Comparative Study on Energy R&D Performance: Gas Turbine Case Study

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EXECUTIVE SUMMARY

Gas turbines have emerged as a strong force in the generation market. Gas and combined cycle power plants dominate current orders from electricity generators. Figure A shows a resurgence of growth in this field during the past decade. This followed the development of gas turbines in the 1940s, their emergence into the peak power market in the 1960s, and the gas turbine slump of the late 1970s and 1980s, during which almost no gas turbines were ordered in the US. This new growth can be explained by the way that R&D advancements interacted with other drivers to gas turbine success. These other drivers were fuel availability, environmental concerns, and changing market conditions stemming from electrical restructuring.

R&D was one of the major keys to gas turbine success. Technical improvements such as material advancements and cooling innovations helped to increase gas and combined cycle turbine efficiency and make them more competitive in the power generation market. Figure B displays a rise of efficiency of gas turbine combined cycle systems.

Natural gas availability was another force that interacted with technical improvements to advance gas turbines. Figure C demonstrates how natural gas prices were high during the same period as the gas turbine slump. Prices peaked during the early 1980s due to natural gas deregulation, a perceived lack of natural gas reserves, and a general trend of rising fuel prices. When additional reserves were discovered and the deregulatory process ended, natural gas prices returned to a more competitive level and could be relied upon as a generally available commodity, driving the gas turbine market.

Other forces interacting with R&D and natural gas availability were environmental concerns and the changing power generation market. Environmental concerns began to show their effect during the 1970s with regulations which drove up the costs of both coal and nuclear power plants. Changing market conditions, hallmarked by electricity restructuring, is changing the way that management decisions are being made about turbine orders. Lower capital costs and higher efficiencies are now driving demand for additional gas and combined cycle turbines.

The success of gas turbine power generation can be explained by the *interaction* of technical R&D with gas availability, environmental concerns, and changing market conditions. As a result, we can see that R&D alone does not ensure success. We have developed a series of criteria for evaluating energy R&D spending:

- It is important to have a sufficient basic research and technology base upon which to build. The military aerospace industry provided this for gas turbines.

- Until the interaction occurs, R&D can be sustained by niche or alternative markets. For gas turbines this included commercial aviation and the peak power market.

- While it is hard to predict the future, there needs to be at least a plausible scenario of the interaction of forces that will make the technology attractive to a larger market. As the 20th century comes to a close, these forces have converged for gas.

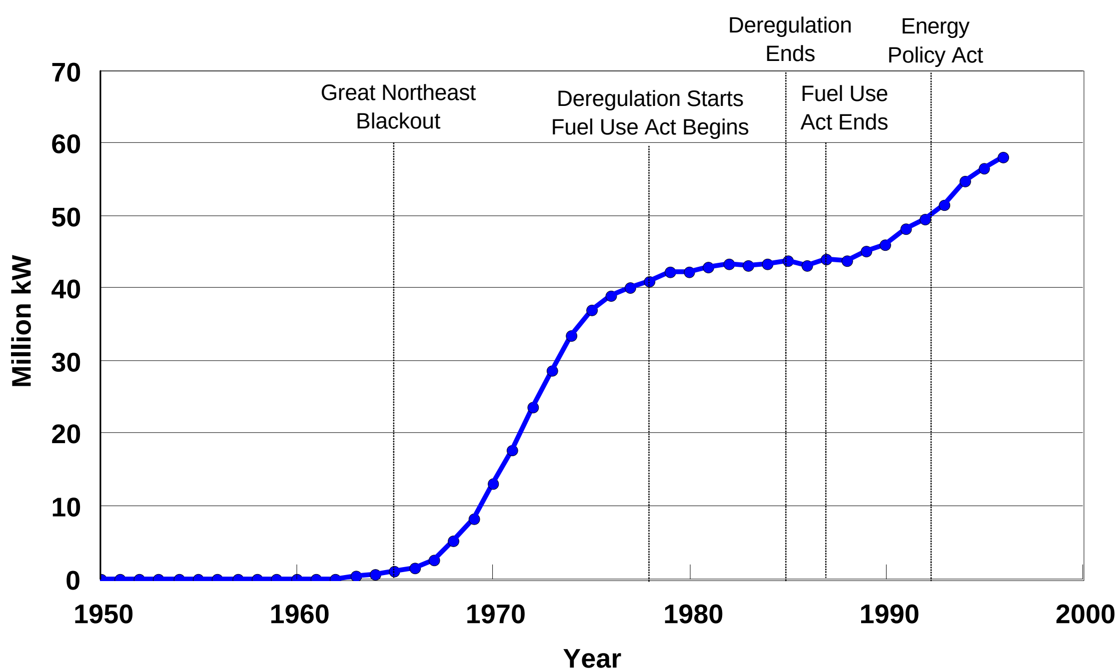

Figure A: Electric utility net summer capability for gas turbines over time. [1]

[1] Energy Information Administration: ftp://ftp.eia.doe.gov/pub/energy.overview/aer/aer8-8.txt Table 8.8. (5/98)

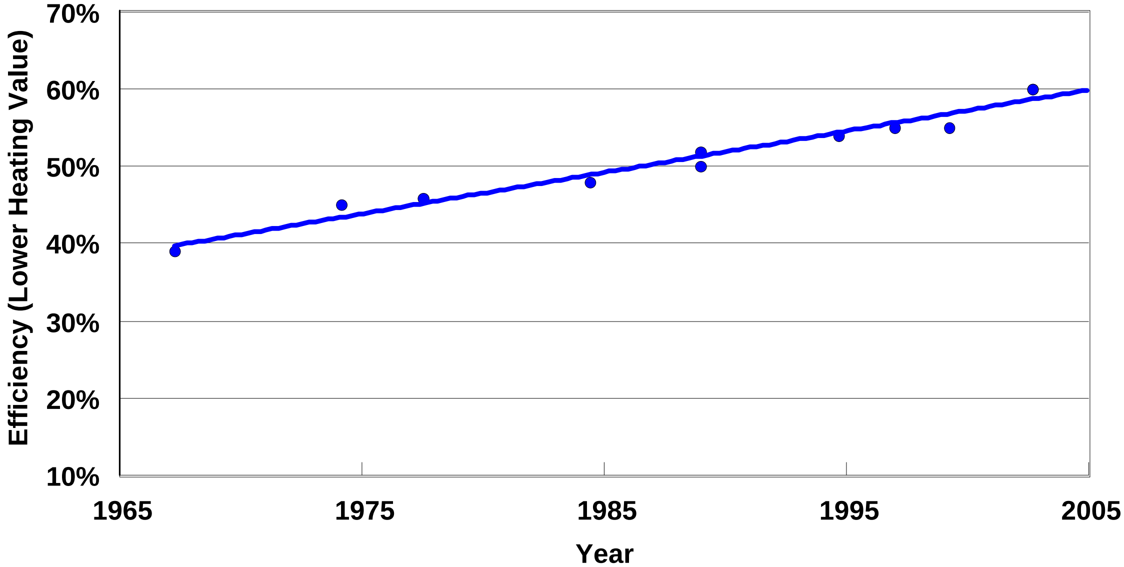

Figure B. Major gas turbine trends and developments over time (Combined Cycle Gas Turbine Efficiency)

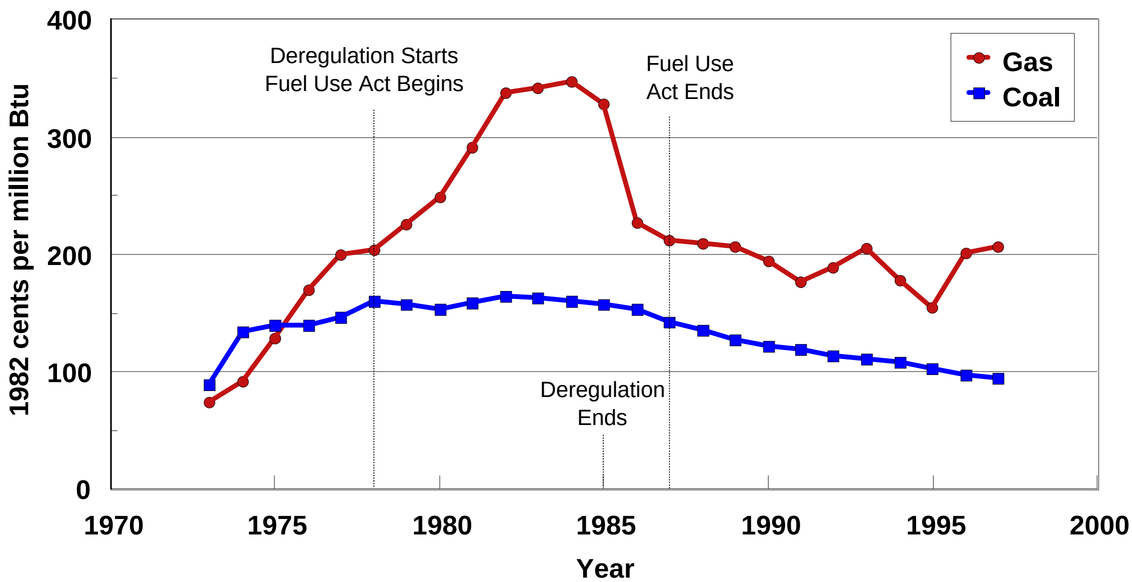

Figure C: Major gas turbine trends and developments over time (Natural Gas Costs for Utility Plants)

1. INTRODUCTION/OVERVIEW

This study for the Central Research Institute of Electric Power Industry (CRIEPI) details the MIT Energy Laboratory case study on gas turbines to help us better understand energy R&D performance. The project included three main tasks:

- Performing a rigorous, documented study of gas and combined cycle turbine improvements. This involved a detailed analysis of the development and deployment of gas and combined cycle turbine technologies through literature review, market examination, and interviews with key industry leaders and researchers.
- Drawing conclusions about energy R&D performance in specific cases. To accomplish this, we used our gas turbine case study in addition to other analyses of generation development.
- Applying the lessons learned from these case studies to emerging energy technologies.

This study focuses on the evolution of gas and combined cycle turbines. These turbines have emerged as a strong force in the power generation market and are marked by both rapid development and high demand. Their success and growth in popularity would not have been possible without decades of previous R&D and ongoing advancements which allowed them to be practical machines when market economics demanded them.

Market success demanded that the power generation industry go beyond simply improving gas turbine technology. Although the technological improvements had been occurring for years, often sustained by non-energy markets, it was not until these advances interacted with three other drivers that a new and substantive shift took place in the gas turbine industry. These other drivers to gas turbine success were fuel availability, restructuring of the electric utility industry, and environmental concerns.

The notion of technical R&D as part of a convergence has a substantive history. For example, when Shell International Petroleum examined the evolution of the world's energy systems, it found that a number of "converging developments" all contributed to the process. Figure 1 shows an example of how various developments played important roles in large changes in the energy field. In this example, automobiles achieved widespread success due to four major inputs: the availability of oil, new and improved materials such as polymers and high-quality steel, new manufacturing techniques such as assembly line production, and a social desire for freedom and consumption.

We find that a similar framework can be used to help explain the large expansion in the gas and combined cycle market in the late 1980s and 1990s. Our study indicates that four major forces and events interacted to contribute to and cause the industry developments. One set of important advancements took place in turbine technology. Materials engineering and cooling improvements allowed gas turbines to operate at higher temperatures and thus increase their efficiencies. Second, the deregulation of natural gas prices led to gas being both plentiful and available at reasonable cost, leading to the increased desire to use this fuel in electrical generation. Third, environmental concerns led to greater constraints on coal and steam-turbine plant emissions, increasing the competitiveness of gas and combined cycle turbines. Finally, the strategic management decisions which corresponded with US electric restructuring and changing market conditions also acted to propel gas and combined cycle development, deployment, and use. After a brief history of gas turbine development, these four interacting drivers for development (Figure 2) are described individually in the following sections.

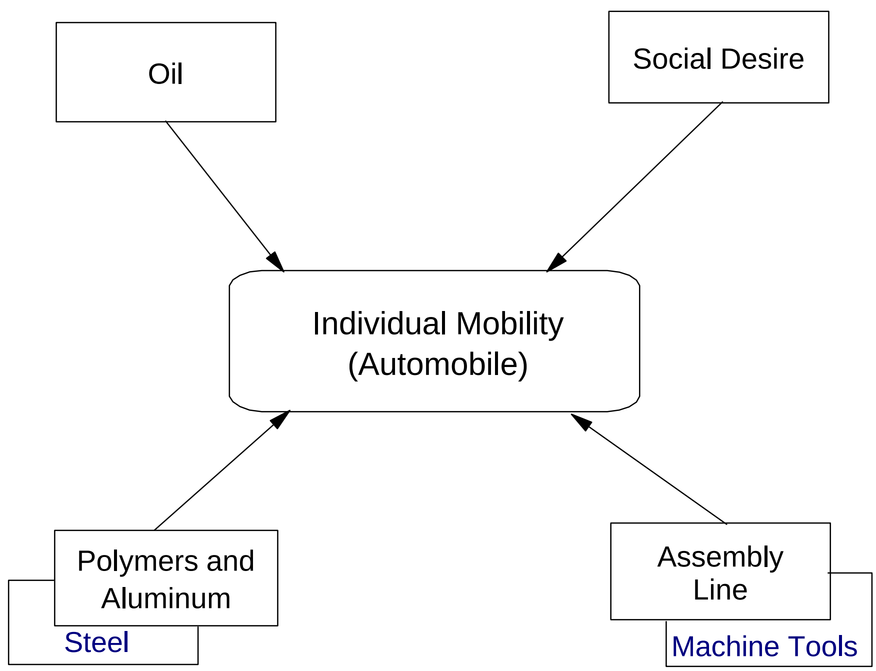

Figure 1. Converging developments in the 1920s leading to success of the automobile. Adapted from Shell Oil Company: *The Evolution of the World's Energy System, 1860-2060*.

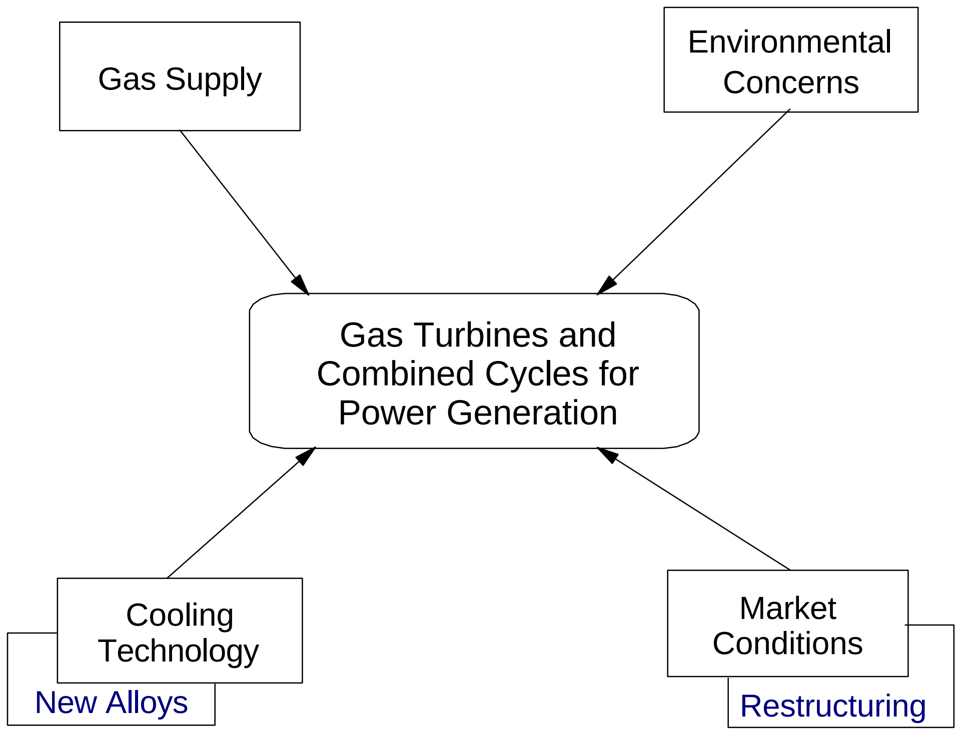

Figure 2. Interacting developments in the 1990s leading to gas turbine success.

2. GAS TURBINE BACKGROUND

Gas, or combustion, turbines were originally developed in the 18th century. The first patent for a combustion turbine was issued to England's John Barber in 1791. Patents for modern versions of combustion turbines were awarded in the late nineteenth century to Franz Stolze and Charles Curtis, however early versions of gas turbines were all impractical because the power necessary to operate the compressors outweighed the amount of power generated by the turbine. To achieve positive efficiencies, engineers would have to increase combustion and inlet temperatures beyond the maximum allowable turbine material temperatures of the day. It was not until the middle of this century that gas turbines evolved into practical machines, primarily as jet engines. Although some prototype combustion turbine units were designed, the developments that led to their practical use were a result of World War II military programs.

The race for jet engines was spurred by World War II and therefore included enormous government subsidization of initial R&D. The gas turbines for power generation were to emerge later from these military advances in technology. Germany's Junkers and Great Britain's Rolls-Royce were the only companies successful enough to enter general production with their engines during the war.[2] Technology transfers began to take place as early as 1941, when Great Britain began working with the US on turbine engines. Engineering drawings were shared between England's Power Jets Ltd. and America's GE Company during this period. American companies such as GE and Westinghouse began development of gas turbines for land, sea and air use which would not prove deployable until the end of the war. Other companies which were to emerge later in the combustion turbine market, such as Solar Turbines (the "Solar" refers only to the name of the company, not the source of energy) also emerged during the war by fabricating high-temperature materials, such as steel for airplane engine exhaust manifolds. The knowledge gained by manufacturers during this time would help them manufacture other gas turbine products in the post war period.

After World War II, gas turbine R&D was spurred in some areas and stunted in others. In an example of R&D expansion, the transfer of detailed turbine plans from Rolls-Royce to Pratt & Whitney was made as a repayment to the US for its assistance to Great Britain under the Lend-Lease agreement.[3, 4] This allowed Pratt & Whitney, previously specialists in reciprocating engines, to emerge as a strong developer of combustion turbines. In contrast, German and Japanese companies were expressly barred from manufacturing gas turbines. These companies were able to emerge later. For example, Siemens began recruiting engineers and designers from the jet engine industry as soon as it was allowed, beginning in 1952.[5]

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[2] William W. Bathie, *Fundamentals of Gas Turbines, 2nd Ed*. p. 7

[3] The Lend Lease Agreement was an agreement between Great Britain and the United States. It was a means by which the US could circumvent previous isolationist/neutrality legislation that barred its transfer of military goods to other nations.

[4] William W. Bathie, *Fundamentals of Gas Turbines, 2nd Ed*. p. 10

[5] W J Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation*, University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p 88.

Most developments in the 1950s and 1960s were geared towards gas turbines for aircraft use. R&D received a boost when turbofan engines were employed by commercial aircraft as well as for military use. For example, GE and Pratt & Whitney engines were used in early Boeing and Douglas commercial planes. This advance of combustion turbines into the commercial aviation market, and in some cases the boat propulsion market, allowed manufacturers to sustain their development efforts even though entrance into the baseload electric power generation market was not yet even on the horizon. Gas turbines also began to emerge slowly in the peaking power generation market. Westinghouse and GE both began to form power generation design groups independent of their aircraft engine designers. Westinghouse would later exit the jet engine business in 1960 while keeping its stationary gas turbine division. Among US turbine manufacturers, only GE was especially able to transfer knowledge between its ongoing aircraft engine and power generation turbine businesses.

The early 1960s saw the beginning of gas turbine "packages" for power generation. This occurred when GE and Westinghouse engineers were able to standardize (within their own companies) designs for gas turbines. This technology marketing innovation took place for two main reasons. First, in order to win over customers from traditional steam turbine or reciprocating engine equipment, manufacturers found that they were more successful if they offered fully-assembled packages, which included turbines, compressors, generators, and auxiliary equipment. Second, this standardization allowed for multiple sales with little redesign for each order, easing the engineering burden and lowering the costs of gas turbines.

The 1960's also marked the introduction of cooling technologies to gas turbines. This advance was the single most important breakthrough in gas turbine development since their practical advent during World War II. The cooling involved the circulation of fluids through and around turbine blades and vanes. These cooling advances were originally part of the military turbojet R&D program, but began to diffuse into the power generation turbine programs about five years later. Advances in cooling, along with continuing improvements in turbine materials, allowed manufacturers to increase their firing and rotor inlet temperatures and therefore improve efficiencies.

Although manufacturers were making great technological strides in gas turbine development, it was not until the Great Northeast Blackout of 1965 that the US utility market truly awoke to need for additional peaking generation capacity. This peaking is exactly what gas turbines were good for; their fast startup times would allow generators to match periods of high demand. Even though simple-cycle gas turbines of the day had dismal efficiencies (only about 25%) compared to those of coal-fired plants, their ability to handle peak loads led to an increase in demand and renewed R&D from manufacturers. The combustion turbine capabilities of US utilities rose dramatically in the late 1960s and early 1970s in response to this trend.

3. TECHNOLOGICAL IMPROVEMENTS

Gas turbines for power generation have improved greatly since their predecessors from the middle of the century. The best way to see how they have advanced is by looking at their rising efficiencies over time (see Figure 3). A doubling of efficiency has occurred for simple cycles, with the introduction of combined cycles causing a tripling in efficiency. Turbine efficiencies, along with cost and reliability, are among the most important criteria when power producers place orders for new plants. Therefore, the gas turbine gains in efficiency, which is the result of technological development, have been crucial for their success.

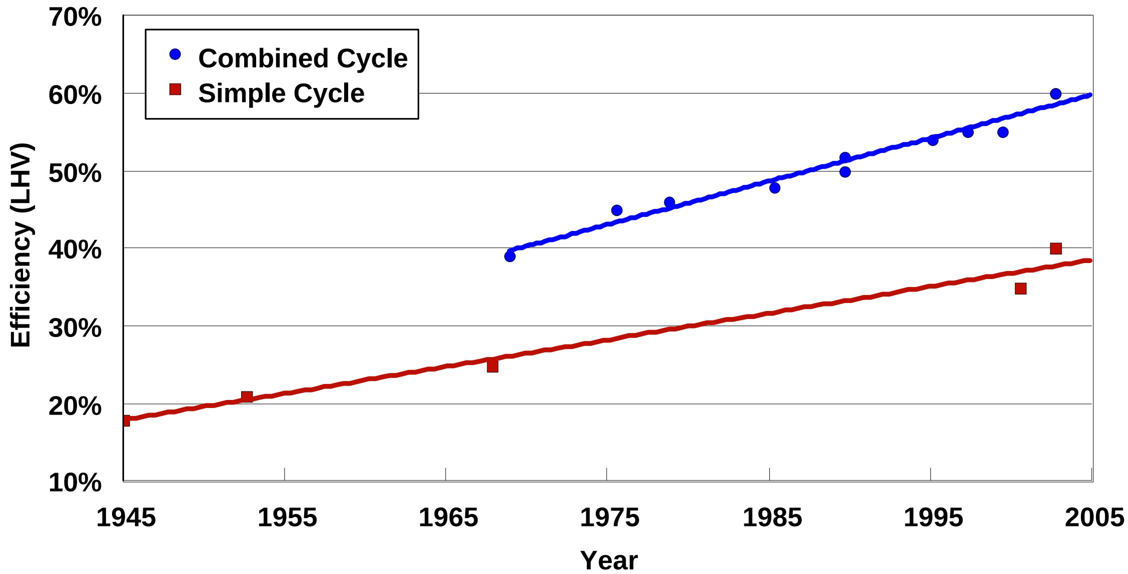

Figure 3. General efficiency increases over time for simple and combined cycle gas turbines.

To increase efficiencies, turbine designers have worked to increase firing temperatures without damaging the turbines themselves. The advantage of having high firing and rotor inlet temperatures (RITs) is that they nudge gas turbine cycles closer to Carnot thermodynamic cycles. However, firing turbines beyond the threshold temperatures of their components threaten their integrity and reliability. R&D addressing this concern has progressed along two major avenues of development: material improvements and cooling advances. Each of these two pathways is discussed in detail below.

Material Improvements

Materials used in gas turbines have gone through many incremental improvements since the first practical turbines were developed in the 1940s. Most R&D efforts led to improved steel alloys for use in turbine vanes, blades, and inlet blocks. This R&D in turbine materials and coatings led to two important effects. First, gas turbines were better able to withstand high temperatures. These more rugged materials allowed for hotter inlet gas to enter the turbine's first stage blades, leading to higher efficiencies. Second, material improvements led to an increase in rotor life and reliability. Gas and combined cycle plants could not have achieved popularity and larger market shares without solving problems such as premature blade cracking or component deformations. Together, the higher temperatures, higher efficiencies, and improved reliabilities have advanced the deployment of gas turbines in the power generation market.

Material improvements have often been marked by iterative advancements through the years. In the 1950s and 1960s, materials were often selected from available in-house steam turbine and jet engine experiences. However, differences between industrial gas turbines and these other types of turbines eventually required that their material paths diverge. For example, aerospace turbines operate under significantly different conditions because turbojets operate in relatively pristine environments and situations for which light weight is a benefit. Many of their materials are not suitable for the corrosive operating environments of power generation gas turbines. Furthermore, jet engines are subject to strict government safety regulations which require inspections at short and regular intervals. In contrast, industrial gas turbines, subject to more commercial considerations, are expected to operate for longer periods of time with less rigorous inspection and maintenance. Steam turbines also differ significantly from gas turbines in their material needs. The main concern in steam turbine blade design is the structural integrity of large blades and dealing with the corrosion due to steam and water passing through the blades and vanes. In contrast, gas turbines have smaller blades which are subject to higher temperatures and different fluids passing through and around them. The unique problems and characteristics of power generation gas turbines required that their material evolution follow a different path of development.

Progress in gas turbine material development often came in the form of alternative stainless steel or metal alloys that had improved heat characteristics. Different parts of gas turbines use a variety of alloy metals, including varying quantities of cobalt, nickel, and chromium. In turbine compressors, manufacturers vary in their metals and manufacturing methods, but initial blades are often made with stainless steel because it is strong and easy to machine.[6] Compressors have not gone through many drastic changes in material over the years. As in cases from decades ago, tertiary row compressor blades may use a 12 percent chrome material because of its high strength, good corrosion resistance, and superior damping characteristics. One example of an addition comes from Westinghouse's use of CuNiIn coating on the compressor blade roots to inhibit fretting.[7]

[6] Interview with Lee McLurin, Westinghouse.
[7] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996., p. 325

Materials in other parts of the turbine have been changed more frequently as the state of the art advanced. This is certainly the case with stationary turbine blades (or vanes). Some early stationary blade designs used welded structures in AISI 310, a 25-20 austenitic stainless steel that had excellent resistance to both corrosion and to oxidation at elevated temperatures, but which had limited strength capabilities.[8] Some turbojets then switched to higher strength, nickel-based alloys, but this proved to be unsuitable for industrial gas turbines because they either lacked corrosion and oxidation resistance or they were too difficult to weld with enough integrity. In the 1960s, engineers began to design these vanes with cobalt alloys for two reasons. First, cobalt alloys have high heat tolerances and can withstand high firing temperatures and corrosion with less cracking or warping. Second, cobalt alloys tend to have favorable welding characteristics. The welding ease of this metal can be extremely important when facing the inevitable fact that turbine vanes will occasionally crack with time and use. Having the ability to adequately repair a vane through welding is far preferable and less costly then having to replace the whole component. In this sense, material improvements in stationary blades and vanes have improved heat characteristics and increased rotor life by reducing turbine damage and allowing easier maintenance. Cobalt alloys are still used today, although the type of alloy has been improved to increase creep and oxidation resistance. Another set of improvements took place with a move to the use of more low-chromium alloys. This shift to use of 247 and 979 chromium alloys took place to enhance strength, even though use of these materials sacrificed some resistance to corrosion. Some turbine manufacturers have also increased their use of titanium, a particularly strong but expensive metal, in their gas turbine components.[9]

Rotating turbine blades have also improved with progressions in their materials. These rotating blades tend towards nickel alloys, which also display improved properties with iterative change. Early designs used a variety of nickel-based alloys and even some 12 percent chrome material similar to that used for compressor blades. Development led to the more widespread use of some standard Inconel nickel alloys, which were necessary as firing temperatures increased. In another example, improving from 520 nickel alloy to 750 and 738 alloys have allowed some manufacturers to maintain or improve high heat tolerances while simultaneously improving their production characteristics.[10] Among the most important production characteristics is the determination of whether a blade is cast or forged. Forging and machining a blade may be easier for some cases, but intricate designs and complex configurations may require that a blade be cast instead. Other times, there can be considerable difference between the ability to be able to cast a blade in a press than it is to painstakingly forge and machine one. The casting may be a simpler process that is less expensive. Some turbine material improvements, such as Westinghouse's switch to 738 alloy, have led to the use of more "crystallized" metals that are directionally solidified and more amenable to successful and simple production. Metals used previously would be more likely to crack if they were cast because their internal structure is not as strong as

[8] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996., p. 325.
[9] Interview with Lee McLurin, Westinghouse.
[10] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996. p. 326

today's alloys.[11] This incremental progression in alloys has been instrumental in improving gas turbines.

Future gas turbines may be able to make better use of ceramics materials. The introduction of ceramic parts, with their excellent abilities to withstand heat and corrosion, has the potential to be a great technological breakthrough in the future. Unfortunately, the brittleness of ceramics have prevented their widespread use and dampens the enthusiasm of many engineers for the prospects of this material. So far, attempts have yielded mixed results. Solar turbines, as part of the US government's Advanced Turbine Systems (ATS) project, has been developing and testing the first modern gas turbines with major ceramic components. This research is not yet commercially viable, however the hope is to develop ceramic turbine components that will not shatter and can tolerate even higher rotor inlet temperatures. Current experimental applications with ceramic first stage blades, combustor liners, and nozzles for small turbines have resulted in 37 degree Celsius increases in allowable firing temperatures and corresponding 5.7% increases in efficiency, however the long-term durability of these ceramics are still questionable and require further documentation.[12] This would increase efficiency and, if cooling were no longer necessary, reduce the need to divert compressed air from the engine's compressor for component cooling. Advocates of ceramics hope that these advancement materials can be the next big breakthrough in gas turbines, succeeding the major breakthrough which occurred in the 1960s in the area of turbine cooling.

Cooling Advancements

The introduction of cooling to gas turbines was the most important technological breakthrough in gas turbine development since the end of World War II. Advancements in turbine cooling also helped to advance the penetration of gas turbines in today's power generation market. Like material advancements, cooling innovations allowed power producers to allow higher-temperature inlet gases into the turbine bladepath. Gas turbine operation at these higher temperatures allows for higher efficiencies and make these turbines more viable sources of electric power.

[11] Interview with Lee McLurin, Westinghouse.
[12] Bautista, Paul, "Rise in Gas-Fired Power Generation Tracks Gains in Turbine Efficiency," *Oil & Gas Journal*, Vol. 94, No. 33, August 12, 1996, p. 45.

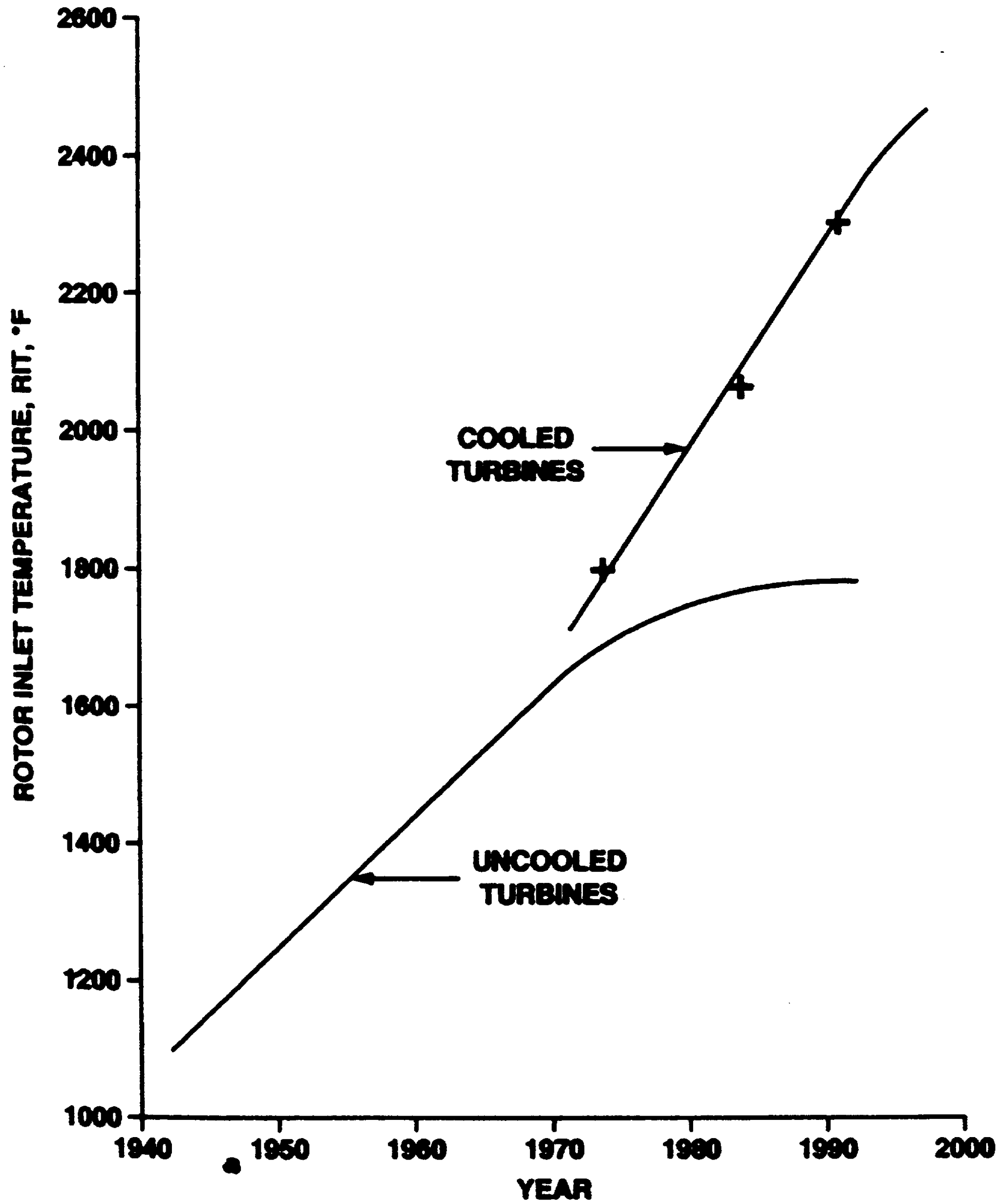

Figure 4: The introduction of cooling allowed a breakthrough in rotor inlet temperatures.[13]

Figure 4 demonstrates how the introduction of cooling helped to increase rotor inlet temperatures. Without it, turbine designers would have been limited to the ordinary heat tolerances of metal alloys and coatings. Firing temperatures would have leveled off after the

[13] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996. p. 325.

1960s at their threshold levels of about 1800°F (1000°C). Instead, rotor inlet temperatures were able to increase and improve turbine efficiencies while minimizing thermal damage. These trends helped gas turbines break into the power generation market.

Cooling usually involves the circulation of air or steam through hot turbine components. This includes extremely intricate pathways, tunnels, and holes to allow for maximum heat transfer to the cooling fluid. The source of the cooling fluid is often another part of the generation process. For example, air-cooled turbines may receive their cooling fluid directly from the compressor. Combined cycle power plants may use steam for cooling because it is readily available from the steam turbine boiler or heat recovery steam generator (HRSG) and the heat transfer and heat capacity coefficients of steam are nearly double those of air.[14] In either case, the cooling fluid follows an extremely complicated and carefully calculated path to maximize circulation and heat transfer.

The progression of cooling has been critical in gas turbine development. Cooling was originally introduced into military turbojet engines in the early 1960s. The advance followed a relatively common trend in gas turbine technology transfer: new developments in the turbines of military turbojets would become available to civilian aircraft about two or three years later, followed by diffusion to the power generation gas turbine industry after about five years.[15] GE and Westinghouse helped to pioneer stationary gas turbine cooling in the mid to late 1960s, beginning with stationary components and then gradually moving to more complex cooling geometries.

Cooling techniques were able to advance with improvements in computer codes and modeling. Engineering required models and tools for finite element analysis, heat transfer, and fluid dynamics to be able to design better and more complicated cooling systems. Initially, engineers were only able to use simple two-dimensional modeling techniques for heat transfer calculations. In this sense, they were technologically limited in the same way as material engineers who were unable to perform complex stress distributions in irregular shapes. To the benefit of both material stress and cooling efforts, finite element analysis codes improved during the following decades. For example, Westinghouse turbine engineers switched codes repeatedly, beginning with tools developed in-house, then moving to general modeling application such as Ansys, which was developed in great part by National Aeronautics and Space Administration (NASA) efforts to model its own materials and devices. Current versions of Ansys, Pro-Engineer (ProE) and computation fluid dynamics remain an integral part of modern turbine development and allow for much faster advancements.[16] As a result, cooling designs have become increasingly intricate and effective. An example of the evolution of cooling technology can be seen in Figure 5, which shows how Westinghouse has improved its 1st row gas turbine blade through the years.

[14] Bautista, Paul, "Rise in Gas-Fired Power Generation Tracks Gains in Turbine Efficiency," *Oil & Gas Journal*, Vol. 94, No. 33, August 12, 1996, p. 45.
[15] Allen Hammond, William Metz, *Energy and the Future: Power Gas and Combined Cycles*, pp. 17-18
[16] Interview with Lee McLurin, Westinghouse.

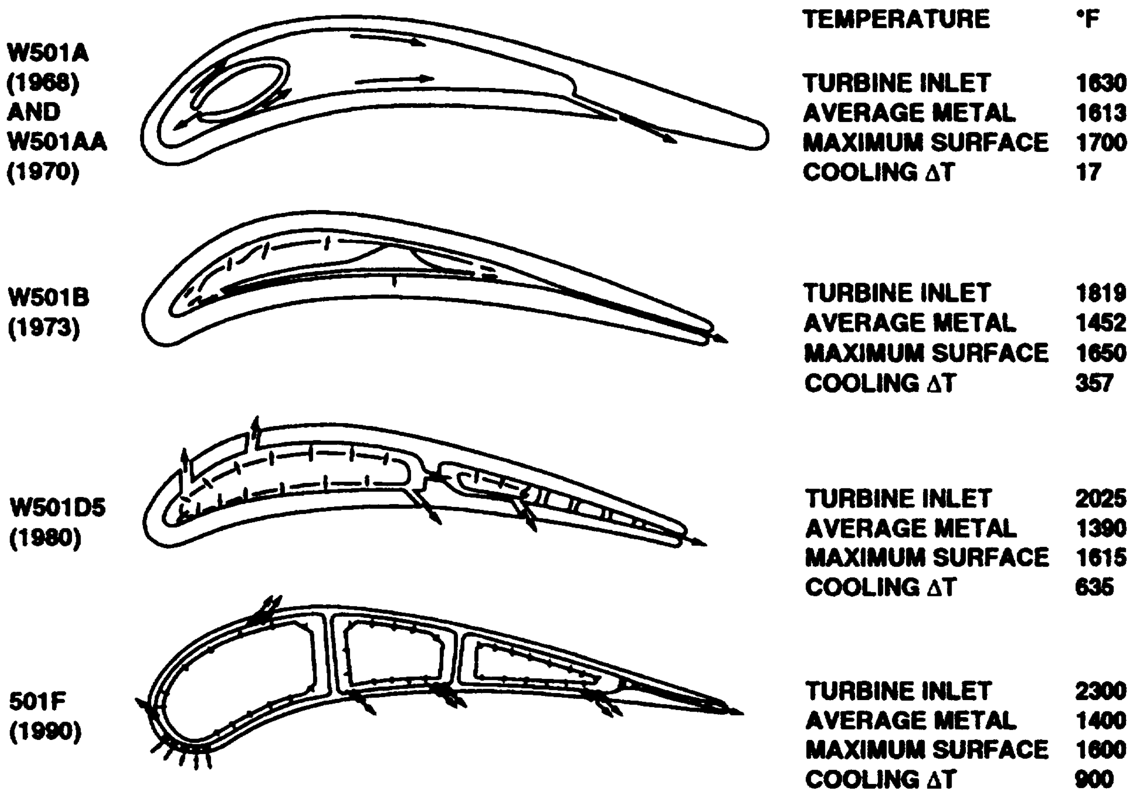

Figure 5: The evolution and complexity of component cooling.[17]

Comparing material improvements and cooling advancements

Material improvements and cooling advancements have been complementary in gas turbine R&D, however each type of development is different. The first points of comparison are the costs involved with each type of advancement. For example, an advantage of material improvements is that they allow for increased turbine performance without necessitating additional machining costs. Unlike intricate cooling schemes, which require expensive machining during the manufacturing of blades with complex fluid pathways, material improvements may simply mean a change in liquid metal alloy that is poured into preexisting molds. In contrast, cooling can boast of the fact that it requires no changes to potentially more expensive materials.

Another major difference between types of development is the nature of their progress. Although both initial material and cooling techniques stemmed from the military aerospace industry, power system engineers soon began adapting each type of technology independently. Material improvements occurred incrementally, only making substantive leaps when parts could advance

[17] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996, p. 324.

to the point where they could be manufactured less expensively. In contrast, cooling advancements were marked by a large breakthrough during their introduction, followed by great strides forward as computer codes and modeling improved. This contrast may be modified in the future if material developments lead to the widespread use of ceramic components, which would be the first real breakthrough in turbine material engineering.

Finally, mechanical and cooling advancements have differed somewhat in their sources and methods of technology transfer. For turbine materials, initial blade structures and material specifications were transferred from the military turbojet industry. Major turbine manufacturers such as GE and Westinghouse Electric Corporation got their start in the gas turbine industry by developing gas turbines for applications in military aviation. These turbojets became the first crude models for power generation gas turbines. As gas turbines became accepted in the field of power generation, engineering and manufacturing companies began to split teams of gas-turbine engineers into “aviation” side and “power generation” sides. (GE also separated its steam turbine engineering groups from its gas turbine engineering groups, whereas Westinghouse kept them together until the 1980s.)[18] The power generation groups then began developing and applying their own lessons for power-producing turbines as opposed to thrust-producing turbines. The power generation engineering efforts let to independent advances in materials applications, including improved heat tolerance and distribution for turbine inlet components. Both power and aviation engineering efforts led to the applications of protective coatings on the high-temperature turbine components.

Advances in cooling technology have four identified sources. The first is development in the aviation industry, which has led to technology transfer to the power generation field. The first cooled turbine concepts were applied to military aircraft and then spread to civil aviation and power generation. A second source of cooling technology transfer is the drilling industry, which also requires that rapidly rotating metal be cooled to prevent damage.[19] A third major resource for cooling advancements came through design codes and programs pioneered by both turbine design engineers and other groups in unrelated fields, such as NASA. Finally, the power generation industry itself has pioneered some efforts in keeping its own product temperatures cool enough to allow inlet temperature increases without the thermal breakdown of turbine components.

Despite their differences, both material improvements and cooling advancements helped to increase the RITs of gas and combined cycle plants. These higher RITs helped to boost the efficiencies shown earlier in this section. Figures 6 and 7 demonstrate this trend. Figure 6 shows how the rotor inlet temperatures increased with time for one manufacturer’s specific family of turbines, in this case the Westinghouse 251 series. It shows its biggest jump in RIT as cooling was introduced in the late 1960s and early 1970s. In this chart, improvements can be seen in differences between the models. The AA model turbines only had their first row stationary vanes cooled. The B model turbines also had the first row blade cooling and compressors similar to earlier versions, but also included second row vane segment cooling. The B8 model included an improved combustion system and temperature profile as well as fine advancements to the first

[18] Interview with Lee McLurin, Westinghouse.
[19] Interview with Craig Tedmon, ABB.

row blade cooling. The B12 model hallmarked considerably improved air flow which allowed improvements to the both the first row blades and vanes. By this time, two levels of blades and three levels of vanes were cooled.

Figure 7 shows similar data for another family of turbines, the larger 501 series by the same company. This figure shows how RITs increased with the use of cooling in the early 1970s, stalled during a period of slow development during the 1980s, then increased when development resumed using advanced computer codes in the 1990s.   As in the case of the 251 series, each successive turbine included improved or expanded cooling. The AA model only cooled the first row stationary vanes. The B model cooled its first row blade and second row vane segment as well. The D model included improved early stage cooling as well as an expansion of cooling the second row blade. The D5 model cooled the first two rows of blades and three rows of vanes.

Figure 8 shows how increased efficiencies and higher RITs are linked for another turbine manufacturer as well. This figure shows how series of GE family turbines improved in both RIT and efficiency.   As before, each letter designates a family of similar machines. The letter designations are company-specific, however they generally reflect groups of turbines which have similar RIT and size (output) characteristics. Together, these figures clearly show how technological improvements have increased firing temperatures and efficiencies.

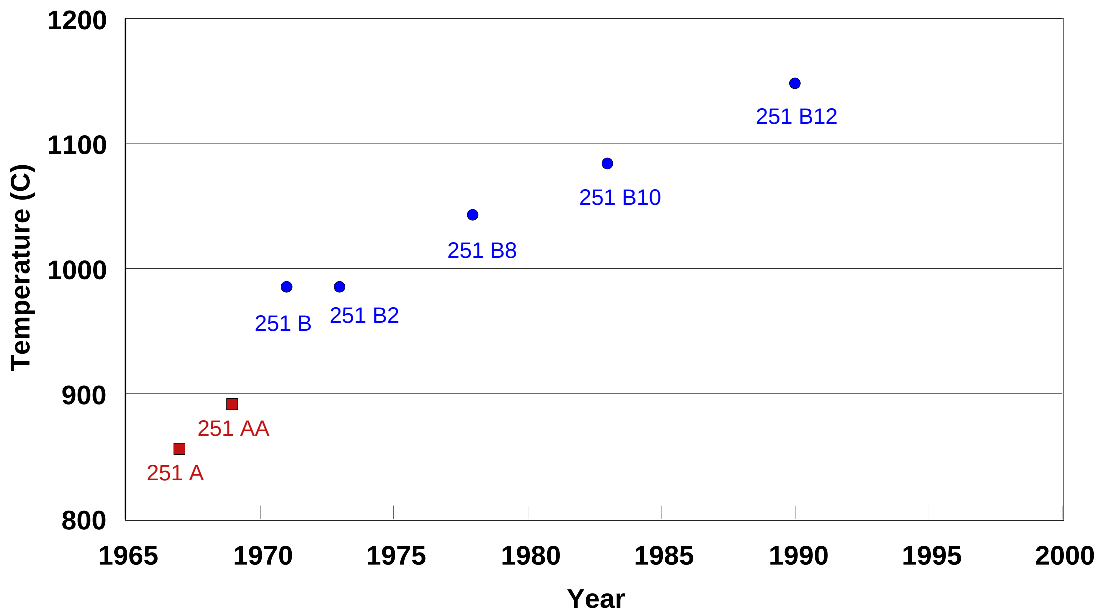

Figure 6. Rotor Inlet Temperatures (RIT) of the Westinghouse 251 Gas Turbine Family.[20]

[20] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996.

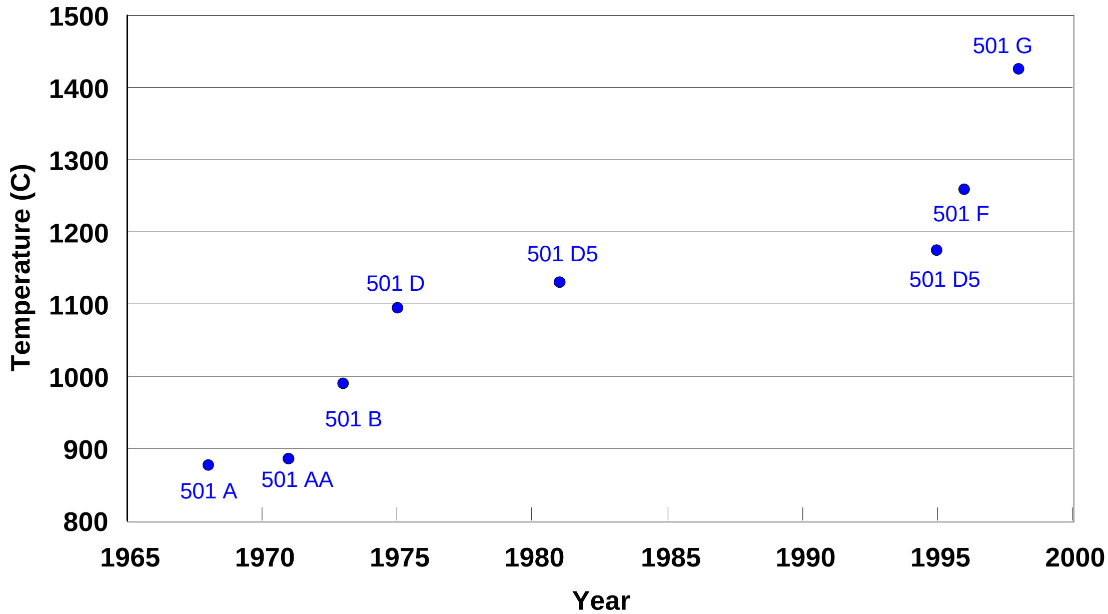

Figure 7. Rotor Inlet Temperatures (RIT) of the Westinghouse 501 Gas Turbine Family.[21]

[21] Bannister et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996.

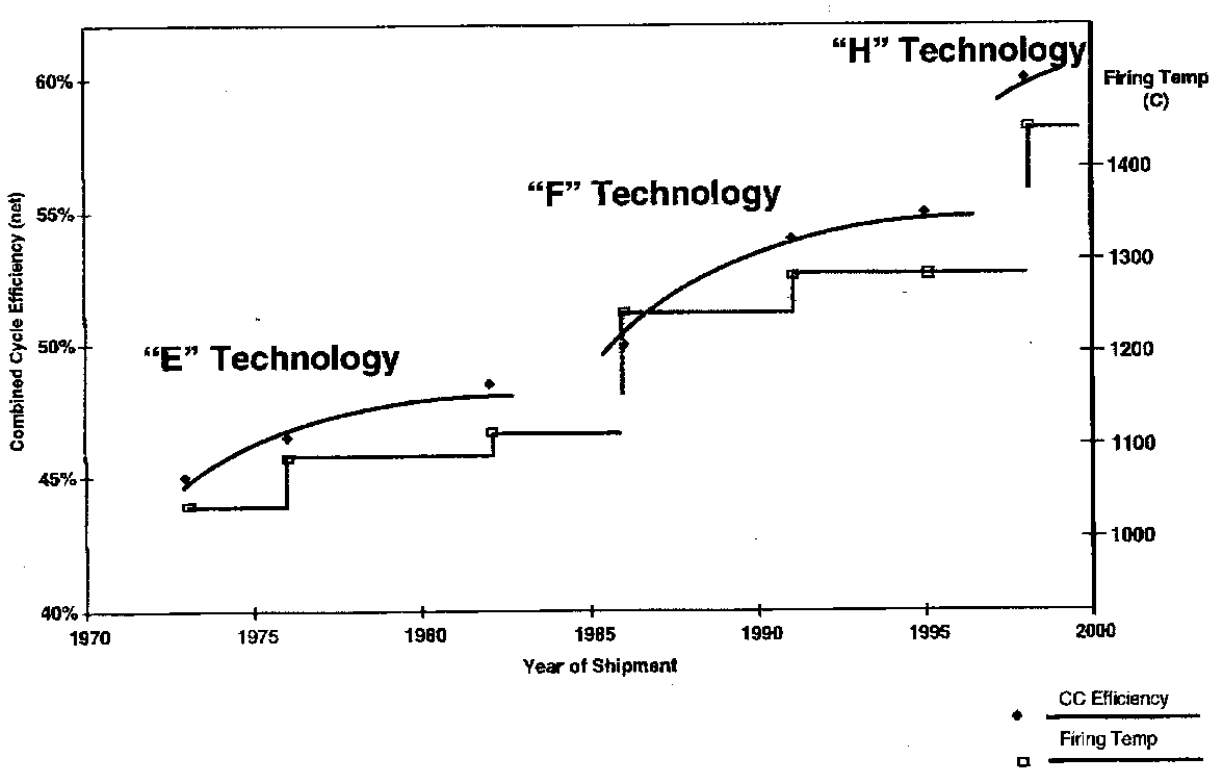

Figure 8. GE Power Systems chart showing advances in both firing temperature and efficiency.[22]

Other Advances

Although material enhancements and cooling evolutions were the main gas turbine technological improvements, R&D did lead to other engineering advances as well. These include the adaptation of steam injection into gas turbines, which first occurred in 1984. This process injects steam from the Heat Recovery Steam Generator (HRSG) into the gas turbine combustor. The high pressure steam is heated, expands in the gas turbine, and boosts power output. Another new advancement was ABB's unique use of sequential combustion (or reheat) which produced some of the benefits of high-temperature firing without causing the same level of thermal damage or the same NO_x levels which result from the more simple type of high temperature combustion.[23] In explaining this advancement, it should be noted that Brown Boveri's closed its own gas turbine business in the mid 1980s because of the slump in the gas turbine market. When it merged with Asea in 1988 to become ABB, it immediately began a brand new development program which was relatively independent from past programs because of the complete break in the business. In addition, ABB hired some key engineers who had previously worked for GE.

[22] Data provided by Joel Haynes, GE

[23] Interview with Craig Tedmon, ABB.

Other advances include industry-wide attempts to reduce harmful emissions by adapting dry low NO_x systems to gas turbines. NO_x reduction techniques began with models and field tests evaluating emission formation. This led to more accurate predictions of combustor operations and variations in their parameters. Water injection for NO_x control was first applied, followed by steam, which was found to be less effective. The goal for both was to reduce flame temperature and subsequently lower the NO_x formation rate, but these injections impose performance penalties and may increase carbon monoxide emissions.[24] More modern methods concentrate on combustor-oriented "dry low NO_x" schemes, which were explored in three areas: premixed lean combustion, rich-lean combustion, and catalytic combustion. Premixed lean combustion occurs in hybrid combustors which mix air and fuel on a molecular level, cause the thermal fixation of atmospheric nitrogen, and reduce harmful emissions.[25] The rich-lean burn approach to NO_x reduction was found to be useful if the fuel contained fuel-bound nitrogen (FBN) which defeated water injection and premixing schemes. In rich-lean burning, the burning is staged to occur in a fuel-rich zone where the oxygen deficiency prevents NO_x formation. Then, a second, lean zone completes the burning process at a temperature low enough to prevent NO_x formation. Finally, catalytic combustion offers a third developmental alternative to emissions reduction. Westinghouse engineers first evaluated this method in 1971, when tests found that catalytic combustion could achieve uniform temperature patterns and drastically reduce NO_x levels. However, the mechanical integrity of the substrate was poor, and the method was not pursued when R&D efforts tapered off during the gas industry stall of the late 1970s and 1980s.[26] Activity resurged with the new market boost and has led to new designs of advanced catalytic systems.

The nature of government in technological advancements

In analyzing the technological development of gas turbines, it is important to note how government involvement has contributed to R&D. The clearest involvement took place in the beginning of the gas turbine era, when defense programs poured money into turbojet research. As noted above, this greatly aided turbine manufacturers such as Westinghouse and General Electric, which went on to transfer much of this technology to industrial turbine use.

Siemens and ABB contrasted in their development of gas and combined cycle turbines. These two European manufacturers are important players on the world market, but followed a different route. Brown Boveri, as noted in Appendix A, was a Swiss manufacturer involved in early version of gas and combustion turbines. However, it was not as closely related to the military turbojet industry as its American counterparts, even though its future partner, Asea, did work with Swedish jet manufacturing. As a result of this relatively nonmilitary (and less government subsidized) course of development, Siemens and ABB had initial designs that were much closer to traditional steam turbine technology. Their initial turbines, compressors, and combustors were

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[24] Paul Bautista, "Rise in Gas-Fired Power Generation Tracks Gains in Turbine Efficiency," *Oil & Gas Journal*, Vol. 94, No. 33, August 12, 1996, p. 46.

[25] Bautista, Paul, "Rise in Gas-Fired Power Generation Tracks Gains in Turbine Efficiency," *Oil & Gas Journal*, Vol. 94, No. 33, August 12, 1996, p. 46

[26] Bannister, et. al. "Evolution of Westinghouse Heavy Duty Power Generation and Industrial Combustion Turbines," *Transactions of the ASME*, April, 1996, pp. 328-329.

essentially bolted together, with only a few (one or two) large combustors resembling a conventional steam boiler. This branch of gas turbine evolution withered and died. In contrast, the integrated gas turbines produced by GE and Westinghouse also drew on steam turbine construction methods in the beginning, but were considerably different on the inside. They contained aero-derived blading and more combustors in an annular ring.[27] These are the companies which led to more substantive developments as a result of their military and government background. Their methods were later adopted by other companies.

Government involvement through aviation R&D continues to this day. The US government alone has spent over $13 billion since 1940 on jet engine development and still spends about $400 million per year on R&D efforts through companies such as GE and Pratt & Whitney.[28] As a result of these efforts, there is a "supermarket of technology" created by the jet engine programs which is slowly being utilized by power equipment companies. As noted above, this supermarket contains everything from new alloys that can withstand higher temperatures to computer codes for advanced turbine blade profiles.[29]

Governments have also devoted some attention to the power generation uses for gas turbines. The 1970s saw the US Department of Energy (DOE) sponsorship of the High Temperature Turbine Technology program and the Japanese Moonlight project. Westinghouse and GE were closely associated with the American project, while Mitsubishi was the lead company for the Japanese work.[30]

A more recent initiative is the US Advanced Turbine Systems (ATS) program, which is being spearheaded by Federal Energy Technology Center and six turbine manufacturers in the US, including GE, Westinghouse, and Solar. The consortium also includes 83 universities and multiple DOE research centers. The goal is to subsidize and coordinate R&D which will lead to the next generation of efficient gas and combined cycle turbines. The goals for technology base research closely parallel the advances noted earlier. They include advanced combustion systems to minimize pollution, heat transfer and aerodynamics to improve turbine blade life and performance, and materials to permit higher operating temperature for more efficient systems.[31] Solar Turbines has experimented with ceramic parts for its share of the project (simple cycle gas turbines less than 20 MW_e) but larger turbine manufacturers have not devoted the effort or government funding to analogous efforts for larger industrial turbines for baseload generation. When they do, it will be for stationary components of the ATS engine. To date, the program has

[27] W. J. Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation,* University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p. 88.
[28] Goncalves, Chuang, and Cohn, "Advanced Gas Turbine Systems," May, 1996, p. 9.
[29] W. J. Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation,* University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p. 91.
[30] W. J. Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation,* University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p. 91.
[31] United States Department of Energy, "Advanced Turbine Systems: The Next Generation of Gas Turbines" Federal Energy Technology Center.

not reached its major goals and is viewed skeptically by many in the field because it is not a major driver of turbine improvements.[32] Nevertheless, turbine manufacturers are continuing in the same directions of higher temperatures and efficiencies.

In conclusion, technological development has played an important role in the advancement of gas and combined cycle turbines. Material improvements and cooling advances have helped to increase RITs and efficiencies. Emission controls have also improved to propel the gas turbine market. Throughout this process, government purchases or sponsored development have affected some of the ways in which technologies progressed. While it did help make the boom possible, technical development alone did not cause the surge in gas turbine purchases. As discussed in the following chapters, other factors were also keys to success.

[32] Bannister, et. al. "Development Requirements for the Advanced Gas Turbine System," *Journal of Engineering for Gas Turbines and Power,* October, 1995. P. 731.

4. GAS SUPPLY AND AVAILABILITY

The availability of natural gas at competitive prices served as a major boost for gas turbine development. Until the early 1970's, the cost of gas for electric utilities was extremely low, but utilities did not consider natural gas to be a reliably available source of fuel. Furthermore, gas turbines were not as advanced, efficient or competitive as they are today, so most gas used by electric utilities was burned mainly as fuel for steam turbine plants. Since coal was cheaper than gas and used for the same purpose of vaporizing water in Rankine cycle plants, electric utility demand for gas remained slight, despite the low price of the fuel.

The 1970s proved to be a turbulent time for the natural gas industry. Prices controls created shortages, first in reserves, then in production as producers failed to supply as much gas as customers were willing to buy at the regulated price. Eventually, prices did begin to rise, and the system became ripe for reform. In 1978, the US Congress passed two landmark pieces of legislation: the Natural Gas Policy Act and the Power Plant and Industrial Fuel Use Act.

The Natural Gas Policy Act (NGPA) set a timetable for deregulating the gas industry by dropping restrictions on the wellhead prices of natural gas. However, the policy was complex and detailed; it deregulated different classes of gas distinctly, depending on when the gas was discovered and in a series of steps. First the NGPA brought intrastate gas under federal price controls. Second, it designated that all gas that had come into production in 1977 or before would remain regulated. This "old gas" would be regulated at a price higher than the previous price and would be allowed to increase with inflation. Third, it established a deregulation schedule for "new gas" that came into production after 1977. Deregulation of "new gas" would occur by 1985 and would involve a series of steps in which the price of gas would rise at a rate roughly four percent higher than the rate of inflation. There were more than 20 price categories for this new gas until it would be totally deregulated in 1985. Fourth, the act specified that certain categories of "high cost" gas would be deregulated about one year after the enactment of the legislation. "High cost" gas, for example, included gas produced from wells deeper than 15,000 feet.[33] This US version of natural gas deregulation was in many ways experimental; the attempt would later serve as a model for other countries in their deregulatory efforts.

The NGPA actually allowed gas prices to increase for several years for four main reasons. First, the oil price shock of the era raised general fuel prices. Gas prices, now partially freed from regulation, rose along with the price of other fuels. Second, the deregulation shocked the system because previous price ceilings had held the price of gas significantly lower than its actual value to consumers. Third, the schedule itself actually included increases for gas prices beyond inflation. Finally, following the previous curtailments, gas pipeline companies began locking up long term gas supplies, almost regardless of cost.[34] However, the increases ended when the last controls on newly-discovered gas reserves were dropped in 1985. With the oil crisis long over,

[33] Legislative summary adapted from Kash and Rycroft, *U.S. Energy Policy*, Oklahoma: University of Oklahoma Press, 1984. p. 208.
[34] Crandall and Ellig, "Economic Deregulation and Customer Choice: Lessons for the Electric Industry," Fairfax, Virginia: Center for Market Processes, 1997. p. 10.

the shock of deregulation passing, and a free market, gas prices plunged to approximately the levels we have today. Gas is now freely available at an economical price for electric utilities. It is not cheaper than coal, but the price is in a window of acceptability. The history of utility gas prices, including the visible price increase that stifled the gas turbine boom during the late 1970s and early 1980s, can be seen in Figure 9.

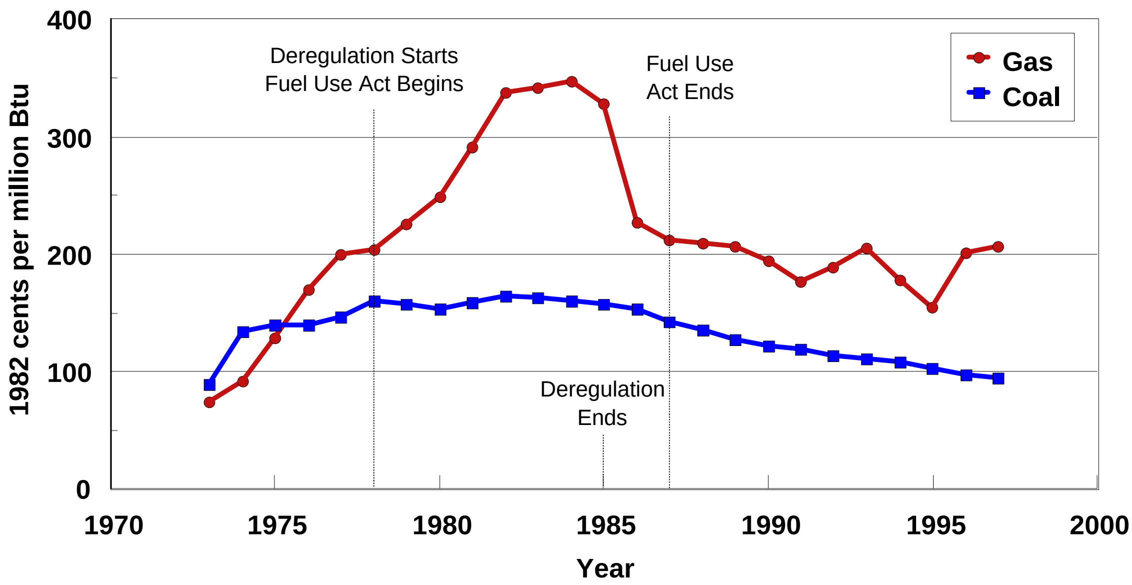

Figure 9. The rise and fall of utility gas prices in the US.

The Power Plant and Industrial Fuel Use Act was enacted in 1978 at the same time as the NGPA. For context, at this time it was believed that supplies of gas were permanently short and remaining supplies should be preserved for residential and commercial customers. However, this belief was disproved once newly discovered natural gas was decontrolled and new gas discoveries increased significantly.[35]

The Fuel Use Act harmed the gas turbine industry in the US. The act took note of the rapidly-increasing price of natural gas and of the lack of new supply. It was believed that the natural gas supply was limited and that gas reserves would expire shortly. Natural gas was deemed too valuable to burn for power generation. As a result, the Fuel Use Act prohibited the burning of

[35] Gray and Nakayama, *U.S.-Japan Energy Policy Considerations for the 1990's,* Maryland: University Press of America, 1988. p. 46.

natural gas or oil in most new industrial boiler facilities and all new power plants. The goal was to preserve natural gas for residential and commercial customers. Until the early 1980s, the notion of the imminent expiration of both US and world gas reserves remained; producers which had little interest in raising their production earlier had not invested heavily in new exploration, so predictions on the future of gas as an available source were pessimistic. Figure 10 shows a graphical history of natural gas reserves in both OECD and Non-OECD countries. It demonstrates how, from 1977 to 1981, the number of reserves failed to increase substantially, fueling fears of a permanent shortage. Some estimates predicted that the world would run out of accessible natural gas within 20 years.

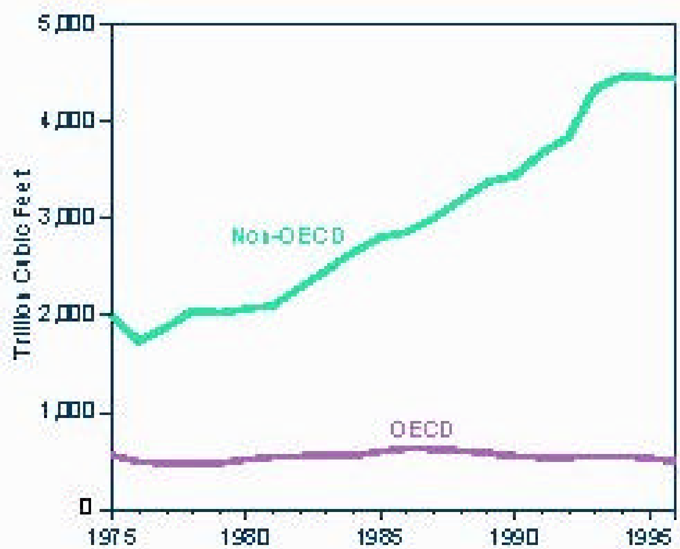

Figure 10. OECD and Non-OECD Natural Gas Reserves, 1975-1997.[36]

During this time, the Fuel Use Act virtually shut down the US installation of gas turbines. In an example of its effect on turbine purchases, orders for GE's "Frame 7" turbine fell from 37 to 5 in the year following its passage.[37] Although turbine manufacturers could not expect to produce many gas turbines for the US utility market, GE continued with R&D during this difficult period and shifted its focus to Europe.[38] However, it should also be noted that the European

[36] Sources: 1975-1996 International Petroleum Encyclopedia: Worldwide Oil and Gas at a Glance (Tulsa, OK: Pennwell Publishing Co.) various issues. 1997: "Worldwide look at Reserves and Production," Oil and Gas Journal, Vol 93, No. 52 (December 25, 1996) pp. 44-45. Generally, http://www.eia.doe.gov/oiaf/ieo96/gas.html (5/98)
[37] Richard Tabors and Thomas Lee, *Energy Aftermath*, Boston: Harvard Business School Press, 1990, p. 149.
[38] Interview with Craig Tedmon, ABB.

Community (EC) also issued a directive in 1975 restricting the use of gas for power generation.[39] During this same period, Brown-Boveri, a European turbine manufacturing company, virtually shut down its gas turbine business. Westinghouse allowed its gas turbine development program to flounder and almost sold it to its partner, Mitsubishi Heavy Industries (MHI) in 1987.

New reserves were discovered throughout the 1980s and concerns about the rapid expiration of gas supply vanished later in the decade. Exploration activity from 1980-1986 showed that natural gas could be found in prolific quantities. By 1986, the US was found to have over 50 years of conventional gas resources.[40] The Fuel Use Act was finally rescinded in 1987 and spurred a large growth in interest in gas turbines.[41] The EC directive restricting gas use in power generation was also lifted.

Estimates of gas reserves have continued to grow, assuring generators that gas will remain an available fuel. Over the last two decades, estimated reserves have increased by 94 percent.[42] By 1991, estimates of natural gas reserves ranged from 4384-4682 trillion cubic feet.[43] By 1996, the world proven gas reserves had expanded to 4933 trillion cubic feet. Proven reserves are the estimated quantities that analysis of geological and engineering data demonstrate with reasonable certainty to be recoverable in future years from known reservoirs under existing economic and operating conditions. On a worldwide basis, these known reserves would be sufficient to maintain production at current rates for over 60 years.[44]

It is important to note that natural gas demand is expected to grow by over 76 percent over current levels by 2015, increasing from 70 trillion cubic feet per year to about 133 trillion cubic feet per year.[45] Despite this increase in demand, the current estimates of gas reserves are so tremendous that GE estimates that the currently-known supply of gas should exceed almost 70 years. This can be seen in Figure 11, which shows how the years of gas supply stagnated during the late 1970s, but have increased since then. This implies that the availability of fuel stretches past the horizon of expected plant life of any turbine manufactured in this generation. As such, this assurance of a future natural gas supply helps to build utility and non-utility generators' demand for gas and combined cycle turbines, in turn fueling greater manufacturer research and development in the field.

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[39] W J Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation,* University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p. 89.
[40] Gray and Nakayama, *U.S.-Japan Energy Policy Considerations for the 1990's,* Maryland: University Press of America, 1988. p. 46.
[41] Goncalves, Chuang, and Cohn, "Advanced Gas Turbine Systems," May 1996, p. 16.
[42] EIA, "Natural Gas" www.eia.doe.gov/oiaf/ieo96/gas.html#head p. 2
[43] EIA, Office of Oil and Gas, "International Oil and Gas Exploration and Development, 1991" November, 1993, Appendix B.
[44] EIA, "Natural Gas" www.eia.doe.gov/oiaf/ieo96/gas.html#head p. 3
[45] EIA, Ibid., p. 1

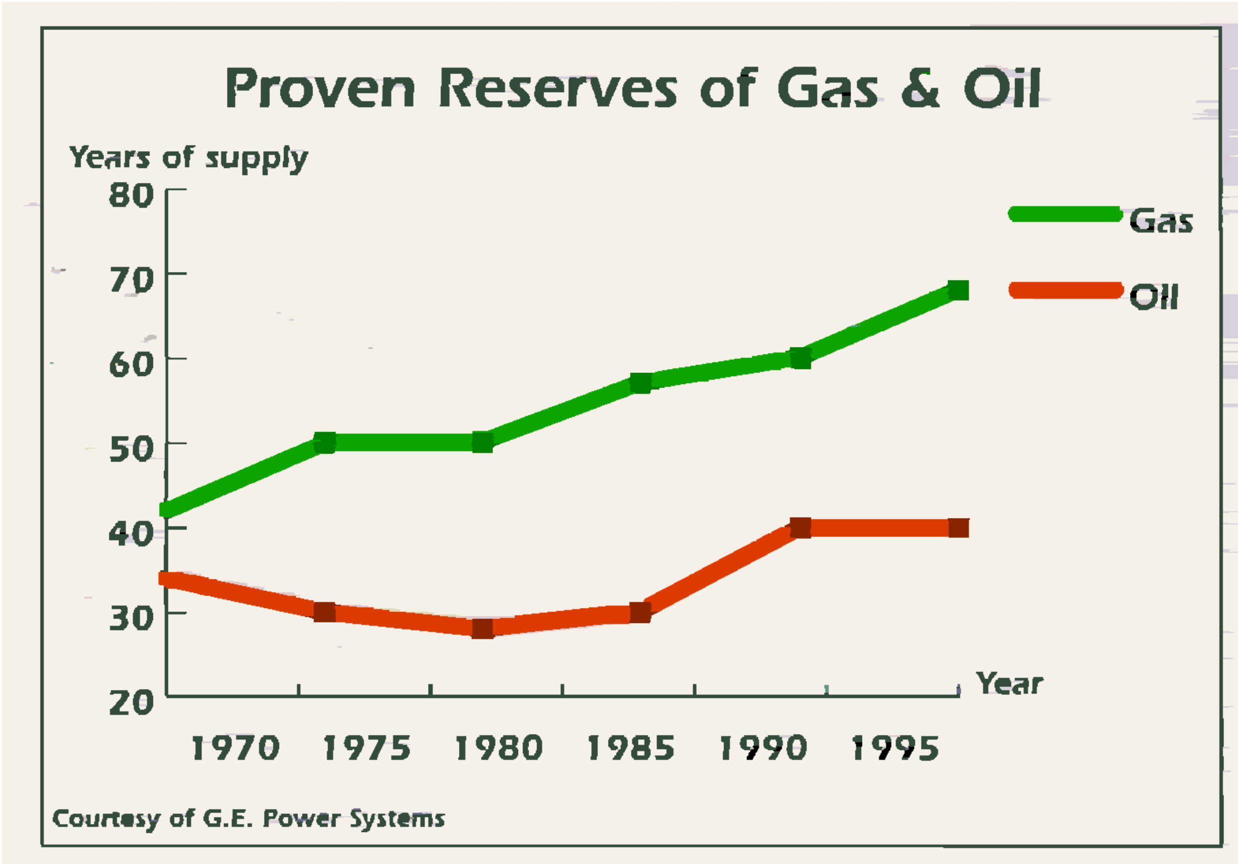

Figure 11. Years of supply remaining given currently proven reserves of gas and oil.[46]

In conclusion, the availability of natural gas also enables gas turbines to thrive in the power generation market. Economic developments, government policy, and resource discoveries all affected natural gas prices and availability. While these price and availability factors helped drive gas turbine sales, the convergence of causes would also include environmental policy.

[46] Courtesy of GE Power Systems, Hank Stein, Turbomachinery International, Nov/Dec 97

5. ENVIRONMENTAL CONCERNS

Growing social awareness of air pollution associated with fossil fuel use has contributed to advances in gas and combined cycle turbines. This section outlines three major ways that environmental concerns prompted gas turbine development. First, regulations drove up the cost of the polluting competitors to natural gas, making combustion turbines more competitive. Second, environmental sustainability affected decisions on fuel choice. Finally, environmental pressures forced gas turbine manufacturers to develop emission reduction techniques for their own relatively clean machines.

The U.S. passage of the Clean Air Act in 1970 demonstrated the first major federal commitment to restrictions on power plant emissions. These restrictions had a profound impact on the power generation market. The major fossil fuel for power generation, coal, has significant and pronounced environmental disadvantages. For example, coal combustion leads to considerably more particulate and SO_2 production than natural gas combustion. In contrast, natural gas plants have only traces of SO_2 (typically between 0.001 and 0.002 lbs of SO_2 per MMBtu since sulfur is removed from gas before it enters the pipeline) and negligible amounts of particulates.[47] Environmental laws spurred by social concerns turn those environmental disadvantages into economic costs which must be considered by power producers. In effect, environmental regulations turn negative environmental externalities into real costs which can be seen in the construction and operation of power plants,

The real costs of environmental legislation manifest themselves through regulation compliance. Gas turbines benefit from the application of these costs because of their “clean” nature relative to coal and nuclear plants. For example, Table 1 shows some typical incremental costs to control SO_x, NO_x and Hg from coal-fired power plants. If these costs for environmental control were considered part of the fuel costs, it can be seen that controlling coal for SO_x and NO_x makes its fuel costs roughly equal to that of gas. If Hg control becomes mandated, coal would effectively cost more than gas.

[47] Steven I. Freedman, “The Role of Natural Gas in Electric Power Generation 1990-2020,” *MIT Energy Laboratory Conference: Energy and the Environment in the 21st Century*, March 26-28, 1990, p. DI39.

Table 1. Cost of Environmental Controls

	Incremental Control Cost ($/ton coal)	Cumulative Equivalent Fuel Cost ($/$10^6$ Btu)
Base Coal		1.4
SO_x	9-15	1.75-2
NO_x	8-12	2.1-2.5
Hg	4-13	2.2-3
Base Gas		2.3-2.6

Environmental sustainability and fuel choice

Environmental concern over the sustainability of fuels has also impacted gas turbine development. For example, the passage of the Fuel Use Act in 1978, and its deleterious effect on the US gas turbine market, was prompted by predictions of imminent natural gas reserve shortages. However, the discovery of new reserves during the 1980s counteracted this trend and led to a new environmental view on the desirability of gas turbines. As noted previously, the revelation that this cleaner fuel was also plentiful helped to spur further development.

Emission reduction for gas turbines

Finally environmental concerns over NO_x has impacted gas turbine emission development. Air quality issues were first a pure boon for gas turbines because they were a relatively clean alternative to coal power plants. However, gas turbine emissions were soon to come under scrutiny as well. Regulation and environmental forces would induce manufacturers to invest in emissions research for Breyton cycles. The Clean Air Act of 1970 gave the Environmental Protection Agency the task of establishing aircraft exhaust emissions levels. The EPA published these levels in 1973 and assigned a compliance date of 1979. While this did not directly affect power generation gas turbines because their sales were weak in the late 1970s and 1980s, this manifested an initial way in which environmental concerns would lead to direct impacts in turbine design . Although the gas turbine industry as a whole benefited from environmental pressures such as Clean Air Act amendments and acid rain legislation, further environmental policies forced changes in combustion turbines as well.

Some design changes prompted by environmental regulations were detailed in Chapter 3 in a discussion of technological improvements on NO_x reduction. These changes included wet and dry low NO_x efforts. However, environmental legislation and administrative rulemaking continue to force new environmental technologies for gas turbines. Many state environmental regulatory agencies prompt power generators to submit to Lowest Achievable Emission Rate (LAER) or Best Available Control Technology (BACT) standards. There are substantive differences between these two types of standards. For example, LAER standards usually allow for play in the word "achievable," and allow generators to include economic reasons why a new, expensive emission control technology might not be feasible. On the other hand, BACT standards tend to be more absolute, requiring a generator to use an environmental technology if it exists, regardless of cost.

Despite their differences, LAER and BACT standards have continued to be technology-forcing forms of regulation and environmental policy. They helped usher in the new era of Selective Catalytic Reduction, (SCR) which became a standard control system for natural gas turbines. They may also bring forward the next generation of emission control, an alternative catalyst system (currently made by only one company under the trade name of $SCONO_x$). The method in which the policy acts is of interesting note because it is local, not federal policy which begins the technology push. For example, the state of California includes the coastal Water Management District which is considering implementing BACT standards which would force generators to either use $SCONO_x$ or a better technology - not yet invented - to comply. The threat of this action has made the SCONOx product extremely lucrative; even though it is not a fully tested product, it may be given virtual monopoly and a captive market.

Generating companies are trying to push back against the regulation by urging regulatory bodies to delay the forced use of this expensive new technology until it proven to be fully effective. As proof that the new emission control technology may not be effective, they point to turbine manufacturers such as GE, ABB, and Siemens Westinghouse, which have refused to guarantee the performance of their turbine emissions when $SCONO_x$ is attached.

ABB, sensing the momentum and the likely new regulatory drive towards regulation requiring the new technology, is tilting the balance. ABB has decided not only to guarantee its turbines' performances with $SCONO_x$, but has entered into a licensing and manufacturing agreement with the designers of the control technology. This decimates the generators' arguments that the new product they dislike must be delayed until a later date. It also takes full advantage of the monopolistic benefits of a new product with an automatic, virtually required, demand. In this way, local regulations and policies, such as the implementation of new BACT and LAER standards, may have tremendous effects on the future of gas turbine generation.

These examples demonstrate how environmental policies continue to affect the development of gas turbines. Environmental legislation and policies have been crucial to promoting the relative value of "clean" gas turbines in the power generation market. They create economic incentives for utilities and generating companies to purchase gas turbines. In promoting gas turbines, these environmental policies converge with another major regulatory thrust: the move towards electric market restructuring.

6. ELECTRIC RESTRUCTURING AND CHANGING MARKET CONDITIONS

Major changes in the electricity market led to management decisions to pursue gas turbine development. There are four main reasons why electrical restructuring is helping to drive the turbine market:

- the changing and new market conditions favor power plants with lower capital costs and shorter payback periods.
- restructuring benefits projects with short construction lead times.
- high efficiency plants are likely to thrive in a competitive market.
- generation competition leads to more dynamic and fast-changing power markets which are well suited by combustion turbines.

All four of these major effects create circumstances in which gas and combined cycle turbines may win favor if they are reliable and efficient. Indeed, the emergence of gas turbines is partially attributable to restructuring in addition to technological developments. To understand how they interact, it is important to begin with some background on the structure of the power market.

Electric restructuring refers to the partial deregulation of the electric power industry. The power industry has historically consisted of regulated monopolies which controlled vertically integrated markets. As such, utilities controlled the generation, transmission, and distribution of electric power in a certain geographic region. In the US, these utilities were regulated primarily by state authorities which controlled the rates that utilities could charge to customers. The utilities retained monopolistic benefits because they had a guaranteed set of customers. Consumers maintained some leverage through the state regulation which prevented price gouging. The system worked because the power industry was generally deemed to be a “natural monopoly” since it would produce more efficiently if competing utilities were not battling for customers by haphazardly building power lines everywhere or inputting whatever power they could into the grid and causing system congestion.

Under regulation, coal and nuclear plants were generally favored for electric power generation. The only exception for gas turbines took place in the peak power market. Gas turbines gained favor for peak power generation after 1965, when the Great Northeast Blackout occurred. This incident in the US and similar blackouts in other countries forced utilities to recognize the need to acquire additional peak power capacity for emergencies or periods of high demand. Steam turbines tend to be reliable, but do not start or stop quickly or cheaply. In contrast, gas turbines are ideal peaking units because they take only a few hours to start and can be put on-line quickly. Predictably, gas turbine orders increased in the 1970s as a result of greater concern for peaking needs. However, management strategy for baseload generation remained unchanged with the continuance of regulation.

Coal and nuclear plants used to dominate the market for three main reasons. First, they benefited from economies of scale. Coal and nuclear plants were large and successful in an era when demand was growing rapidly and electricity was cheaper to produce if it was generated in bulk.

Second, the fuel costs for these types of power stations were low. Coal and nuclear fuel materials were not lacking in the US and could readily be used to generate cheap power. Finally, utilities did not have to be concerned about large capital outlays or long payback periods. Regulation allowed them to pass costs onto consumers without fear that their customers could leave them in favor of another power generator. Making fast returns on their investments were not an overriding factor in the decisions of most utilities. Regulated rates of return allowed them to avoid making traditional business decisions regarding the benefits of their investments and power generation purchases.

In contrast, gas turbine generation was generally shunned by US utilities under regulation. Gas turbines were used almost exclusively for peak power, and even then only after emergencies convinced utilities that gas turbines were necessary and useful. Simple cycle gas turbines were embryonic and inefficient relative to large coal plants. Furthermore, gas was not always readily available. When it was, the cost per Btu of gas became higher than that of coal since 1975 and has remained higher ever since. These reasons kept gas turbines from reaching their potential during this regulated period.

The era of complete electric utility regulation has come to an end. The introduction of non-utility power producers helped to increase consumer awareness that the generation market might not be a natural monopoly. In the US, passage of the Public Utilities Regulatory Policies Act (PURPA) in 1978 opened the door to non-utility generation of power and showed that this electricity could successfully be integrated into existing power grids. The act also provided incentives for alternative power sources. The resulting entrance of new, non-utility qualifying facilities and independent power producers (IPPs) into the electricity market would later lead to consumer demand for cheaper power through competition in electric power generation. The 1992 Energy Policy Act opened the door for electric restructuring in the US.

Similar restructuring forces were at work in other countries. Great Britain, parts of Canada, Norway, Chile, and even New Zealand led the charge in electric restructuring. Although restructuring efforts vary worldwide, a basic scheme remains; the vertically integrated monopoly is to become a relic of the past. Although transmission and distribution may remain regulated, restructuring is introducing competition into the electric power generation market. This unbundling process is providing new opportunities for gas and combined cycle turbines which did not exist previously.

As the era of generation regulation ends, the high capital costs of large power plants have become huge liabilities for utilities. Utility management has been burned by the US nuclear experience, in which utilities were urged through incentives to build nuclear power plants. As noted in the previous section, regulations stemming from safety and environmental concerns increased costs for these types of plants. Nuclear plants now require enormous capital and fixed operation costs and represent stranded costs for utilities which can no longer simply pass costs to consumers in an unregulated market.

Similar capital cost problems plague coal-fired turbine power plants. With coal plant sizes varying from a few hundred megawatts to well over a gigawatt each, these plants are necessarily large and require huge investments. Use of coal also requires specific and expensive siting needs or an advanced transportation system so that trains or barges can bring fuel directly to the plant. The air standards mentioned previously also impact the initial construction fees and drive up capital costs.

In contrast, gas turbine capital outlays remain low. They tend to be considerably smaller than other plants and can be operated more efficiently and less expensively in smaller sizes than can steam or nuclear facilities.[48] In addition, they pollute less and therefore have fewer regulatory-imposed initial outlays for waste fuel disposal or scrubber technology. Finally, natural gas is now easily available by pipeline and allows for cheaper power plant siting. In some cases, plant siting may be so easy and capital costs so cheap that distributed generation takes hold and calls for even more gas turbine use. In other cases, such as in countries with weak national power grids, distributed generation may be preferable anyway in comparison to the costs of establishing an expansive and costly transmission and distribution system. In such a situation, gas turbines again have a natural advantage if they are technologically efficient enough to run cost-effectively.

Figure 12 displays how the capital costs for gas turbines are low relative to other sources of power. It shows how, at $325/kW gas turbines have the lowest capital cost outlays. As noted the previous section on technological advances, improvements in the 1990's brought cost reductions on gas and combined cycle turbines to allow the effect seen here. Average actual cost estimates vary: one estimate shows that the capital cost of combined cycle generating capacity dropped from $600/kW in 1991 to $350/kW in 1996.[49] The Energy Information Agency (EIA) pins the current costs at $400/kW instead. Despite some variation, it is clear to see from the figure that simple cycle and combined cycle gas turbines have considerably lower costs than competing energy technologies.

[48] Lee Langston, "Reasons for the Revolution" Global Gas Turbine News, Vol. 36, 1996, No. 3, p. 10.
[49] Hansen and Smock, "Gas Turbines Aim at World Power Market Dominance," *Power Engineering*, Vol. 100, No. 6, June 1996, p. 23.

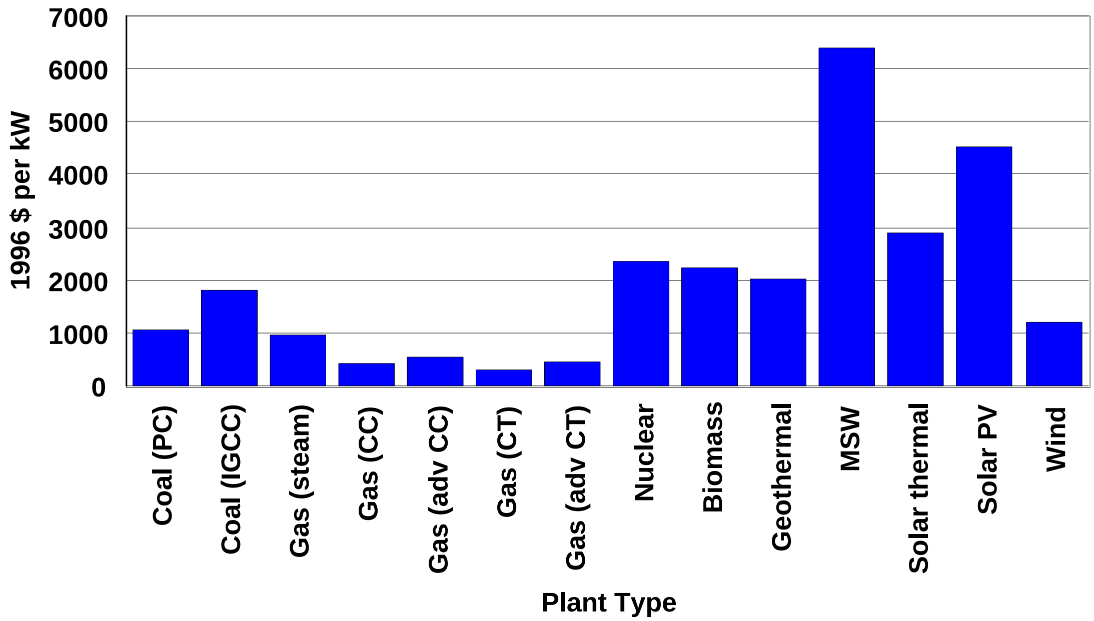

Figure 12. A key factor in the new power market is the initial capital costs for various power plants.[50]

The low capital costs of small gas and combined cycle turbines make them particularly attractive in today's market. First, less-expensive plants are the choice of favor for IPPs and non-utility generators which cannot always raise capital as easily as large investor-owned or municipally-owned utilities. Second, the ongoing changes in the market are leading to risk-averse behavior in power generation management, leading to greater interest the iterative capacity increases possible with the orders of smaller turbines. Third, once the major changes are complete and a restructured power market emerges, large investments continue to shunned because sales will no longer be guaranteed as they were during the regulated era. This merges with the risk aversion to explain why restructuring is spurring the gas turbine industry to greater heights.

Gas turbines have short construction lead times which, in conjunction with low capital costs, lead to shorter payback periods. Faster returns on investment are often preferred in a competitive setting, whereas they were less important during a fully regulated era. Small, packaged simple cycle gas units are small and easy to fuel. Gas fired combined cycle power generation can be on

[50] Costs are standard costs for the USA. Cost differences due to regional distinctions are calculated by applying regional multipliers. Adapted from Energy Information Administration, 1998 AEO, Appendix, Table 37.

line in about 2 years.[51] These short times compare favorably to lead times of ten years or even more which have been noted for some large coal and nuclear plants. Such long lead times are unacceptable in a competitive and dynamic marketplace, giving gas turbines another advantage.

A competitive market demands for high efficiency plants. When generators are forced to compete against other generators, only those who can provide electricity at low cost will survive. To reduce costs, they must achieve high levels of production operation for as little fuel as possible. A good analog of simple efficiency is heat rate, which is the number of Btu's necessary for each kWh_e of plant operation. The lower the heat rate is, the more efficient the plant will be. Figure 13 shows how combined cycle gas turbines have the lowest heat rates among all types of fossil plants. This correlates well with their high and unmatched efficiencies, which are currently reaching 60%.

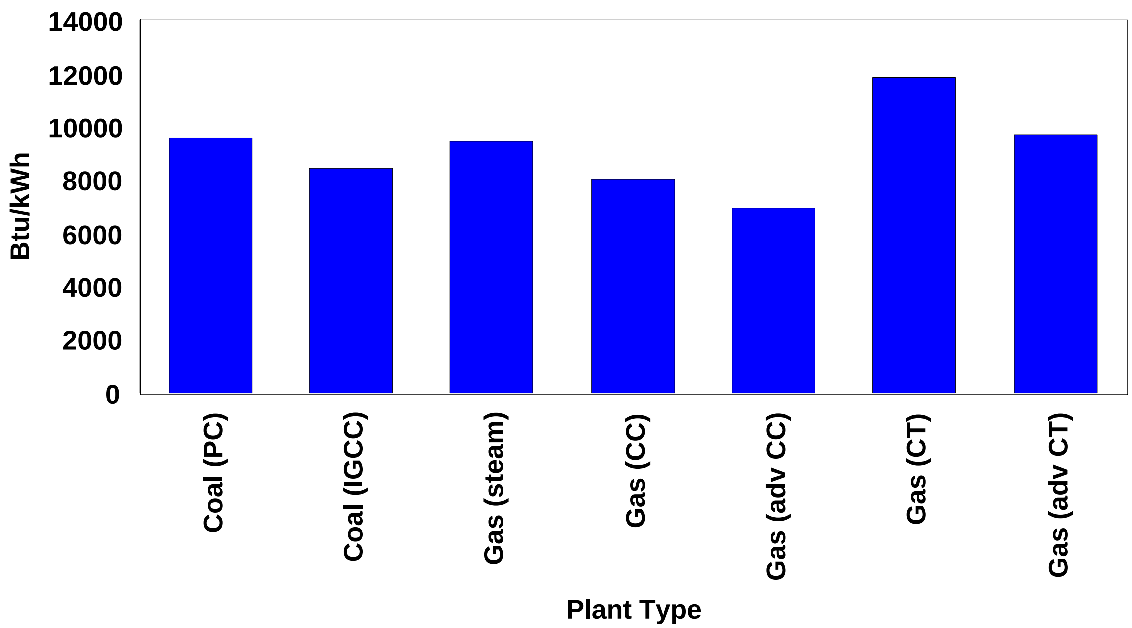

Figure 13: A major factor in the new power market is overall efficiency as illustrated by the above heat rates.[52]

[51] Gray and Nakayama, *U.S.-Japan Energy Policy Considerations for the 1990's*, Maryland: University Press of America, 1988. p. 46.
[52] Costs are standard costs for the USA. Cost differences due to regional distinctions are calculated by applying regional multipliers. Adapted from Energy Information Administration, 1998 AEO, Appendix, Table 37.

A final reason for the superiority of gas turbines in a restructured market is their ability to be dynamic in a fast-changing and unpredictable generation system. A restructured marketplace leads to another source of uncertainty for suppliers of electricity: they do not know how much electricity to provide. Although demand has always been in flux, now generators must deal with both the electricity demanded by consumers and the electricity produced by competitors. The new markets may be operated by either power exchanges or independent system operators (ISOs) which serve as market mechanisms for exchange. This complication means that individual generators do not know how much electricity to provide to a regional power pool or how little notice they will receive from an ISO before they must provide power. As electricity becomes more of a commodity in this setting, spot markets may emerge causing unprecedented dynamism in generation. If a generator receives short notice from an ISO that its electricity will be sellable in a matter of hours, it will require versatility from its generating equipment. As in the late 1960s and early 1970s, the ability of gas turbines to start and stop quickly proves to be an advantage over steam turbines, which require entire days and great expense to repeatedly fire up and cool down. Such a dynamic situation would have been unimaginable in a fully regulated power market. However, restructuring provides these new and unique circumstances for which combustion turbines are well suited.

In conclusion, electric market restructuring was among the major forces which promoted gas turbines. These market changes favored gas turbines for the four major reasons detailed in this chapter. First, gas turbine plants have lower capital costs and shorter payback periods. Second, they also have short construction lead times. Third, they have efficiencies high enough to thrive in a competitive market. Finally, gas turbines are flexible and well suited for a dynamic power market.

7. DRIVER INTERACTIONS

The four main drivers, technical improvements, gas supply, environmental concerns, and changing market conditions, were all instrumental to gas turbine development. Individually, these forces alone did not cause the gas and combustion turbine boom; it was their interaction that made success possible.

To capture the nature of this interaction, we reexamine recent gas turbine history, beginning with the period when the rise in natural gas costs strangled the new expansion of gas turbines. The late 1970s and early 1980s proved to be slow and difficult years for the gas turbine industry. This can be seen in Figure 14, which shows how US gas turbine capability stopped increasing during this period. The rest of the gas turbine history is traced along this figure with allusions to some key events.

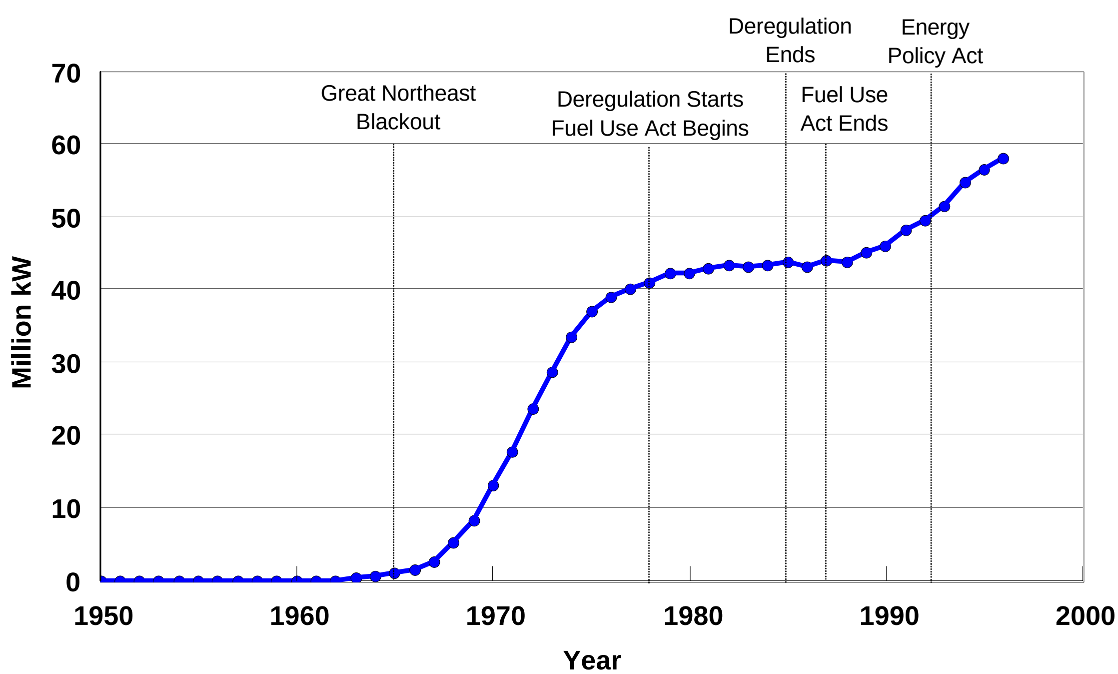

Figure 14. Electric utility net summer capability for gas turbines over time.[53]

Some factors induced manufacturers to increase R&D spending, such as the passage of the 1970 Clean Air Act which would decrease the economic attractiveness of relatively dirty coal plants.

[53] Energy Information Administration: ftp://ftp.eia.doe.gov/pub/energy.overview/aer/aer8-8.txt Table 8.8. (5/98)

However, this positive development for gas was mitigated by several negatives. A key negative development was the lack of availability (both perceived and actual) of natural gas. Gas became an uneconomical and unpopular fuel during these years, virtually shutting down utility orders of gas power plants. The flat period of Figure 14 is consistent with Figure 9, which showed how gas prices increased dramatically during the same period as a result of shortages and the US gas deregulation process which occurred from 1978-1985. In addition to these high prices, the supply of natural gas was underestimated during this period, leading many to believe that it was an unreliable fuel. Finally, the 1978 Fuel Use Act barred most utility companies from using natural gas in any new plants. Manufacturers, utilities, governments, and other potential R&D sponsors all commensurately lost interest. However, development efforts continued for the sake of international power generation and aircraft engine markets. With the help of advances in computer engineering tools (including those developed for aerospace purposes and in technology transfers from other markets) companies made incremental improvements in materials and cooling technologies, but the gas turbine market was essentially flat during this period.

Market interest in gas turbines surged in the late 1980s and 1990s when gas availability increased and gas prices dropped, and additional gas reserves had been discovered. These discoveries allowed power planners to assume that natural gas would be available for the entire life span of any gas turbines that they chose to order. The Fuel Use Act was rescinded in 1987, allowing utilities a free hand in ordering new gas turbines.

Electricity restructuring and changing market conditions were also key to the resurgence of combustion turbines. Uncertainty and impending competition led both utility and non-utility power producers to seek fast, low-capital projects such as gas turbines and high-efficiency projects such as combined-cycle turbines so that they could earn appreciable rates of return. Passage of the 1992 Energy Policy Act buttressed the deregulatory atmosphere in the US by allowing retail competition between electric generators. As competition was introduced internationally, the power generation industry continued to pursue development of low-risk, fast-starting gas turbines.

The gas turbine manufacturing industry was waiting for these other drivers to meet with their own developments. When environmental concerns, gas availability, and electric restructuring merged to create an atmosphere favorable for gas turbine deployment, manufacturers were ready to jump back into industrial turbine development. Gas turbines were primed to fill the power generation gap; technological improvements such as steam injection and advanced computer design codes had improved gas and combined cycle turbine during the earlier demand slump. The rapid rise in gas turbine popularity led to major rededication to gas turbine R&D. Brown Boveri, which had shut down its own gas turbine business in the mid 1980s, merged with Asea to become ABB and immediately began a brand new development program. Westinghouse had also reduced its combustion turbine development efforts dramatically and closed down its domestic large gas turbine manufacturing facilities, transferring its production to MHI.[54] It

[54] WJ Watson, *"The 'Success' of the Combined Cycle Gas Turbine" Opportunities and Advances in International Power Generation*, University of Durham Conference Publication, March 18-20, 1996, London: Institution of Electrical Engineers, 1996. p. 89.

almost left the gas turbine business entirely by nearly selling it to MHI in 1987.[55] However, it charged back two years later with major new development programs in the face of renewed demand. Siemens later announced plans to buy Westinghouse's Power Generation Business Unit by which it would acquire all the institutional knowledge, workers, and patents for the US manufacturer's gas turbines. Westinghouse/Siemens is currently redistributing its engineering personnel towards combustion turbines at the expense of steam turbines. The power generation market and external drivers have finally interacted with the technological developments that have been ongoing since the 1930s, propelling the entire gas turbine industry. Orders for gas turbines are again increasing as generators respond to turbine improvements, market changes and the need for more dynamic generation capability in the future. This boom can again be seen in Figure 16 by examining the most recent decade.

Today, the most important players in turbine R&D include manufacturers, purchasers, and governments. Major manufacturers include the General Electric Company, Siemens AG, Solar Turbines, Westinghouse Electric Corporation (whose power generation business has recently been acquired by Siemens), Mitsubishi Heavy Industries, and Asea Brown Boveri. These companies have growing groups of partners who are entering the expanding field. Other companies, such as Rolls-Royce and Pratt & Whitney, excel at jet engine development which sometimes lead to power generation spinoffs. Turbine purchasers are utilities and non-utility power producers worldwide. Finally, governments have also played a role in gas turbine R&D by promulgating policies and programs that affect power generation technologies.

The outlook for gas and combined turbines looks bright. While Figure 16 showed how utilities had ordered gas turbines, Figure 15 shows how utility management used the gas turbine capacity they had purchased. As narrated by the history, the utilities used the gas turbines they purchased following the 1965 Great Northeast Blackout. Then, as capacity stagnated and gas prices rose, they made less of their electricity with their gas turbines. When improved gas turbines reemerged in the market in the late 1980s and 1990s, utilities began to both order more gas turbines and operate them more often.

[55] Interview with Lee McLurin, Westinghouse.

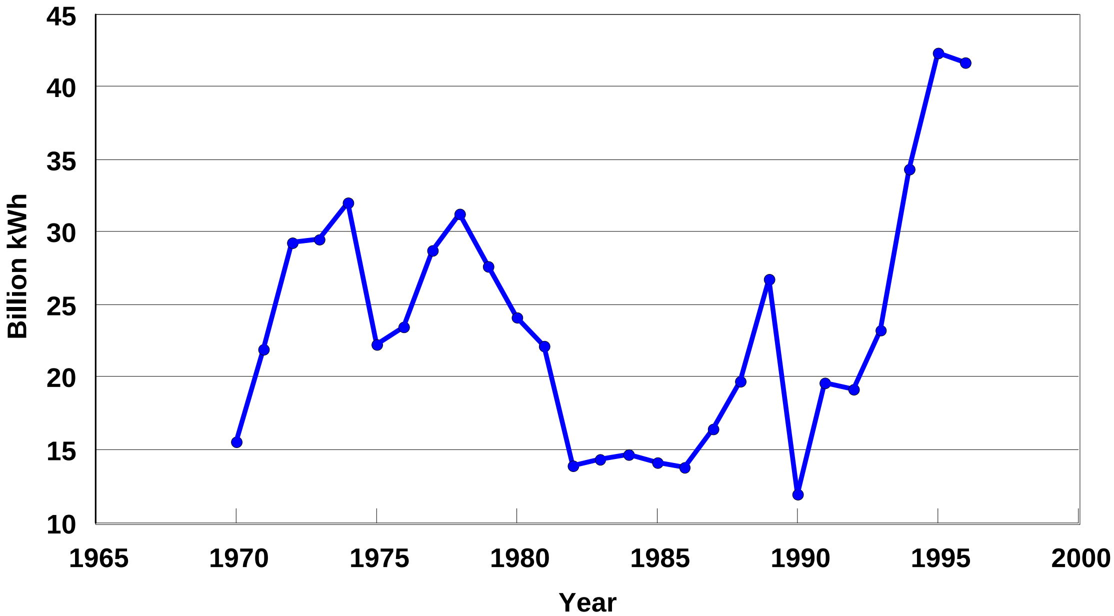

Figure 15. Net generation of gas turbine electricity at utility plants.

In addition, Figures 16 and 17 demonstrate how gas and combined cycle turbines dominate current power plant orders. Worldwide, orders for combined cycle generation totaled only 3.9 GW in 1988. By 1994, that had exploded to 26 GW with another 25 GW ordered in 1995.[56] In terms of new wattage capacity, combustion turbines alone account for over half of all new orders in the US. Combined cycle capacity is increasing by over 33% in less than a decade.[57] Combined, these two types of turbines account for almost 70% of both utility and non-utility orders domestically.

[56] Hansen and Smock, "Gas Turbines Aim at World Power Market Dominance," *Power Engineering*, Vol. 100, No. 6, June 1996, p. 23.
[57] Adapted from Energy Information Agency data which considers both existing capacity and current plant construction schedules.

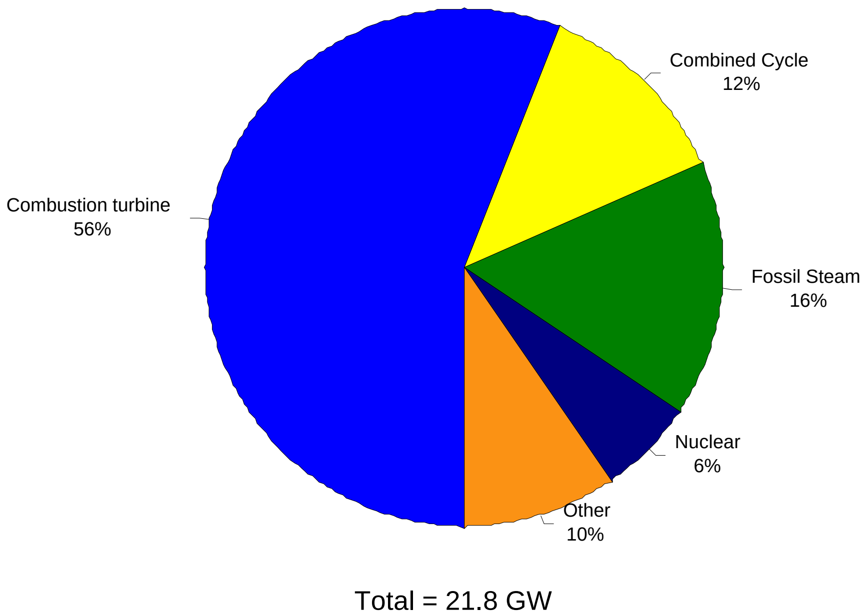

Figure 16. Combustion and combined cycle turbines dominate planned capacity additions for 1996-2000.[58]

58 Source: Utility Data: Energy Information Administration, Form EIA-860, "Annual Electric Generator Report," (1995). Nonutility Data: Energy Information Administration, Form EIA-867, "Annual Nonutility Power Producer Report," (1995).

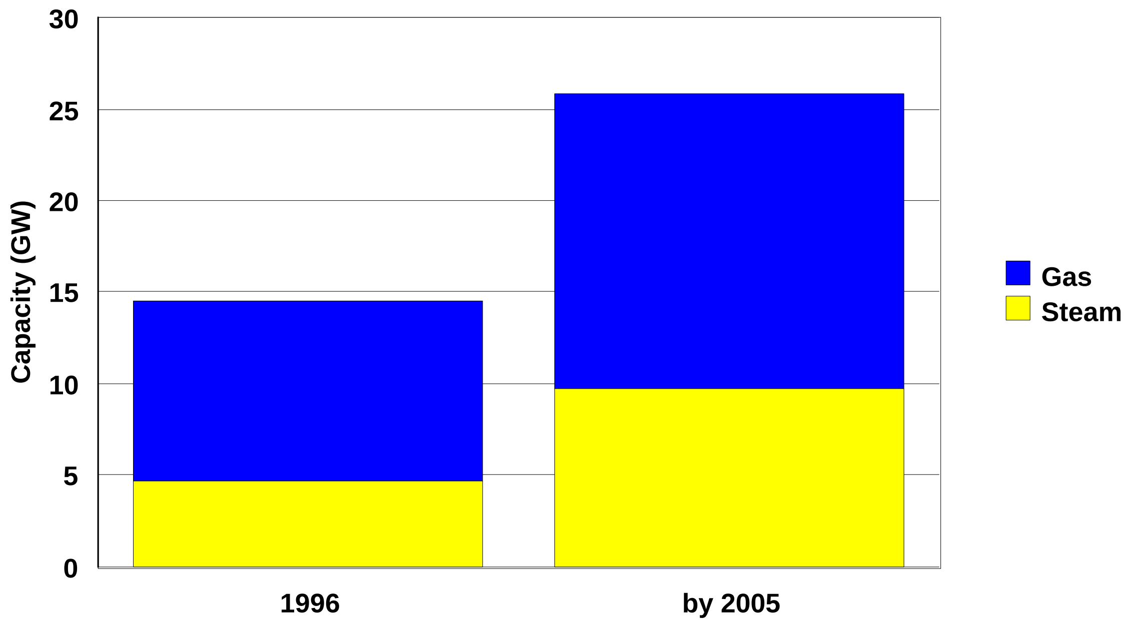

Figure 17. Projected growth of combined cycle generating capacity.

Review of the success of gas turbines reveals that development has flourished with the interaction of four major driving forces. Some of the drivers, such as material and cooling advances, include technology transfers from other fields and independent advances in the power generation engineering. Other drivers, such as gas supply, environmental concerns, and management strategy in response to market changes, are non-technological forces which nevertheless spur development. Together, these diverse influences have prompted development in the gas and combined cycle turbine industry and led to their significant entry in the power generation market.

8. LESSONS FROM OTHER CASE STUDIES

The gas turbine R&D case study is one of a series of cases analyzed for this report. The MIT Energy Laboratory also draws upon previous MIT studies in wind energy and advanced gas turbine systems. These two reports, "Technological Change and Public Policy: A Case Study of the Wind Energy Industry" and "Advanced Gas Turbine Systems" included conclusions which can be incorporated here. These are the summaries of their findings.

Wind

The wind study examined the advancement of wind turbines in the power generation market[59]. It focused on government efforts and detailed both technological innovations and policy steps which contributed to wind turbine development. According to this report, attempts to advance this field took two forms: supply push and demand pull. Each of these was a way in which governments could help to spur the wind turbine market.

Technologically, wind turbines have developed significantly since their practical inception in beginning of this century. They first became viable in areas where fuel supply was problematic for other forms of power generation. As oil, coal, and gas became more readily accessible worldwide, the wind power market floundered. Interest resurged in the 1970s when environmental and fuel pressures once again raised awareness of renewable energy.

Wind turbines progressed in materials, structure, cost, efficiency, and electronic controls. For example, blade materials have switched from wood to fiberglass. They have also advanced in geometry from simple and uniform slats to tapered, twisted, aerodynamic shapes. Structurally, some turbines advanced by combining their hubs and blades rather than requiring separable parts. The introduction of sophisticated control systems also helped these turbines with orientation, generator synchronization, and variable speed generation. However, most changes have been incremental and many basic concepts have not changed since Danish efforts of the 1950s.

Some of these advancements that did occur were made as a result of demand-side policies. The Public Utilities Regulatory Policy Act (PURPA) was instrumental because it mandated that utilities buy power from small power producers. Although it did not specifically address wind power, it promoted renewable energy technologies, from which wind turbines benefited. Government was also involved with two other forms of demand-side encouragement. The first was economic: a set of tax incentives and subsidies for use of renewable energies, making such energy commercially viable. The second was social: information dissemination and diffusion which allowed a multitude of research efforts to learn from the experiences of others.

Supply-side policies were also instrumental in wind turbine development. The largest portion of this type of support, which more directly funds R&D, was the US government's Mod program,

[59] Jeff Loiter and Vicki Norberg-Bohm, "Technological Change in Public Policy: a Case Study of the Wind Energy Industry," MIT Environmental Technology and Public Policy Program Working Paper, 1997.

which was a centralized research program which unsuccessfully attempted to develop a large-scale wind turbine that could be mass produced and would generate cost-competitive electricity. This effort was spearheaded by the National Aeronautics and Space Administration (NASA) and the Department of Energy (DOE). Research was also conducted within the DOE network of national research laboratories, which produced a few commercial wind turbines.

Both demand-side and supply-side policies related to wind energies in the US were short-lived, leading to an inconsistent overall effort. This was one of the major reasons why wind power has not achieved full commercial viability in the power market.

The wind report concluded with an analysis of which policies were successful, which were not, and why. It found that the supply-side policies were unsuccessful because there was no market to sustain development of a commercially successful turbine. In addition, there were other problems with the supply-side attempts at development. These flaws included a harmful bias towards earlier design models and poor integration of participating firms despite high costs. These problems led to incremental improvements in turbines rather than radical breakthrough technologies. Finally, it was argued that supply-side technological pushes may be unnecessary if economies of scale are utilized to make existing wind turbines competitive.

On the demand side, government market-pull policies did help in technology diffusion, but were too inconsistent to create a lasting industry. The drop in energy prices counteracted attempts to increase demand for wind energy by lowering the price of its competition. Additionally, government incentives were rushed and also failed to distinguish between turbines of various kinds and benefits, leading to the support of some low-quality turbines and degrading the field.

The wind study took special note of the importance of a consistent market for success and indicated that inconsistent government policies had failed to create such a market. It recommended improved and more consistent demand-side policies in conjunction with more path-independent supply-side efforts.

Advanced Gas Turbine Systems

The advanced gas turbine system investigation examined a subject more closely related to this case study[60]. It examined primarily combined cycle and steam injected gas turbines and their impact on the electric power industry. The report began with an analysis of the structure of the electric power and equipment industries. Then, the study focused on the innovation development process and the factors involved in the emergence of new technologies.

The historical section of the advanced gas turbine system study set the stage for the industry structure into which advanced turbines would emerge. This overview included a review of US regulatory policy, the development of electric utilities, and the nature of the turbine manufacturing industry. It then traced the driving and sustaining forces of turbine innovation.

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[60] Paolo Goncalves, Cynthia Chuang, and Adam Cohn, "Advanced Gas Turbine Systems: Innovation Development and Impacts on the Electric Power and Equipment Industries," Unpublished MIT Study, 1996.

Driving forces for innovation were deemed to be government regulatory changes such as PURPA and the Fuel Use Act. These led to technological needs from nonutility generators which had previously not existed. The shortcomings of existing turbine equipment and the improvements in modern turbine technologies were also initial drivers in the report.

Sustaining forces were of three varieties: economic, technical and structural. Economically, gas turbines were attractive because of their low capital, O&M, and fuel costs. Technically, combustion turbines gained market share because of their high efficiencies and low environmental impacts. Structurally, gas turbines benefited from the slow demand growth which led to demand for incremental, modular growth with short lead times.

The study encapsulated the innovation development process as a reinforcing cycle of advancements leading to demand, which led to more advancements. Its conclusion was that the spark to the innovation cycle were the government regulatory changes. Further, it concluded that many of the gas turbine technical advancements would have happened without the regulatory spark, but that then gas and combined cycle turbines “would not have been the revolutionary technologies that have transformed the electric power sector,” suggesting that gas turbines may have been a driver to electric restructuring.

9. CONCLUSIONS AND LESSONS

This case study focused on gas and combined cycle turbine success. These machines are technologically very complicated, far advanced from the simple aero-offshoots that gave birth to the modern industrial gas turbine industry. Multiple factors and sources went into the advancement of gas turbines into the power generation market. This report detailed how the interaction of technical R&D with other drivers led to gas turbine success.

R&D focused on improvements to turbine efficiency, reliability and emissions, with the most intense work on materials and cooling to allow high firing temperatures. Advancements continued for over 40 years before the interactive period when the current market boom began. Until then, R&D advancements were sustained by a variety of ways. Government funding of military projects were instrumental in the beginning, followed by a few smaller government industrial turbine programs. Many technologies were transferred or adapted from other industries. As the industrial turbine field grew, it emerged with more of its own independent advances. Industry managed to continue this R&D by finding niche or alternative markets which allowed them to continue gas turbine developments outside of the baseload generation market.

Other MIT case studies, such as those on advanced gas turbine systems and wind energy, point out some conclusions which can be incorporated. The study on technological change and wind energy noted that government R&D incentives did lead to innovations, but that these innovations were not marketable without commercial support; success required the interaction of markets and technological developments. It further stated the importance of continuity as a necessary factor in advancing technology. Finally, it also noted that energy prices and social factors such as environmental concerns affected development. The other study on advanced gas turbine systems pointed out that government regulatory steps were crucial to the gas turbine transformation of the electric power industry. Further, it concluded that many of the gas turbine technical advancements would have happened without the regulatory spark, but that then gas and combined cycle turbines "would not have been the revolutionary technologies that have transformed the electric power sector."

Unlike wind energy, gas and combined cycle turbines have not been heavily subsidized by government, with the notable exception of technology transfers from military turbojets. However, some key conclusions can be drawn:

- Interaction is essential. R&D is crucial, but there must be a market to support the product begin developed. This did not occur for wind energy, where the market flattened without government subsidies. The free market did not meet the product developed.

- Until the interaction occurs, developments in energy technologies can be sustained or incubated in non-energy or unrelated markets. Finding an alternative or niche market can be key to sustaining a developmental technology on its path to the baseload power generation market. In the case of gas turbines, alternative markets included military turbojets, commercial aviation, and industrial turbines for the peak power market.[61]

From these, we can glean some lessons which might be applied to future technologies. First, until drivers interact and the power generation market expands to incorporate the new technology, other applicable markets should exist - or have potential to exist - for successful and sustained R&D. In addition, there should be potential spurs for expanded demand in R&D. These spurs may be viewed as equivalents to the 1965 blackout which first prompted major interest in gas turbines. A future spur might be concern over global warming and CO_2 emissions.

A series of criteria for future R&D spending may be proposed with these lessons.

- Past performance. The level of technological development may be key to future success. It is important to have a basic research and technology base upon which to build. For example, one reason fusion energy is still a distant dream is that key basic technologies still need to be developed.

- Present opportunities. This can include an evaluation of any niche or alternative markets available. Governments may in some cases provide a niche market through its own purchasing power or through subsidization of a market.

- Future outlook. The alternative market is meant to be a stepping stone; at some point in the future, there should be a plausible interaction of forces similar to those seen in this study. This anticipated interaction should drive new demand for the new technology.

The gas and combined cycle turbine successes resulted from a complicated series of innovations, technology transfers, social concerns and market drivers. Once the recent boom was spurred, the market created a loop of technological improvement followed by implementation and increased market demand for additional improvement. With wise R&D efforts, this path may be emulated by other energy technologies.

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[61] It is interesting to note how these alternative markets can apply to other developmental technologies which are related to this study. For example, solar energy was used in space applications long before it achieved more practical uses in power generation. A future niche market for this technology might emerge in the peak power industry in certain locations. Another example of applying developments to alternative markets is the case of battery technology, which is of importance to such diverse industries and electric automobiles and laptop computers.

APPENDIX A: TURBINE TIMELINE

Early History:

1791	John Barber patent for elementary combustion turbine-compression outweighed power generation.
1873	Franz Stolze (Berlin) applies for combustion turbine patent - rejected.
1895	Charles Curtis granted US patent for complete gas turbine.
1897	Franz Stolze reapplies for patent (multistage turbines for compression and expansion) - granted.
1904	Stolze prototype in Berlin - unlikely that it ran under its own power.
1905	Armengaud (France) gas turbine developed with carborundum combustor lining (1^{st} ceramic application - demonstration only).

Modern History:

1930	Whittle applies for assistance from British Air Ministry; turned down.
1936	Brown Boveri (BB) "accidentally" created an operational gas turbine while making turbines and compressors for a Sun Oil Company process requiring superchargers in petroleum refineries.
1936	Power Jets, Ltd. is formed; platform for Whittle.
1937	Testing of first demonstration jet engine (Independent British and German efforts).
1939	Brown Boveri built first sizable gas turbine expressly for power generation. Terminal output of 4000kW; designed for standby power only (first industrial gas turbine in commercial service).
1939	(8/27) First turbojet-powered flight was made in Germany.
1941-45	British efforts (Power Jets Ltd.) fly turbojet aircraft with centrifugal compressors. Germany abandons centrifugal compressors in favor of axial compressors.
1941	Power Jets Ltd. sends engine drawings to General Electric in the US. GE makes some mechanical changes and tests its first engine, known as the I engine.

Early 40s	Wright Aeronautical Corporation, upon learning of the Power Jets Ltd. developments, tries unsuccessfully to obtain an American license for the manufacture of the Whittle engine.
1941	Westinghouse Electric Corporation, through a US Navy contract, works on an axial-flow compressor turbojet engine known as the 19. Led to first test flight in 1943 and W's first industrial gas turbine in 1949.
1942	(10/42) A modification of the first GE engine, the I-A, was first flown in a Bell P-59A.
1942	(March) Germany makes first flight with Junkers 004 engine. (Flight tested in late 1941.)
1943	(6/12) British make first flight with Rolls-Royce Welland engine. Note: The Junkers 004 and RR Welland were the only turbine engines that entered production before the end of WWII. They both had approximately the same turbine inlet temperature.
1941	GE begins work on an axial-flow turbojet engine. It later becomes the J35. (Production in 1947.)
1941	Westinghouse had already begun work on another axial-flow engine which would become the J40.
1941	Westinghouse starts development of a land-based gas turbine generator set (W12) that would have an efficiency of 18%.
Post-WWII	Pratt & Whitney Aircraft Company, which had been working on air-cooled reciprocating engines during most of the war, was not deeply involved in gas turbine work. As partial payment for the Lend-Lease during WWII, Pratt & Whitney was given the plans and details for the Rolls-Royce Nene engine and a layout of the Rolls-Royce TAY engine. These were developed further and later become the Pratt & Whitney J42 and J48 engines, respectively. Siemens, along with all other German and Japanese companies, were prevented by a ban from manufacturing combustion turbines. They did, however, recruit engineers, such as the chief designer of Junkers to work on their first designs starting in 1952.

1946	Turbine inlet temperatures of various turbojet engines: GE I16: 1472F RR Derwent I: 1560F Junkers 004-B4 (Jumo): 1472F (The only axial of those listed here) GE I40: 1472F [62]
1948	(Nov. 14) GE built the second gas turbine locomotive. It was experimental, but successful enough for an order to be placed 12/50 and the first commercial units delivered 1/52.
1949	First stationary gas turbine built in the US for the purpose of generating electric power went into service in Oklahoma City on 7/29/49. Unit was 3500 kW and had a turbine inlet temperature of 1400F.
1949	Brown Boveri placed a 10,000 kW, double-shaft unit with intercooling, regeneration, and reheat in operation in Lima, Peru.
Late 40s	Westinghouse forms a design group independent of the aircraft group to develop gas turbines for land based application.
1950	(4/50) Brown Boveri delivers the first commercial gas turbine locomotive to Great Western Railway in England.
1952	West Texas Utilities helps pioneer commercial combustion turbine baseload generation with a 5000 kW (W) unit. The new W81 combustion turbine achieves 21% efficiency at an inlet temperature of 1350F. Other technical advances included removable blading (a steam turbine spinoff) and more aerodynamic design of five-stage turbine (taken mainly from Westinghouse aircraft engine design practice).
1954	Boeing 707 makes maiden flight with four Pratt & Whitney JT-3 turbojet engines.
1954	Westinghouse offers a 5000 kW basic power generation turbine with a rotor inlet of 1350F and a full-load efficiency of 29%. Another turbine provides 15,000 kW and reaches 34% efficiency with the addition of intercooling to the regenerative cycle.
1956	GE begins development for first US turbofan engine (the CJ805-23.) It is tested on 12/27/57 and enters airline service in the 1960s.
Late 50s	Introduction of light-weight simple-cycle gas generators and gas turbines into the power generation market. They have pressure ratios of about 12 and thermal efficiencies of about 25%.

[62] William W. Bathie, Fundamentals of Gas Turbines, 2nd Ed. Ch. 1.

By the late 1950's, firing temperatures had reached 1450F.

1960	Pratt and Whitney continues development on its turbofan engine (the JT3D) until it makes its first test flight on a Boeing 707-120 on 6/22/60. It was later installed in some DC-8's.
	Cooling develops for turbojet engines
1961	General Electric designed the first "packaged" or "standardized" gas turbine power plant (turbine, generator, exciter, auxiliary equipment, etc.)
1962	Westinghouse designed the first "packaged" or "standardized" gas turbine power plant (turbine, generator, exciter, auxiliary equipment, etc.)
1965	(November '65) The "Northeast Blackout" ushers in new age of gas turbines as manufacturers are swamped with orders for peaking power plants. Gas turbine development accelerated and technical staffs expanded.
	Blade and vane cooling, pioneered by aircraft engine industry, becomes available for use in industrial turbine engineering and begin to emerge in initial designs.
Post 1965	Rotor Inlet Temperatures (RITs) approached 1550F with efficiencies of 25%.
1967	West Texas Utilities San Angelo Power station achieves a US-record 39 percent combined cycle efficiency. (W 301 turbine, 25 MW, 1450F firing temp.)

The 1960's had many utilities install simple-cycle gas turbine engines as peaking units. Generally selected due to nature of size, short lead time, and low capital costs.

Late 1960's saw the introduction of GE pre-engineered heat recovery combined cycles for power generation. The early units were from 11 MW to 21 MW.

1970	Clean Air Act charges EPA with establishing aircraft exhaust emission levels. These are published in 1973 and the first compliance date is 1/1/79.
1971	Large GE combined cycles introduced in the form of a New Jersey 340 MW plant.
1978	Natural Gas Policy Act is enacted to deregulate the natural gas industry in the United States. The deregulatory process is to happen over seven years.
	The Power Plant and Industrial Fuel Use Act bars use of gas in all new power plants. US manufacturers turn to international markets, but gas turbine industry suffers. Gas is deemed "too valuable to burn" for industrial purposes. The number of gas turbine orders at US utilities begins to flatten.

1984 Gas prospects improve with discoveries of additional reserves.

1984 First steam-injected gas turbine introduced.

1986 ABB commissions a combined cycle plant with an inlet temperature of 1070C and efficiency of 51.8%.

1980-86 showed great strides in gas exploration and the determination that natural gas could be found in prolific quantities.

This period and the late 1970s were also marked by strides in computer-assisted engineering tools which could be applied to gas turbine design.

1987 Industrial Fuel Use Act is rescinded, clearing way for use of new natural gas plants

The end of the 1980s saw the first installation of combined-cycle power plants with thermal efficiencies of greater than 50%.

Improvements over the 1990's brought cost breakthrough on combined cycle turbines. Cost of combined cycle generating capacity dropped from $600/kW in 1991 to $350/kW in 1996.[63]

1992 Congress passes the Energy Policy Act, setting the stage for deregulation of the power generation industry

1996 State of the art in simple cycle gas turbines: RIT=2300F, Efficiency = 32%.

1998 Gas turbine engineering development seeing inlet temperatures increase to around 2600F.

The late 1990's sees breaking the 60% efficiency barrier with combined cycle plants.

[63] Hansen and Smock, p. 23

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APPENDIX C: EXPERTS INTERVIEWED

Dr. Janos M. Beer, MIT Department of Mechanical Engineering (1/98)

Rep. Richard Gephardt, (D-MO) Minority Leader of the U.S. House of Representatives (11/97)

Dr. Joel Haynes, General Electric - Combustion Research, (4/98)

Sen. John Kerry, (D-MA) U.S. Senate Committee on Commerce, Science and Transportation (4/98)

Mr. Lee McLurin, Westinghouse Electric Corporation, Manager of Combustion Turbine Engineering (5/98)

Mr. David Miller, Westinghouse Electric Corporation, Combustion Turbine Sales and Marketing (5/98)

Mr. Ryan Pastrana, Westinghouse Electric Corporation - Power Generation (2/98)
General Electric - Power Systems (4/98)

Ms. Holly Propst, Legislative Assistant to Congressman Daniel Schaeffer (R-CO) Chairman of the House Commerce Subcommittee on Energy and Power (11/97)

Mr. Joseph Schlepko, Westinghouse Electric Corporation - Combustion Turbine Division (1/98)

Mr. Kirk Speer, Westinghouse Electric Corporation - Power Generation (4/98)

Dr. Craig Tedmon, Retired Director of ABB Research and Development (2/98)

Dr. David Gordon Wilson, MIT Department of Chemical and Fuel Engineering (1/98)