance, we have not systematically studied effects of corporate strategy (Bowman and Helfat, 2001), corporate financing (O’Sullivan, 2006), or cross-segment financial flows on the performance of ABB, GE, Siemens, and Westinghouse in CCGT.

#### 4. Industry dynamics in CCGT: a high-odds technological race

The story of CCGT has a long prehistory, dating back to the technological discontinuity occurring when advanced gas turbines and CCGT were introduced in the 1940s and late 1960s, respectively.<sup>18</sup>

##### 4.1 A brief introduction to CCGT

CCGT effectively combines two established building blocks—the gas turbine and the steam turbine—resulting in electrical efficiencies that are almost 50% higher than those of other fossil fuel power stations. Technically, the system can be described as in Figure 2. The combined cycle gas turbine operates through a continuous combustion process, where compressed air and fuel are injected into the gas turbine’s combustion chambers and the hot combustion gases are expanded through a turbine. This creates a rotation movement that drives an electrical generator. The exhaust gases are fed into a heat recovery steam generator. This in turn produces steam that drives a steam turbine, resulting in additional power. In most cases, about 2/3 of the

<sup>18</sup>For an elaborated account of the early history of CCGT, see Watson (1997).

capacity stems from the gas turbine and about 1/3 of the capacity originates from the steam turbine.

From a CoPS perspective, we may distinguish between three hierarchy levels in the product system: the CCGT system as a whole, subsystems (primary ones as e.g., the gas turbine and the steam turbine as well as secondary ones as e.g., the heat recovery boiler and the generators) and components of the subsystems. The gas and steam turbine subsystems are CoPS too, which consist of a number of components. Gas turbine components include compressors, turbine blades and vanes, cooling technology, and combustors.

In terms of industrial organization, CCGT firms are in general very similar. They specialize mainly in overall systems integration, including system specifications and control systems. Gas turbines and steam turbines are usually produced in-house, whereas many other subsystems and components are purchased from suppliers (with the main exception being generators). For example, most CCGT firms provide specifications of the heat recovery boiler, but leave the production to companies such as Deutsche Babcock, Lentjes, Steinmuller, or Vogt (Watson, 1997).<sup>19</sup>

In this article, our primary focus is the “heart” of the CCGT—the advanced gas turbine subsystem—which provides the main added value of the CCGT system. Developments in gas turbine design, capacity, and efficiency have contributed to the majority of advances in CCGT performance over the past 30 years. Whilst steam turbines and heat recovery boilers have also improved, such improvements have been modest by comparison. Even small improvements in gas turbine thermal efficiency imply great customer benefits: One single percentage point increase in efficiency can reduce operating costs by USD 20 million over the life cycle of a typical 400–500 MW CCGT plant (Curtis, 2003). Achieving such improvements may, thus, bring competitive advantage to a CCGT firm and it is, thus, perhaps not that surprising that all CCGT firms have chosen to keep the development and manufacturing of this subsystem in-house. However, they still source some critical turbine components from suppliers, for example turbine blades and vanes, which are made by casting companies such as Howmet and PCC Airfoils (Curtis, 2003).

#### *4.2 Prologue: the breakthrough of advanced gas turbines and CCGT*<sup>20</sup>

During the early history of CCGT in the 1970s and 1980s, products were offered in the market by several companies experimenting with the technology, including GE and Westinghouse in North America; Siemens, ASEA, Brown Boveri, GEC, and Alstom in Europe; and Toshiba, Mitsubishi, and Hitachi in Asia. In the course of

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<sup>19</sup>One of the reasons for this is early experience with heat recovery boiler manufacture. GE and Westinghouse in particular found that their early boiler designs were unreliable—and that boiler manufacture was a lower value activity than turbine design and production (Watson, 1997).

<sup>20</sup>This section is based on Watson (2004).

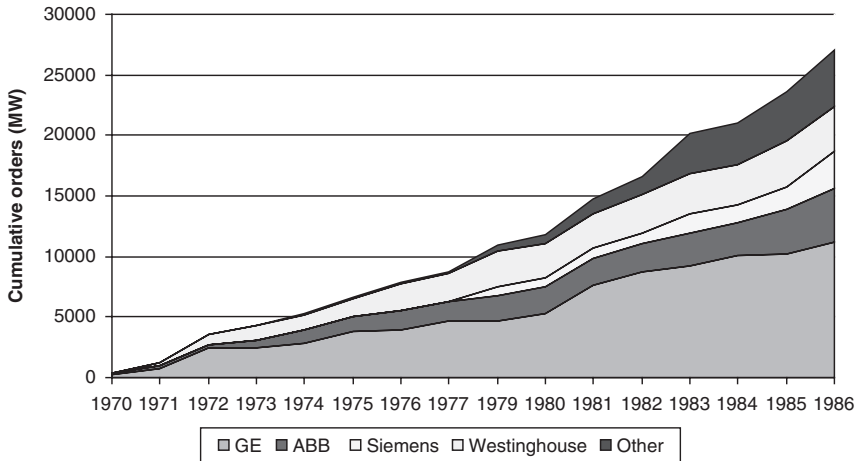


Figure 3 Cumulative CCGT orders 1970–1986.

events, however, few of these were able to accumulate any substantial order stock (Figure 3).

At the end of 1986, the total installed base amounted to  $\sim 25,000$  MW. Of this, over 90% corresponded to orders given to GE, ASEA, Brown Boveri, Siemens, Alsthom, Westinghouse, and Mitsubishi. While most of these suppliers had developed their own proprietary technology, Alsthom manufactured under license from GE and Mitsubishi did so with a license from Westinghouse.

With its cumulative market share of 41% GE both had a larger stock of installations and more experience of the CCGT technology than any other company, followed at some distance by ABB (16%), Westinghouse (14%), and Siemens (11%). The scene was set for the next period of CCGT development, which started with the introduction of the GE Frame 7F gas turbine in 1987.

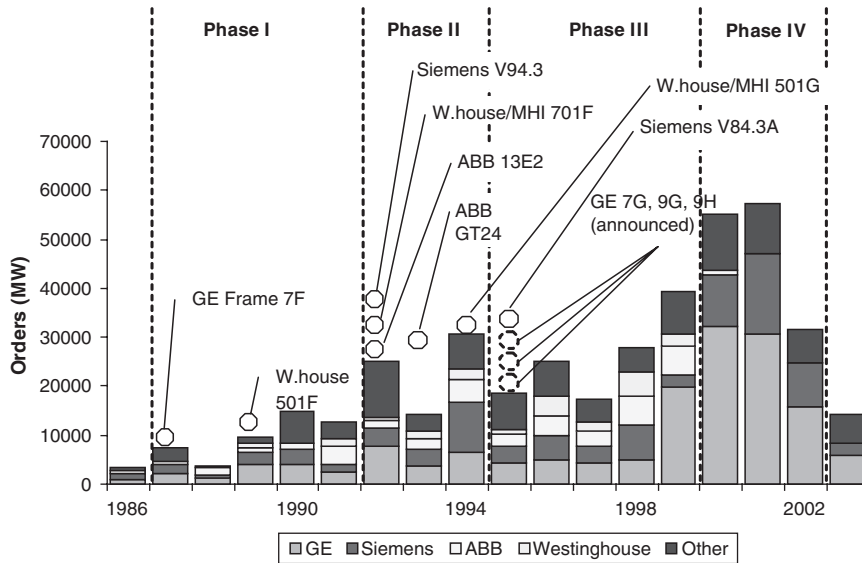
#### 4.3 Industry dynamics 1987–2002: an intense technology race

Figure 4 summarizes key data on product launches, market development, and market shares 1987–2002.<sup>21</sup> Based on varying characteristics in these dimensions, we have divided the period into four phases, which will be used for the more detailed description of technology evolution and industry dynamics.

##### 4.3.1 Phase I (1987–1991): the take-off phase

In 1987, a unique deal was concluded between General Electric and Virginia Electric Power for the utility's Chesterfield power plant, which included the first of a new

<sup>21</sup>Data for 1986 and 2003 are provided as well as background information.



**Figure 4** Market development, market share and product launches in CCGT in 1986–2003.

generation of high efficiency gas turbines. The new GE gas turbine known as the “Frame 7F” embodied technology, which enabled a significant advance in performance (Johnston, 1994). The 147 MW power output of the Frame 7F was almost double that of GE’s previous vintage of large gas turbine. In addition, the simple cycle thermal efficiency increased from 32% to over 34%. As the basis of a new CCGT plant, the Frame 7F could facilitate an unprecedented thermal efficiency of  $\sim 54\%$ —4 percentage points higher than its predecessor.

The large gas turbines offered by Westinghouse, ABB, and Siemens were much smaller (power outputs of 100 MW or less), and had combined cycle efficiencies that struggled to reach 50%. Thus, the GE Frame 7F gas turbine implied a substantial step in efficiency in comparison to the state-of-the-art technology of the time. This “secondary discontinuity” marked the beginning of a period of rapid market expansion, successive product launches, and intensified technological competition.

The market expansion was triggered both by the technical improvements in available CCGT-systems and by a general fall in oil and gas prices from 1986. As a consequence, the utilities’ previous reluctance to embrace CCGT technology disappeared and the potential of the CCGT was recognized both by large-scale Asian utilities such as the Tokyo Electric Power Company and the new breed of independent power companies in the UK and the USA, who were keen to use the CCGT as a way of entering newly liberalized electricity markets. In spite of GE’s technological advantage, the still rather small market was divided fairly evenly between the major competitors, with GE as the top company and Siemens, ABB,

**Table 2** Westinghouse, Siemens, and ABB react to GE's "Frame 7F"

Company	Turbine model	Capacities		Efficiencies (%)		Key dates	
		GT	CCGT	GT	CCGT	Announced	First order
GE	Frame 7F	150 MW	230 MW.	34.2	53	1987	1987
Westinghouse	501F	150MW	230 MW	35.4	54	1989	1989
Siemens	V94.3	200 MW	300 MW	35.7	54	1990	1992
ABB	GT13E2	164 MW	250 MW	35.7	54.7	1992	1992
	GT24	165 MW	250 MW	37.5	57.5	1993	1993

Source: Watson, 1997.

and Westinghouse (including its licensee Mitsubishi) sharing the second place (Table 4).<sup>22</sup>

#### 4.3.2 Phase II (1992–1994): the phase of technical competition

Faced with the challenge from GE, the other manufacturers had to improve their own designs (see Table 2 for details). Westinghouse responded already in 1989, with the launch of its own "F technology" gas turbine, the 501F, developed in collaboration with Mitsubishi.<sup>23</sup> The 501F design embodied performance characteristics very similar to those of GE's Frame 7F.<sup>24</sup> In 1991, Siemens unveiled its 200 MW V94.3 machine based on the results of a long-term development program that had started in the aftermath of the 1970s oil crises (Neidel, 1995). The new design embodied many advanced features such as supersonic blades in the compressor and cooling in three of the four turbine blade stages (Farmer, 1992) and its performance matched the turbines of GE and Westinghouse.

ABB that had been formed by the merger of ASEA and Brown Boveri in 1987 responded by launching the GT13E2 gas turbine in 1992. This was rapidly followed by an announcement of its next design GT24/26.<sup>25</sup> With a combined cycle efficiency

<sup>22</sup>It should be noted here that no company had privileged access to any market in the period studied (1987–2002).

<sup>23</sup>Mitsubishi had already taken over manufacture of large Westinghouse gas turbines in the mid-1980s (Watson, 1997) and had also developed its technological strength through Japanese government R&D programmes.

<sup>24</sup>A close examination of some of the new technology for the "501F," particularly the complexity of cooling passages on the first stage turbine blades, shows that this similarity extends to the way in which the advances were achieved (Scalzo *et al.*, 1989).

<sup>25</sup>GT26 is a 50 Hz version of GT24.

**Table 3** The GT24 heralds another new generation of gas turbines

Company	Turbine model	Capacities		Efficiencies (%)		Key Dates	
		GT	CCGT	GT	CCGT	Announced	First order
ABB	GT24	165 MW	250 MW	37.5	57.5	1993	1993
Westinghouse	501G	230MW	345MW	38.5	58	1994	1997
Siemens	V84.3A	170 MW	245 MW	38	58	1995	1995
GE	Frame 7G	240 MW	350 MW	39.5	58	1995	none
	Frame 7H	n/a	400 MW	n.a.	60	1995	2004
	Frame 9H	n/a	480 MW	n.a.	60	1995	1998

Source: Watson, 1997.

three percentage points higher than the state-of-the-art, this turbine leapfrogged the performance of the new turbines from GE, Westinghouse, and Siemens. It embodied two radical developments: “sequential combustion”, i.e., a two-stage combustion process in two separate chambers, and a compressor with an unusually high compression ratio of over 30:1.<sup>26</sup> Despite concerns about the wisdom of using such a large compressor, ABB soon won several major orders for its new turbine including a 2,000 MW CCGT in South Korea, a 720 MW CCGT in the UK, and a 360 MW CCGT in New Zealand.

As the 1990s progressed, mainstream utilities in many countries joined the early movers and embraced the CCGT as the technology of choice, and the market began to expand. The average orders per year doubled, from <10,000 MW in the previous period to over 23,000 MW in this period. GE (including its European licensee GEC-Alsthom) strengthened its market leader position; Siemens caught up somewhat; and ABB and Westinghouse competed for the position as number three in the industry (Table 4).

#### 4.3.3 Phase III (1995–1998): The phase of returning problems

ABB’s GT24/26 design received a quick response from the other competitors (Table 3). Westinghouse was the first company to announce its next generation—the 501G—which was developed with technology from a number of different sources (Watson, 1997). This time, Westinghouse not only collaborated with Mitsubishi, but also sought cooperation with the jet engine industry, and Rolls Royce assisted with the design of the first two rows of turbine blades. Further technological input came

<sup>26</sup>This technique, which had already been used by Brown Boveri during the 1950s, allows the unit thermal efficiency to be raised without increasing the turbine’s firing temperature.

from work conducted under a US Department of Energy Advanced Turbine Systems (ATS) R&D program.<sup>27</sup>

In contrast to ABB, the new V84.3A turbine from Siemens was based largely on its previous vintage, with increases in firing temperature and compressor airflow to improve performance. Some of the new technology, such as blade designs, high temperature materials, and cooling configurations, was contributed by Pratt & Whitney.<sup>28</sup> GE's next generation of gas turbines was announced in 1995. This was the Frame H, operating with an advanced closed-loop steam cooling technology, which was tailor-made for CCGT applications.

The intense battle for the highest efficiency following the introduction of GE's Frame 7F and culminating with the launch of GE's H technology (Tables 2 and 3) implied a great challenge for the companies. Efficiency improvements this size could not be achieved by incremental changes, but required access to state-of-the-art knowledge in several fields. For example, the key to the improvements in efficiency and power output for the 7F was a significant increase in firing temperature and compressor airflow, which required advanced materials and blade cooling techniques. But the intense competition in power output and efficiency came at a cost. In the mid-1990s, the problems of reliability, which had plagued the CCGT-technology before 1986 returned with a vengeance, and all major manufacturers had to devote significant efforts to "after-launch redevelopment" and problem solving.

In its annual report 1995, GE announced that a major challenge was the resolution of rotor issues on its F class gas turbine: "This was the highest priority and involved mobilizing GE and supplier resources to restore customers to service in the shortest possible time . . ." To rectify these problems, the rotors were taken out of the faulty turbines and flown back to GE's plants in the US. These problems affected the confidence in GE's products and its major competitors were able to catch up in terms of orders received.

However, in 1996 and 1997, respectively, the utilities operating on ABB and Siemens equipment also began experiencing major problems. ABB did not mention any technical problems in its annual reports and did not slow down its sales efforts. The materials problems caused by overheating in its turbines did not go away, however, and customers were not inclined to any lenience. Finally, ABB had to terminate further deliveries, compensate clients for losses and damages, and dedicate increasing resources to problem solving (Carlsson and Nachemsson-Ekwall, 2003).

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<sup>27</sup>The output of this work was most visible in the 501G's use of steam cooling in the "transition piece" between the combustors and the turbines.

<sup>28</sup>These techniques, which were first developed for aircraft engine blades in the 1970s, create a particularly "uniform" material structure that is able to withstand the increased stress associated with firing temperatures in excess of the F technology standard. Although these advanced blades do not constitute a new innovation, their use on large industrial gas turbines presents several challenges, including a substantial scaling-up (Neidel, 1995).

Siemens was more public in recognizing its problems, announcing in the 1997 annual report: “. . . with advanced technologies come added challenges that need to be addressed when meeting deadlines and ensuring a high level of quality.” This comment referred to substantial delays in the introduction of its new turbines. In the two following years, Siemens continued to report vibration problems associated with its new turbines, and the cost associated with rectifying these predicaments caused the entire power generation segment to lose money in 1999.

Westinghouse managed to keep its own reliability issues out of the press and did not mention them in its official statements or reports. This did not mean that Westinghouse had less trouble than other companies. The gas turbines delivered by Westinghouse suffered from significant reliability problems, particularly after further upgrades were implemented in the compressor systems. These difficulties, however, were dwarfed by the company’s tribulations in its nuclear power business, which were frequently discussed in its annual reports, such as tube degradation in steam generators for nuclear steam supply systems. As a result, the company incurred major litigation costs and had to report significant losses in its power systems segment for all years 1995–1997, from MUSD 200 to almost MUSD 500 in 1996.

GE solved its rotor issues fairly quickly and regained its leading technology position when demand (in particular in the US) took off in the late 1990s. In addition to the advantage of having a properly working F generation gas turbine, GE announced the Frame H generation gas turbines in 1995, tailor-made for CCGT applications. This new technology was partly a result of GE’s participation in the Department of Energy ATS program alongside Westinghouse. Some of the advantages accruing to steam cooling were higher efficiencies (Table 3) and lower NO<sub>x</sub> emissions (Curtis, 2003). Despite the improved performance promised by the H generation, GE did not manage to sell any plants for several years.<sup>29</sup>

As the problems started to appear, demand stagnated in spite of a rapidly expanding market for power generation equipment in general. GE and Siemens lost some market share, whereas ABB managed to keep up the appearance by not making its problems public (Table 4). As a result of sales of its 501F turbine Westinghouse came out strong in this period in terms of CCGT market share, but its Power Systems segment suffered huge losses.<sup>30</sup> When after-delivery problems hit the gas turbine and CCGT business, there were no resources to cope with the new challenges. After a new disappointing year, it was decided in 1997 to restructure the entire corporation and divest power generation.

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<sup>29</sup>The reason for this is a combination of utility caution following the F technology reliability problems, and the incremental improvements to this technology, which eroded the H technology’s advantages.

<sup>30</sup>Westinghouse also experienced a bumpy road on a corporate level during the entire 1990s, with several restructuring campaigns and sell-out of major divisions.

**Table 4** Market shares

Company	1987–1991	1992–1994	1995–1998	1999–2002
GE	28%	26%	22%	54%
GEC-Alstom/Alstom <sup>a</sup>	9%	14%	6%	15%
ABB	18%	12%	17%	
Siemens	19%	24%	21%	22%
Westinghouse	5%	7%	13%	
Mitsubishi <sup>b</sup>	13%	8%	12%	8%
Other	8%	9%	9%	1%

<sup>a</sup>GE licensee in the first three phases. In the fourth phase, Alstom acquired ABB's power generation business. (In 1989, the energy and transport businesses of Alstom merged with GEC, forming GEC-Alstom.)

<sup>b</sup>Westinghouse licensee in the first phases.

#### 4.3.4 Phase IV (1999–2002): market expansion and sealed fate of the incumbents

This phase was characterized by a surge in demand with CCGT orders moving from 27,000 MW in 1998 to a peak of over 57,000 MW in 2001. Much of this increase was due to large rise in orders from power companies in the US. With its own problems solved, and its European competitors still struggling, GE was in an excellent position. Having a reliable F generation turbine as well as a new advanced H generation on offer with a booming home market, GE regained the trust of the market. Increased sales and market share (Table 4) were almost a foregone conclusion. Although the H technology did not catch on, this was offset by the success of GE's existing technologies. For its competitors, this was the moment of truth.

In 1998, Westinghouse divested its Power Generation business to Siemens. After increasing difficulties in reigning in the problems with the GT 24/26 turbines, ABB too opted for a full-scale retreat. In 1999, its power generation segment was first merged into a joint venture with its counterpart division in Alstom (the new name for GEC-Alstom). A year later, ABB sold out to Alstom altogether. The French firm was to devote another 3 years to the turbine problems, which contributed to a serious financial crisis. In 2002—6 years after the problems started to appear—it finally announced that they had been solved.

The other European contender, Siemens, announced in its report for year 2000 that it “made solid progress in meeting technical challenges with its new gas turbine technology.” Only in 2001 these problems seem to have been convincingly solved, however. Through the acquisition of Westinghouse's power generation, the company inherited the 501F design and also gained access to the steam-cooling technology developed during the US government ATS program.

Table 4 gives an overview of market performance during this phase. GE dominated, with a total market share of over 50%. Siemens was able to remain a strong number two with just over 20% of the market. Westinghouse and ABB exited the field in 1998 and 1999/2000, respectively. Alstom, that acquired ABB's power generation segment, was left to struggle at a distant third place. With the exception of Mitsubishi, all other companies, including the new entrants during the gas turbine boom in the 1990s, virtually disappeared.

## 5. The technological capabilities of the incumbents

How could this dramatic difference in outcome be explained? An assumption of this article is that the chief suspect is differences between the companies in terms of technological capabilities. Since we view technological capabilities as constituted by two main dimensions—strategies and activities—the four incumbent firms will be described along these two dimensions.

### 5.1 *Technology strategies*

#### 5.1.1 Technology leadership, technology scope, and cost focus strategies

At the power generation segment level, GE seems to be the most focused company, emphasizing its “unwavering commitment to technological leadership” in a few selected areas, where gas turbines and CCGT consistently emerge as the most important: “This technology leadership is most evident in . . . the new ‘F’ gas turbine models . . .” (1988), “GE leadership in gas turbine technology was demonstrated by the successful operation of the first advanced ‘F’ gas turbine . . .” (1990), “. . . our Power Systems business had a fabulous year because of its global leadership in gas turbine technology . . .” (2001) (see Table 5 and Appendix C).

ABB, on the other hand, seems eager to present itself not only as a technology leader in power generation and CCGT (Table 5), but also as the most complete supplier (Table 6), having “the most complete range of products, systems and service available on the market” as demonstrated by the large number of power generation technologies mentioned each year. It also has a recurring corporate and segment level emphasis on being the “world low-cost producer in core businesses,” including power generation (Table 7).

The strategy of Siemens is positioned somewhere in-between GE and ABB. At a couple of occasions it claims to be “pacesetters in power generation” and refers to a “world record for efficiency” set by its gas turbine power plant, but in general Siemens is less focused than GE on technological leadership (Table 5). As for scope, Siemens mentions more power generation technologies than GE, but fewer than ABB (Table 6). Some references to a cost focus strategy are found on the corporate level (Table 7), but in power generation the company seems to be more of a follower than a leader in this respect: “We have responded to these cost pressures by launching extensive productivity enhancing programs . . .” The development and sales of gas

**Table 5** Espoused technology strategies: technology leadership

Technology leadership				
Year	GE	Siemens	ABB	Westinghouse
1987	X	–	Not available	Not available
1988	X	X	X	
1989	X	x	X	X
1990	X	x	–	–
1991	X	–	X	–
1992	X	–	X	X
1993	X	X	X	–
1994	X	X	X	X
1995	X	X	X	–
1996	X	X	X	–
1997	X	–	X	–
1998	X	X	X	Not available
1999	X	–	Not available	
2000	X	–		
2001	X	–		
2002	X	–		

X, segment level statements; x, corporate level statements.

turbines and combined cycle plants figure prominently in the reports of its power generation segment, an indicator of its importance in the segments' overall strategy.

Westinghouse's annual reports generally contain much fewer strategic statements than those of the other companies, which makes it somewhat difficult to form a clear picture of its strategy. Only on a couple of occasions it refers to a technology leadership strategy in power generation and CCGT (Table 5). In the years 1989–1992 there are several references to a broad scope. In 1989, for example, the annual report mentions coal-fired power plants, combustion turbines, solar power, steam turbines, nuclear fuel, and services as well as designs of new types of nuclear reactors. After 1992 the focus is narrower, maybe a result of continuing economic problems and strategic instability of the corporation (Table 6). Similar to Siemens, Westinghouse espouses the importance of increased cost efficiency rather than cost leadership on a segment level (Table 7).

### 5.1.2 Technology sourcing strategies

As mentioned earlier, technology-sourcing strategy here refers to whether companies source technological knowledge internally or externally. In the following, particular attention will be given to the companies' access to—and ability to absorb—key

**Table 6** Espoused technology strategies: broad technology scope

Broad technology scope								
Year	GE		Siemens		ABB		Westinghouse	
1987	–	(4)	X	(8)	Not available		Not available	
1988	–	(4)	X	(8)	X	(7)		
1989	–	(4)	–	(6)	X	(7)	–	(6)
1990	–	(4)	–	(7)	X	(7)	–	(6)
1991	–	(3)	X	(4)	X	(7)	X	(6)
1992	–	(3)	–	(6)	X	(8)	–	(5)
1993	–	(3)	X	(8)	–	(8)	X	(4)
1994	–	(4)	–	(6)	X	(8)	–	(4)
1995	–	(4)	–	(6)	X	(8)	–	(3)
1996	–	(5)	–	(5)	X	(8)	–	(4)
1997	X	(4)	–	(5)	X	(7)	–	(4)
1998	X	(4)	X	(7)	–	(9)	Not available	
1999	X	(2)	–	(6)	Not available			
2000	–	(5)	X	(5)				
2001	–	(3)	X	(5)				
2002	–	(4)	–	(3)				

*Note:* All statements refer to the power generation segment. Numbers refer to the number of technology categories mentioned of 13 in total (see Table 1 and Appendix C).

technologies from aircraft jet engines. The reason for this is that many of the new F technology innovations to improve efficiency and power output were based on temperature increases and, thus, built on better materials and blade cooling techniques. Due to high levels of government support for military and civil jet engine programs, the aircraft engine companies' competence in these areas were far in advance of their industrial counterparts in the 1990s (Watson, 1997).<sup>31</sup>

GE sourced most of its CCGT knowledge internally, both from within the Power Systems division and from other divisions, such as GE Aircraft Engines and GE Corporate Research and Development. GE was in a unique position due to its incorporation of both industrial gas turbine and jet engine divisions.<sup>32</sup> When GE introduced its new F technology industrial gas turbines during the late 1980s, it was

<sup>31</sup>Al Dolbec of the Electric Power Research Institute described this in terms of an “aero-engine technology supermarket” (Dolbec, 1995), possible to make use of in industrial machines.

<sup>32</sup>GE is one of the three major producers of jet aircraft engines in the world. (The other two are Pratt & Whitney and Rolls Royce.) (Curtis, 2003).

**Table 7** Espoused technology strategies: Cost focus

Cost focus				
Year	GE	Siemens	ABB	Westinghouse
1987	X	x	Not available	Not available
1988	–	–	X	
1989	–	–	X	–
1990	–	–	–	–
1991	–	–	X	X
1992	–	x	–	–
1993	x	X	–	–
1994	–	x	–	X
1995	X	–	X	–
1996	–	–	X	–
1997	–	x	X	–
1998	–	–	–	Not available
1999	–	–	Not available	
2000	–	–		
2001	–	–		
2002	–	–		

X, segment level statements; x, corporate level statements.

keen to stress the use of jet engine technology in many aspects of this new vintage—from compressor design to blade cooling techniques. Many technologies transferred to the GE Frame 7F can be traced back to the “high bypass” jet engine programs of the late 1960s (Makansi, 1995), including turbine blade cooling configurations and aero-engine design techniques for transonic compressor stages (Boardman *et al.*, 1993).

Westinghouse, GE’s US rival, had also had access to its own aircraft engine technology in the past. However, the company left this business already in 1960 and stopped hiring new aircraft engineers with skills in areas such as aerodynamics in the 1970s (Watson, 1997). By the 1990s, Westinghouse’s knowledge was insufficient to keep up with its competitors. A combination of this and general financial difficulties led the company to rely increasingly on its strategic partner, Mitsubishi Heavy Industries. Further external sourcing was secured for performance upgrades with the conclusion of a technology alliance with Rolls Royce in 1992, which provided knowledge in aircraft engine technology (Curtis, 2003).<sup>33</sup>

<sup>33</sup>Westinghouse also held an alliance agreement with Fiat Avio (Curtis, 2003).

Siemens' engineers had to make use of commercially available materials for critical components such as the turbine blades, since they did not have direct access to a jet engine company. In 1990, however, Siemens commenced a fruitful alliance with Pratt & Whitney, which "gave Siemens exclusive rights to Pratt & Whitney's technology in so far as it can be applied to heavy-duty land-based gas turbines" (Baxter, 1995). This alliance was a key reason for the performance improvements embodied in the V94.3A and V84.3A gas turbines introduced in 1994 and 1995. Siemens also relied extensively on other external sources of technology, such as university researchers, government laboratories and testing facilities, and the casting companies Howmet and PCC Airfoils. Finally, through the acquisition of Westinghouse, Siemens sourced further knowledge about large steam turbines and gas turbines (Curtis, 2003).

ABB sourced most of its key technology internally, which contributed to some idiosyncratic design features such as the sequential combustion process. In addition, the Swiss-Swedish firm tried external sourcing through various technology alliances. Its efforts in this regard were not as successful, though. Although it was first to negotiate an alliance—with Rolls Royce in 1988—this partnership was dissolved 4 years later due to a difference of opinion on the "way forward" (Mukherjee, 1995). As a result, ABB decided to follow a different technological path than its competitors for its GT24 and GT26 models. Nevertheless, it also made use of jet engine technology from Motoren-und Turbinen Union (MTU), a German jet engine company, and recruited a number of jet engine specialists from the former Soviet Union (Watson, 1997).<sup>34</sup>

In sum, GE's introduction of the F technology, thus, provided the catalyst for a series of deals between its competitors and the other two large aircraft engine suppliers (Rolls Royce and Pratt & Whitney). These are summarized in Table 8.

## 5.2 *Technological activities*

The second dimension of technological capabilities measured relates to the technological activities of firms. Our principal variables here are patenting in relevant areas, product launches, and reported problem-solving activities.

### 5.2.1 R&D activity in terms of patenting

As described earlier, we have used five different search strategies in order to capture the four companies' patenting activity in the CCGT field (see Section 2). The combined results of the searches are shown in Figure 5. Except for the two first years, GE clearly outperformed all the other three competitors in terms of sheer numbers

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<sup>34</sup>More recently, Alstom—the company that purchased ABB's industrial turbine business—has changed tracks. In 2002, it announced a new alliance with Rolls Royce to access advanced jet engine technology (Alstom, 2002).

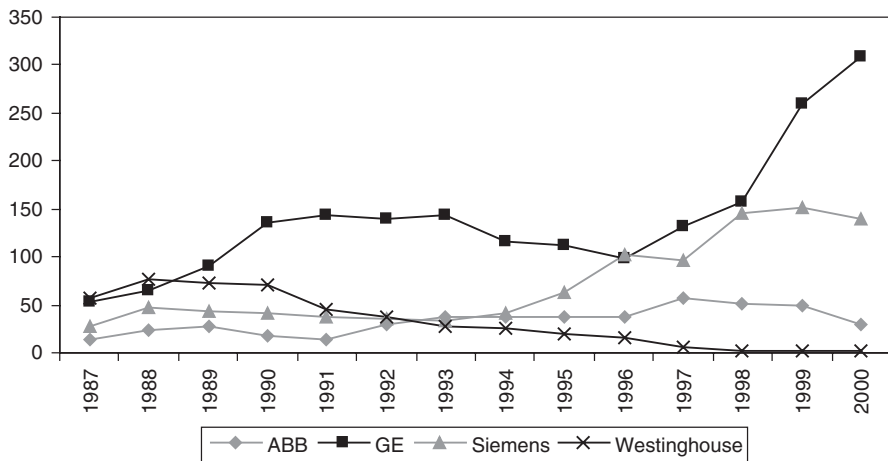
**Table 8** Technological Alliances between ABB, Siemens, Westinghouse, and Aircraft Engine companies

Companies	Year(s)	Scope
Westinghouse with Rolls Royce	1960s–72	Periodic design advice
ASEA with Pratt and Whitney	1972–76	Technology for a new 100 MW gas turbine
ABB with Rolls Royce	1988–92	Compressor and turbine blade technology
Siemens with Pratt & Whitney	1990–?	Compressor and turbine blade technology
Westinghouse/Siemens with Rolls Royce	1992–?	Two-way technology exchange
ABB with Saturn (Russia)	1993–1999?	To supply turbine parts and expertise
ABB with MTU	1993?–1999?	Periodic design advice

*Note:* MTU (Motoren und Turbinen Union) is a German jet engine supplier.

*Source:* ‘ASEA and United Aircraft Co-operate in the development of gas turbines and turbo-generators,’ *ASEA Journal*, 45 (4) (1972), 121; ‘New Gas Turbine Unveiled,’ *ASEA Journal*, 48 (1) (1975), 23; Baxter, A. ‘Partners See Growth Potential,’ *Financial Times*, Survey of Power Generation Equipment, 17th May 1994, p. 4; Interviews with employees of Siemens, ABB, Westinghouse, and Rolls Royce.

*Source:* Watson, 1997.



**Figure 5** Total number of patents, all searches combined (per application date).

throughout the period studied. The patenting activity of Westinghouse was higher than ABB and Siemens in the first period, but then decreased continuously. The patenting of Siemens and ABB was on approximately the same level in the first two phases, after which Siemens’s patenting increased more rapidly.

**Table 9** Number of patents in different areas (1987–2002) in total and indexed

	GE	Siemens	ABB	Westinghouse
Combined cycle <sup>a,b</sup>	78 (5.2)	35 (2.3)	43 (2.9)	15 (1.0)
Gas turbine engine (incl. measuring and testing) <sup>b,c</sup>	865 (3.9)	685 (3.0)	220 (1.0)	227 (1.0)
Gas turbines <sup>b</sup>	1031 (5.1)	293 (1.4)	204 (1.0)	217 (1.1)

*Note:* Numbers in brackets show the ratio of the number of patents of a particular firm in a certain category and the lowest number of patents of all firms in that category. For example, in the first category ABB's ratio (2.9) equals 43 (the number of patents of ABB) over 15 (the number of patents of Westinghouse, which has the lowest number of patents in that category of all the firms).

<sup>a</sup>Thomson keyword search, granted patents applied for 1987–2002.

<sup>b</sup>USPTO patent class search (see Appendix A), granted patents applied for 1987–2000.

<sup>c</sup>Thomson manual code search, granted patents applied for 1987–2002.

This overall level does not tell us much about the specific technological activities of the four companies. We, therefore, need to study the different technology areas represented by the different searches more in detail. The results are summarized in Table 9, in which the five searches described earlier have been condensed into three categories containing patents related to the same USPTO patent classes. The activities are presented for the entire period instead of for each phase, partly because there are too few patents in some searches to divide them, partly because it is problematic to assign patent applications to particular time periods due to the time lag between R&D activities and time of patent application.

The first category includes the two searches that were designed to capture the *architectural or systemic aspects* of CCGT, using the search term “combined cycle” in the Thomson Derwent database and the corresponding patent classes in the USPTO database. GE obviously has a much larger number of patents in total in this category than the other three companies. The difference between ABB and Siemens is not very large, although ABB comes out as slightly stronger than Siemens. Westinghouse has the lowest number of patents, almost half the number of ABB and Siemens and less than a fifth of GE's.

The second category includes the search in the Thomson/Derwent manual code “gas turbine engine” and the largest USPTO classes related to this code. When we studied these patents in more detail, we saw that they concern different aspects of measuring and testing. Again, GE is ahead of the other companies, having 1.3 times more patents in total than Siemens and almost four times as many patents as ABB and Westinghouse. Siemens outperform both ABB and Westinghouse quite clearly.

Finally, we searched our own database for patents in classes who according to industry experts are related to *gas turbines* (Bergek *et al.*, forthcoming), a key component of a CCGT plant. GE dominates in this category as well. ABB, Siemens, and Westinghouse are on a similar level, although there is a slight Siemens advantage (Table 9).

In summary, GE has many more patents than the other three firms, both in total and in the three subfields we have studied. However, Siemens' large activity in measuring and testing should be noted. Although sheer numbers of patents cannot be taken as a solid sign of capability, it is not a farfetched thought that GE's absolute dominance indicates superior technical competence in three areas of importance for CCGT. Moreover, GE's long history of patenting in the field of combined cycles indicates that they may have had the time to build up deep technological capabilities.

ABB and Westinghouse compete for the distant third and fourth places in all subcategories except in the combined cycle field. In this category, ABB is number two, but a large share of its patents in this category is related to pressurized fluidized bed combustion (PFBC), i.e., a related but quite different combined cycle technology. If we include patents applied for before our time period of study, Westinghouse has roughly the same number of patents in total as ABB and Siemens in this category. Indeed, here Westinghouse was the first to patent and the dominant patentee up until 1986. Any early mover advantages built up in this period seem to have been lost in the following years, though.

### 5.2.2 Product launching

The mere development and launching of new turbines does not seem to have been a discriminating factor for firm success. As described earlier, all firms managed to launch new turbines at about the same rate. After GE's initial launch of the Frame 7F, the three other companies followed quickly, and when ABB developed its GT24 turbine, its advantage was soon caught up by the others as well. Thus, this variable will not be discussed further in the remainder of the paper.

### 5.2.3 Problem solving

One salient feature of the evolution of total CCGT orders as they unfolded during the 1990s is the stagnation and loss in relative share of total power plant orders in the second half of the decade. Although several factors shaped these market dynamics, it is reasonable to assume that the problems encountered by all manufacturers in the F generation of turbines contributed to the loss of shares on a growing market. This pattern indicates that the ability to orchestrate complex problem-solving processes is a core technological activity in CoPS. Despite the scattered data obtained so far, it seems as if the four manufacturers reacted differently when facing technical problems and that the efficacy in dealing with these problems showed even higher degrees of divergence.

GE seems to have reacted in a very determined way when reports about turbine problems began to surface in the mid 1990s. Faulty turbines were rapidly decommissioned and brought to the US; problem-solving teams were put together with experts from relevant divisions. The company publicly announced its problems and the measures taken to rectify them, and within 2 years it had solved the issues with the rotors. GE was able to use its long experience in this technological domain, both in aero-engines as well as in stationary gas turbines.

Much in the same vein, Siemens publicly announced its problems with the new generation of turbines. However, the German company had much less rapid success than GE. For a several consecutive years, Siemens had to devote considerable resources to these technical problems. It was not until the beginning of the new millennium that the company could announce that they were on the right track again.

Reports on problem-solving efforts at ABB are more difficult to come across. Despite being aware of problems with the new GT24/26 design, the company continued selling its turbines and CCGT applications until it was no longer possible. In hindsight, it is clear that ABB was overambitious in its hurried introduction of this design, perhaps because it was the last to launch an F technology product. This, combined with a unique design, laid the ground for the problems that emerged. The company never managed to rectify the technical problems, but these were to be inherited by Alstom when they acquired ABB's Power Generation business towards the end of the 20th century.

Westinghouse's problems were even less public than ABB's. It is difficult to find published acknowledgement that problems were experienced with Westinghouse or Mitsubishi turbines. However, many in the gas turbine industry acknowledge that Westinghouse had its own reliability problems (Lukas, 2003; Smith, 2003).

## **6. Analysis: what were the main differences and can they explain (part of) the outcome?**

This article set out to analyze late industry dynamics in mature science-based industries, using the case of CCGT technology to explore the influence of technological capabilities on the outcome. Earlier, we described how GE, Westinghouse, ABB, and Siemens launched products with advanced technical performance in the 1980s and early 1990s. At the end of the 1990s, however, GE came out as number one in the industry and Siemens followed as a strong number two, whereas Westinghouse and ABB divested its power generation segment. Why did the fate of these big four come to be so different? Can differences in technological capabilities (Table 10) explain the outcome? To identify the main distinguishing factors, we will start by discussing GE in relation to the other companies. After that

**Table 10** Technological capability characteristics

	GE	Siemens	ABB	Westinghouse
Strategies				
Technology leadership	Segment and technology level	Segment level	Segment level	–
Technology scope	Narrow	Medium	Broad	Medium
Cost focus	–	Competitiveness (segment level)	Leadership	–
Technology sourcing	Internal (cross-divisional)	External (alliances and acquisition)	Internal (some external alliances)	External (alliances)
Activities				
Patenting	Strong	Medium	Weak	Weak
Product launching	Launched several turbines	Launched several turbines	Launched several turbines	Launched several turbines
Problem-solving	Quick concentrated efforts	Slow extensive efforts	Slow failed efforts	Slow unclear efforts; lack of resources

we will do the same for the remaining trio, with a focus on the difference between Siemens on the one hand and ABB and Westinghouse on the other.

### 6.1 What distinguishes GE from the other companies?

To begin with, GE was the one to introduce the F generation of gas turbines, which we distinguish as a “secondary discontinuity” (cf. Olleros, 1986; Davies, 1997) in comparison to the basic architectural innovation—the integration of gas and steam turbines—introduced by Brown Boveri decades earlier. The F generation was the key event initiating the new dynamics with a surge in demand and a stream of product launches. Being first allowed GE to take the lead and profit from the growing demand, but the other companies were quick to respond, and GE started to lose market shares. How did GE manage to turn the negative trend around and avoid becoming yet another example of the “burnout of pioneers” (Olleros, 1986) phenomenon? Can we find the answer in GE’s set of technological capabilities?

Looking at the capability dimension, GE has three distinguishing characteristics in comparison to the less successful companies. First, with regards to technological

scope, GE was much more focused on a few technological areas (of which CCGT was the most prominent) and had a clearer technology leadership strategy within this area than the other companies.

Second, the high patenting activity suggests that GE had a pool of knowledge in the chosen focus area, which was both deeper and broader than those of the other firms. In combination with its long experiences in design, manufacturing, operation, and service of CCGT plants this may be one of the explanations for GE's superior problem-solving abilities. ABB, Siemens, and Westinghouse had less total experience and were forced to launch new products very quickly, as they struggled to catch up with GE. It seems reasonable to assume that they had less time for extensive testing and interaction with selected "lead customers," and thus, were not able to learn and accumulate experience from experimentation to the same extent as GE.

Third, and in part as a result of the first two characteristics, GE's showed proof of true technology leadership when its customers started to experience turbine problems, and managed to solve these problems quickly through a concentrated effort. This problem-solving ability was key to regaining market trust and becoming well positioned before the market "exploded" in the late 1990s.

The differences with respect to technology sourcing are less clear-cut. GE and ABB primarily used internal technology sourcing, whereas Siemens and Westinghouse used external alliances. In contrast to GE, however, ABB neither had internal aircraft engine competence, nor the same competence in gas turbines and CCGT (as indicated by the lower patenting activity).

## 6.2 *What about Siemens, ABB, and Westinghouse?*

If the factors outlined earlier can explain GE's relative success, then what about the other three companies? They had been active in the industry since long before the discontinuous F generation gas turbine was introduced by GE and soon after that launched their own advanced gas turbines. They obviously had the willingness and ability to respond initially. We may note that Siemens was neither the fastest follower, nor the quickest to launch a new generation of turbines. Siemens could, thus, hardly benefit from any distinct "second-mover" advantages. In terms of market position, the three companies ran neck-to-neck at least until 1998 in a fast-growing market. Can we distinguish any capability-related factors pointing to Siemens' becoming the industry's number two?

In comparison to ABB, Siemens was technologically more focused, had less of a cost focus and made more effective use of external technology sourcing. Although ABB teamed up with a number of different companies, little seems to have been transferred from these alliances to ABB's development of CCGT, whereas Siemens was able to get full access to aircraft engine competence through its alliance with

Pratt & Whitney. Both ABB and Siemens aimed at technology leadership, but Siemens had a much more clear ambition to be the industry pacesetter in power generation than ABB. The differences between Siemens and ABB with regards to technological activities were smaller, but still significant in terms of total number of gas turbine-related patents, which indicates that Siemens had a stronger basis both for effective design and for “after-delivery development.”

The strategic differences between Siemens and Westinghouse in power generation are less accentuated. Both companies had similar scope and neither of them had an explicit cost focus. Both used external sourcing and had fruitful external alliances. Both companies were able to launch several successive products with similar performance. An important difference, however, was Westinghouse’s strong commitment to nuclear power.

Westinghouse’s patenting activity was much lower than Siemens, though, indicating less ability to design effective turbines, and much gas turbine competence pertaining to the original design was transferred to Westinghouse’s Japanese partner Mitsubishi. In addition, there are strong indications that corporate effects had a detrimental effect on Westinghouse (Annual Reports 1993–1997; cf. Bowman and Helfat (2001) and O’Sullivan (2006)). The company tried several times to cut off bleeding business segments from its highly diversified portfolio and suffered from continuous turmoil at the senior management level. The power generation segment exhibited a similar pattern of trying to narrow the technological scope, making the company even more dependent on its nuclear business, which in turn was fraught with liability claims and costs. With accumulating losses in its power systems segment from 1993 and onwards, and insufficient depth in CCGT-technology, the company lacked technological, financial, and managerial resources to meet the continuing challenges in this high-odds technology race, especially when substantial efforts had to be deployed to solve after-delivery problems.

## **7. Discussion and conclusions**

The purpose of this article was to analyze the role of technological capabilities for the competitive outcomes in mature, complex systems-oriented industries facing technological change.

We started by noting the dominant focus in much of the innovation literature on early shakeouts and the lack of research on the evolution of industries in their mature stages (cf. Klepper, 1997). Through our study of the CCGT case, we have shown that mature industries may indeed be characterized by substantial dynamics in terms of technological changes, market shares and survival/shake-out patterns: there was rapid introduction of radically better gas turbines; market leadership positions

changed several times between the incumbent firms; but no new entrants appeared on the scene. Thus, in line with the CoPS literature (Davies, 1997; Hobday, 1998), this study provides a contrast to the standard industry life cycle literature and demonstrates that mature industries neither have to be characterized by stable market share division among incumbents, nor do they have to be overtaken by new entrants taking advantage of the technological discontinuities (cf. also Granstrand and Sjölander, 1990). Most importantly, however, we saw how two out of four large and old companies were forced to exit one of their main business areas in a late shakeout.

In our analysis in the previous section, we made the case that the differences between the four incumbent firms in terms of performance and survival may be related to differences in their technological capabilities. We saw that two companies with superior technological capabilities (GE and Siemens), in comparison to the other two incumbents (ABB and Westinghouse), came out as number one and two in the CCGT “race.” We will here highlight the most important observations in relation to this.

First, this article demonstrates the importance of having a large and relevant capability base, built up by R&D activities, as a foundation for product development in complex technology fields. This corresponds well with the findings of previous research (cf. Prencipe, 2000; Wang and von Tunzelmann, 2000). In particular, however, our study emphasizes the importance of integrating knowledge from several different technology fields in order to develop new subsystems. Whereas all CCGT firms were able to source and integrate external knowledge related to some components and subsystems, e.g., alloys and coatings for turbines and blades, there was a divergence among firms in how they organized the sourcing and integration of critical capabilities related to the core of the CCGT plant—the advanced gas turbine—from the aircraft engine field.

This finding generates questions regarding the organization of systems integration in CoPS firms. In contrast to most previous research on this matter (Brusoni *et al.*, 2001; Dosi *et al.*, 2003; Prencipe, 2003), our study highlights the challenges involved in integrating knowledge from “parallel” industries rather than from other parts of the vertical supply chain. In this study, all firms were vertically integrated as far as the gas turbine was concerned, but the successful firms managed to source relevant complementary knowledge from another sector—the aero engine industry. This implies that the notion of integrative (Henderson and Cockburn, 1994), relational (Lorenzoni and Lipparini, 1999), or network (Prencipe, 2003) capabilities needs to be broadened to also include related and complementary industries.

Moreover, while it was true that GE had access to more relevant aero engine knowledge in-house than its competitors, we may note that the case of Siemens shows that not all capabilities need to be available in-house. Although we, thus, cannot say whether internal or external sourcing is better per se, we can make two

observations from this case: (i) Internal sourcing requires internal capabilities in relevant areas. This was true for GE, but when ABB tried internal sourcing it lacked the necessary depth in related fields in-house. (ii) External sourcing requires effective management of alliances on both strategic and operational levels. Siemens and Westinghouse seem to have been more effective in utilizing their alliances than ABB, but a more detailed answer with regards to why they were so requires further research. Indeed, the major discrepancies between these three firms in the way they succeeded in establishing, maintaining, and gaining from external sourcing imply that an important task for future research is to better understand how firms can maintain sufficient integration also in more loosely coupled constellations, such as technology alliances, when underlying knowledge is systemic and complex.

Second, a focused technology strategy on the segment level seems to be positively related to performance (cf. also Bergek *et al.*, forthcoming). In this study, the companies that focused on a limited number of technologies on the segment level were more successful than the ones that had a broad technology scope. In particular, it seems likely that ABB's broad scope diverted attention and resources from CCGT to other technologies, such as PFBC, which never became a commercial success (Watson, 2004). It is also noticeable that ABB, in contrast to GE and Siemens, did not express any explicit aim to be the first to introduce new product generations within power generation and/or CCGT. Broad scope was difficult to combine with a technological leadership strategy in this demanding segment.

The consequence of this observation is that technological depth is preferable to technological breadth. At a first glance, this may seem to contradict the literature on technological diversification (Granstrand *et al.*, 1997; Fai, 2003; Torrisi and Granstrand, 2004) and the literature on systems integration (Prencipe, 2000; Wang and von Tunzelmann, 2000). However, the diversification literature has most often studied diversification on a corporate level, which may still give an advantage. Indeed, diversification on a corporate level was important for GE, since it could source aircraft competence internally.<sup>35</sup> Moreover, the finding supports the general idea that systems integration firms have to economize on their cognitive efforts by

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<sup>35</sup>In addition, the technological diversification literature often makes a distinction between technological diversification and product diversification (cf. Granstrand and Sjölander, 1990; Gambardella and Torrisi, 1998; Garcia-Vega, 2000). Whereas there, as mentioned previously, is evidence that technological diversification is positively related to performance, the benefits of product diversification has been questioned (cf. Gambardella and Torrisi, 1998; Garcia-Vega, 2000). In CoPS, the distinction between technology and product is not always easy to make empirically, since even "generic" technologies (i.e., technologies used in several application areas), such as steam turbine technology, has to be adapted to each specific application.

finding an appropriate scope and division of labor in its technological activities (cf. Dosi *et al.*, 2003).

Third, the study shows that the development and launching of new products may not be as important as implicitly assumed in much of the capabilities literature (Teece *et al.*, 1997; Cockburn *et al.*, 2000; Eisenhardt and Martin, 2000). In this case, all companies were able to launch successive generations of turbines at about the same rate and with similar performance in terms of efficiency. However, all companies also suffered from periods of customer-experienced problems in their delivered machines (perhaps because of the forced launch rate), and had to devote considerable resources to problem-solving activities. Solving these after-delivery problems and safeguarding high operational reliability in these complex machines seem to have been the moment of truth. This implies that after-launch redevelopment may be more important than initial product development in cases with rapid introduction of new product generations.

Perhaps this is a consequence of the CoPS character of CCGT; the complexity, degree of customer adaptation, and sheer scale implies that full load tests cannot be made by the supplier before a new product is launched on the market (cf. Hobday, 1998). When there is both rapid technology and market development, products may already be widely spread by the time problems are noticed. To handle the resulting large-scale problem of redevelopment is a great challenge that all firms are not equally equipped to handle. In learning from previous mistakes (cf. Helfat and Raubitschek, 2000), the abovementioned aspects—a deep competence base in relevant fields, ability to source relevant knowledge, and a focused strategy—seem to be a decisive advantage. Indeed, GE's outstanding ability of after-launch redevelopment demonstrated true technology leadership and showed that the strategic statements in annual reports were not “all talk,” but consistent with actual operational capabilities.

To sum up, this article has explored (i) technological competition and discontinuities in mature industries, and (ii) the importance of technological capabilities in explaining the resulting “late shakeouts.” Mainly our study fills a void in the existing CoPS literature, where there is a lack of studies relating technological evolution with market outcomes and changes in industry structures. Our findings indicate that when applying traditional models of industry life cycles to CoPS industries, they need to be amended to incorporate the possibilities of successive discontinuities and changes in industry leadership based on the technological capabilities of incumbent firms.

Our conclusions regarding technological discontinuities, late shakeouts, and the importance of technological capabilities in the CCGT case may offer insights also for the study of the dynamics in “non-CoPS” industries. One case in point is the automotive industry. Here, in a once mature industry, the challenges of global climate change,

emissions regulation, and resource limitations have initiated a new wave of technological competition and innovative activity, as measured for example by patenting and product launches. As a result, there may be late shakeouts related to variations in technological capabilities also in this sector (Magnusson and Berggren, 2007). This raises further questions regarding the dominant industry life cycle models and underlines the need for further research on how to operationalize and measure technological capabilities. Through the development and application of a broader approach than in most previous studies, this article takes one step further in that direction.

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## Appendix A: CCGT patent classes (Linköping database)

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SEARCH	CLASS	DESCRIPTION/TITLE
COMBINED-CYCLE	60/39.182	<b>POWER PLANTS:</b> Combustion products used as motive fluid: . Multiple fluid-operated motors: .. Different fluids: ... Steam and combustion products:
	60/772	<b>POWER PLANTS:</b> Combustion products used as motive fluid: . Process
	60/783	<b>POWER PLANTS:</b> Combustion products used as motive fluid: . Process .. Combined with diverse nominal process:
GAS TURBINES	310	<b>ELECTRICAL GENERATOR OR MOTOR STRUCTURE</b>
	415	<b>ROTARY KINETIC FLUID MOTORS OR PUMPS</b>
	416	<b>FLUID REACTION SURFACES (I.E., IMPELLERS)</b>
MEASURING & TESTING	073	<b>MEASURING AND TESTING</b>
	324	<b>ELECTRICITY: MEASURING AND TESTING</b>
	374	<b>THERMAL MEASURING AND TESTING</b>

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## **Appendix B: Sources for market database**

The market order database has been compiled from a number of sources, including:

- Manufacturer reference lists, obtained from the companies
- Utility web sites
- Trade magazines: *Gas Turbine World*, *Modern Power Systems*, *Asian Electricity Power*, and *Turbomachinery International*
- World bank publications
- US Department of Energy (for US utility plants)

## Appendix C: Espoused technology strategies

Year	General electric	Siemens	ABB	Westinghouse
<b>Broad technology scope<sup>a</sup></b>				
1987	– Technology categories: 1, 2, 3, 5	“... begun to diversify the products and services within its principal areas of activity” Technology categories: 1, 2, 5, 6, 9, 11, 12, 13	Not available—ASEA and BBC had not yet merged.	Not available
1988	– Technology categories: 1, 2, 5, 12	“... constructing power plants of every kind.” “... re-enforcing our expertise as a major producer of power plants of every kind...” Technology categories: 1, 2, 5, 6, 9, 11, 12, 13	“ABB offers solutions for practically all power generation needs.” Technology categories: 1, 2, 3, 4, 5, 6, 12	
1989	– Technology categories: 1, 5, 11, 12	– Technology categories: 1, 2, 5, 6, 9, 12	“ABB can meet virtually every need of clean and highly efficient power generation for utilities and industry.” Technology categories: 1, 2, 3, 4, 5, 6, 11	– Technology categories: 1, 2, 3, 5, 9, 11
1990	– Technology categories: 1, 5, 11, 12	– Technology categories: 1, 2, 4, 5, 9, 12, 13	“... ABB’s complete line of power plant systems.” “Its technology base covers virtually every type of power generation equipment.” Technology categories: 1, 2, 3, 4, 5, 6, 11	– Technology categories: 1, 2, 5, 9, 11, 13

1991	– Technology categories: 1, 5, 12	“By offering a complete range of power generating technologies, we...” Technology categories: 1, 5, 10, 12	“The company has in place a full range of power generation systems...” Technology categories: 1, 2, 3, 4, 5, 6, 11	“Today, the Power Systems group offers products and services that span the full range of the global power generation market.” Technology categories: 1, 2, 5, 11, 13, 13
1992	– Technology categories: 1, 2, 5	– Technology categories: 1, 2, 5, 6, 9, 11	“... established ... as a leader in the full range of power generation systems.” Technology categories: 1, 2, 3, 4, 5, 6, 11, 12	– Technology categories: 2, 5, 11, 13, 13
1993	– Technology categories: 1, 2, 5	“Indeed, we are one of the few companies in the world that supplies virtually all products, systems and services needed to convert fossil fuels, nuclear energy and renewable energy sources into electricity” Technology categories: 1, 2, 3, 4, 5, 6, 9, 11	– Technology categories: 1, 2, 3, 4, 5, 6, 11, 12	One of four “strategies for growth” in Power Generation: “Expand the breadth ... of our power projects portfolio” Technology categories: 1, 2, 5, 11
1994	– Technology categories: 1, 2, 3, 5	– Technology categories: 1, 2, 5, 9, 10, 11	“The aim is to deliver a full range of equipment and service...” “... an example of this full range approach.” Technology categories: 1, 2, 3, 4, 5, 6, 11, 12	–
1995	– Technology categories: 1, 2, 3, 5	– Technology categories: 1, 2, 5, 10, 11, 13	“... the widest scope of expertise in the industry...” Technology categories: 1, 2, 3, 5, 6, 8, 11, 12	– Technologies: 1, 5, 11

(continued)

## Appendix C Continued

Year	General electric	Siemens	ABB	Westinghouse
1996	– Technology categories: 1, 2, 5, 11, 12	– Technology categories: 1, 2, 5, 11	“... the most complete range of products, systems and service available on the market.” “the industry’s broadest range of technology and products.” Technology categories: 1, 2, 3, 4, 5, 6, 11, 12	– Technology categories: 1, 2, 5, 11
1997	“... a portfolio of innovative services and products.” Technology categories: 1, 5, 11, 13	– Technology categories: 1, 2, 5, 6, 11	“A key to our approach is the ability to offer the broadest scope of power generation systems and equipment in the industry.” “Our uniquely broad scope of supply...” Technology categories: 1, 2, 3, 5, 6, 11, 12	– Technology categories: 1, 2, 5, 11
1998	“We continued expanding our portfolio of products, services and capabilities...” Technology categories: 1, 7, 11, 10	“Our broad range of products and services...” Technology categories: 1, 2, 5, 6, 8, 10, 11	– Technology categories: 1, 2, 3, 4, 5, 6, 7, 11, 12	Not available—Westinghouse’s fossil fuel power plant business was divested to Siemens in 1998.
1999	“GE Power Systems continued expanding its portfolio of product and service solutions for the energy industry...” Technology categories: 1, 7	– Technology categories: 1, 2, 5, 6, 11, 13	Not available—ABB’s power generation activities were transferred to ABB Alstom Power and later divested to Alstom.	

2000	– Technology categories: 1, 2, 6, 7, 11	“... cover the entire array of energy solutions” Technology categories: 1, 2, 5, 6, 11
2001	– Technology categories: 1, 11, 13	“... cover the entire array of energy solutions” Technology categories: 2, 5, 6, 10, 11
2002	– Technology categories: 1, 2, 7, 8	– Technology categories: 1, 2, 11

**Cost focus**

1987	“This drive – to be the high-quality, low-cost global competitor – is the heart of our leadership strategy...”	Corporate level: “In order to keep our prices competitive, we are continuing to work energetically on lowering our costs.”	Not available—ASEA and BBC had not yet merged.	Not available
1988	–	–	“...ABB’s strategic objective is to become a low-cost producer...”	–
1989	–	–	Corporate level: “... we want to be the low-cost producer and technology leader.”	–
1990	–	–	–	–
1991	–	–	“... focusing on programs to become the low cost producer...”	Corporate level: “... being a low-cost producer will require...”
1992	–	Corporate level: “We are accelerating operational processes and reducing costs throughout the Company.”	–	–

(continued)

Appendix C Continued

Year	General electric	Siemens	ABB	Westinghouse
1993	Corporate level: "... become the lowest-cost producer of high-quality goods and services in the world."	"KWU's competitive strength ultimately depends on further reducing costs." Corporate level: "... we are now pursuing a comprehensive strategy to reinforce our competitiveness... This entails slashing costs..."	–	–
1994	–	Corporate level: "Our overall corporate objective is to provide our customers with products and systems based on outstanding technology at the lowest possible prices..."		Two of five "strategies for growth": "Position for... lower-cost sourcing through increased globalization" and "Optimize cost efficiency and process effectiveness..."
1995	"... cost and technology leadership, along with superior quality and customer service, will be the keys to our success"	–	Corporate level: "... keep or attain the 'low-cost producer' positions."	–
1996	–	–	"... uniquely positioned to tap the growing demand for cost-effective... energy solutions"	–

1997	–		Corporate level: “Our goal is to offer customers the finest technologies . . . at the most competitive prices.”	“ . . . ABB has taken a major step towards achieving the most cost efficient global structure in the industry.”	
1998	–	–	–	–	Not available—Westinghouse’s fossil fuel power plant business was divested to Siemens in 1998.
1999	–	–	–	Not available—ABB’s power generation activities were transferred to ABB Alstom Power and later divested to Alstom.	
2000	–	–	–		
2001	–	–	–		
2002	–	–	–		
<b>Technology Leadership<sup>b</sup></b>					
1987	“To maintain technology leadership, GE placed on test its . . . 7F gas turbine . . .”	–		Not available—ASEA and BBC had not yet merged.	Not available
1988	“This technology leadership is most evident in . . . the new ‘F’ gas turbine models . . . which set new standards for efficient use . . .”	“This top technological position . . .”		“A second goal [for the Power Plant segment] is to maintain or strengthen ABB’s technological position . . .” Corporate level: “The Group is committed to continuing its policy of remaining at the forefront of technological developments . . .” “ . . . a global program . . . to be the technology leader in the electro-technical field.”	

(continued)

## Appendix C Continued

Year	General electric	Siemens	ABB	Westinghouse
1989	“GE’s technology leadership is gaining added importance . . .”	Corporate level: “. . . we make every effort to maintain our position as a technology pacesetter in all fields in which we operate.”	<p>“The objectives of ABB’s strategy in power generation are to further strengthen ABB’s technological leadership position . . .”</p> <p>“A recently delivered combined-cycle plant holds the world record with a thermal efficiency rate of 52%.”</p> <p>“This combined-cycle power station in Utrecht is the world’s most efficient fossil fuel plant”</p> <p>Corporate level: “. . . we want to be the low-cost producer and technology leader.”</p>	“Westinghouse power generation equipment set new records for availability . . .”
1990	<p>“GE leadership in gas turbine technology was demonstrated by the successful operation of the first advanced ‘F’ gas turbine . . .”</p> <p>“. . . technology leadership is key to sustain current market positions for all GE Industrial and Power Systems businesses . . .”</p> <p>“GE commitment to technology and market leadership. . .”</p>	Corporate level: “We aim to be . . . a pacesetter for the advancement of technology.”	–	–

1991	<p>“...an unwavering commitment to technological leadership. One example: GE’s advanced ‘F’ gas turbine design ... This world-leading technology [was enhanced by 1991’s introduction of the 9F—the worlds most powerful gas turbine...”</p>	–	<p>“ABB has been in the forefront of power plant engineering for more than a century...”</p> <p>Corporate level: “ABB’s technological leadership...”; “... commitment to develop and produce the most technologically advanced products...”</p>	–
1992	<p>”Clear technological leadership across our major product lines drove the 1992 orders success, with GE’s ‘F’ technology gas turbine designs breaking world records for in-service output and combined-cycle efficiency.”</p>	–	<p>“ABB’s state-of-the-art ... turbine designs...”</p> <p>Corporate level: “... ABB’s ambition to be a leader in its core technologies.”; “... the Group’s commitment to maintain its leadership in chosen core technologies.”</p>	<p>“Both the power generation and energy systems units are ... at the leading edge of the technologies, products and services offered industry-wide...”</p>
1993	<p>“Technology leadership continued to drive our orders success, with GE advanced gas turbines setting the pace again in 1993. The first 7FA model broke records for output and efficiency...”</p>	<p>“Siemens will continue to set industry standards in energy technology”</p>	<p>“ABB is setting a new standard in energy efficiency with its revolutionary GT24 and GT26 ... gas turbines.”</p> <p>“ABB demonstrated its ongoing commitment to technological innovation with the launch of a new generation of gas turbines that set a new industry standard for energy efficiency.”</p> <p>“ABB ... can deliver superior technology in the clean and reliable generation ... of electricity.”</p> <p>“... anticipating customer needs with the best technology.”</p>	–

(continued)

## Appendix C Continued

Year	General electric	Siemens	ABB	Westinghouse
1994	“... technological leadership in output, efficiency and environmental friendliness...”	<p>“Our combined-cycle power plants are setting world-class benchmarks...”</p> <p>“Our leading-edge technologies, products and services...”</p> <p>Corporate level: “Our overall corporate objective is to provide our customers with products and systems based on outstanding technology at the lowest possible prices...”; “... we will continue to act as a technological catalyst in establishing industry benchmarks”</p>	“... the world’s most efficient gas turbines in combined-cycle operation—ABB’s GT24 and GT26.”	<p>“Power Generation also established its world leadership position in combustion turbine technology with the introduction of the 501G combustion turbine, the largest and most efficient of its type in the world.”</p> <p>One of five “strategies for growth” in Power Generation: “Leverage global presence through technology and market leadership”</p>
1995	<p>“... our ‘H’ technology is the first commercial offering to break through the 60% energy-efficiency barrier.”</p> <p>“cost and technology leadership, along with superior quality and customer service, will be the keys to our success”</p>	<p>“... our latest generation of environmentally friendly gas-turbine power plants has set a world record for efficiency.”</p> <p>“We are pacesetters in power generation...”</p>	“... ABB’s breakthrough GT24/ GT26... gas turbine technology”	–

1996	“We continued to revitalize our technology leadership... to assure that GE products remain the world standard.”	“With our new gas turbine, we have been able to raise the efficiency of our combines-cycle... power plants to a record 58%.”	“Leading technology” (heading) “The GT24 has set a new industry standard for output, efficiency and emissions...”	–
1997	“... our ‘H’ gas turbine technology... has the potential to... lead the next generation of advanced combined cycle turbines.”	–	Corporate level: “Innovative technology and leadership” (heading); “... being first with innovative, cost-effective and total system solutions.”	–
1998	“... affirming GE’s continued leadership in gas turbine technology...”	“We intent to further reinforce and expand our position as the industry pace setter in power plant technology.”	“... with its leading technologies...” “... ABB’s Powerformer, a breakthrough in generator technology...” Corporate level: “With a strong commitment to technology leadership...”	Not available—Westinghouse’s fossil fuel power plant business was divested to Siemens in 1998.
1999	“‘H’ gas turbine technology, the world’s most advanced...”	–	Not available—ABB’s power generation activities were transferred to ABB Alstom Power and later divested to Alstom.	
2000	“... the ‘H’ turbine, the world’s highest-efficiency turbine generator.”	–		

(continued)

## Appendix C Continued

Year	General electric	Siemens	ABB	Westinghouse
2001	<p>“... our Power Systems business had a fabulous year because of its global leadership in gas turbine technology...”</p> <p>“The ‘H’ will be the power industry’s first combined-cycle system capable of achieving 60% efficiency.”</p> <p>Strong leadership in technology???</p>	–		
2002	<p>“... next generation H System, which ... will be the largest and most efficient power generating system ever.”</p> <p>“... Power Systems’ focus on long-term growth through technological leadership.”</p> <p>Corporate level: “Our strategy for growth is based on five key elements: Technical leadership... Technology is at the heart of the strategy...”</p>	–		

<sup>a</sup>Technology category numbers refer to: (1) gas turbines/CCGT; (2) steam turbines/“conventional” power plants; (3) combustion/heating/CHP; (4) advanced coal (e.g. IGCC, PFBC); (5) nuclear power; (6) hydro power; (7) distributed power (e.g., micro turbines); (8) wind energy; (9) solar energy; (10) fuel cells; (11) control systems; (12) environmental technology; (13) other.

<sup>b</sup>Unless otherwise specified, all statements refer to the Power Generation segment (or similar) of each company.