Advanced HIPPS for the 21st Century

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ABSTRACT

If coal is to continue as a primary fuel for generating electricity in the future, processes that use coal cleanly and efficiently are required. The U.S. Department of Energy-sponsored High Performance Power System (HIPPS) cycle cleanly produces electricity from coal at high thermal efficiencies by using an indirectly fired gas turbine and a conventional steam cycle. The performance of HIPPS is greatly affected by the chosen technology level of both steam conditions and gas turbine characteristics. Improvements in materials are expected to permit steam conditions to reach higher temperatures and pressures, and DOE's Advanced Turbine Systems program is providing enhanced gas turbine performance. To quantify these effects, each technology area (steam conditions and gas turbine characteristics) was individually analyzed for one HIPPS configuration, then the combination of different steam conditions with a variety of gas turbines was analyzed. Depending on which technology level is chosen, the HIPPS cycle efficiency can be increased from 45% to nearly 53% (higher heating value basis) and the coal fraction (fraction of heat input by coal to the system) can change by up to 28 percentage points. Also, the costs fluctuate between 35 and 43 mills/kWh, depending on what assumptions are used. This paper primarily compares cycle efficiency and coal fraction and presents preliminary estimates for capital cost and cost of electricity. The results of this analysis show the potential of HIPPS as a highly-efficient, advanced coal-based option for power generation in the 21st century.

BACKGROUND

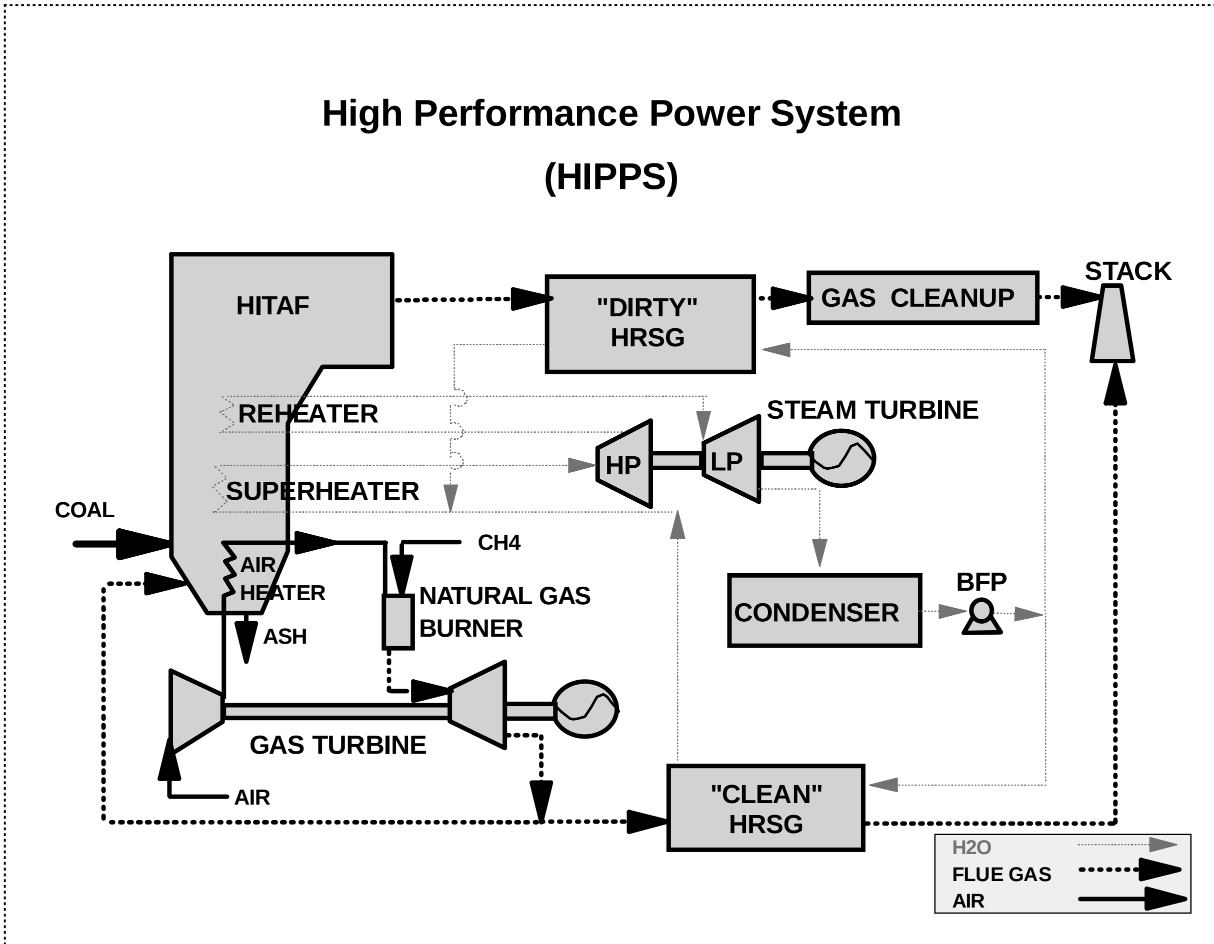
The High Performance Power Systems (HIPPS) Program is part of the Department of Energy's (DOE) Combustion 2000 Program. The objective of Combustion 2000/HIPPS is to develop advanced, coal-based power systems that offer significant improvements over today's conventional power plants with respect to thermal efficiency, environmental performance, and cost of electricity. By focusing on the development and demonstration of cost-effective, environmentally sound technologies that promise more efficient use of coal, our most abundant fossil fuel resource, the nation's dependence on potentially unreliable energy supplies can be reduced without threatening the environment.

The HIPPS cycle is based on the indirectly-fired combined cycle (Figure 1). In this cycle, only clean gas is expanded in the gas turbine, thus protecting the blades from erosion and corrosion. This is accomplished by indirectly heating the air from the gas turbine compressor in a coal-fired high-temperature advanced furnace (HITAF). Either natural gas or a clean coal-derived fuel gas is used to boost the temperature to the desired turbine inlet temperature. The vitiated air is then expanded in the gas turbine producing more than half of the cycle's power output. Heat is recovered from both the coal-fired furnace flue gas and the gas turbine exhaust to drive a conventional Rankine steam cycle. Some of the turbine exhaust air may also be recycled as preheated combustion air for the HITAF. Although ceramics may be needed for the most highly efficient systems that fire only coal, current HIPPS concepts, like the one analyzed in this paper, avoid the use of ceramic heat exchangers by using high-temperature alloys and innovative furnace designs that protect heat-transfer surfaces from corrosive gaseous components and coal ash.

The current HIPPS Program targets are to: generate electricity at 47% or better efficiency (higher heating value - HHV), reduce emissions to one-tenth of New Source Performance Standards (NSPS), use more than 95% coal on a Btu basis (early commercial systems can use coal at levels of 65%), reduce the cost of electricity by 10% compared to current coal-fired plants that meet NSPS, and be commercially available by 2004.

Several previous analyses have demonstrated the potential of the HIPPS cycle. The thermal efficiency of HIPPS was shown to approach that of a natural gas combined cycle at a cost competitive with today's best coal-fired power plants while significantly reducing emissions relative to other coal-based technologies (Klara, 1993 and 1994). Another study determined that repowering an existing pulverized coal-fired power plant with HIPPS technology was both technically viable and economically attractive (Klara et al., 1996). The HIPPS-repowered unit experienced a significant increase in efficiency with major reductions in emissions at competitive operational costs, which improved its utilization and dispatch. Further, a previous study of HIPPS with an advanced gas turbine and supercritical steam cycle estimated that a plant efficiency of more than 49% could be achieved (Klara et al., 1995). This study considered only one potential configuration; the impact of the advanced technologies on the capital cost and the cost of electricity was not determined.

Figure 1
HIPPS Layout



This previous HIPPS analysis motivated the current study, which quantifies the efficiency and cost effects of the two parameters that have significant impact on the performance of the HIPPS cycle: steam cycle conditions and gas turbine performance. The impacts of both elevated steam temperatures and pressures, and increased expansion efficiency in the steam turbine were assessed. These parameters were analyzed individually and in combination.

An advantage of the HIPPS cycle is its flexibility to raise steam to advanced conditions in the HITAF, independent of the gas turbine exhaust temperature. As throttle pressures and throttle and reheat temperatures are increased, the steam cycle efficiency increases. This study assesses the benefits of supercritical steam cycles for which there is a large, commercial experience base. The former Soviet Union (FSU) has the largest number of supercritical units in service - 220 fossil-fueled supercritical cycle plants accounting for 40% of all FSU fossil power plant capacity (EPRI, 1992). The United States has the second largest number of supercritical power plants. Of the 157 operating supercritical power plants, about 20 are double reheats (EPRI, 1985 and EPRI, 1986). As of 1994, 116 units burn coal, 40 burn natural gas, and 1 burns oil (EEI, 1994). The well-known 325 MWe Eddystone Unit 1 of Philadelphia Electric Company was designed for the highest steam conditions in the U.S. (5000 psia/ 1210°F/ 1050°F/ 1050°F). Currently, it continues to operate at 4500 psia/ 1150°F/ 1050°F/ 1050°F.

The benefits of gas turbine development for natural gas simple- and combined-cycles can also be realized by the HIPPS cycle. The primary driver for higher gas turbine efficiencies is higher gas turbine inlet temperatures (GTITs). Currently, the highest temperature gas turbines (not using ceramics) are the General Electric “H” system (Cook et al., 1996) and the Westinghouse “G” technology (McQuiggan et al., 1996), both designed to operate at 2600°F. The development of these two gas turbines is partially funded through DOE’s Advanced Turbine Systems program. Other areas of research include improved cooling techniques, better materials for the hot-gas path, lower-NO_X emissions, fuel flexibility, reheat gas turbines, etc. All of these can affect the GTIT, pressure ratio, turbine efficiency, and size.

BASE CASE ASSUMPTIONS

The base case configuration is shown in Figure 1, and the generic process was described in the Background Section. The assumptions include indirect air heating up to 1800°F and conventional subcritical steam conditions of 2400 psia/ 1000°F/ 1000°F. The gas turbine “clean” heat recovery steam generator (HRSG) superheats, boils, and heats feedwater. The HITAF superheats and reheats the steam and indirectly heats the gas turbine’s compressed air. The HITAF’s “dirty” HRSG boils and heats feedwater. The system has a wet-limestone flue gas desulfurization unit. For all the cases, the air was indirectly heated to 1800°F, the same coal (Pittsburgh #8) was used, and the general layout of the heat recovery system was maintained. The ASPEN Plus Process Simulator, version 9.2, was used for all the thermodynamic and chemical calculations.

STEAM CYCLE EFFECTS

To determine how steam conditions affect the HIPPS cycle, a series of steam cycle configurations were analyzed, ranging from a conventional subcritical steam cycle (2400 psia/ 1000°F/ 1000°F) to an advanced supercritical steam cycle (6000 psia/ 1300°F/ 1300°F/ 1300°F). As the steam conditions increase, there are two driving forces that increase the overall cycle efficiency: the elevated steam conditions (temperature and pressure) and the increased expansion efficiency in the steam turbine (technology level). For the supercritical cases, the individual effects of each driving force were calculated in addition to the overall effect, as can be seen below in Table 1. In summary, by configuring HIPPS with a conventional supercritical steam cycle (4725 psia/ 1100°F/ 1100°F/ 1100°F) instead of a conventional subcritical steam cycle, the net HHV efficiency improved by 2 percentage points. Another 2½ percentage points can be achieved by increasing the supercritical steam conditions. Generally, to increase the steam cycle conditions, more coal is required in the HITAF; hence, the coal fraction will increase.

Table 1
Sub- vs. Super-critical steam condition in HIPPS

Case #	Steam Cycle Conditions (psia/°F)	HIPPS net efficiency (HHV %)	Supercritical Improvement By (percentage points):		
			Steam Conditions	Expansion Efficiency	TOTAL
1	(2400/1000/1000)	47.23	n/a	n/a	n/a
2	(4725/1100/1100/1100)	49.33	0 (Base Case)	0 (BC)	0 (BC)
3	(5500/1200/1200/1200)	50.69	0.69	0.67	1.36
4	(6000/1300/1300/1300)	51.69	0.62	0.38	1.00
Supercritical Improvements		**2.36**	**1.31**	**1.05**	**2.36**
Total Improvements		**4.46**	n/a	n/a	n/a

The conventional subcritical steam cycle (Case 1) was based on a Stone & Webster evaluation of a Virginia Electric and Power Company unit. The conventional supercritical steam cycle (Case 2) was based on the Sargent & Lundy SOAPP Concept (Henry, 1992). The conventional supercritical steam cycle has a gross turbine efficiency about 4 percentage points above that of the subcritical steam cycle (44% -> 48%). Since the steam turbine generates about half the power in a HIPPS cycle, a net 2 percentage points increase in the HIPPS cycle is expected. As reported in Table 1, Case 2 is 2.10 percentage points more efficient than Case 1.

A sensitivity study on the supercritical steam conditions was performed by varying both the temperature/pressure conditions and the expansion efficiency assumed for the steam turbine. Three cases were analyzed: the conventional supercritical cycle mentioned above (Case 2); an advanced supercritical cycle (Case 4) using similar assumptions as a previous analysis (White, 1995); and an intermediate supercritical cycle (Case 3: 5500 psia/ 1200°F/ 1200°F/ 1200°F). For each supercritical cycle, the improvement attributed to the increase in steam conditions is isolated from the improvement caused by the increased steam turbine expansion efficiency.

The subcritical cycle consisted of a single reheat, with both the throttle and the reheat temperatures equal. The supercritical cycle consisted of a double reheat, with the throttle and both reheat temperatures equal for each case. Table 1 lists the results of the four cases. A total of 4½ percentage points can be realized by increasing a subcritical steam cycle to an advanced supercritical steam cycle in a HIPPS configuration. In addition to improving the HIPPS cycle efficiency, increasing the steam cycle conditions (from Case 1 to Case 4) also increases the coal fraction by 5 percentage points, from 64½% to 69½%.

GAS TURBINE CYCLE EFFECTS

A two-part study quantified how gas turbine characteristics affect the HIPPS cycle performance. This study consisted of a sensitivity analysis of five key gas-turbine design parameters followed by an analysis of 12 actual gas turbines, all within a HIPPS-cycle design. During the sensitivity analysis, the net HHV HIPPS cycle efficiency varied by 7 percentage points, and the coal fraction by 30 percentage points, depending on the gas turbine characteristics. These ranges narrowed to 5 and 25, respectively, when the HIPPS cycle was analyzed with actual gas turbines. Typically, coal fraction decreases as efficiency increases when natural gas is used as the topping fuel, possibly negating the operating-cost advantage of higher efficiencies. Based on these results, the selection of a gas turbine should be given careful consideration. One alternative to using natural gas as the topping fuel is using a HIPPS design that has a coal-derived syngas as a topping fuel, which may have different effects on the operating cost.

To model a gas turbine, at least five independent parameters are required. The HIPPS cycle model uses the following parameters for the gas turbine: the inlet temperature (GTIT), compressor pressure ratio (PR), polytropic efficiency of the compressor (ηc), isentropic efficiency of the expander (ηe), and cooling flow design (CF). Unfortunately, this information is not readily available to the public. Most public turbine specifications include the PR, heat rate (HR), power (PWR), and expander exit temperature (GTET). Sometimes, but not often, the GTIT is given.

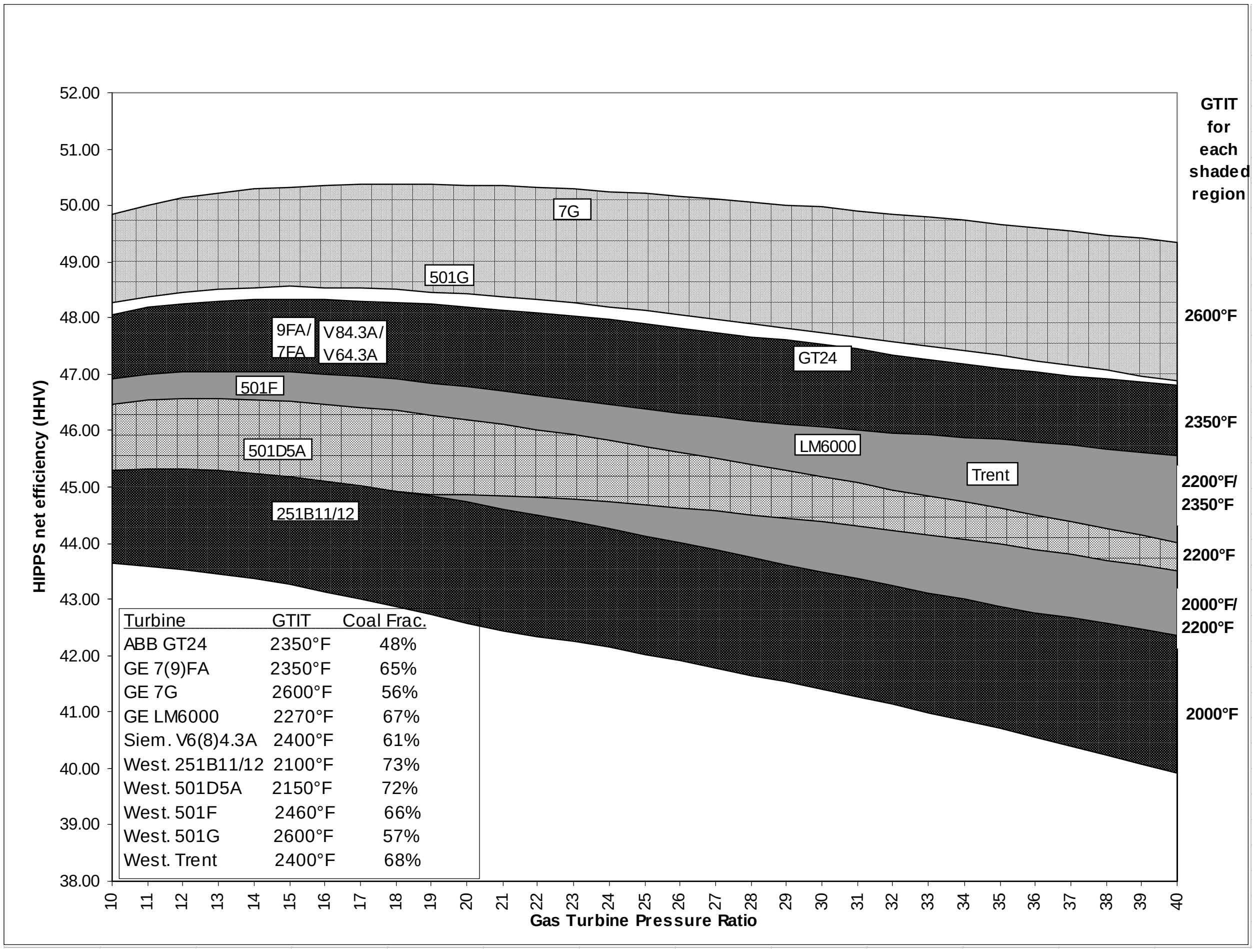
To model a gas turbine for HIPPS, the gas turbine is first modeled in simple-cycle using the publicly available information (GTIT, PR, HR, PWR, & GTET). From this simple-cycle model, the HIPPS parameters for the gas turbine (GTIT, PR, ηc, ηe, & CF) are calculated. A series of sensitivity analysis was performed to quantify how different gas-turbine parameters affect the HIPPS cycle.

Using typical values for each parameter (see Table 2), regions of HIPPS-cycle efficiencies were plotted for each GTIT. These are represented by the shaded regions, by GTIT, shown on Figure 2. The three general trends resulting from this analysis are that (1) as the GTIT increases, the cycle efficiency increases and the coal fraction decreases; (2) as pressure ratio increases, the cycle efficiency increases until about 12-20 atmospheres (depending on GTIT), then decreases; and (3) the coal fraction generally remains the same for each GTIT-class over all pressure ratios.

Table 2
HIPPS-Cycle Gas Turbine Parameters

Param.	Values
GTIT	2000°F, 2200°F, 2350°F, 2600°F
PR	10 to 40
ηc	89% to 91% polytropic efficiency
ηe	88% to 92% isentropic efficiency
CF	8% to 11% (of the total inlet air flow) for blade cooling

Figure 2
The Effect of Pressure Ratio and Gas Turbine Inlet Temperature on the Efficiency (Sensitivity and Actual Gas Turbines)[1]



The next step was to model actual gas turbines and plot those results against the sensitivity-analysis results. Twelve gas turbines were picked to represent the spectrum of likely gas turbines for use in a HIPPS cycle. This sample was selected to compare the following gas turbine characteristics: both low and high GTITs, heavy-frame and aeroderivative machines, machines available today and advanced ones, standard expansion and reheat expansion, 50 Hz and 60 Hz machines, and the ability to burn fuel gas in addition to natural gas and oil. One criterion for all selected turbines was that enough information was publicly available to model the turbine. Gas turbines from the four leading manufacturers were picked: Asea Brown Boveri (ABB), General Electric (GE), Siemens (Siem.), and Westinghouse (West.). Table 3 lists the selected gas

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[1] *NOTE:* On the graph above, each shaded band represents one (or a mixture of two) GTITs for the sensitivity study. The boxes containing the gas turbines names correspond to the HIPPS analysis using actual gas turbines, and are plotted based on pressure ratio and efficiency. The majority of the actual gas turbines fall within their respective shaded region (or band) as predicted by the sensitivity study, based on GTIT.

turbines, their published parameters, and the primary reason that they were chosen (GTWH, 1996; GTWH, 1993; and TMIH, 1996). As can be seen from the table, the inlet temperatures range from 2100°F to 2600°F, pressure ratios from 14 to 35, lower heating value (LHV) efficiencies from 32.5% to 41.5%, power from 40 MW up to 240 MW, and exit temperatures from 1130°F down to 800°F. This sampling of gas turbines is expected to yield a good representation of what can be expected from a HIPPS cycle, based only on the gas turbine parameters.

Table 3
Publicly Available Gas Turbine Parameters

Gas Turbine	GT Inlet Temp (°F)	Pressure Ratio	Heat Rate (Btu/kWhr) LHV	Power (kW)	GT Exit Temp (°F)	Key Feature
ABB GT24	2350	30.0	8,980	173,000	1130	Reheat GT
GE 7FA	2350	15.0	9,500	159,000	1100	Heavy Frame
GE 7G	2600	23.0	8,640	240,000	1062	High GTIT
GE 9FA	2350	15.0	9,570	226,500	1093	50 Hz.
GE LM6000	2270	30.0	8,775	40,010	866	Aeroderivative
Siem. V64.3A	2400	16.6	9,270	70,000	1049	Heavy Frame
Siem. V84.3A	2400	16.6	8,980	170,000	1044	Heavy Frame
West. 251B11/12	2100	15.3	10,440	49,200	968	Fuel Gas
West. 501D5A	2150	14.2	9,890	121,300	1001	Low GTIT
West. 501F	2460	14.0	9,460	167,000	1105	Fuel Gas
West. 501G	2600	19.2	8,740	235,240	1099	High GTIT
West. Trent	2400	35.0	8,210	51,190	799	Aeroderivative

The results for the actual gas turbines in a HIPPS cycle were as expected, falling into the areas designated by the earlier sensitivity analysis, as can be seen in Figure 2. The sensitivity analysis results are depicted by the shaded region for each assumed GTIT and the actual gas turbine results are depicted by the boxes, based on pressure ratio and efficiency. The highest HIPPS-cycle efficiency used the General Electric 7G technology (49%; the air-cooled version of their new, steam-cooled "H" technology system), but this had one of the lowest coal fractions (56%). The HIPPS-cycle configuration with the highest coal fraction (73%) used the Westinghouse 251B11/12 gas turbine, but this configuration also had the lowest efficiency (44%). Table 4 lists the HIPPS results using actual gas turbines, ranked by decreasing net HHV cycle efficiency. As for the coal fraction, it was driven primarily by the GTIT. Higher GTITs require more clean, gaseous fuel, thus lowering the coal fraction. To get a coal fraction in the 60's, the GTIT should be around 2300°F to 2400°F, fractions in the 70's need GTITs around 2100°F, and 2600°F GTITs yielded coal fractions in the 50's. The only exception was the reheat gas turbine (ABB GT24) which has a GTIT around 2350°F, but a coal fraction around 50%, not 65%. A reheat gas turbine is similar to a reheat steam turbine in that the hot combustion gases are expanded down from the GTIT in the turbine, but only across one stage, before more fuel is added to raise the temperature of the vitiated air back up to the GTIT. The flow is then expanded across the remaining stages. As with reheat steam turbines, reheat gas turbines are more efficient than non-reheat gas turbines. The coal fraction is low because reheating the air to 2350°F results in a fuel:air ratio similar to that seen in 2600°F- to 2700°F-class turbines.

Table 4
HIPPS Results with Actual Gas Turbines

Gas Turbine	HIPPS HHV efficiency (%)	Coal Fraction (% Input)	Net Power (kW)
GE 7G	49.33	56.14	402,875
West. 501G	48.50	57.37	383,352
GE 9FA	47.91	64.95	402,075
Siem. V84.3A	47.64	61.09	300,856
ABB GT24	47.55	48.22	279,931
GE 7FA	47.43	64.64	276,227
Siem. V64.3A	47.42	60.92	127,170
West. 501F	46.51	65.53	284,110
GE LM6000	45.96	67.07	75,265
West. 501D5A	45.44	72.08	229,402
West. Trent	45.26	67.51	94,620
West. 251B11/12	44.42	73.35	99,221

There are two types of gas turbines that were not analyzed that may have a significant impact on the performance of HIPPS. One type incorporates highly-integrated steam cooling, as proposed by the new GE "H" technology machine. This machine uses steam to cool the first couple of rotors and stators. The other turbine type that was not analyzed is the intercooled aeroderivative. This configuration may increase both the coal fraction and the cycle efficiency over the aeroderivatives analyzed in this study. Unfortunately, there is not a lot of information publicly available to design a detailed model of these turbines at this time.

COMBINED STEAM AND GAS TURBINE CYCLE EFFECTS

After analyzing the individual effects of advanced steam conditions and different gas turbines on the HIPPS cycle, the performance of various combinations of the technology levels was analyzed. For the cases discussed in this section, the choice of the steam conditions changes the net HHV HIPPS cycle efficiency by as much as 5 percentage points and the coal fraction by as much as 6 percentage points. Depending on which gas turbine is modeled, the net HHV HIPPS cycle efficiency varies by as much as 4 percentage points, and the coal fraction by as much as 16 percentage points. Typically, the coal fraction increases with advanced steam conditions, but decreases with advanced gas turbine technology; and the cycle efficiency increases with both the advanced steam conditions and advanced gas turbine technology.

The same four steam conditions described in the Steam Cycle Effects section were analyzed for the combination cases. These are shown in Table 5.

Table 5
Steam Cycle Parameters for Combination Analysis

Steam Condition	Status
2400 psia/1000°F/1000°F	Subcritical - available today
4725 psia/1100°F/1100°F/1100°F	Supercritical - available today
5500 psia/1200°F/1200°F/1200°F	Supercritical - available in the future
6000 psia/1300°F/1300°F/1300°F	Supercritical - advanced case

Based on the analysis described in the Gas Turbine Cycle Effects section, five gas turbines were chosen for the combination case. Table 6 lists these five turbines and the reason for their inclusion in this section of the analysis.

Table 6
Gas Turbine Cycle Parameters for Combination Analysis

Gas Turbine	Why?
General Electric 7FA	Base Case - Heavy Frame
General Electric 7G	Highest Efficiency
General Electric LM6000	Aeroderivative
Westinghouse 501D5A	High Coal Fraction
Westinghouse 501F	Fuel Gas Capable

Table 7 lists the results from the 20 combination cases outlined by Tables 5 and 6. Trends in efficiency and coal fraction were covered in the previous two sections, Steam Cycle Effects and Gas Turbine Cycle Effects.

As can be seen from Table 7, changing the steam cycle conditions had similar effects on efficiency, coal fraction, and net power for each gas turbine. The efficiency increased between 3½ and 5 percentage points, the coal fraction increased between 4 and 7 percentage points, and the net power increased by 27%-31%. Therefore, the effect of changing the steam condition is somewhat independent of the chosen gas turbine (i.e. high GTIT or low GTIT, heavy frame or aeroderivative, capable of using fuel gas or not).

Table 7
Effect of Combining Advanced Steam Conditions with Advanced Gas Turbines in a HIPPS Cycle

Gas Turbine	HIPPS HHV efficiency (%)	Coal Fraction (% Input)	Net Power (MW)
General Electric 7G			
2400 psia/1000°F/1000°F	49.33	56.1	403
4725 psia/1100°F/1100°F/1100°F	50.71	60.5	460
5500 psia/1200°F/1200°F/1200°F	51.90	62.4	495
6000 psia/1300°F/1300°F/1300°F	52.88	63.4	518
General Electric 7FA			
2400 psia/1000°F/1000°F	47.43	64.6	276
4725 psia/1100°F/1100°F/1100°F	49.47	67.0	309
5500 psia/1200°F/1200°F/1200°F	50.80	68.6	333
6000 psia/1300°F/1300°F/1300°F	51.78	69.6	351
Westinghouse 501F			
2400 psia/1000°F/1000°F	46.51	65.5	284
4725 psia/1100°F/1100°F/1100°F	48.68	67.9	319
5500 psia/1200°F/1200°F/1200°F	50.08	69.4	345
6000 psia/1300°F/1300°F/1300°F	51.10	70.5	364
General Electric LM6000			
2400 psia/1000°F/1000°F	45.96	67.1	75
4725 psia/1100°F/1100°F/1100°F	48.24	69.4	85
5500 psia/1200°F/1200°F/1200°F	49.69	70.9	92
6000 psia/1300°F/1300°F/1300°F	50.76	71.9	97
Westinghouse 501D5A			
2400 psia/1000°F/1000°F	45.44	72.1	229
4725 psia/1100°F/1100°F/1100°F	47.76	74.1	260
5500 psia/1200°F/1200°F/1200°F	49.25	75.4	282
6000 psia/1300°F/1300°F/1300°F	50.34	76.2	299

One advantage of combining the above technology levels is that if a particular gas turbine yields a high coal fraction but a low efficiency in a HIPPS cycle, using advanced steam conditions increases the efficiency. Take, for example, the Westinghouse 501D5A. The efficiency is increased from 45% with a subcritical steam cycle to 48%-50% with advanced supercritical steam cycles. Additional benefits include an increased coal fraction from 72% to 74%-76% and an increase in net power from 230 MW to 260-300 MW.

Another advantage of combining advanced gas turbines with advanced steam cycles is the ability to increase the HIPPS cycle efficiency to over 50%. For example, when the General Electric 7G machine is used in conjunction with a subcritical steam cycle, the HIPPS efficiency is 49% and the coal fraction is only 56%. However, when the advanced supercritical steam cycle is used, the efficiency increases to 53% and the coal fraction jumps to 63%.

CAPITAL COST ANALYSIS

Total Plant Costs (TPC) have been developed for eight of the twenty combination cases considered in this study using the Electric Power Research Institute (EPRI) guidelines for reporting costs. The conceptual capital cost estimates were developed based on several major data sources, including equipment quotes, in-house cost data, and conceptual estimating for the material and equipment not commercially available. The capital costs were calculated in accordance with EPRI Technical Assessment Guide (TAG) methodology (EPRI, 1993) for the cost of every significant piece of equipment in a Code of Accounts format. Table 8 presents the subcritical and the three supercritical GE7FA cases. The 4725 psia/ 1100°F/ 1100°F/ 1100°F steam cycle yielded the lowest capital cost among the supercritical steam cycle cases, primarily due to the increased material costs required for the higher temperature and pressures in the other two supercritical cases. Therefore, the remaining HIPPS cases in Table 7 were evaluated at the 4725 psia/ 1100°F/ 1100°F/ 1100°F steam cycle condition, as shown in Table 9. The following figure is a summary of the capital costs for all eight cases:

Figure 3
Summary of Capital Costs

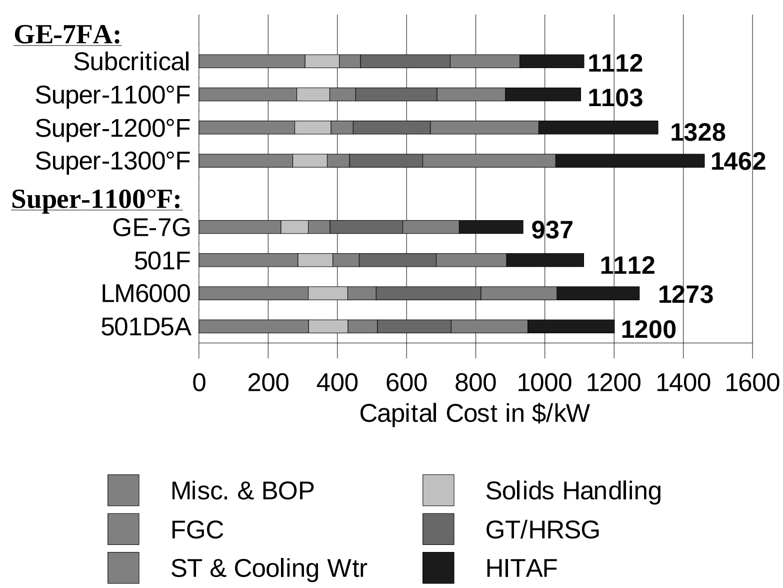


Table 8
Capital Cost Comparison Between Various HIPPS Concepts*
Using GE-7FA Gas Turbine

Account Number	**Parameter**	**Subcritical GE 7FA**	**Supercritical GE7FA** 4725/1100/1100/1100	**Supercritical GE7FA** 5500/1200/1200/1200	**Supercritical GE7FA** 6000/1300/1300/1300
	Net unit Output, MWe	276	309	333	352
1.0	Coal & Sorbent Handling	6,261	6261	8152	8152
2.0	Coal & Sorbent Prep. & Feed	9351	9444	10465	10797
3.0	Misc. B.O.P. Systems	8001	8562	9281	9679
4.0	HITAF & Accessories	41271	53951	92616	121876
5.0	Flue Gas Cleanup	13475	18590	17208	18169
6.0	Combustion Turbine & Accessories	37936	37936	37936	37936
7.0	HRSG, Ducting & Stack	19705	20425	22030	22173
8.0	Steam Turbine Generator	30841	35352	69919	94767
9.0	Cooling Water System	13726	13934	14046	14167
10.0	Ash/Spent Sorbent Handling System	6317	7926	9486	9486
11.0	Accessory Electric Plant	21501	20859	22124	22730
12.0	Instrumentation & Control	10904	11867	12552	13086
13.0	Improvements to Site	3847	3945	4088	4303
14.0	Buildings & Structures	23980	25255	26246	26984
	Bare Erected Cost	247115	274308	356151	414304
	Engineering Costs	19769	21945	28492	33144
	Process Contingency	0	0	0	0
	Project Contingency	40033	44438	57696	67117
	Total Plant Cost	$306917	$340690	$442339	$514566
	(+) $/kW	1112	1103	1328	1462

(*) Cost Year : December 1996; $x1000
(+) Dollar ($) per total plant kilowatt (kW)

Table 9
Capital Cost Comparison Between Various HIPPS Concepts*
Using Conventional Supercritical Steam Cycle

Account Number	**Parameter**	**Supercritical GE 7G** 4725/1100/1100/1100	**Supercritical 501F** 4725/1100/1100/1100	**Supercritical LM6000** 4725/1100/1100/1100	**Supercritical 501D5A** 4725/1100/1100/1100
	Net unit Output, MWe	459	319	255	260
1.0	Coal & Sorbent Handling	9101	7694	6261	7512
2.0	Coal & Sorbent Prep. & Feed	10600	10164	9312	9258
3.0	Misc. B.O.P. Systems	10347	8966	7908	8344
4.0	HITAF & Accessories	68363	57157	48853	52240
5.0	Flue Gas Cleanup	23113	19482	16757	17714
6.0	Combustion Turbine & Accessories	52222	36856	43795	26892
7.0	HRSG, Ducting & Stack	25511	20417	18580	17778
8.0	Steam Turbine Generator	47397	37657	32112	33100
9.0	Cooling Water System	12985	14563	12975	13322
10.0	Ash/Spent Sorbent Handling System	9435	7959	7926	6992
11.0	Accessory Electric Plant	25009	22124	19512	20196
12.0	Instrumentation & Control	16564	12665	10695	10874
13.0	Improvements to Site	4873	4111	3694	3732
14.0	Buildings & Structures	30756	25717	22977	23232
	Bare Erected Cost	346276	285532	261356	251186
	Engineering Costs	27702	22843	20908	20095
	Process Contingency	0	0	0	0
	Project Contingency	56097	46256	42340	40692
	Total Plant Cost	$430075	$354631	$324604	$311972
	(+) $/kW	937	1112	1273	1200

(*) Cost Year : December 1996; $x1000
(+) Dollar ($) per total plant kilowatt (kW)

All eight plant costs were based on the following assumptions:

- Plant in service year is 1997.
- TPC are expressed in 1996 dollars.
- $/kW based on total net plant kilowatts.
- Costs are grouped according to a process/system oriented code of accounts; all reasonably allocable components of a system or process are included
- The estimate boundary limit is defined as the total plant facility within the "fence line," including natural gas transmission from the main (10 miles away), coal receiving and water supply system, but terminating at the high side of the main transformers. Onsite fuel transportation equipment, such as yard locomotive, bulldozers, etc., is not included.
- All materials, components and systems are assumed commercially available, therefore, no process contingency is allocated to any case.
- Project contingency is set at 15% of the Total Plant Cost.
- Engineering, Overhead, Construction Management, & Fees are set at 8% of the base erected cost on an individual account basis. Assumed exempt from sales tax.
- Indirect labor cost is estimated at 7% of direct labor.
- The estimates represent mature technology plant, or “Nth plant”.
- All gas turbine prices are from the Gas Turbine World Handbook (GTWH, 1996).

The LM6000 cost exceeds the others because of the higher quantity of equipment required to compare with the other seven plants in the 250- to 450-MWe range. It was assumed that no one would build a plant less than 250 MW since the auxiliaries alone would make such a small plant size economically unattractive. Therefore, three gas turbines generator packages with individual heat recovery steam generators for each gas turbine were used. One benefit is that this layout provides a performance turndown capability that the other cases could not match. Although multiple gas turbine units where scoped out for this case, the remaining balance of plant equipment, wherever possible, was sized for the larger plant size.

ECONOMIC ANALYSIS

A cost of electricity (COE) analysis was performed to evaluate the impact of capital, fuel, and operating costs for the eight advanced HIPPS cases. Supercritical cycles with temperatures ranging from 1100°F to 1300°F were compared to a subcritical base case in the first set of analysis. The impact of alternate gas turbines at the supercritical steam cycle condition of 4725 psia/ 1100°F/ 1100°F/ 1100°F was evaluated in a second set of analysis.

The EPRI’s revenue requirements approach for calculating the levelized COE for the economic life of a project (EPRI, 1993) was used for this analysis. The economic criteria used for this analysis are summarized in Table 10.

Table 10
Economic Criteria

Constant dollar analysis (1997 $'s)	Service year 2000
Economic life 30 year	Plant capacity factor 0.75
Inflation rate 3.0%	Fixed charge rate 9.4%
Discount rate 4.3%	Interest during construction 7.4%
Capital real escalation 0.0%	O&M real escalation 0.0%

Fuel cost assumptions were based on the Energy Information Administration's (EIA's) 1997 projections (EIA, 1996) for a nominal energy cost scenario, which is presented in the following table:

Table 11
EIA Cost Scenario

Energy Assumptions	Nominal Value
Natural Gas, $/MMBtu	2.01
Natural gas real escalation, %/yr	1.00
Coal, $/MMBtu	1.32
Coal real escalation, %/yr	-0.9%

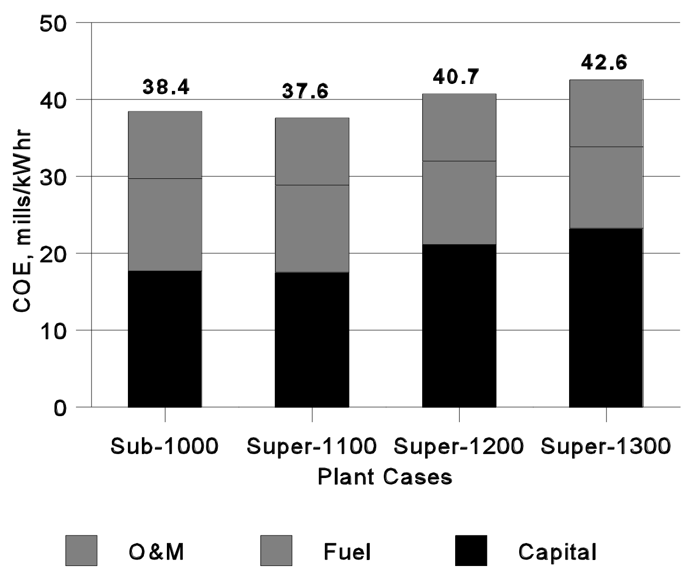
Operating and maintenance (O&M) costs used in these analysis are based on a vendor estimate. The Fixed O&M was $38.9/kW-yr and the Variable O&M was 2.8 mills/kWhr. No attempt was made to evaluate variations in O&M costs for the supercritical cases or the alternate gas turbines.

In the first set of analysis, COE's were estimated for supercritical HIPPS cycles with the following steam conditions and were compared with a base subcritical cycle case, all using the GE-7FA gas turbine. (NOTE: A portion of Table 7 reports the technical results for these cases.)

Base case	Sub-1000	2400 psia/ 1000°F/ 1000°F
Supercritical	Super-1100	4725 psia/ 1100°F/ 1100°F/ 1100°F
Supercritical	Super-1200	5500 psia/ 1200°F/ 1200°F/ 1200°F
Supercritical	Super-1300	6000 psia/ 1300°F/ 1300°F/ 1300°F

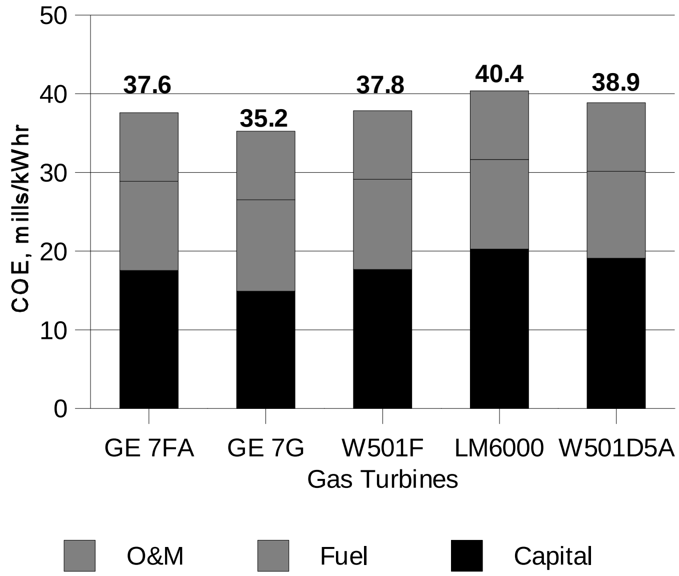
Figure 4 compares the COE for these four cases. The Super-1100 case resulted in the lowest COE and was 0.8 mills less than the base case. The contribution of capital costs to the COE was essentially equivalent for the Sub-1000 and Super-1100 cases; however, the increased plant efficiency resulted in a slight COE reduction for the supercritical case. The supercritical cases at higher temperatures had significantly higher capital costs reflecting the use of high temperature materials. As a result, the capital contribution to COE offset the reduced fuel costs resulting from efficiency gains.

Figure 4
Steam Cycle Options
Using GE-7FA Gas Turbine



Gas turbine alternatives were also evaluated on a COE basis. The reference case for this analysis was the Super-1100 case which was based on the GE 7FA turbine used with a steam cycle operating at 4725 psia/ 1100°F/ 1100°F/ 1100°F. Figure 5 compares the COE for the various turbines. As expected, the efficiency gains for the F- and G-class machines results in lower plant COE's. The lowest COE of 35.2 mills/kWhr is estimated for the G-class machine and the least cost-effective option (40.4 mills/kWhr) is the LM6000 case, which uses three small aeroderivative engines.

Figure 5
Gas Turbine Options
Using Conventional Supercritical Steam Cycle



CONCLUSION

As can be seen from Figures 2, 4, & 5 and Tables 1, 4 & 7, the HIPPS' cycle performance is greatly affected by both the steam conditions and the gas turbine that are used. The efficiency can change by 5 percentage points depending on the steam cycle and by 5 percentage points depending on the gas turbine, for a combined HIPPS efficiency range of 44% to 53% (net HHV), using the parameters outlined in this paper. The coal fraction can change by 6 percentage points depending on the steam cycle and by 28 percentage points depending on the gas turbine, for a combined HIPPS coal fraction range of 48% to 76% coal when using the parameters outlined in this paper. As the economics analysis indicated, both the choice of the steam cycle condition and of the actual gas turbine changed the cost of electricity by 5 mills/kWh each, for a combined range of 35 to 42 mills/kWh. Hence, the decision of which steam cycle and gas turbine is used has a great impact on the HIPPS cycle performance. Based on the parameters from this study, a path to a HIPPS efficiency of 53% (HHV) is possible using commercially available gas turbines (i.e., the GE 7G). If the GE 7H was used, the expected increase in efficiency would be 2 percentage points (assuming the relationship between a HIPPS-7G and a HIPPS-7H would be the same as between a Natural Gas Combined Cycle 7G and 7H), or a net HHV HIPPS efficiency of 55%.

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