FINAL REPORT

EXTERNAL REVIEW OF THE THERMAL ENERGY
STORAGE (TES)/COGENERATION
STUDY ASSUMPTIONS

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SUMMARY

This report is to provide a detailed review of the basic assumptions made in the design, sizing, performance, and economic models used in the thermal energy storage (TES)/cogeneration feasibility studies conducted by Pacific Northwest Laboratory (PNL) staff and documented in written reports PNL-8298 and PNL-8717. This report is the deliverable required under PNL contract 216743-A-R3.

A simple gas turbine cogeneration plant, as well as a combined-cycle cogeneration plant, has been integrated with oil/rock, molten salt, and Hitec salt TES systems to provide peak and/or intermediate electric power as well as a 24-hour steam load to an industrial user. The results of the PNL studies indicate that the oil/rock TES system can be economically combined with a simple gas turbine cogeneration plant for the dual functions. However, the molten salt TES system showed poor economics for either providing low pressure steam load in a simple gas turbine integrated system, or providing a high-pressure superheated steam load in the combined-cycle integrated system. PNL concluded that the reason was the extremely close approach temperatures at the heat recovery media heaters, which makes them large and expensive.

A peer-review of the PNL work in both studies was performed by Chicago Bridge & Iron (CBI). The results of the PNL work were successfully reproduced and verified. It was found that, in general, the design and economic models developed by PNL were reasonable. However, the economic model for the salt heat recovery units used an incorrect calculation for the exchanger surface area, resulting in excessively high costs and poor economics for the plants with salt systems. CBI found that the surface areas of the heat recovery units used by PNL in the cost equations were the total extended surfaces as calculated in the technical model. However, bare tube surface areas should be used in the cost equations. This correction will dramatically reduce the heater capital cost. Quotations obtained from Foster Wheeler Energy Corporation appear to confirm the validity of the cost equations of the heat recovery media heaters. CBI recommends that PNL re-assess and modify the cost models to adjust for this based on these quotations. The PNL cost data for

the media-heated steam generators could not be verified because no responsive quotes were received from vendors. However, the figures appear reasonable.

Although the other cost equations appeared reasonable, care must be exercised when the equipment size is outside the range of the correlated data or when maximum equipment size is limited and multiple units may be required. For example, in PNL-8298 the gas turbine cost equation should not be directly used to establish turbine cost above 150 MWe - the cost of multiple units is needed. Therefore, some gas turbine (G-T) cost estimations made in PNL-8298 may be unreliable for some large G-T plants.

Included in this report are CBI's replication of the PNL plant configurations and the corresponding economic analyses. Actual levelized cost analyses performed by CBI indicate that the plant economics are actually better than those reported in the PNL studies, especially for the plants with the molten salt TES system.

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1.0 INTRODUCTION

The integration of thermal energy storage system (TES) with either a simple gas turbine cogeneration plant or a combined-cycle cogeneration plant is potentially an attractive concept for the electric utility industry. The integrated system has the benefits of decoupling electric power generation and process heat production. Electric power can be generated whenever peak power capacity is needed by the utility, thus increasing the value of the power produced. The TES system captures and stores thermal energy from the gas turbine exhaust for immediate or future use of process heat. The integrated system consists of a gas turbine prime mover, heat recovery media heaters, thermal energy storage system, and media-heated steam generators. For the integrated simple gas turbine plant, low-pressure process steam is produced continuously from the TES system and delivered to the process user. For the integrated combined-cycle system, high-pressure superheated steam is produced continuously from the TES system to power a back-pressure steam turbine and then, low-pressure process steam is discharged and delivered to the process user. The additional materials and equipment necessary for a TES system will increase the initial capital cost of the integrated system. This increased cost of the integrated system must be offset by increased value and quantity of electricity generated during the peak hours.

Two studies performed by Pacific Northwest Laboratory (PNL)^(a) [PNL-8298 (Somasundaram, Brown, and Drost 1992) and PNL-8717 (Somasundaram, Brown, and Drost 1993)] have been conducted and have analyzed TES integration with simple gas turbine and combined-cycle cogeneration systems, respectively. Both studies were based on incorporating various TES systems to the integrated power systems. Their relative performances and the costs of power produced were determined and compared with conventional cogeneration and combined-cycle plants. They were all designed to provide a constant 24-hour, 181,440 kg/hr (400,000 lb/hr) steam load to a process user through oil/rock and/or molten salt, or Hitec salt TES systems. The PNL-8298 study focused on providing the

^(a) Operated for the U.S. Department of Energy by Battelle Memorial Institute under Contract DE-AC06-76RLO 1830.

constant saturated steam at two pressure levels, 690 kPa (100 psia) and 3448 kPa (500 psia). In the PNL-8717 study, it was assumed the TES system will recover and store heat, and generate high-pressure superheated steam to power the steam turbine. Then, a constant steam load (process) at 690 kPa (100 psia) is supplied by the exhaust of the steam turbine.

High-temperature thermal energy storage systems and their associated equipment are capital intensive. Reliable cost information is essential to justify those additional capital investments for integrated TES systems when compared with the costs of conventional cogeneration systems. Comparisons of assessing economic performance are made on the basis of plant energy costs levelized over plant operating lifetime (\$/kWh). Levelized costs over the plant operating lifetime were used as the basis of economic evaluation. The results of the studies indicate that oil/rock TES systems could be economically combined with a simple gas turbine cogeneration system to produce intermediate and/or peak power loads, while supplying a constant 24-hour low-pressure steam load to a process user. However, both studies showed economically less attractive results for integrating molten salt TES systems into the conventional power plant systems. Both studies showed that the system with Hitec salt TES had better economics than that of molten salt TES. PNL concluded that the primary cause of the poor economics of the molten salt TES is attributed to the extremely close approach temperatures at the heat recovery media heaters, which makes them very large and expensive.

PNL requested proposals to perform an independent review of the previous PNL studies, and placed a subcontract with Chicago Bridge & Iron (CBI). During their review, CBI found that the heat recovery exchanger surface areas calculated in the PNL reports were the total extended surface areas, not bare tube areas. Because the cost equations required the use of bare tube area, the cost of the heat recovery units were estimated at nearly an order of magnitude higher than required. Heat recovery exchanger designs were verified by quotations from Foster Wheeler Energy Corporation.

This document represents the deliverable resulting from a contract (216743-A-R3) initiated to perform a peer review of the technical and economic

assumptions of the PNL work. This report summarizes the work that CBI performed to verify the accuracy and reasonableness of the work described in the PNL reports.

2.0 REVIEW OF THE BASIC TECHNICAL ASSUMPTIONS

2.1 PLANT DESIGN ASSUMPTIONS

Common assumptions used in both PNL-8298 and PNL-8717 were:

1. Generic gas turbines (G-T) are used.
2. The recoverable heat energy in the G-T is measured relative to 25°C (77°F).
3. The following relationship is applied for the G-T generating capacity (kWe) and the recoverable thermal energy (kWt):
$$(\text{kWt}) (3413) = (\text{Heat Rate} - 3413) (\text{kWe}) (T_{\text{exh}} - T_r) / (T_{\text{exh}} - 77)$$

where: T_{exh} = temperature of the G-T exhaust gas
 T_r = temperature of the reject temperature of the G-T exhaust
4. Options for thermal storage media:
 - Heat transfer oil/rock TES
 - Molten salt
 - Hitec salt
5. All TES storage systems have a 99% thermal efficiency. An overall thermal efficiency of 97% is used for oil/salt heaters (thermal losses of 1% for the storage system and 2% for the parasitic losses of pumps and motors).
6. An overall heat transfer coefficient of 150 W/m²°C (26.6 Btu/hr-sq.ft-F) is used for sizing heat recovery steam generator (HRSG) and oil/salt heaters.
7. An overall heat transfer coefficient of 846 W/m²°C (150 Btu/hr-sq.ft-F) is used for sizing oil/salt steam generators.
8. Molten salt is a mixture of 60 wt% of sodium nitrate and 40 wt% of potassium nitrate.
9. Hitec salt is a mixture of 7 wt% of sodium nitrate, 53 wt% of potassium nitrate, and 40 wt% of sodium nitrite.
10. One-tank design for oil/rock TES system; two-tank design for salt TES system.

11. Efficiency of gas-fired boiler is 81%.
12. Saturated steam is generated from 49°C (120°F) saturated liquid water.
13. When combined with TES, two operating modes of G-T operation are considered: a 12-hour per day operation and an 8-hour per day operation.
14. The G-T is sized for twice the base case for 12-hour TES and three times the base case for 8-hour TES.

The following assumptions were used only in PNL-8298:

1. A heat rate of 11,500 Btu/kWh for G-T < 180 MWe, and a heat rate of 11,000 Btu/kWh for G-T ≥ 180 MWe.
2. G-T exhaust temperature (T_{exh}) is 526°C (988°F).
3. Reject temperatures (T_r) of G-T exhaust gas were set at 203°C, 299°C, and 203°C (400°F, 575°F, and 400°F), respectively, for oil/rock, molten salt, and Hitec salt TES systems for 690 kPa (100 psia) steam production. For the case of 3448 kPa (500 psia) steam production, the corresponding temperatures of 258°C, 299°C, and 203°C (500°F, 575°F, and 400°F) were used.
4. Operating temperature ranges were set from 148°C to 288°C (300°F to 550°F), 288°C to 505°C (550°F to 950°F), and 175°C to 450°C (350°F to 850°F), respectively, for oil/rock, molten salt, and Hitec salt TES systems with 690 kPa (100 psia) steam production. For the case of 3448 kPa (500 psia) steam production, the corresponding temperature ranges of 225°C to 288°C (440°F to 550°F), 288°C to 505°C (550°F to 950°F), and 175°C to 450°C (350°F to 850°F) were used.

The following assumptions were used only in PNL-8717:

1. A heat rate of 11,500 Btu/kWh for G-T < 100 MWe, and a heat rate of 11,000 Btu/kWh for G-T ≥ 100 MWe.
2. G-T exhaust temperature (T_{exh}) is 533°C (1000°F).
3. Reject temperatures (T_r) of G-T exhaust gas were set at 189°C to 230°C (375°F and 450°F), respectively, for the combined oil/rock and molten salt system, and the Hitec salt TES system.
4. Operating temperature ranges were set from 120°C to 288°C (250°F to 550°F), 288°C to 505°C (550°F to 950°F), and 175°C to 450°C (350°F to 850°F), respectively, for the oil/rock and molten salt system, and Hitec salt TES storage media.

5. For steam turbine calculations:

- turbine efficiency = 90%
- generator efficiency = 98%
- parasitic power loss = 2%

6. Steam turbine inlet conditions:

- Flow = 181,440 kg/hr (400,000 lb/hr)
- Pressure = 8275 kPa (1200 psia)
- Temperature = 423°C (800°F)

Most of the plant design assumptions listed above appear technically feasible and reasonable. A few comments are given as follows:

- 1) The overall heat transfer coefficient of 150 W/m²°C (26.6 Btu/hr-sq.ft-F) used for sizing HRSG and oil/salt heaters was originated from that of a pulverized-coal-fired salt heater study. With the small pressure drop limitation in the gas turbine exhaust [about 25.4 cm (10 in.) of water gauge], this value may be optimistic and needs to be verified. Note that Foster Wheeler Energy Corporation's quote shows the design of overall heat transfer coefficient (U) is about 79 W/m²°C (14 Btu/hr-sq.ft-F). Although the lower U would produce greater area, it should have only a minor effect on the economics of the system.
- 2) The areas calculated using the overall U above are total extended tube areas. These calculated areas should be converted to bare tube areas based on a specific finned-tube configuration when substituted into the economic model.
- 3) The heat rates of G-T should be used with care. Some are defined for the high heating value (HHV) of the fuel, and some are based on the low heating value (LHV). For the heat recovery of the plant design, the G-T heat rate should be based on LHV because only sensible heat is recovered.
- 4) The heat rates for the G-Ts as noted above appear high relative to the efficient units that are available today. Because fuel cost is also significant in the economics of the system, it would probably be good to modify the design model to permit the user to use actual turbine data rather than generic information.

- 5) Most heat recovery units are designed for continuous service. The long-term effects of daily cyclic service for recovering heat from the intermittently operated G-T are unknown at this time.

2.2 REPRODUCTION AND EVALUATION OF PNL'S PLANT CONFIGURATIONS

The base-case system is a conventional boiler plant, as shown in Figure 1. A conventional gas turbine cogeneration system is schematically shown in Figure 2. Both systems are designed for a base-load operation to supply the same steam loads. Schematic diagrams of the simple gas turbine plants with oil/rock, molten salt, and Hitec salt TES systems are shown in Figures 3 through 5. Figure 6 shows a schematic of a conventional combined-cycle cogeneration plant. Figures 7 and 8 show schematics of the combined-cycle plants with oil/rock and molten salt combined TES system, and Hitec salt TES system.

Figures 9 through 19 show the load curves of steam generators for various plant designs. These curves confirm that the operating temperature ranges selected by PNL, specified for different storage media are technically feasible and reasonable. Although the operating range of 120°C to 285°C (250°F to 550°F) is typical for heat transfer oil, the oil/rock TES system is forced to operate at a higher temperature (smaller operating temperature range) because of the pinch-point problem at the steam load (see Figures 11 and 12).

Using the assumptions listed in Section 2.1, various PNL plant configurations have been successfully reproduced. Tables 1, 2, and 3 are the ratings and sizes of the system components from PNL-8298 and PNL-8717. Tables 4, 5, and 6 are the corresponding results reproduced by CBI using PNL's plant design procedures.

FIGURE 1. Conventional Boiler Plant

FIGURE 2. G-T Plant with Cogeneration

Toil = 300 F for 100 psia steam generation
 440 F for 500 psia steam generation

FIGURE 3. Gas-Turbine Plant with Oil/Rock TES System

FIGURE 4. Gas-Turbine Plant with Molten Salt TES System

FIGURE 5. Gas-Turbine Plant with Hitec Salt TES System

FIGURE 6. Combined-Cycle Plant with Cogeneration

FIGURE 7. Combined-Cycle Plant with Oil/Molten Salt TES System

FIGURE 8. Combined-Cycle Plant with Hitec Salt TES System

FIGURE 9. Gas-Turbine Plant with Conventional Cogeneration HRSG (100 psia Steam)

FIGURE 10. Gas-Turbine Plant with Conventional Cogeneration HRSG (500 psia Steam)

FIGURE 11. Gas-Turbine Plant with Oil-Rock TES Oil Steam Generator (100 psia Steam)

FIGURE 12. Gas-Turbine Plant with Oil-Rock TES Oil Steam Generator (500 psia Steam)

FIGURE 13. Gas-Turbine Plant with Molten Salt TES Salt Steam Generator (100 psia Steam)

FIGURE 14. Gas-Turbine Plant with Molten Salt TES Salt Steam Generator (500 psia Steam)

FIGURE 15. Gas-Turbine Plant with Hitec Salt TES Salt Steam Generator (100 psia Steam)

FIGURE 16. Gas-Turbine Plant with Hitec Salt TES Salt Steam Generator (500 psia Steam)

FIGURE 17. Combined-Cycle Plant with Conventional Cogeneration HRSG (1200 psia, 800°F Steam)

FIGURE 18. Combined-Cycle Plant with Oil-Molten Salt TES Oil/Salt Steam Generator (1200 psia, 800°F Steam)

FIGURE 19. Combined-Cycle Plant with Hitec Salt TES Salt Steam Generator (1200 psia, 800°F Steam)

TABLE 1. Component Sizes of Various Gas-Turbine Plants - PNL Design at 100 psia

400000 lb/hr Saturated Steam @100 psia (328 F)						
	G-T	Steam	HRSG	Oil/Salt	TES	Oil/Salt
	(MW)	Produced	(SQ.FT)	Heater	(MWht)	Steam Gen.
		(lb/hr)		(SQ.FT)		(SQ.FT)
Boiler Plant	-	400000	-	-	-	-
Simple G-T (24-hr)	89	0	-	-	-	-
(12-hr)	89	0	-	-	-	-
(8-hr)	89	0	-	-	-	-
24-hr Cogen	89	400000	49782	0	0	0
12-hr TES (oil/rock)	194	400000	-	140012	1562	34803
12-hr TES (M. salt)	276	400000	-	1098035	1562	6988
12-hr TES (H. salt)	194	400000	-	393241	1562	11872
8-hr TES (oil/rock)	291	400000	-	223510	2083	34803
8-hr TES (M. salt)	413	400000	-	1646992	2083	6988
8-hr TES (H. salt)	291	400000	-	589840	2083	11872

TABLE 2. Component Sizes of Various Gas-Turbine Plants - PNL Design at 500 psia

400000 lb/hr Saturated Steam @500 psia (467 F)						
	G-T	Steam	HRSG	Oil/Salt	TES	Oil/Salt
	(MW)	Produced	(SQ.FT)	Heater	(MWht)	Steam Gen.
		(lb/hr)		(SQ.FT)		(SQ.FT)
Boiler Plant	-	400000	-	-	-	-
Simple G-T (24-hr)	90.0	-	-	-	-	-
(12-hr)	90.0	-	-	-	-	-
(8-hr)	90.0	-	-	-	-	-
24-hr Cogen	90.0	400000	70937	0	0	0
12-hr TES (oil/rock)	237.0	400000	-	182100	1587	73824
12-hr TES (M. salt)	281.0	400000	-	1115470	1587	9203
12-hr TES (H. salt)	198.0	400000	-	399485	1587	21611
8-hr TES (oil/rock)	355.0	400000	-	273139	2116	73824
8-hr TES (M. salt)	420.0	400000	-	1673144	2116	9203
8-hr TES (H. salt)	296.0	400000	-	599206	2116	21611

TABLE 3. Component Sizes of Various Combined-Cycle Plants - PNL Design at 100 psia

400000 lb/hr Steam @100 psia									
	G-T	S-T	Steam Produced	HRSG	Oil/Salt Heater	TES	Oil/Salt Steam Generator		
	(MW)	(MW)	(lb/hr)	(SQ.FT)	(SQ.FT)	(MWht)	(SQ.FT)		
Boiler Plant	-		400000	-	-	-	-		
C-C Plant (24-hr)	94.2	50.0	-	-	-	-	-		
(12-hr)	94.2	50.0	-	-	-	-	-		
(8-hr)	94.2	50.0	-	-	-	-	-		
24-hr Cogen	94.2	24.4	400000	econ. boiler suph'r	62926 66123 11205	0	0	0	
12-hr TES (oil/rock & (M. salt) w/2 GT's	207.0	24.4	400000	-	198078 700257	597 1233	econ. boiler suph'r	25607 19806 2400	
12-hr TES (H. salt) w/2 GT's	235.0	24.4	400000	-	572210	1830	econ. boiler suph'r	13304 21410 4607	
8-hr TES (oil/rock & (M. salt) w/3 GT's	309.9	24.4	400000	-	297116 1050386	795 1644	econ. boiler suph'r	25607 19806 2400	
8-hr TES (H. salt) w/3 GT's	351.9	24.4	400000	-	858314	2440	econ. boiler suph'r	13304 21410 4607	

TABLE 4. Component Sizes of Various Gas-Turbine Plants - PNL Design (reproduced by CBI) at 100 psia

400000 lb/hr Saturated Steam @ 100 psia (328 F)						
	G-T	Steam	HRSG	Oil/Salt	TES	Oil/Salt
	(MW)	Produced	(SQ.FT)	Heater	(MWht)	Steam Gen.
		(lb/hr)		(SQ.FT)		(SQ.FT)
Boiler Plant	-	400000	-	-	-	-
Simple G-T (24-hr)	85	0	-	-	-	-
(12-hr)	85	0	-	-	-	-
(8-hr)	85	0	-	-	-	-
24-hr Cogen	85	400000	49616	0	0	0
12-hr TES (oil/rock)	186	400000	-	148980	1562	35892
12-hr TES (M. salt)	264	400000	-	1099564	1562	6934
12-hr TES (H. salt)	186	400000	-	393608	1562	12070
8-hr TES (oil/rock)	278	400000	-	223461	2083	35892
8-hr TES (M. salt)	396	400000	-	1649285	2083	6934
8-hr TES (H. salt)	278	400000	-	590391	2083	12070

TABLE 5. Component Sizes of Various Gas-Turbine Plants - PNL Design (reproduced by CBI) at 500 psia

400000 lb/hr Saturated Steam @500 psia (467 F)						
	G-T	Steam	HRS	Oil/Salt	TES	Oil/Salt
	(MW)	Produced	(SQ.FT)	Heater	(MWht)	Steam Gen.
		(lb/hr)		(SQ.FT)		(SQ.FT)
Boiler Plant	-	400000	-	-	-	-
Simple G-T (24-hr)	85.0	0	-	-	-	-
(12-hr)	85.0	0	-	-	-	-
(8-hr)	85.0	0	-	-	-	-
24-hr Cogen	85.0	400000	69581	0	0	0
12-hr TES (oil/rock)	227.0	400000	-	182099	1587	72560
12-hr TES (M. salt)	268.0	400000	-	1116675	1587	9236
12-hr TES (H. salt)	188.0	400000	-	399734	1587	21280
8-hr TES (oil/rock)	340.0	400000	-	271716	2115	72560
8-hr TES (M. salt)	402.0	400000	-	1674994	2115	9236
8-hr TES (H. salt)	282.0	400000	-	599594	2115	21280

TABLE 6. Component Sizes of Various Combined-Cycle Plants - PNL Design (reproduced by CBI) at 100 psia

400000 lb/hr Steam @100 psia									
	G-T	S-T	Steam Produced	HRSG	Oil/Salt Heater	TES	Oil/Salt Steam Generator		
	(MW)	(MW)	(lb/hr)	(SQ.FT)	(SQ.FT)	(MWht)	(SQ.FT)		
Boiler Plant	-		400000	-	-	-	-		
C-C Plant (24-hr)	94.33	50.0	-	-	-	-	-		
(12-hr)	94.33	50.0	-	-	-	-	-		
(8-hr)	94.33	50.0	-	-	-	-	-		
24-hr Cogen	94.33	24.4	400000	econ. boiler suph'r	61652 64861 11203	0	0	0	
12-hr TES (oil/rock) & (M. salt) w/2 GT's	207.4	24.4	400000	-	198612	600	econ. boiler suph'r	22020	
				-	697338	1235		18891	2448
12-hr TES (H. salt) w/2 GT's	235.6	24.4	400000	-	573932	1835	econ. boiler suph'r	12937	
								20693	4575
8-hr TES (oil/rock) & (M. salt) w/3 GT's	311.1	24.4	400000	-	297919	799	econ. boiler suph'r	22020	
				-	1046007	1647		18891	2448
8-hr TES (H. salt) w/3 GT's	353.4	24.4	400000	-	860900	2446	econ. boiler suph'r	12937	
								20693	4575

CBI has the following comments concerning the results of the reproduction of these plant configurations:

- Thermal energy storage capacity (MWht) should be independent of the media type used because the same total energy must be transferred in the steam generator, and the storage efficiencies were assumed to be identical for all storage media. TES storage capacity should only be based on the number of hours of storage desired (e.g., 12 or 16 hours). Table 1 of PNL-8298 indicated varying size of TES capacity (MWht) for varying TES media, although we understand that these were adjusted before using in the economic model; the values in Table 1 of PNL-8298 should be corrected for clarity. Note that Table 3.1 of PNL-8717 correctly showed consistent MWht for varying TES media.
- CBI calculates lower G-T MWe capacity than PNL in PNL-8298 (see Table 1 vs. Table 4). CBI suspects PNL may have applied the generator efficiency (98%) and its parasitic losses (2%) as those defined for the steam turbine in PNL-8717 study, for PNL-8298. However, kWe should be directly calculated from the equation in Section 2.1, item 3 of this report.
- The steam turbine of the combined-cycle/cogeneration plant described in Table 3.1 of PNL-8717 should be a back-pressure steam turbine, and its size should be 24.4 MWe, the same as those for other plants with TES systems.
- The assumption of using generic gas turbines should be used carefully in plant sizing. For instance, the largest gas turbine available in the market place is believed to be 226.5 MWe. Some of the gas turbines reported in PNL-8298 were as large as 420 MWe. Proper sizing would be to use multiple G-T units to achieve the total power output; otherwise, erroneous conclusions may occur in the economic model.
- There is an alternate design approach for sizing the gas turbine. Instead of presetting a reject temperature (T_r) of the G-T exhaust and using the relationship of the gas turbine heat rate as stated in Section 2.1, a train of multiple actual gas turbines can be sized more realistically by using the exhaust gas flow rate and its exhaust temperature.

Comparing the PNL studies (Tables 1 through 3) to CBI's reproduction of the designs (Tables 4 through 6), all other equipment sizes seem to agree. Separately, technical specifications of the heat recovery media heaters and media-heated steam generators were prepared and sent to vendors for budgetary installed quotations. The only responding vendor was Foster Wheeler Energy Corporation, who only quoted on the heat recovery units and not the steam generators.

3.0 REVIEW OF BASIC ECONOMIC ASSUMPTIONS

3.1 ECONOMIC EVALUATION ASSUMPTIONS

Common assumptions used in both PNL-8298 and PNL-8717 were:

1. Availability of a base-load plant is 320 days/year (or 7680 hr/yr).
2. Financial parameters used:

System economic life	30 years
System depreciable life	20 years
Nominal discount rate	9.3% per year
General inflation rate	3.1% per year
Capital inflation rate	3.1% per year
Operation and maintenance (O&M) inflation rate	3.1% per year
Natural gas inflation rate	7.0% per year
Combined state and federal income tax rate	39.1%
Property tax and insurance rate	2.0%
System construction period	2 years
Price year	1990
First year of system operation	1995

3. Natural gas cost is \$2.92/MMBtu in 1990 dollars.
4. All cost equations represent the completed construction cost including direct construction cost, indirect construction costs, sales tax, and contingency. Indirect costs were estimated at 25% of the direct cost. Contingency was estimated at 15% of the sum of direct and indirect costs. State and local sales taxes were estimated at 3% of the sum of direct and indirect costs.
5. All cost equations represent the completed construction cost, and do not include allowances for start-up and working capital, which were calculated separately.
6. For oil heaters, a carbon steel tube-and-shell construction is assumed. For salt heaters, a stainless steel tube-and-shell construction is assumed.
7. For TES storage systems, the cost models are derived from a single tank design and two tank design, respectively, for an oil/rock TES system and a salt TES system.

8. To calculate the costs of the TES storage system and storage medium, the thermal storage capacity (MWht) is adjusted to a pseudo capacity (MWht_x) to reflect its physical size by the following relationship:

$$(MWht)_x = (MWht) (\text{referenced operating temp. range} / \text{operating temp. range } x)$$

where referenced operating temp. range = 148°C (300°F) for oil/rock TES

referenced operating temp. range = 258°C (500°F) for salt TES

9. For oil-heated steam generator, a carbon steel shell-and-tube construction is assumed. For salt-heated steam generator, a stainless steel shell with carbon steel tubing construction is assumed.
10. For the boiler, HRSG, and oil/salt heated steam generator, a pressure-related cost factor is applied for each 100 psi increase in steam pressure above 100 psia. That is,

$$\text{Pressure-related cost factor} = 1 + [0.0001 * (\text{pressure} - 100)]$$

11. TES media costs are based on \$0.37/lb for Hitec salt and \$0.33/lb for molten salt.

The following assumptions were used only in PNL-8298:

1. Fuel cost calculation is based on a heat requirement of 1110 Btu/lb for producing 690 kPa (100 psia) saturated steam from 49°C (120°F) water in a boiler plant. For 3448 kPa (500 psia) saturated steam, 1117 Btu/lb is used.

The following assumptions were used only in PNL-8717:

1. Fuel cost calculation is based on a heat requirement of 1075 Btu/lb for producing 690 kPa (100 psia) steam from 49°C (120°F) water in a boiler plant.

All of the above financial parameters and economic assumptions have been thoroughly reviewed. The annual inflation rates of 3.1% for capital, O&M, and general goods seem to be on the low side. It appears that a higher escalation rate, such as 4% to 5%, is more reasonable for estimating the long-term levelized costs. Future natural gas prices and availability for utility use is quite uncertain. It depends on the stability of oil prices and the rate of economic growth. Its future price has been forecasted to increase in the range of 4.29% per year to 9.09% per year (Brown et al. 1987; Electric Power Research Institute (EPRI) 1989; Gas Turbine World 1992-93). Recent gas prices (1993) have been dropping. Therefore, an annual escalation rate of 7% for projecting the long-term natural gas prices seems to be a reasonable

assumption. However, because fuel price has a major affect on economics, the economics should be evaluated to determine levelized cost sensitivity to gas price escalation. It appears that all other parameters and assumptions used are reasonable except the materials selected for salt-heated steam generators. They should be all stainless steel construction for both shell and tubing instead of a stainless steel shell and carbon steel tubing, because the salt is normally on the shell side. Although Foster Wheeler Energy Corporation did not quote the media-heated steam generators, they did recommend that a typical steam generator design has the steam on the shell side for less than 1379 kPa (200 psia) low-pressure steam. Therefore, in this low-pressure steam case, carbon steel shell and tubesheet can be used. As far as the capital cost estimating equations for the major components, CBI has the following comments:

- The capital cost model of the gas turbine was based on the raw cost data of only two plant sizes presented in Electric Power Research Institute Technical Assessment Guide (TAG) (1989) and is scaled from a 80-MWe G-T. Any cost equation will lose its accuracy when used outside the range of its correlated data. Therefore, gas turbine capital cost estimations made in PNL-8298 may be unreliable for some larger G-T plants because the largest gas turbine rating available on the market is 226.5 MWe. Multiple units for the G-Ts should be used, similar to what was done in PNL-8717.
- The capital cost model of the oil/rock TES system was based on and scaled from various sources of solar central receiver studies in early 1980s. Oil/rock storage tanks are usually made of carbon steel. Their designs and material requirements are similar to those of hot asphalt tanks. It seems that the relationships used for estimating the capital cost of the oil/rock TES system are reasonable.
- The capital cost of the molten salt TES hardware was based on the cost data from two utility solar central receiver studies sponsored by DOE in 1988. The studies were conducted by Arizona Public Service (1988) and Bechtel National, Inc. (1988). A complete construction cost estimating equation was developed from the average direct capital cost data in the studies and adjusted to include indirect construction cost, contingency, and sales tax. It appears that the estimating procedures used by PNL are reasonable.
- The capital cost equation of the Hitec salt TES hardware was modified similar to that of the molten salt TES hardware in that the relative effect of the volumetric heat capacity was adjusted for their average operating temperature range. It appears that the adjusting procedure is reasonable.

- The capital costs of heat recovery media heaters and media-heated steam generators were estimated from published estimating cost data and procedures based on the heat exchanger types and the design conditions encountered. Exchanger surface areas (extended areas) as calculated in the PNL reports, were used in the cost equations. The heat exchanger areas in the PNL cost equation are supposed to be bare tube areas. Therefore, the areas calculated by the PNL technical model must be converted to bare tube areas to provide a more accurate heater cost. CBI prepared specifications for those heat exchangers to obtain budgetary quotations from Foster Wheeler Energy Corporation; ABB Combustion Engineering Systems; Babcox & Wilcox; Zurn Industries, Inc.; Henry Vogt Machine Company; and Waste Cogeneration Technology Corporation. Foster Wheeler Energy Corporation was the only vendor to respond, and they only quoted the heat recovery media heaters. Therefore, the PNL cost data for the media-heated steam generators could not be verified. The Foster Wheeler Energy Corporation quote indicated that the ratio of a fin-tube area to bare-tube area is approximately 10:1. By comparing the Foster Wheeler Energy Corporation's quotation and the estimation from the PNL cost model, it seems that the cost model should have a multiplier of 275 instead of 224 for the salt heater if the same finned-tube configurations are used. The multiplier for the oil heater is reasonable.
- Cost equations for start-up, working capital, and operation and maintenance costs of major component systems were developed by PNL from EPRI information. It seems that the estimating relationships are reasonable. However, if any subsystem, particularly TES, cannot be brought on-line as quickly as the cycling and dispatching operation of a gas turbine, higher fuel and O&M costs may be expected. Prevention of salt solidification will also drive up O&M and fuel costs because the salt TES system must be drained or heat must be maintained.
- Care must be emphasized to distinguish if the heat rate of G-T used for plant design is based on the high heating value (HHV) or the low heating value (LHV) of the fuel. It is believed that HHV should be used to calculate the fuel consumption because it is the basis for natural gas pricing. However, LHV should be used to determine the heat recovery in using the generic G-T design procedure (PNL plant design approach) because only sensible heat is recovered. Using HHV in the heat recovery calculations would result in an under-capacity gas turbine.

3.2 REPRODUCTION AND EVALUATION OF PNL'S PLANT ECONOMICS

Using the assumptions listed in Section 2.1 and the total surface area of the heat recovery media heaters, CBI has successfully reproduced the various plant economic results as shown in PNL reports. Tables 7, 8, and 9 show the capital costs, start-up capital, working capital, annual operation and maintenance costs, and annual fuel costs based on the PNL plant

configurations presented in the reports. All data in these tables compare extremely well with the PNL reported data. Tables 10, 11, and 12 are the corresponding cost results based on the corrected bare tube surface areas (same finned-tube configuration as that of Foster Wheeler Energy Corporation quote) for salt heaters in the cost model. Correction for the oil heater is not necessary because a bare tube heater is recommended by Foster Wheeler Energy Corporation to prevent overheating of the oil. Foster Wheeler Energy Corporation recommended limiting heat flux for the oil heater to 181,440 kg/hr (4000 Btu/hr-sq.ft).

As mentioned in Section 2.1, some gas turbine capacities exceed the correlated cost data and the capital costs of the gas turbine were based on PNL cost model using the total G-T MWe in PNL-8298. Therefore, some deceptively low capital costs result in Tables 7, 8, 10, and 11.

All above cost results were compared based on levelized cost analysis. The analysis uses the same simple procedure described in PNL-6128 (Williams, Dirks, and Brown 1987) and the Accelerated Cost Recovery System (ACRS) for depreciation. Note that the levelized energy costs presented in the PNL studies and in this report were performed on a real dollar basis. A real dollar levelized cost is an energy cost that is levelized over time in dollars of constant purchasing power. The levelized energy cost may also be made on the basis of nominal dollar. Nominal dollar levelized cost is levelized over time in the actual dollars of each year. Tables 13, 14, and 15 show the reproduced economic results of plant designs based on PNL's cost data and financial parameters presented in PNL-8298 and PNL-8717 (these tables should be worked with Tables 7, 8, and 9). Tables 16, 17, and 18 are the corresponding economic results after correcting the errors in estimating the heat recovery salt heaters (these tables should be worked with Tables 10, 11, and 12).

TABLE 7. System Costs of Various Gas-Turbine Plants (100 psia Steam Load) - PNL Design
(all in 1990 millions of dollars)

	Capital Cost							Annual	Annual	Start-up Cost	Working Capital	Total	PNL8298	Diff.
	G-T	HRSG	Oil/Salt	TES		Oil/Salt	Total	Fuel	O & M			Capital	Total	
			Heater	Hardware	Medium	Steam Gen.	Const. cost	Cost*	Cost*			Cost	Cost	
Boiler Plant	0	19.56	0.00	0.00	0.00	0.00	19.56	12.30	2.30	0.82	2.53	22.91	22.9	-0.01
Simple G-T (24-hr)	33.18	0.00	0.00	0.00	0.00	0.00	33.18	22.80	5.12	1.53	4.82	39.53		
	(12-hr)	33.18	0.00	0.00	0.00	0.00	33.18	11.40	2.60	1.10	2.50	36.78		
	(8-hr)	33.18	0.00	0.00	0.00	0.00	33.18	7.60	1.75	0.96	1.72	35.86		
24-hr Cogen	33.18	3.22	0.00	0.00	0.00	0.00	36.40	22.80	5.80	1.65	4.95	43.00	42.9	-0.10
12-hr TES (oil/rock)	59.99	0.00	8.59	8.11	5.21	1.00	82.91	24.00	6.50	2.66	5.50	91.07	91.7	0.63
12-hr TES (M. salt)	78.43	0.00	122.70	12.49	24.27	0.39	238.28	34.00	19.20	7.02	10.06	255.36	255.1	-0.26
12-hr TES (H. salt)	59.99	0.00	46.26	10.31	22.33	0.60	139.48	24.00	10.40	4.12	6.43	150.03	150.5	0.47
8-hr TES (oil/rock)	81.65	0.00	13.40	10.82	6.95	1.00	113.82	24.00	6.60	3.29	5.67	122.77	123	0.23
8-hr TES (M. salt)	106.54	0.00	180.35	15.64	32.37	0.39	335.27	34.00	24.70	9.42	11.46	356.15	355.9	-0.25
8-hr TES (H. salt)	81.65	0.00	67.99	12.72	29.78	0.60	192.73	24.00	12.20	5.33	7.00	205.06	205.3	0.24

Notes: * Based on 320 days/year (7680 hours/yr) operation for a base-load plant,
and 1100 BTU/lb for steam generation.

TABLE 8. System Costs of Various Gas-Turbine Plants (500 psia Steam Load) - PNL Design
(all in 1990 millions of dollars)

	Capital Cost							Annual	Annual	Start-up Cost	Working Capital	Total	PNL8298	Diff.
	G-T	HRSG	Oil/Salt	TES		Oil/Salt	Total	Fuel	O & M			Capital	Total	
			Heater	H'ware#	Medium	Steam Gen.	Const. cost	Cost*	Cost*			Cost	Cost	
Boiler Plant	0	20.34	0.00	0.00	0.00	0.00	20.34	12.4	2.40	0.85	2.57	23.76	23.7	-0.06
Simple G-T (24-hr)	33.47	0.00	0.00	0.00	0.00	0.00	33.47	23.20	5.16	1.55	4.89	39.90		
(12-hr)	33.47	0.00	0.00	0.00	0.00	0.00	33.47	11.61	2.61	1.11	2.54	37.11		
(8-hr)	33.47	0.00	0.00	0.00	0.00	0.00	33.47	7.74	1.76	0.97	1.75	36.18		
24-hr Cogen	33.47	4.68	0.00	0.00	0.00	0.00	38.15	23.20	6.00	1.71	5.06	44.92	44.9	-0.02
12-hr TES (oil/rock)	69.85	0.00	11.03	18.74	12.03	1.90	113.55	29.40	8.40	3.54	6.87	123.96	124.4	0.44
12-hr TES (M. salt)	79.50	0.00	124.55	12.64	24.66	0.51	241.86	34.60	19.50	7.13	10.23	259.21	259.3	0.09
12-hr TES (H. salt)	60.93	0.00	46.95	10.42	22.69	1.00	142.00	24.40	10.50	4.18	6.53	152.71	152.7	-0.01
8-hr TES (oil/rock)	94.96	0.00	16.21	24.98	16.04	1.90	154.10	29.40	8.90	4.39	7.15	165.64	166.6	0.96
8-hr TES (M. salt)	107.91	0.00	183.06	15.83	32.88	0.51	340.19	34.60	25.00	9.55	11.63	361.38	361.1	-0.28
8-hr TES (H. salt)	82.71	0.00	69.02	12.87	30.25	1.00	195.85	24.40	12.40	5.42	7.11	208.38	208.5	0.12

Notes: * based on 320 days/year (7680 hours/yr) operation for a based-load plant,
and 1117 BTU/lb of steam generation.

TABLE 9. System Costs of Various Combined-Cycle Plants (100 psia Steam Load) - PNL Design
(all in 1990 millions of dollars)

	Capital Cost									PNL8717 Total Const.\$	Diff.	Annual		Start-up Cost	Working Capital	
	G-T	S-T	HRSG	Oil/Salt Heater	TES		Oil/Salt Steam Gen.	Sub- Total	Total Const.\$							
					H'ware	Medium										
Boiler Plant	0	0	19.56	0.00	0.00	0.00	0.00	19.56	19.56	19.6	0.04	11.90	2.27	0.81	2.46	
C-C Plant (24-hr)	34.65	22.15	13.29	0.00	0.00	0.00	0.00	70.08	70.08	70.1	0.02	25.90	4.35	2.26	5.39	
(12-hr)	34.65	22.15	13.29	0.00	0.00	0.00	0.00	70.08	70.08	70.1	0.02	12.90	2.44	1.85	2.91	
(8-hr)	34.65	22.15	13.29	0.00	0.00	0.00	0.00	70.08	70.08	70.1	0.02	8.60	1.80	1.72	2.08	
24-hr Cogen	34.65	18.10	econ. boiler suph'r	4.46 7.08 1.75	0.00	0.00	0.00	0.00	57.21 7.08 1.75	66.03	66.0	-0.03	24.60	5.40	2.20	5.30
12-hr TES (oil/rock & (M. salt)	74.43	18.10	0.00	12.37 82.85	3.57 10.51	1.66 19.16	econ. boiler suph'r	0.87 1.00 0.26	111.00 113.51 0.26	224.77	224.7	-0.07	25.50	16.81	6.39	8.18
12-hr TES (H. salt)	81.97	18.10	0.00	68.39	13.05	30.78	econ. boiler suph'r	0.52 1.06 0.44	212.79 214.30 1.06	214.3	0.00	29.00	14.68	6.07	8.35	
8-hr TES (oil/rock & (M. salt)	111.48	18.10	0.00	18.55 0.00	3.98 124.28	2.21 25.55	econ. boiler suph'r	0.87 1.00 0.26	155.20 163.81 0.26	319.27	319.2	-0.07	25.50	21.70	8.68	9.46
8-hr TES (H. salt)	122.79	18.10	0.00	102.58	16.37	41.04	econ. boiler suph'r	0.52 1.06 0.44	301.40 302.90 1.06	302.8	-0.10	28.90	18.34	8.14	9.39	

Notes: * Based on 320 days/year (7680 Hours/yr) operation for a based-load plant,
and 1075 BTU/lb of steam generation.

TABLE 10. System Costs of Various Gas-Turbine Plants (100 psia Steam Load) - PNL Design
(with corrected salt heater costs) (all in 1990 millions of dollars)

	Capital Cost							Annual	Annual	Start-up Cost	Working Capital	Total	PNL8298	Diff.
	G-T	HRSG	Oil/Salt	TES		Oil/Salt	Total	Fuel	O & M			Capital	Total	
			Heater	Hardware	Medium	Steam Gen.	Const. cost	Cost*	Cost*			Cost	Cost	
Boiler Plant	0	19.56	0.00	0.00	0.00	0.00	19.56	12.30	2.30	0.82	2.53	22.91	22.9	-0.01
Simple G-T (24-hr)	33.18	0.00	0.00	0.00	0.00	0.00	33.18	22.80	5.12	1.53	4.82	39.53		
	(12-hr)	33.18	0.00	0.00	0.00	0.00	33.18	11.40	2.60	1.10	2.50	36.78		
	(8-hr)	33.18	0.00	0.00	0.00	0.00	33.18	7.60	1.75	0.96	1.72	35.86		
24-hr Cogen	33.18	3.22	0.00	0.00	0.00	0.00	36.40	22.80	5.80	1.65	4.95	43.00	42.9	-0.10
12-hr TES (oil/rock)	59.99	0.00	8.59	8.11	5.21	1.00	82.91	24.00	6.50	2.66	5.50	91.07	91.7	0.63
12-hr TES (M. salt)	78.43	0.00	15.03	12.49	24.27	0.39	130.61	34.00	19.20	4.87	9.52	145.00	255.1	110.10
12-hr TES (H. salt)	59.99	0.00	5.67	10.31	22.33	0.60	98.89	24.00	10.40	3.31	6.23	108.43	150.5	42.07
8-hr TES (oil/rock)	81.65	0.00	13.40	10.82	6.95	1.00	113.82	24.00	6.60	3.29	5.67	122.77	123	0.23
8-hr TES (M. salt)	106.54	0.00	22.10	15.64	32.37	0.39	177.03	34.00	24.70	6.25	10.67	193.95	355.9	161.95
8-hr TES (H. salt)	81.65	0.00	8.33	12.72	29.78	0.60	133.07	24.00	12.20	4.14	6.70	143.91	205.3	61.39

Notes: * Based on 320 days/year (7680 hours/yr) operation for a base-load plant,
and 1100 BTU/lb for steam generation.

TABLE 11. System Costs of Various Gas-Turbine Plants (500 psia Steam Load) - PNL Design
(with corrected salt heater costs) (all in 1990 millions of dollars)

	Capital Cost							Annual Fuel Cost*	Annual O & M Cost*	Start-up Cost	Working Capital	Total Capital Cost	PNL8298	
	G-T	HRSG	Oil/Salt Heater	TES		Oil/Salt Steam Gen.	Total Const. cost						Total Cost	Diff.
				H'ware#	Medium									
Boiler Plant	0	20.34	0.00	0.00	0.00	0.00	20.34	12.4	2.40	0.85	2.57	23.76	23.7	-0.06
Simple G-T (24-hr)	33.47	0.00	0.00	0.00	0.00	0.00	33.47	23.20	5.16	1.55	4.89	39.90		
	(12-hr)	33.47	0.00	0.00	0.00	0.00	33.47	11.61	2.61	1.11	2.54	37.11		
	(8-hr)	33.47	0.00	0.00	0.00	0.00	33.47	7.74	1.76	0.97	1.75	36.18		
24-hr Cogen	33.47	4.68	0.00	0.00	0.00	0.00	38.15	23.20	6.00	1.71	5.06	44.92	44.9	-0.02
12-hr TES (oil/rock)	69.85	0.00	11.03	18.74	12.03	1.90	113.55	29.40	8.40	3.54	6.87	123.96	124.4	0.44
12-hr TES (M. salt)	79.50	0.00	15.26	12.64	24.66	0.51	132.57	34.60	19.50	4.94	9.68	147.20	259.3	112.10
12-hr TES (H. salt)	60.93	0.00	5.75	10.42	22.69	1.00	100.80	24.40	10.50	3.36	6.32	110.48	152.7	42.22
8-hr TES (oil/rock)	94.96	0.00	16.21	24.98	16.04	1.90	154.10	29.40	8.90	4.39	7.15	165.64	166.6	0.96
8-hr TES (M. salt)	107.91	0.00	22.43	15.83	32.88	0.51	179.56	34.60	25.00	6.34	10.83	196.73	361.1	164.37
8-hr TES (H. salt)	82.71	0.00	8.46	12.87	30.25	1.00	135.29	24.40	12.40	4.21	6.81	146.31	208.5	62.19

Notes: * based on 320 days/year (7680 hours/yr) operation for a based-load plant,
and 1117 BTU/lb of steam generation.

TABLE 12. System Costs of Various Combined-Cycle Plants (100 psia Steam Load) - PNL Design
(with corrected salt heater costs) (all in 1990 millions of dollars)

	Capital Cost									PNL8717	Diff.	Annual	Annual	Start-up	Working		
	G-T	S-T	HRS	Oil/Salt Heater	TES		Oil/Salt Steam Gen.	Sub- Total	Total Const.\$	Total Const.\$		Fuel	O & M				
					H'ware	Medium						Cost*	Cost*			Cost	Capital
Boiler Plant	0	0		19.56	0.00	0.00	0.00	19.56	19.56	19.6	0.04	11.90	2.27	0.81	2.46		
C-C Plant (24-hr)	34.65	22.15		13.29	0.00	0.00	0.00	70.08	70.08	70.1	0.02	25.90	4.35	2.26	5.39		
(12-hr)	34.65	22.15		13.29	0.00	0.00	0.00	70.08	70.08	70.1	0.02	12.90	2.44	1.85	2.91		
(8-hr)	34.65	22.15		13.29	0.00	0.00	0.00	70.08	70.08	70.1	0.02	8.60	1.80	1.72	2.08		
24-hr Cogen	34.65	18.10	econ. boiler suph'r	4.46 7.08 1.75	0.00	0.00	0.00	0.00	57.21 7.08 1.75	66.03	66.0	-0.03	24.60	5.40	2.20	5.30	
12-hr TES (oil/rock & (M. salt)	74.43	18.10		0.00	12.37 10.15	3.57 10.51	1.66 19.16	econ. boiler suph'r	0.87 1.00 0.26	111.00 40.82 0.26	152.08	224.7	72.62	25.50	9.90	4.36	6.66
12-hr TES (H. salt)	81.97	18.10		0.00	8.38	13.05	30.78	econ. boiler suph'r	0.52 1.06 0.44	152.79 1.06 0.44	154.29	214.3	60.01	29.00	8.98	4.39	7.10
8-hr TES (oil/rock & (M. salt)	111.48	18.10		0.00	18.55 0.00	3.98 12.99	2.21 25.55	econ. boiler suph'r	0.87 1.00 0.26	155.20 54.76 0.26	210.22	319.2	108.98	25.50	11.32	5.64	7.19
8-hr TES (H. salt)	122.79	18.10		0.00	12.57	16.37	41.04	econ. boiler suph'r	0.52 1.06 0.44	211.38 1.06 0.44	212.89	302.8	89.91	28.90	9.78	5.63	7.51

Notes: * Based on 320 days/year (7680 Hours/yr) operation for a based-load plant,
and 1075 BTU/lb of steam generation.

TABLE 13. Economic Results for Various Gas-Turbine Plants (100 psia Steam Load) - PNL Design
(capital, O&M and fuel costs are in 1990 millions of dollars)

	Plant Size (MWe)	Annual Fuel Cost	Annual O & M Cost	Initial Capital Cost	Working Capital	Start-up Cost	Present Value			Annualized	Steam*	Breakeven*	Electric
							Capital	O & M	Fuel	Cost	Levelized Cost (\$/Klb)	Levelized Elect. rate (\$/KWh)	Revenue (\$/yr)
Boiler Plant	-	12.30	2.30	19.56	2.53	0.82	26.55	35.72	353.78	38.04	9.015	-	-
Simple G-T (24-hr)	89	22.80	5.12	33.18	4.82	1.53	45.79	79.51	655.78	71.23		0.076	51,856,099
(12-hr)	89	11.40	2.60	33.18	2.50	1.10	42.68	40.38	327.89	38.34		0.082	27,909,108
(8-hr)	89	7.60	1.75	33.18	1.72	0.96	41.64	27.18	218.59	27.36		0.087	19,916,489
24-hr Cogen	89	22.80	5.80	36.40	4.95	1.65	49.82	90.07	655.78	72.71		0.037	25,239,451
12-hr TES (oil/rock)	194	24.00	6.50	82.91	5.50	2.66	105.72	100.95	690.30	84.26		0.045	33,646,003
12-hr TES (M. salt)	276	34.00	19.20	238.28	10.06	7.02	296.62	298.18	977.92	152.90		0.079	83,619,139
12-hr TES (H. salt)	194	24.00	10.40	139.48	6.43	4.12	174.26	161.51	690.30	98.86		0.059	44,276,148
8-hr TES (oil/rock)	291	24.00	6.60	113.82	5.67	3.29	142.59	102.50	690.30	89.36		0.050	37,363,565
8-hr TES (M. salt)	413	34.00	24.70	335.27	11.46	9.42	413.80	383.59	977.92	176.26		0.095	100,622,761
8-hr TES (H. salt)	291	24.00	12.20	192.73	7.00	5.33	238.24	189.47	690.30	109.96		0.070	52,355,577

* This levelized cost is based on a real dollar basis.

TABLE 14. Economic Results for Various Gas-Turbine Plants (500 psia Steam Load) - PNL Design
(capital, O&M, and fuel costs are in 1990 millions of dollars)

	Plant Size (MWe)	Annual Fuel Cost	Annual O & M Cost	Initial Capital Cost	Working Capital	Start-up Cost	Present Value			Annualized	Steam* Levelized Cost (\$/Klb)	Breakeven* Levelized Elect. rate (\$/KWh)	Electric Revenue (\$/yr)
							Capital	O & M	Fuel	Cost			
Boiler Plant	-	12.40	2.40	20.34	2.57	0.85	27.54	37.27	356.65	38.56	9.139	-	-
Simple G-T (24-hr)	90	23.20	5.16	33.47	4.89	1.55	46.23	80.14	667.29	72.36		0.076	52,680,295
(12-hr)	90	11.61	2.61	33.47	2.54	1.11	43.08	40.53	333.93	38.94		0.082	28,346,765
(8-hr)	90	7.74	1.76	33.47	1.75	0.97	42.03	27.33	222.62	27.78		0.088	20,223,399
24-hr Cogen	90	23.20	6.00	38.15	5.06	1.71	52.05	93.18	667.29	74.30		0.038	26,017,097
12-hr TES (oil/rock)	237	29.40	8.40	113.33	6.87	3.54	143.66	130.45	845.62	105.72		0.054	48,892,519
12-hr TES (M. salt)	281	34.60	19.50	241.86	10.23	7.13	301.11	302.84	995.18	155.44		0.079	85,088,582
12-hr TES (H. salt)	198	24.40	10.50	142.00	6.53	4.18	177.37	163.07	701.80	100.43		0.059	45,040,236
8-hr TES (oil/rock)	355	29.40	8.90	154.10	7.15	4.39	192.39	138.22	845.62	112.98		0.060	54,172,756
8-hr TES (M. salt)	420	34.60	25.00	340.19	11.63	9.55	419.86	388.25	995.18	179.01		0.095	102,247,238
8-hr TES (H. salt)	296	24.40	12.40	195.85	7.11	5.42	242.10	192.57	701.80	111.77		0.070	53,293,008

* This levelized cost is based on a real dollar basis.

TABLE 15. Economic Results for Various Combined-Cycle Plants (100 psia Steam Load) - PNL Design
(capital, O&M, and fuel costs are in 1990 millions of dollars)

	G-T Size (MWe)	S-T Size (MWe)	Annual	Annual	Initial	Working Capital	Start-up Cost	Present Value			Annualized Cost	Steam*	Breakeven*	Electric Revenue (\$/yr)
			Fuel Cost	O & M Cost	Capital Cost			Capital	O & M	Fuel		Levelized Cost (\$/Klb)	Levelized Elect. rate (\$/KWh)	
Boiler Plant	-		11.90	2.30	19.56	2.46	0.81	26.46	35.72	342.27	37.01	8.771	-	-
C-C Plant (24-hr)	94.2	50	25.90	4.40	70.08	5.39	2.26	90.21	68.33	744.95	84.11		0.055	61,233,588
(12-hr)	94.2	50	12.90	2.80	70.08	2.91	1.85	86.94	43.48	371.04	48.39		0.064	35,228,350
(8-hr)	94.2	50	8.60	2.10	70.08	2.08	1.72	85.86	32.61	247.36	36.34		0.072	26,455,531
24-hr Cogen	94.2	24.4	24.60	5.40	66.03	5.30	2.20	85.32	83.86	707.56	81.52		0.036	32,404,187
12-hr TES (oil/rock & (M.salt)	207	24.4	25.50	16.30	224.77	8.18	6.39	278.06	253.14	733.44	124.78		0.065	63,898,675
12-hr TES (H. salt)	235	24.4	29.00	14.10	214.30	8.35	6.07	265.71	218.97	834.11	128.99		0.061	66,966,297
8-hr TES (oil/rock & (M.salt)	309.9	24.4	25.50	21.40	319.27	9.46	8.68	392.08	332.34	733.44	147.16		0.082	80,191,204
8-hr TES (H. salt)	351.9	24.4	28.90	17.90	302.90	9.39	8.14	372.34	277.99	831.23	148.34		0.074	81,046,835

* This levelized cost is based on a real dollar basis.

TABLE 16. Economic Results for Various Gas-Turbine Plants (100 psia Steam Load) - PNL Design
(with corrected salt heater costs) (capital, O&M, and fuel costs are in 1990 millions of dollars)

	Plant Size (MWe)	Annual Fuel Cost	Annual O & M Cost	Initial Capital Cost	Working Capital	Start-up Cost	Present Value			Annualized Cost	Steam* Levelized Cost (\$/Klb)	Breakeven* Levelized Elect. rate (\$/KWh)	Electric Revenue (\$/yr)
							Capital	O & M	Fuel				
Boiler Plant	-	12.30	2.30	19.56	2.53	0.82	26.55	35.72	353.78	38.04	9.015	-	-
Simple G-T (24-hr)	89	22.80	5.12	33.18	4.82	1.53	45.79	79.51	655.78	71.23		0.076	51,856,099
(12-hr)	89	11.40	2.60	33.18	2.50	1.10	42.68	40.38	327.89	38.34		0.082	27,909,108
(8-hr)	89	7.60	1.75	33.18	1.72	0.96	41.64	27.18	218.59	27.36		0.087	19,916,489
24-hr Cogen	89	22.80	5.80	36.40	4.95	1.65	49.82	90.07	655.78	72.71		0.037	25,239,451
12-hr TES (oil/rock)	194	24.00	6.50	82.91	5.50	2.66	105.72	100.95	690.30	84.26		0.045	33,646,003
12-hr TES (M. salt)	276	34.00	19.20	130.61	9.52	4.87	168.27	298.18	977.92	135.61		0.067	71,029,670
12-hr TES (H. salt)	194	24.00	10.40	98.89	6.23	3.31	125.87	161.51	690.30	92.34		0.053	39,530,567
8-hr TES (oil/rock)	291	24.00	6.60	113.82	5.67	3.29	142.59	102.50	690.30	89.36		0.050	37,363,565
8-hr TES (M. salt)	413	34.00	24.70	177.03	10.67	6.25	225.16	383.59	977.92	150.84		0.078	82,119,355
8-hr TES (H. salt)	291	24.00	12.20	133.07	6.70	4.14	167.12	189.47	690.30	100.37		0.061	45,379,835

* This levelized cost is based on a real dollar basis.

TABLE 17. Economic Results for Various Gas-Turbine Plants (500 psia Steam Load) - PNL Design
(with corrected salt heater costs) (capital, O&M, and fuel costs are in 1990 millions of dollars)

	Plant Size (MWe)	Annual Fuel Cost	Annual O & M Cost	Initial Capital Cost	Working Capital	Start-up Cost	Present Value			Annualized	Steam*	Breakeven*	Electric
							Capital	O & M	Fuel	Cost	Levelized Cost (\$/Klb)	Levelized Elect. rate (\$/KWh)	Revenue (\$/yr)
Boiler Plant	-	12.40	2.40	20.34	2.57	0.85	27.54	37.27	356.65	38.56	9.139	-	-
Simple G-T (24-hr)	90	23.20	5.16	33.47	4.89	1.55	46.23	80.14	667.29	72.36		0.076	52,680,295
(12-hr)	90	11.61	2.61	33.47	2.54	1.11	43.08	40.53	333.93	38.94		0.082	28,346,765
(8-hr)	90	7.74	1.76	33.47	1.75	0.97	42.03	27.33	222.62	27.78		0.088	20,223,399
24-hr Cogen	90	23.20	6.00	38.15	5.06	1.71	52.05	93.18	667.29	74.30		0.038	26,017,097
12-hr TES (oil/rock)	237	29.40	8.40	113.33	6.87	3.54	143.66	130.45	845.62	105.72		0.054	48,892,519
12-hr TES (M. salt)	281	34.60	19.50	132.57	9.68	4.94	170.81	302.84	995.18	137.89		0.067	72,308,459
12-hr TES (H. salt)	198	24.40	10.50	100.80	6.32	3.36	128.25	163.07	701.80	93.82		0.053	40,222,856
8-hr TES (oil/rock)	355	29.40	8.90	154.10	7.15	4.39	192.39	138.22	845.62	112.98		0.060	54,172,756
8-hr TES (M. salt)	420	34.60	25.00	179.56	10.83	6.34	228.38	388.25	995.18	153.21		0.078	83,465,632
8-hr TES (H. salt)	296	24.40	12.40	135.29	6.81	4.21	169.91	192.57	701.80	102.04		0.061	46,212,258

* This levelized cost is based on a real dollar basis.

TABLE 18. Economic Results for Various Combined-Cycle Plants (100 psia Steam Load) - PNL Design
(with corrected salt heater costs) (capital, O&M, and fuel costs are in 1990 millions of dollars)

	G-T Size (MWe)	S-T Size (MWe)	Annual	Annual	Initial	Working Capital	Start-up Cost	Present Value			Annualized Cost	Steam*	Breakeven*	Electric Revenue (\$/yr)
			Fuel Cost	O & M Cost	Capital Cost			Capital	O & M	Fuel		Levelized Cost (\$/Klb)	Levelized Elect. rate (\$/KWh)	
Boiler Plant	-		11.90	2.30	19.56	2.46	0.81	26.46	35.72	342.27	37.01	8.771	-	-
C-C Plant (24-hr)	94.2	50	25.90	4.40	70.08	5.39	2.26	90.21	68.33	744.95	84.11		0.055	61,233,588
(12-hr)	94.2	50	12.90	2.80	70.08	2.91	1.85	86.94	43.48	371.04	48.39		0.064	35,228,350
(8-hr)	94.2	50	8.60	2.10	70.08	2.08	1.72	85.86	32.61	247.36	36.34		0.072	26,455,531
24-hr Cogen	94.2	24.4	24.60	5.40	66.03	5.30	2.20	85.32	83.86	707.56	81.52		0.036	32,404,187
51 12-hr TES (oil/rock & (M.salt))	207	24.4	25.50	16.30	152.08	6.66	4.36	189.45	253.14	733.44	112.82		0.056	55,194,225
12-hr TES (H. salt)	235	24.4	29.00	14.10	154.29	7.10	4.39	192.55	218.97	834.11	119.12		0.055	59,780,230
8-hr TES (oil/rock & (M.salt))	309.9	24.4	25.50	21.40	210.22	7.19	5.64	259.16	332.34	733.44	129.23		0.068	67,134,597
8-hr TES (H. salt)	351.9	24.4	28.90	17.90	212.89	7.51	5.63	262.62	277.99	831.23	133.53		0.065	70,269,092

* This levelized cost is based on a real dollar basis.

These results indicate that the plants with molten salt TES systems are not as economically unattractive as reported in the PNL studies. Their economics appear competitive with simple gas turbine and combined-cycle peaking units and comparable to the plants with a Hitec salt TES system. Also, it shows that the plant with an oil/rock TES system has favorable economics in providing low-pressure steam load. When a high-pressure steam load is required, a plant with molten salt TES or Hitec salt TES may become competitive.

4.0 CBI'S RECOMMENDATIONS

There are four major components in the plant designs, namely, gas turbine, heat recovery media heaters, thermal energy storage system, and media-heated steam generators. Because the operating temperature ranges of the storage media and the required steam capacity were fixed, as defined in the assumptions, the thermal energy storage capacity is only dependent on the plant operating schedule. Because the steam load capacity was defined, the media-heated steam generator capacity is also fixed. Therefore, total capital cost of the conceptual plants is mainly dependent on the cost of gas turbine and heat recovery media heaters. Their total cost and the plant's performance may be varied depending on the capacities of gas turbine and heat recovery media heaters. CBI has the following recommendations and comments on this study:

- Future plant designs can be developed more realistically with an actual gas turbine instead of a generic G-T, as suggested in Section 2.2 of this report.
- Although it may have only a minor effect on the economic model, a future sensitivity study is recommended with variables being: storage media operating temperature range, gas turbine capacity, and media heater capacity.
- The capital cost of the gas turbine should only be used in the range of cost data available to provide realistic cost estimates.
- Likely candidates for using this TES technology may be electric utilities and Public Utility Regulatory Policies Act (PURPA) Qualifying Facilities (QF) or Independent Power Producers (IPP). It is believed that this technology is easier to implement in the QF projects because of their "unregulated" power ventures. Incentives provided for QFs and IPPs by the PURPA have helped to promote significant use of simple gas turbines or combined-cycles for electric power generation. The TES system has the opportunity to enhance plant efficiency and economics. Maximizing plant efficiency and economic benefit while still meeting requirements of PURPA is an attractive aspect of integrating TES into conventional cogeneration power plants.
- Data on the cost of media-heated steam generators is needed to verify the PNL cost models. PNL might want to consider hiring one or more equipment vendors to develop these costs. Foster Wheeler Energy Corporation was the only responsive vendor, and they only quoted the heat recovery units.

- A QF or IPP planner will likely evaluate the TES system based on net present value, internal rate of return, or payback. The PNL reports should probably be modified to include this data if the concept is to be presented to non-utility entities.

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