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PERFORMANCE AND PRELIMINARY ECONOMICS OF BLACK LIQUOR GASIFICATION COMBINED CYCLES FOR A RANGE OF KRAFT PULP MILL SIZES

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ABSTRACT

The design of a black liquor gasification/combined cycle (BLGCC) power/recovery system requires the selection of a specific gas turbine. There are many different models from which to choose, but with only a fixed set of output ranges that are determined primarily by original design decisions relating to aircraft applications. A perfect match between the fuel requirement of a gas turbine and the fuel that can be generated by gasifying the black liquor available at a kraft mill will be rare. This paper examines the performance and prospective economics of BLGCC systems involving a fixed-size gas turbine at mills with black liquor processing rates corresponding to mill production rates of 500 to 2000 air-dry metric tonnes per day of pulp. Detailed predictions of powerhouse thermodynamic performance are coupled with cost estimates for BLGCC powerhouses (assuming the technology has reached commercially-mature costs) and Tomlinson powerhouses developed with input from the Bechtel Corporation. The analysis indicates that *(i)* powerhouse capital investment requirements per unit of black liquor processed for BLGCC systems are comparable to those for new Tomlinson systems across the range of mill sizes considered, *(ii)* the annualized cost (including O&M, fuel, and capital charges) will be higher for a BLGCC system than for a new Tomlinson system, but the higher value of the electricity produced, even at an electricity price as low as 3 ¢/kWh, will far outweigh the added cost, and *(iii)* the incremental economics of a BLGCC powerhouse relative to a new Tomlinson powerhouse are optimized when the gas turbine is sized to match the mills' black liquor throughput.

INTRODUCTION

Full replacement of Tomlinson boiler/steam turbine systems with black liquor gasifier/combined cycle (BLGCC) systems will involve a fundamental change in prime mover technology for the kraft pulp industry—from steam turbines to gas turbines. Conventionally, the design of a mill's power/recovery area is determined by expected liquor throughput: the Tomlinson boiler is sized accordingly, and the steam turbine is sized to handle the steam generated by the boiler. In contrast, the design of a BLGCC power/recovery system requires the selection of a particular gas turbine model. There are many different models from which to choose [1], but only within a fixed set of output ranges determined primarily by original design decisions regarding gas turbines for aircraft applications. A perfect match between the fuel requirement of a specific gas turbine and the fuel that can be generated by gasifying the black liquor available at a kraft mill will be rare, because black liquor availability is determined by considerations related to pulp and paper production (and, possibly, the cost-effectiveness of generating excess power for sale), while the size of the gas turbine is determined by the few specific size ranges available on the market.

Earlier studies of the performance of BLGCC systems at kraft mills have not taken account of the discrete sizes in which gas turbines are manufactured. For example, Berglin [2], McKeough *et al.* [3], and Ihren [4] consider "rubber" gas turbines, i.e., turbines that match a specified black liquor rate, but with performance that does not necessarily correspond to any commercial machine. Larson *et al.* [5,6] consider gas turbine characteristics representing a commercial machine, but set the black liquor flow rate to exactly match the fuel requirements of the turbine.

This paper extends the work by Larson *et al.* [5,6] to examine the performance and preliminary economics of BLGCC systems involving a fixed-size gas turbine at mills with different black liquor processing rates. For specificity, the characteristics of a Siemens KWU 64.3a gas turbine are selected to represent a 70 MW_e-class (simple cycle) gas turbine. [Similar results would be obtained for turbines of other manufacturers that are of the same basic type (heavy-duty industrial), same power output class, and same generation of technology. For example, the General Electric 6001FA is very similar to the Siemens KWU64.3a.] In this work, BLGCC systems are designed around this particular gas turbine for black liquor recovery, for process steam delivery, and for power generation at mills with production capacities from 500 to 2000 air-dry metric tonnes per day of kraft pulp. For comparison, a consistent set of performance and cost estimates are developed for conventional Tomlinson-based powerhouse systems over this same mill size range.

Modeling of the overall energy performance of both BLGCC and Tomlinson powerhouses has been done using a computation model that accurately predicts the full-load, design-point performance of complex gas-steam power cycles [7], including those using black liquor as a fuel. The gas turbine performance predictions here account for adjustments in operating parameters and minor hardware modifications that would be required when burning a fuel like gasified black liquor, which has a lower energy content than natural gas. Details of the computational modeling of the BLGCC systems are described by Consonni, *et al.* [8] and Larson, *et al.* [9].

POWERHOUSE DESIGN CRITERIA AND EQUIPMENT CONFIGURATIONS

Figure 1 shows a simplified schematic of the BLGCC plant configurations considered here. In the gasification island, black liquor (at 75% dry solids) is gasified in oxygen at high pressure (25 bar) and the resulting gas is available for combustion in the gas turbine. Green liquor is returned to the causticizing area. The hot gas turbine exhaust is used to raise steam in a heat recovery steam generator (HRSG) for expansion through a back pressure steam turbine. The amount of steam raised this way typically falls short of steam needs for process, so a power boiler is included to supplement steam production. Biomass is considered as the fuel for the power boiler in the results presented here. In addition to different mill sizes, we also consider three levels of process steam demand, as indicated in Fig. 1. Process steam is delivered at 4 bar and 10 bar in a 2:1 mass ratio.

We define our "base case" as the situation in which the available gasified black liquor is just sufficient to meet the full-load fuel demand of the gas turbine. The heat and mass balance for this situation (Fig. 2) illustrates the level of detail behind all performance calculations presented in this paper. Figure 3 shows a detailed heat and mass balance for a Tomlinson-based powerhouse with the same black liquor rate and same process steam demand. In all of our calculations, we assume 1.74 metric tonnes of black liquor dry solids (tds) are generated per air-dry metric tonne of pulp (tp). With this assumption, the base case mill production is 1322 tp/day, with a process steam demand of 16.3 GJ/tp. Table 1 summarizes powerhouse performance in the base cases.

We consider two variants of the base case. In *Case 1* the available gasified black liquor is insufficient to meet the full-load fuel demand of the turbine (oversized gas turbine). The gas turbine fuel is supplemented with natural gas (Fig. 1).[1] In *Case 2* there is more gasified black liquor than is needed to fuel the gas turbine (undersized gas turbine). The excess gas is bypassed to a duct burner ahead of the HRSG for combustion in oxygen-carrying gas turbine exhaust gases to boost HRSG output (Fig. 1).

It is important to note that, while our results will be presented as a function of mill size for a fixed-size gas turbine, a powerhouse designer will typically encounter just the opposite case, i.e. mill size will be fixed and the choice of gas turbine must be made from a limited number of models - none of which exactly matches the mill throughput. In this context, our results can be interpreted not so much in terms of absolute mill size, but rather in terms of the extent of "mismatch" between the mill and the gas turbine. Said another way, our results illustrate the effects of undersizing, oversizing, and matching a gas turbine to the size of the mill. These results should be applicable in a general way to

[1] Alternatively, the turbine could be run at part-load with gasified black liquor as the only fuel. However, there would be significant efficiency penalties in combined cycle operation. This alternative is not considered here.

gas turbines of any size within the studied range of mill sizes. Future work may extend this study to include explicit calculations using a number of different gas turbines.

BLGCC PERFORMANCE RESULTS

Figure 4 shows the variation in BLGCC system fuel inputs (black liquor, biomass, and natural gas), electric power output, and overall electric generating efficiency as a function of mill size for a mill process steam demand of 16.3 GJ/tp. In the base case (1322 tp/day) the black liquor gasifier output exactly matches the fuel requirements of the gas turbine. As the mill size decreases (to the left of the base case), the fixed-size gas turbine becomes increasingly oversized, and an increasing amount of natural gas is required (Fig. 4b) to meet turbine fuel demand. As the ratio of natural gas to black liquor increases, the overall system efficiency (Fig. 4a) increases because using natural gas does not entail the efficiency penalty associated with gasifying black liquor. (As the mill size falls with a fixed-size gas turbine, the system increasingly resembles a stand-alone natural gas-fired combined cycle power plant with its associated high system efficiency.) In addition, the amount of biomass needed in the power boiler to meet process steam demand drops with decreasing mill size because absolute process steam demand is falling, while the absolute level of process steam generated from the gas turbine waste heat remains approximately constant. Overall power output falls primarily because the reduced biomass use means less power is generated at the steam turbine.

Table 1. Summary of base case BLGCC and Tomlinson powerhouse performances. Detailed heat and mass balances are provided in Fig. 2 and Fig. 3.

	Tomlinson	BLGCC
Powerhouse Fuel Consumption		
Black liquor,[a] tds/day	2,300	2,301
MW	382	382
Biomass,[b] dry t/day	420	999
MW	97	231
Electricity Generation		
Gross gas turbine power (MW_e)	n.a.	93.3
Gross steam turbine power (MW_e)	51.8	63.2
Auxiliaries (MW_e)	1.7	21.0
Net power output (MW_e)	50.0	135.5
Net electricity prod. (kWh/tds)	522	1,413
Net efficiency, % HHV	10.4	22.1
Process steam production		
Process steam, GJ/hour	904	903
MW	251	251
Process steam, GJ/tds	9.4	9.4
Steam efficiency, % HHV	52.4	41.0
Elec.-to-process steam (kWh/GJ)	55	150

(a) Black liquor dry solids' higher heating value is assumed to be 14.363 GJ/metric tonne.
(b) Each system includes a biomass boiler generating additional steam to meet process demand. The assumed higher heating value of biomass is 20.0 GJ/dry tonne.

When the gas turbine is undersized relative to the gasifier output (cases to the right of the base case in Fig. 4), excess syngas is diverted around the gas turbine and burned in a duct burner at the entrance of the HRSG. For these cases, the percentage of the syngas diverted to the duct burner is shown as the dotted line in Fig. 4b. Natural gas flow is zero. Diverting syngas from the topping cycle to the bottoming cycle decreases overall electrical efficiency (Fig. 4a), because the diverted gas is used only in the steam cycle for power generation, not in the full combined cycle. In addition, as an increasing fraction of the syngas is diverted directly to the HRSG, the absolute amount of biomass required rises only modestly because the diverted syngas essentially replaces additional biomass that would otherwise be needed to meet process steam demand. Power output climbs steadily with increasing mill size because of the increasing contribution from the steam turbine.

Performance for different process steam demands is shown in Fig. 5. Higher steam demands uniformly necessitate higher rates of biomass consumption, leading to higher power generation. However, because an increased fraction of the power is generated in the bottoming rather than in the topping cycle, overall system efficiency decreases with increasing process steam demand. The flows of black liquor and natural gas, which fuel only the fixed-size topping cycle, are invariant to the process steam demand level.

ECONOMICS

We now examine the prospective economics of BLGCC powerhouses as a function of mill size and make comparisons with Tomlinson-based powerhouses.

Basis of Cost Estimates

The underlying basis for the powerhouse economics described here are capital and operating cost estimates for both the BLGCC and Tomlinson base cases (Figs. 2 and 3), assuming BLGCC technology costs have reached commercially mature cost levels. These base case cost estimates are derived directly from cost estimation work by

Table 2. Capital cost estimates for base case powerhouses.

	Scaling Parameter	Million 1997$
TOTAL INSTALLED BLGCC		**186.8**
Total Installed Overnight Cost		173.4
Gasification Island	3067 tds/day @ 75% dry solids	66.3
Biomass Boiler Island	66.6 kg/s steam @ 90 bar, 520 C	37.4
Combined Cycle Island		
70-MWe gas turbine generator	fixed cost	38.2
Heat recovery steam generator	41.1 kg/s steam @ 90 bar, 520 C	13.7
Steam turbine/generator	63.2 MWe	17.7
Interest during construction		13.4
TOTAL INSTALLED TOMLINSON		**190.8**
Total Installed Overnight Cost	3067 tds/day @ 75% dry solids	177.0
Interest during construction		13.7

the Bechtel Corporation for powerhouse systems with equipment configurations identical to those shown in Figs. 2 and 3 [10]. Bechtel has considerable experience with the engineering of gasification and power systems, and a sizable database of cost factors for equipment used in such applications. A set of general criteria intended to be representative of conditions at a typical bleached-grade kraft mill in the Southeastern U.S. were developed and used by Bechtel as a basis for providing consistent and reasonable cost estimates for both systems. The study criteria were defined to make cost comparisons between technologies as consistent and transparent as possible. For example, "greenfield replacement" of an existing Tomlinson powerhouse was assumed, i.e., the costs were developed to represent new construction without including costs for demolition, site remediation, and other factors that tend to be mill-specific, while not being especially relevent to a comparison between technologies. Larson *et al.* [5,6] provide detailed discussion of the Bechtel estimates.

Estimates of the capital cost for the BLGCC base case and the Tomlinson base case (Fig. 2 and Fig. 3) are given in Table 2.[2] The total cost is broken down only by the plant components whose sizes change independently of each other with changes in black liquor throughput, biomass throughput, and/or process steam demand. (Bechtel's original estimates included capital and installation costs for each major piece of equipment in the powerhouse. These have been aggregated here for simplicity.) To estimate costs for powerhouses other than the base cases, the numbers in Table 2 were scaled according to the indicated scaling parameter, using a 0.6 power law. The base case cost estimates are extended over a wide range (+50% and -60%) using this simple scaling law, which introduces some uncertainty in the results. For the purposes of discussion and illustration, we shall treat costs as though they are exact.

Table 3. O&M cost estimates for base case powerhouses with performance indicated in Table 2.

	Million 1997$ per year
BLGCC base case, total O&M	**11.511**
Fixed O&M Costs	6.655
Variable O&M Costs	
Gasification Island	1.791
Biomass Boiler Island	1.272
Combined Cycle Island	1.934
Tomlinson base case, total O&M	**8.197**
Fixed O&M Costs	3.557
Variable O&M Costs	4.640

Table 3 shows estimates for the operating and maintenance costs (excluding fuel costs) for the two base cases based on original estimates by Bechtel [5]. To estimate O&M costs for powerhouses at different scales, the fixed O&M costs have been kept constant and the variable sub-components were scaled linearly with the installed capital cost for each corresponding sub-component.

Fuel costs are assumed to be $30 per dry tonne for biomass and $2.76/GJ for natural gas (representing an average industrial sector gas price in the US). The value of the black liquor delivered from the mill to the powerhouse is assumed to be exactly offset by the value of the green liquor and the process steam delivered from the powerhouse to the mill.

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[2] The cost estimates in Table 2 are scaled directly from estimates in Larson, *et al.* [5]. The estimates of Larson, *et al.* [5] for the BLGCC assumed that green liquor scrubbing of the gas could be utilized for H_2S recovery. Subsequent analysis indicated that if this method of H_2S recovery were, in fact, implemented, it would result in a substantial increase in the required lime cycle capacity at a mill and hence in the overall system cost [6]. However, alternative H_2S recovery methods that avoid this problem and yield capital costs comparable to those given in Table 2 have been identified (as discussed by Larson *et al.* [6]), so results discussed in this paper based on Table 2 are reasonable.

Cost Results

The total installed capital costs for new BLGCC and new Tomlinson systems are graphed as a function of mill size in Fig. 6. The Tomlinson capital cost estimates reflect an exact 0.6 scaling law.[3] The BLGCC curve is slightly flatter due to the fixed cost of the fixed-size gas turbine. The most noteworthy feature of the comparison is that the estimated capital investment for the BLGCC system is roughly the same as for the Tomlinson system across most of the full size range considered here. (Figure 6 suggests that the BLGCC system will actually be less costly at larger scales.) In contrast to capital requirements, annual operation and maintenance costs, also shown in Fig. 6, are significantly higher with the BLGCC for all mill sizes. The relative flatness of the O&M cost curves compared to the capital costs is due to the significant fraction (almost 60% for the base case) of the O&M cost that is fixed with respect to scale.

With comparable total capital costs, the BLGCC and Tomlinson powerhouses have comparable investment requirements per kilogram of black liquor processed. Since the large additional power output with a BLGCC system (Fig. 4a) is clearly the most important economic driver for introducing the technology [6], it is appropriate to examine the overall economics of BLGCC systems in terms of power generating cost.

Figure 7 highlights the key difference in the economics of power generation with the BLGCC and the Tomlinson systems. Total annualized costs, including capital at a 15% annual charge rate, are shown there for both technologies over the full range of mill sizes. Also shown are the annual electric power outputs, assuming 8000 hours/year of operation (91% capacity factor). Note that across the full mill size range, the power output of the BLGCC system is greater than the Tomlinson system by a roughly constant amount--approximately the output of the gas turbine. In the BLGCC case, both the annualized cost and annual power production rise by roughly a factor of 1.7 as the mill size increases from 500 to 2000 tp/day, suggesting a roughly flat cost per kWh for electric power. In contrast, the annualized cost for the Tomlinson system increases by a factor of about 2.2 over the mill size range considered, while annual power production increases by more than a factor of four,[4] indicating a significant scale dependence of the cost per kWh with the Tomlinson technology.

As anticipated from Fig. 7, the total power generating cost per kWh (Fig. 8) is relatively insensitive to mill size. It is also relatively insensitive to process steam demand level. The capital and O&M contributions are largely invariant with scale and make up the bulk of the electricity cost (Fig. 8). The minimum total cost is reached in the base case, wherein the gasifier output exactly matches the fuel requirements of the gas turbine.

Given the flat contributions of capital and O&M with mill size, the V-shape of the total cost curve is primarily a result of the underlying costs assumed for natural gas and biomass auxiliary fuels. (Each is shown separately with dotted lines in Fig. 8). The rise in cost-per-kWh with mill size for mills larger than the base case reflects the decreasing electric efficiency shown in Fig. 4a. If a cost for black liquor were explicitly included, the cost would increase more sharply with mill size. For mill sizes smaller than the base case, electricity costs again rise modestly. This is due primarily to the increasing natural gas/biomass ratio and the consequent increase in the average cost of the auxiliary fuel. If the price of natural gas and biomass were equal, the total cost of electricity would fall monotonically with decreasing mill size.

In contrast to the relative insensitivity of electricity costs to mill size for BLGCC systems, electricity cost from a Tomlinson powerhouse increases dramatically with decreasing mill size (Fig. 9), due to the more rapid drop in power output with the Tomlinson system (see footnote 4). The cost of electricity from the Tomlinson system is also considerably higher than from the BLGCC system across the full range of mill sizes.

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[3] Our base case Tomlinson cost estimate agrees well with industry sources of data for new Tomlinson units [6,11]. Cost estimates by Industra [11] for a Tomlinson recovery boiler of comparable size to our base case and one 20% as large suggest a scaling factor of 0.7 for this technology. The overall results presented here would not be qualitatively different if we were to use a scaling factor of 0.7 instead of 0.6.

[4] The larger percentage increase in power output for the Tomlinson system compared to the BLGCC system is attributable to the much lower level of power output from the Tomlinson system at the small end of the mill size range considered here. Note that at zero black liquor throughput, the power output of the Tomlinson powerhouse would be zero, while the BLGCC output would roughly equal the output of a natural-gas fired 70-MW_e gas turbine.

Incremental Economics

As highlighted in Fig. 7, BLGCC systems incur higher annualized total cost, but produce significantly more electric power than a Tomlinson system. The ratio of the cost differential to the power output differential gives a measure of the incremental economics of a BLGCC relative to a Tomlinson powerhouse. This ratio of "incremental cost" to "incremental electricity" is shown in Fig. 10 disaggregated into fuel, O&M, and capital contributions. The total incremental cost-per-kWh is relatively low—reaching 1.3 ¢/kWh in the base case and rising in a V-shape with larger and smaller mill sizes. This graph suggests that the economic advantage of a BLGCC system relative to a Tomlinson system is optimized when the gas turbine is matched to the mill's black liquor supply. The relevance to overall powerhouse economics of the low incremental costs shown in Fig. 10 becomes clearer when the enormous difference in power generated by the two systems is taken into consideration. Figure 11 compares the total annual incremental operating credits to a mill (net of revenue from incremental power and expenditures for incremental O&M and fuel) with the incremental initial capital investment required. The incremental capital is small (or negative), while operating credits are positive (or very positive) when power is valued at 2.5 ¢/kWh or more. The annual incremental operating credits per tonne of pulp are shown in Fig. 12.

SUMMARY

Preliminary economics have been reported here for BLGCC powerhouse systems involving a fixed-size gas turbine at kraft mills producing between 500 to 2000 tonnes per day of pulp. The analysis has shown that

- powerhouse capital investment requirements per unit of black liquor processed for BLGCC systems are comparable to those for new Tomlinson systems across the full range of mill sizes considered.
- total cost of power generation from a BLGCC powerhouse is very substantially lower than from a new Tomlinson powerhouse, with the differential increasing with decreasing mill size.
- the annualized cost (including O&M, fuel, and capital charges) is higher for a BLGCC system than for a new Tomlinson system, but the value of the electricity produced, even at an electricity price as low as 3 ¢/kWh, far outweighs the added costs.
- the incremental economics of a BLGCC powerhouse relative to a new Tomlinson powerhouse are optimized when the gas turbine is sized to match the mills' black liquor throughput.

These results suggest a favorable long-term outlook for the economics of BLGCC technology, but the results are sensitive to the underlying cost assumptions. Each mill has a unique set of conditions (energy prices, black liquor values, electricity values, etc.) that may not be reflected in the results presented here. The work reported here can be viewed as a methodology template that can be re-applied using mill-specific assumptions and that can be updated as more accurate technology cost information becomes available. In an effort to improve the general utility of the results here, we are presently exploring the possibility of incorporating the cost database and analytical methodology used here into a tool that can be used by individual paper companies to carry out preliminary assessments of the prospective economics of BLGCC systems taking account of their unique conditions. This ongoing effort is supported by the US Department of Energy and the Union Camp Corporation.

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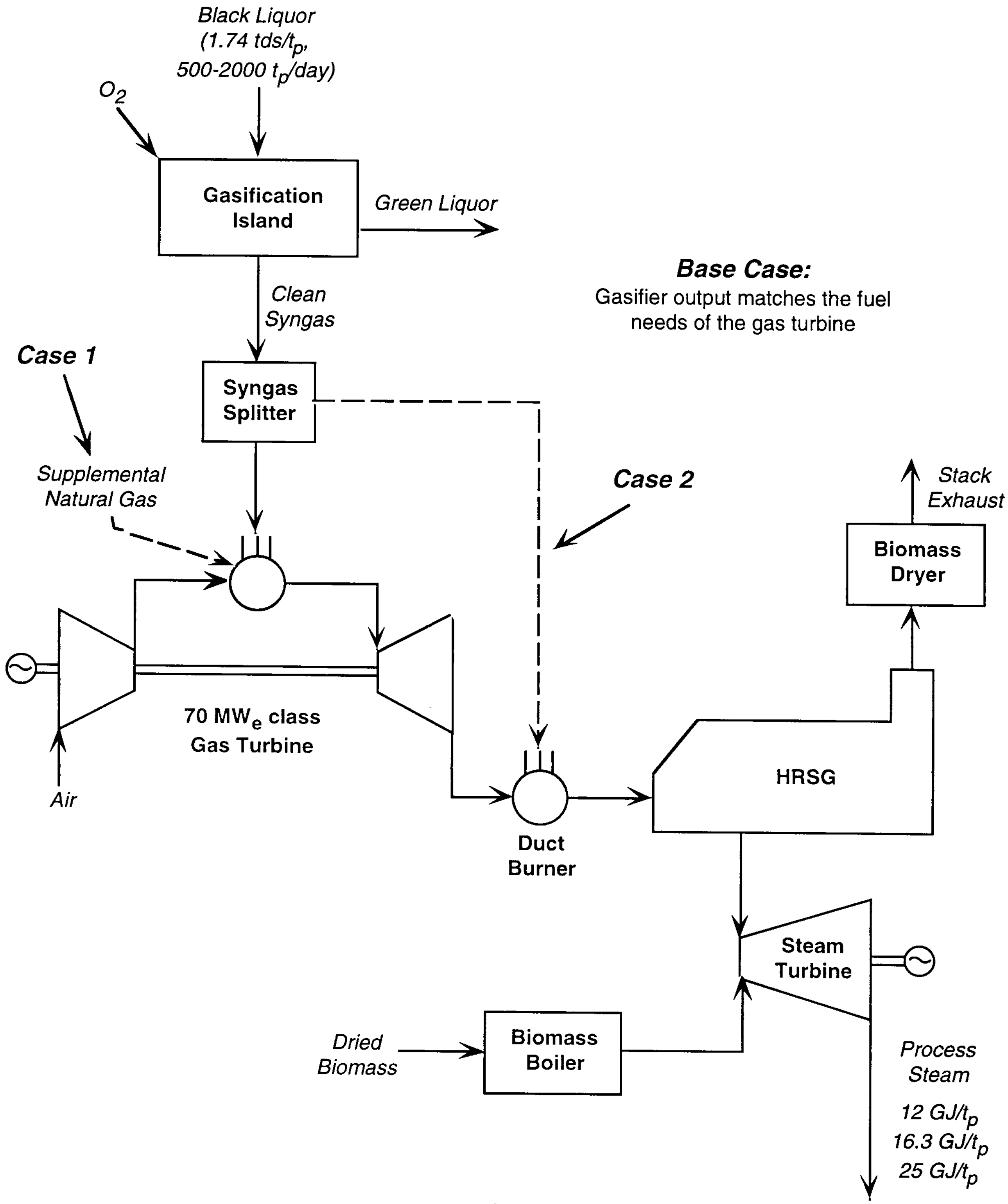

Fig. 1. Schematic of BLGCC systems analyzed in this paper. The gas turbine is either: 1) oversized, 2) undersized, or 3) exactly matched (the "base case") to the black liquor flow rate.

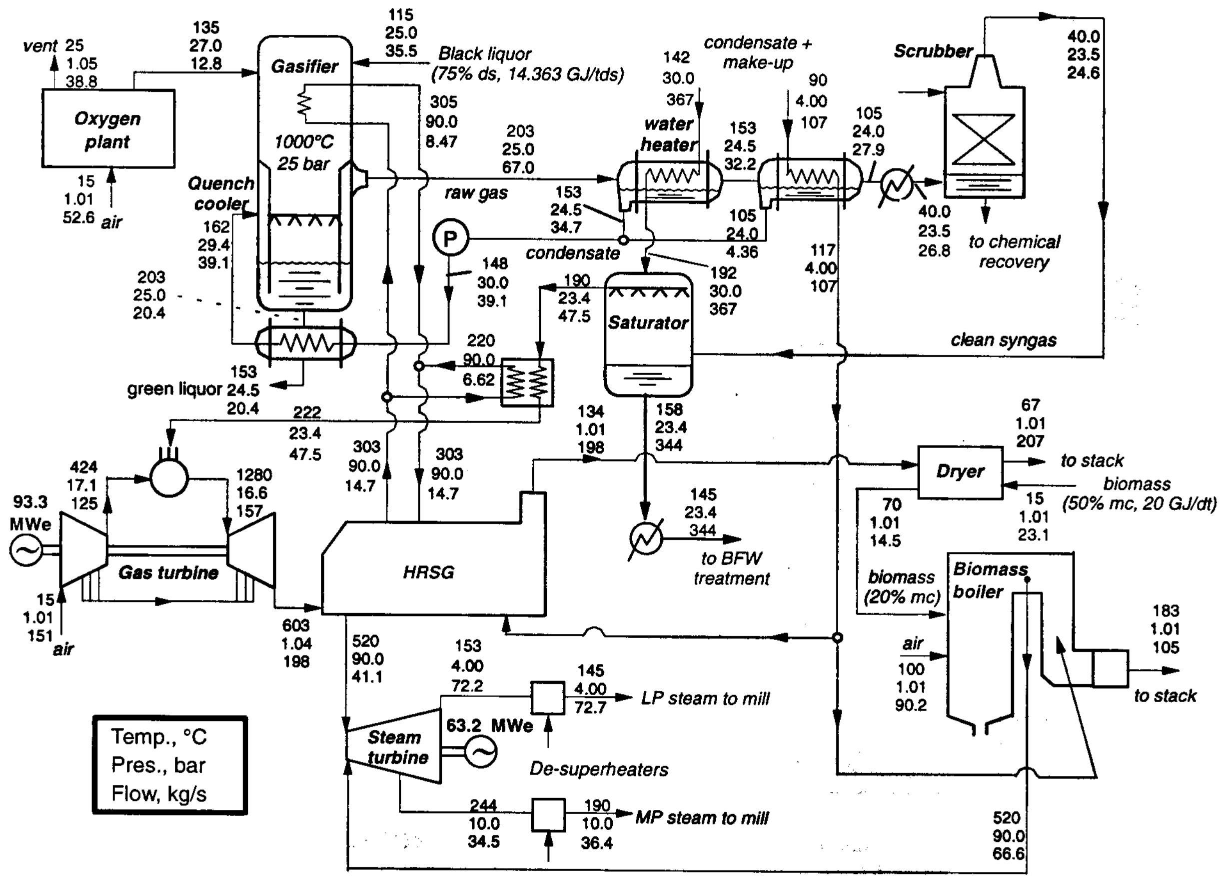

Fig. 2. Plant configuration for the base case BLGCC powerhouse, including pressurized oxygen-blown black liquor gasification, 70-MW$_e$ class gas turbine, biomass power boiler, and single-extraction back-pressure steam turbine. The black liquor dry solids flow rate (2300 tds/day) corresponds to a pulp mill production of 1322 air-dry metric tonnes per day (tp/day), assuming 1.74 tds/tp. The process steam production for the case shown here is 16.3 GJ/tp. Table 1 gives overall performance indicators for the flowsheet shown here.

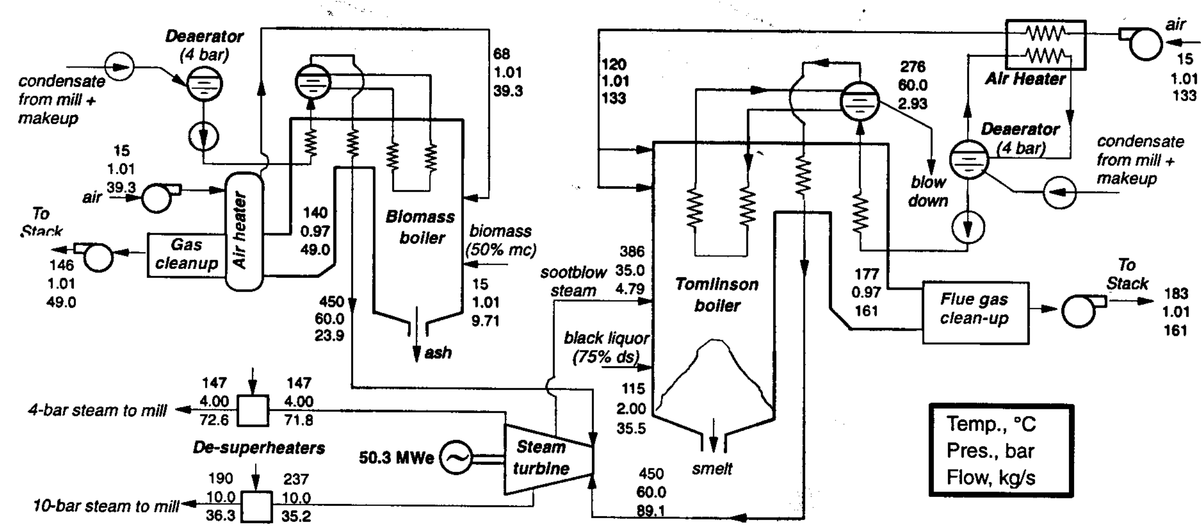

Fig. 3. Plant configuration for the base case Tomlinson powerhouse, including a biomass power boiler and single-extraction back-pressure steam turbine. The black liquor dry solids flow rate (2300 tds/day) corresponds to a pulp mill production of 1322 air-dry metric tonnes per day (tp/day), assuming 1.74 tds/tp. The process steam production for the case shown here is 16.3 GJ/tp. Table 1 gives overall performance indicators for the flowsheet shown here.

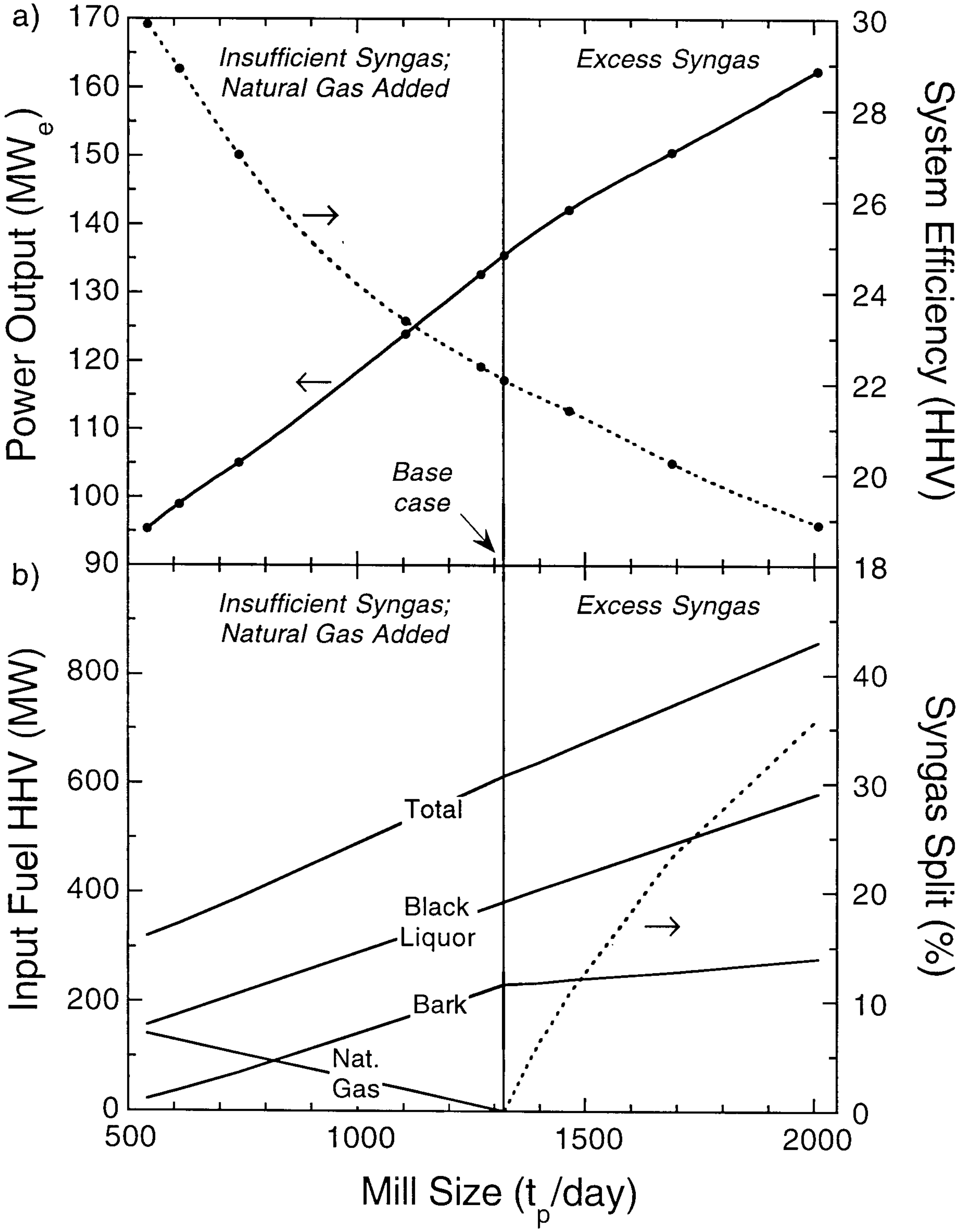

Fig. 4. BLGCC system inputs, outputs, and overall electric generating efficiency (HHV) as a function of mill size for a fixed 70 MW_e class gas turbine. Process steam demand is 16.3 GJ/t_p.

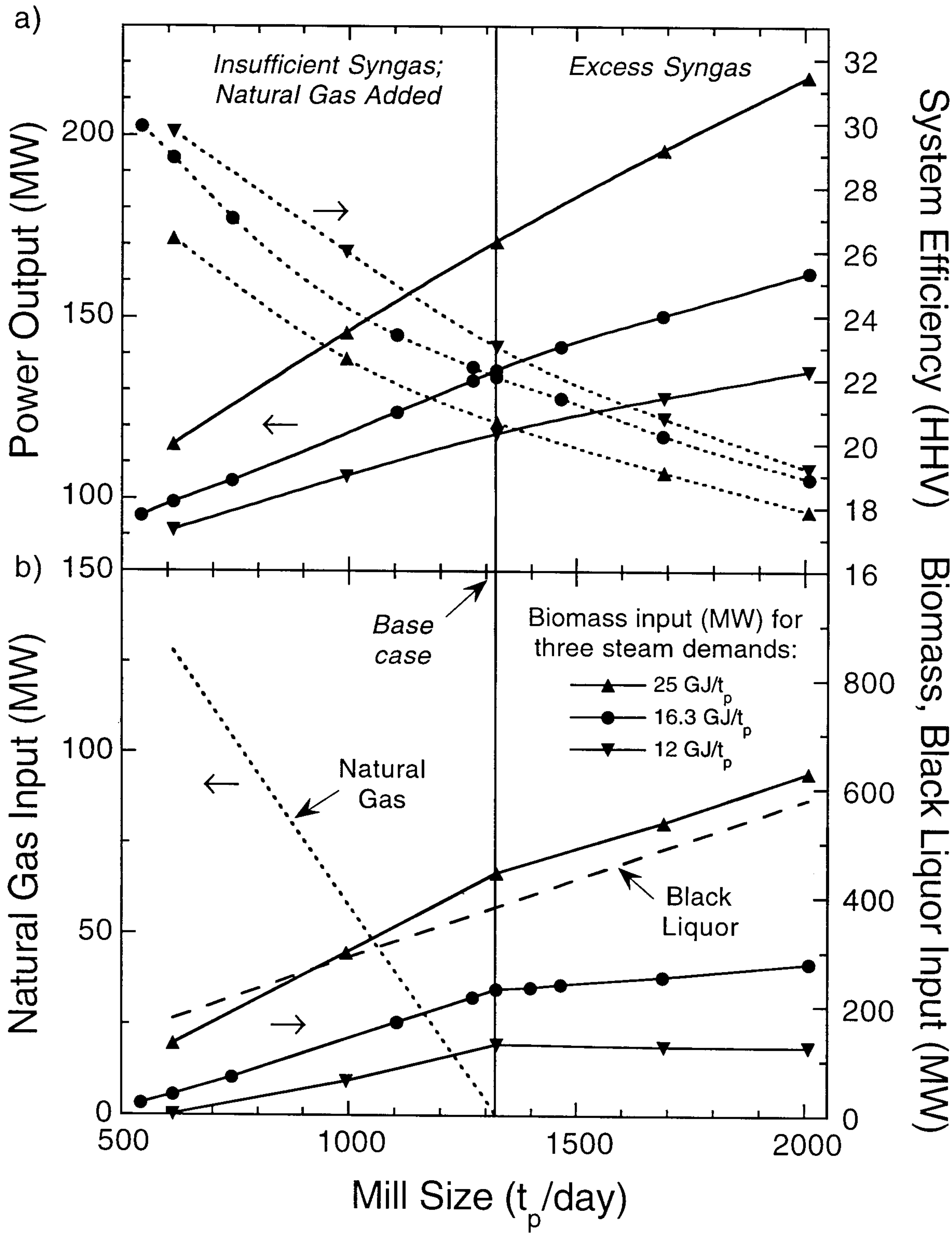

Fig. 5. BLGCC system inputs, outputs, and overall electric efficiency (HHV) as a function of mill size for three different process steam demands.

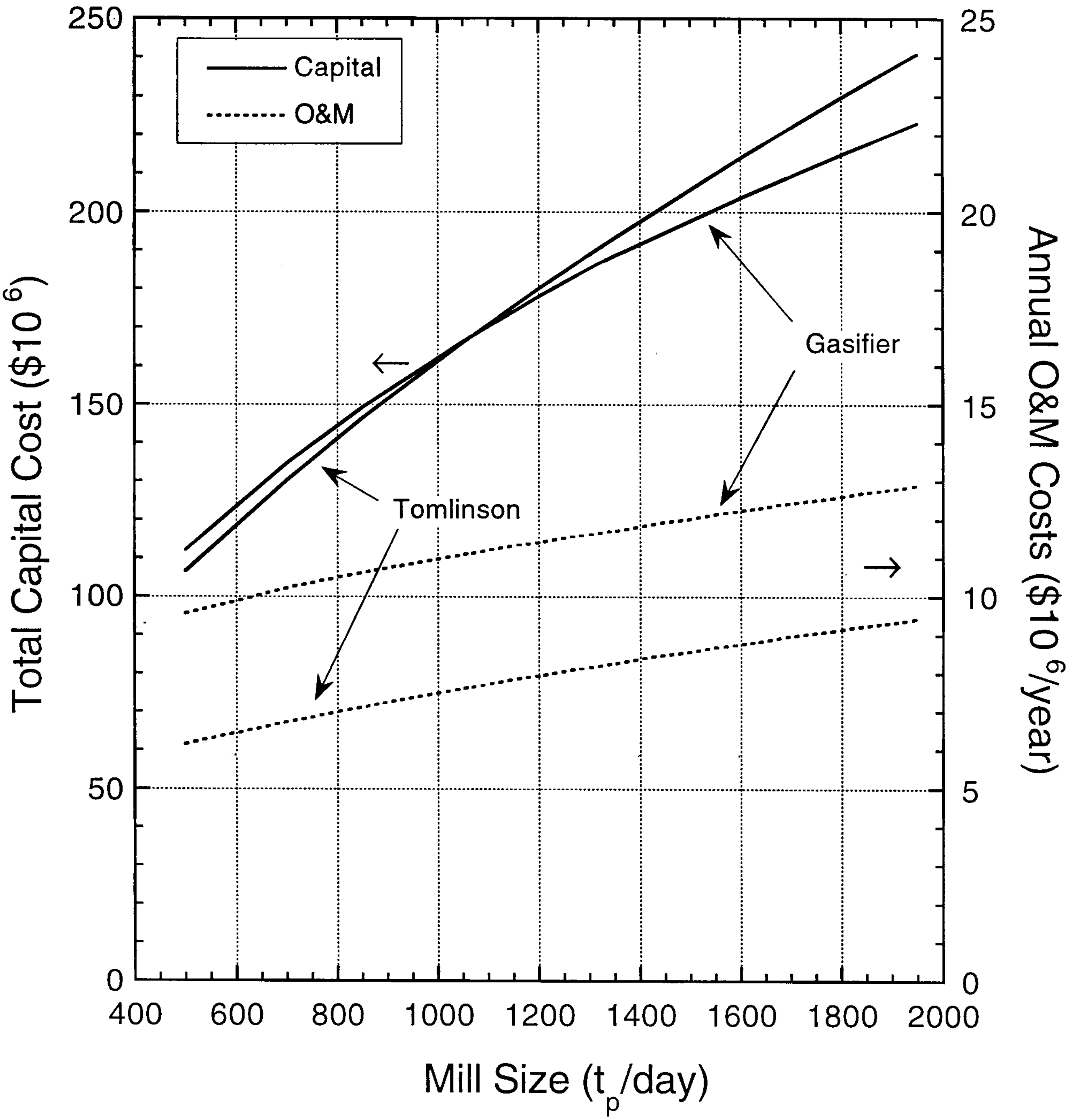

Fig. 6. Total capital costs and annual operation and maintenance costs for BLGCC systems and for Tomlinson recovery systems as a function of mill size.

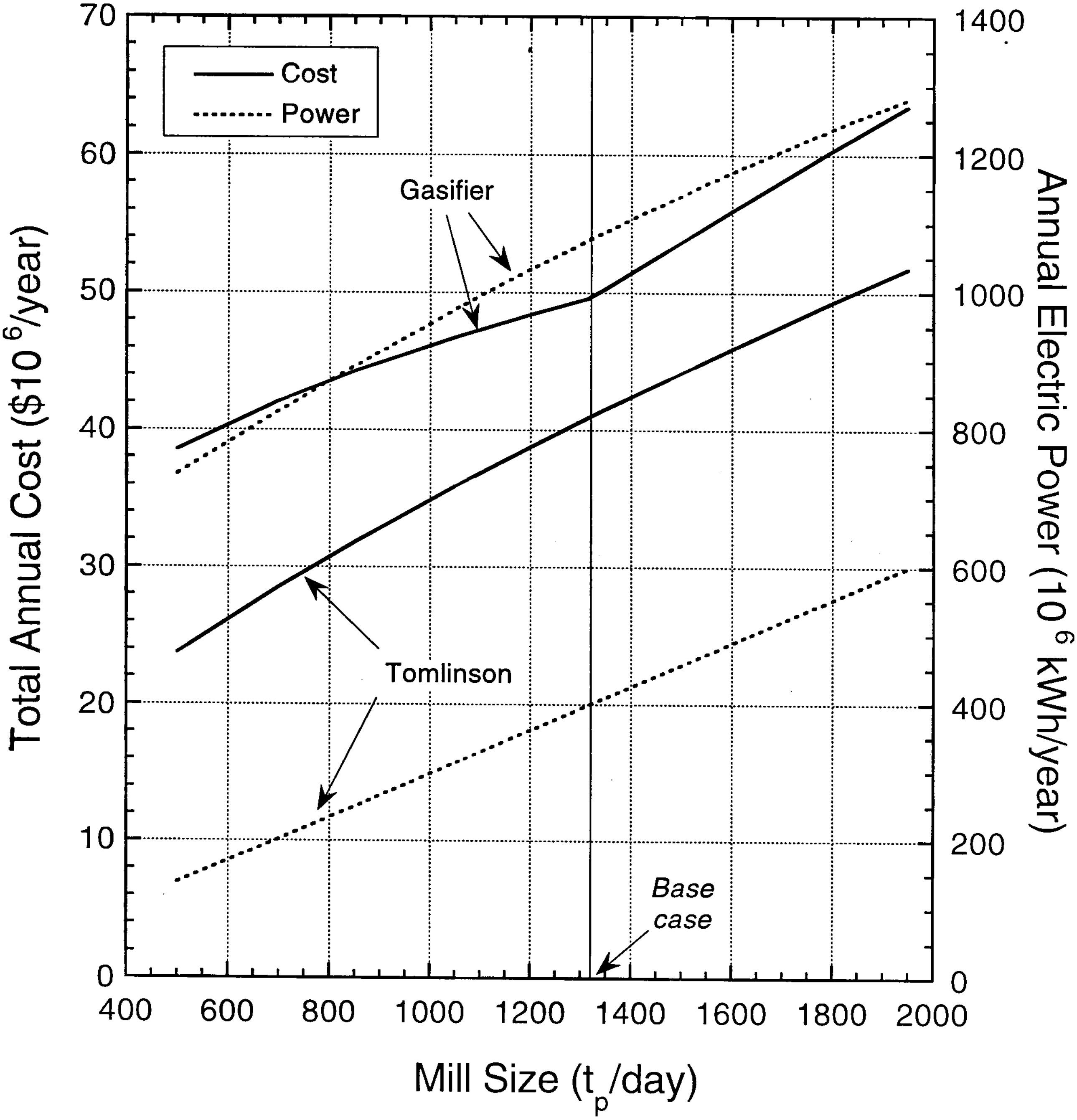

Fig. 7. Total annual cost of owning, maintaining, and operating BLGCC systems and Tomlinson recovery systems (assuming 15% capital charge rate) and annual electric power output as a function of mill size (8000 hr/yr operation).

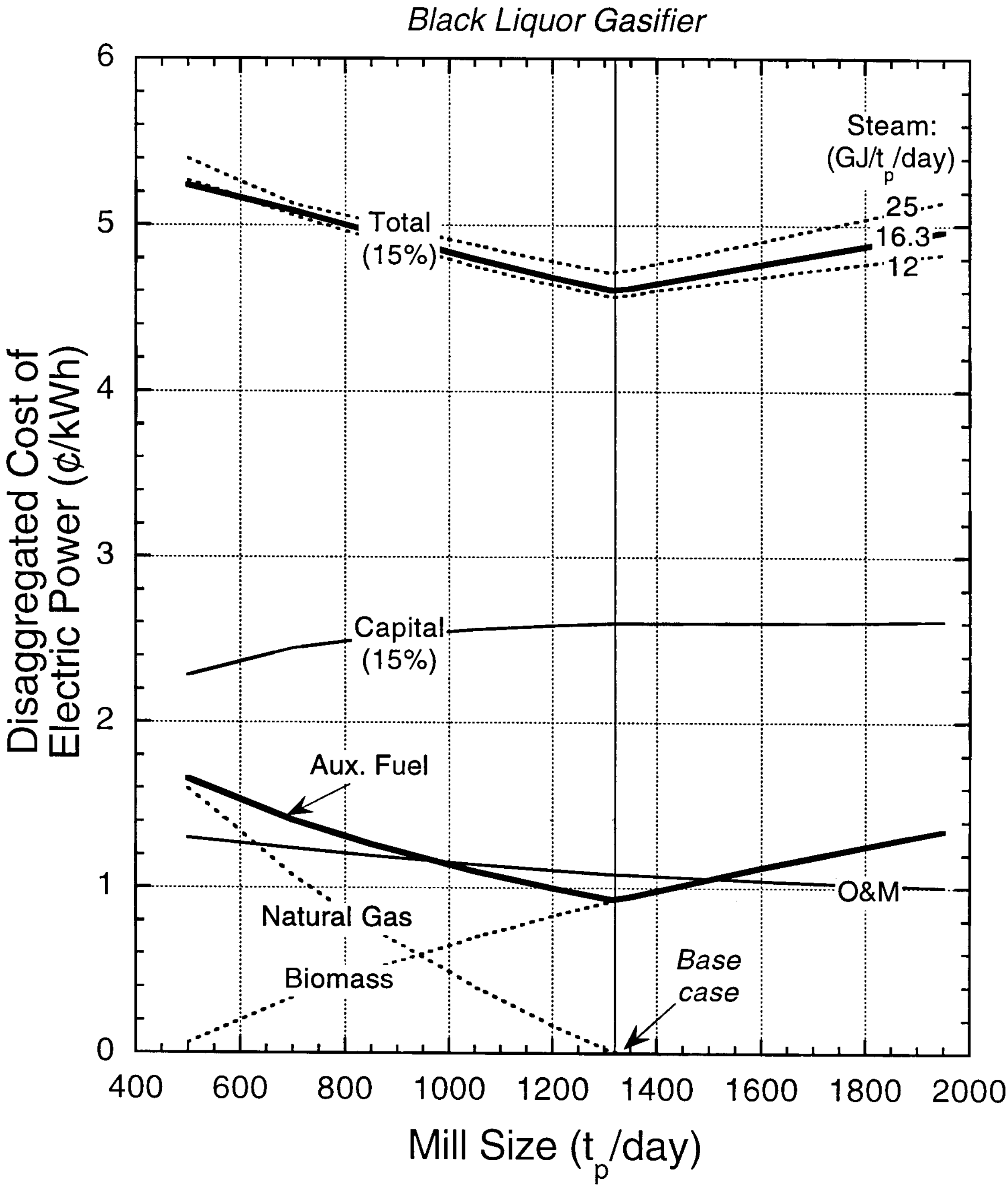

Fig. 8. Total costs per kWh of electric power generated by BLGCC systems for a capital recovery rate of 15% and three steam demands: 12, 16.3, and 25 GJ/t_p. The total cost at 16.3 GJ/t_p is further disaggregated into separate costs for capital, operation and maintenance, and auxiliary fuel. The separate costs for natural gas and biomass are also shown.

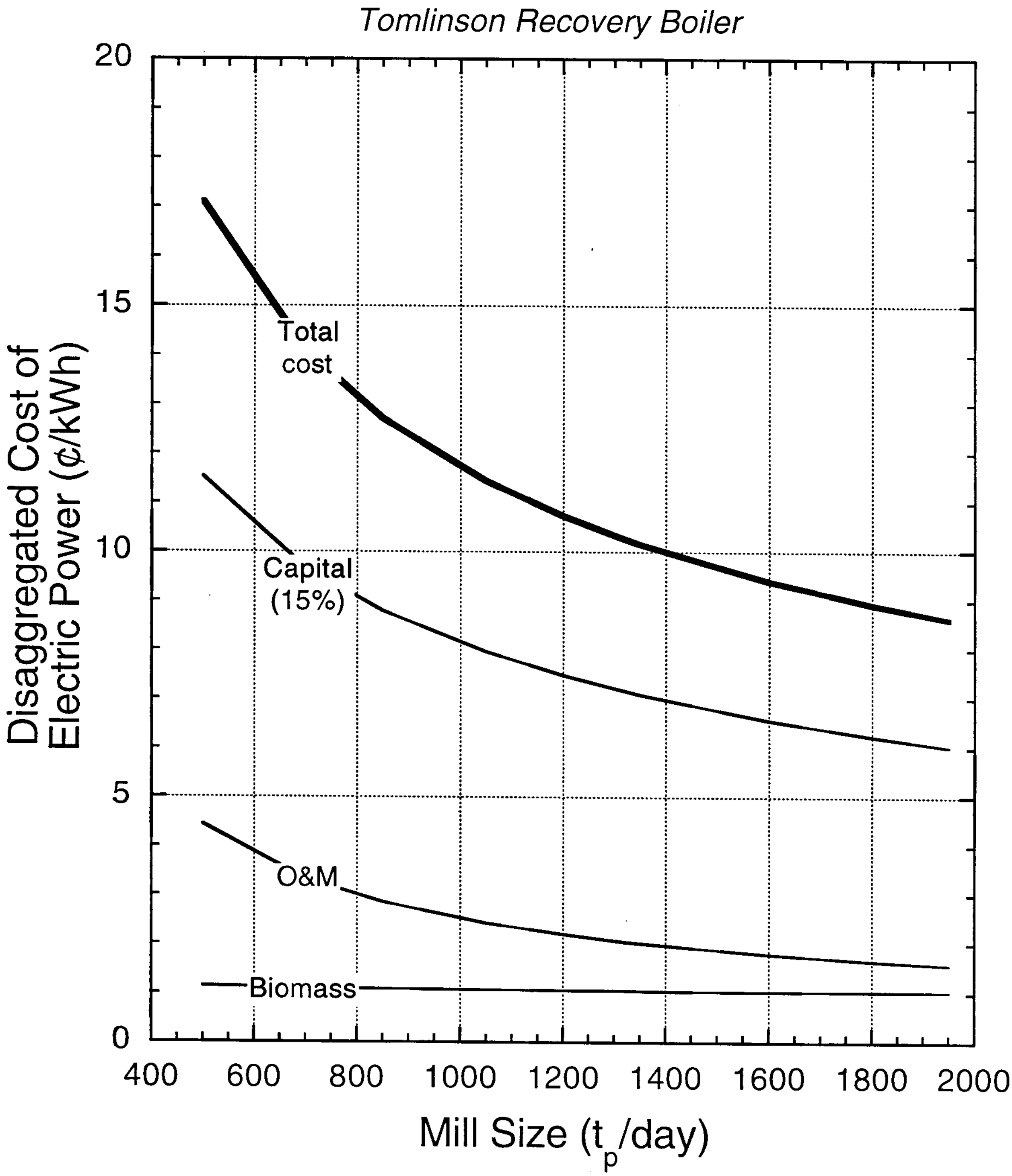

Fig. 9. Costs per kWh of electric power generated by a Tomlinson recovery boiler powerhouse (capital recovery rate=15% per year; steam demand=16.3 GJ/t_p) as a function of mill size, disaggregated into capital, operation and maintenance, and biomass fuel costs.

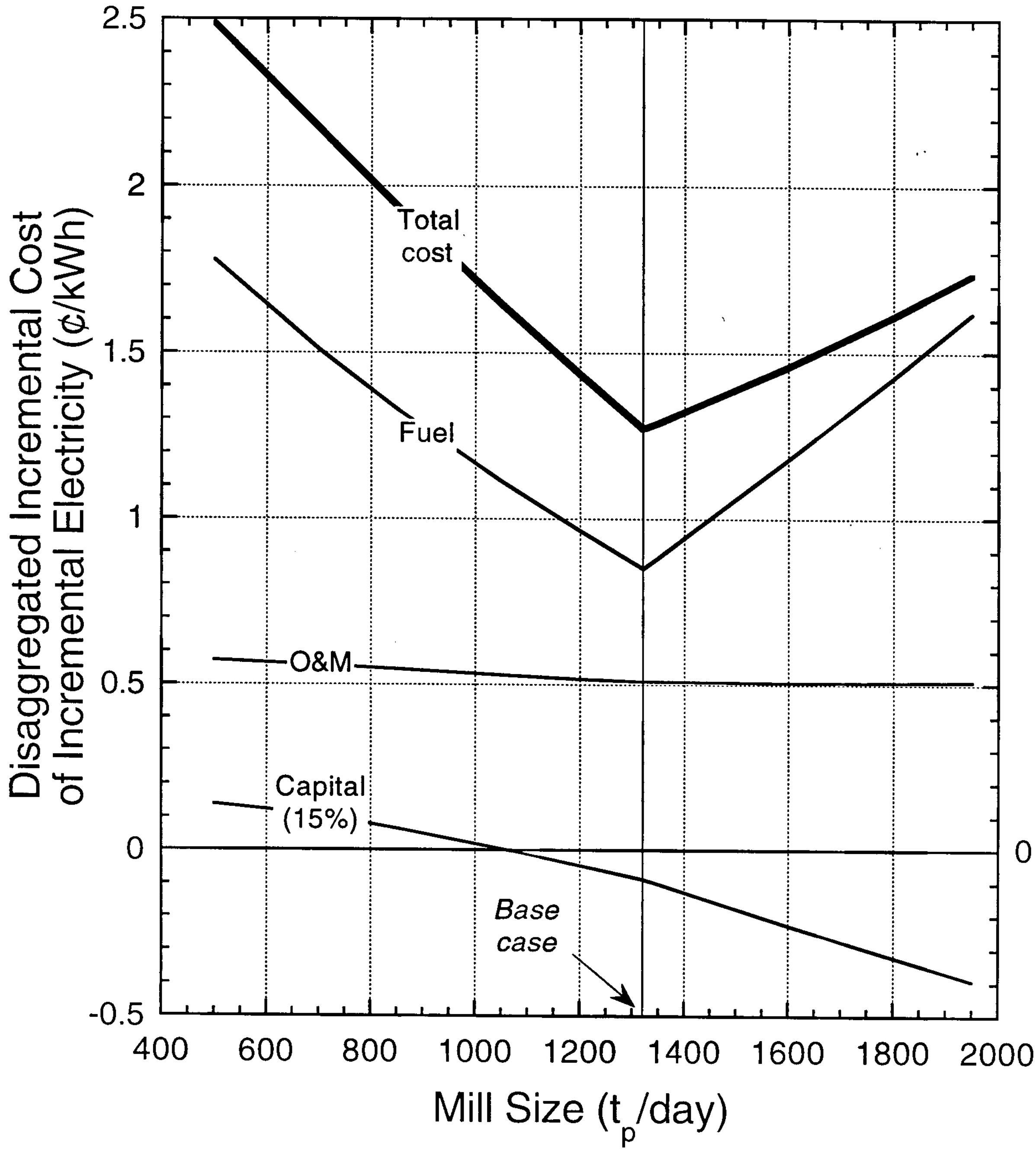

Fig. 10. Cost of owning, maintaining, and operating a BLGCC system in excess of costs for a Tomlinson recovery boiler powerhouse divided by the difference in electricity production (capital recovery rate=15% per year; steam demand=16.3 GJ/t_p).

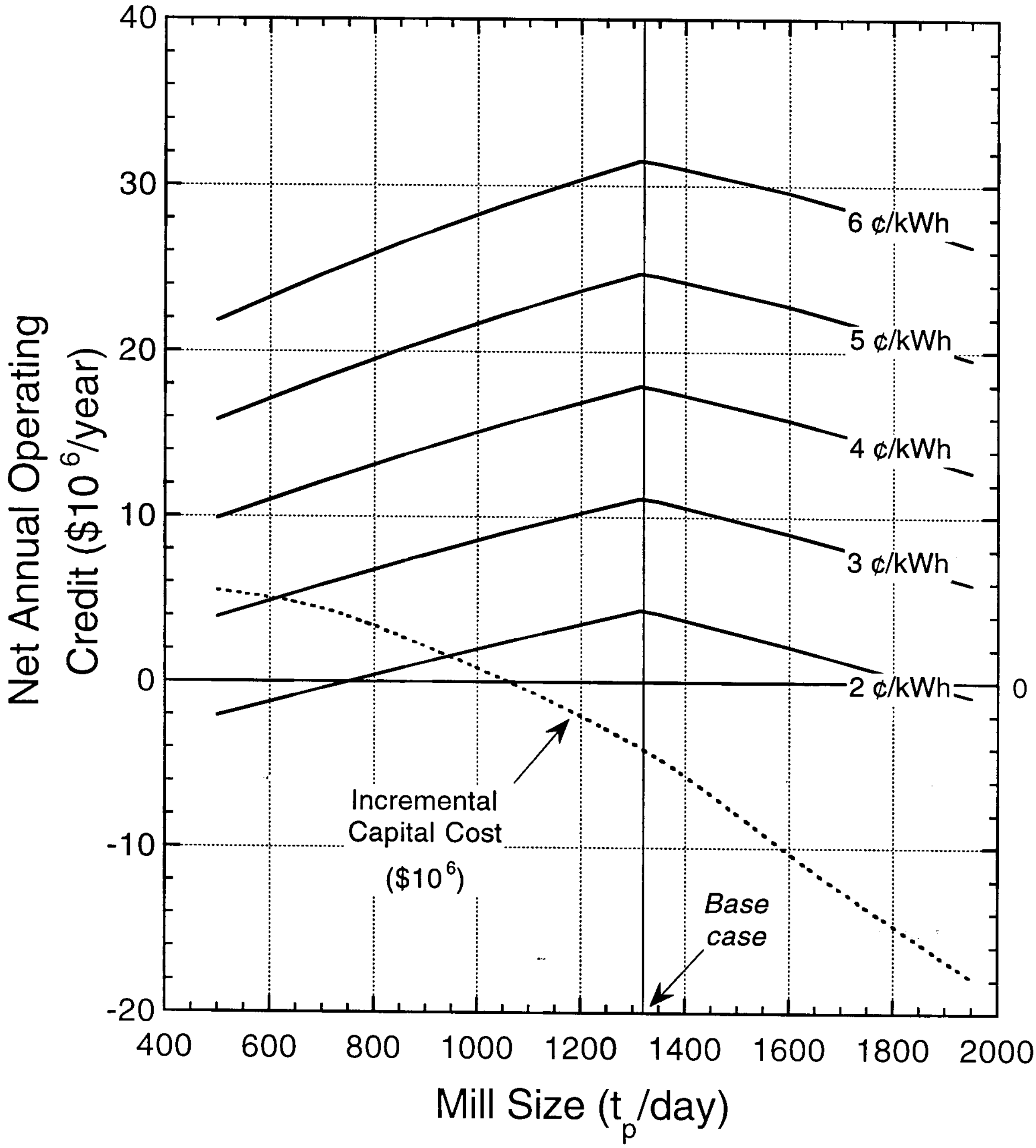

Fig. 11. Annual operating credit with BLGCC systems compared to Tomlinson recovery systems as a function of mill size and unit electricity value (steam demand=16.3 GJ/t_p). Also shown is the difference between the total installed capital cost for the BLGCC system and that for the Tomlinson system.

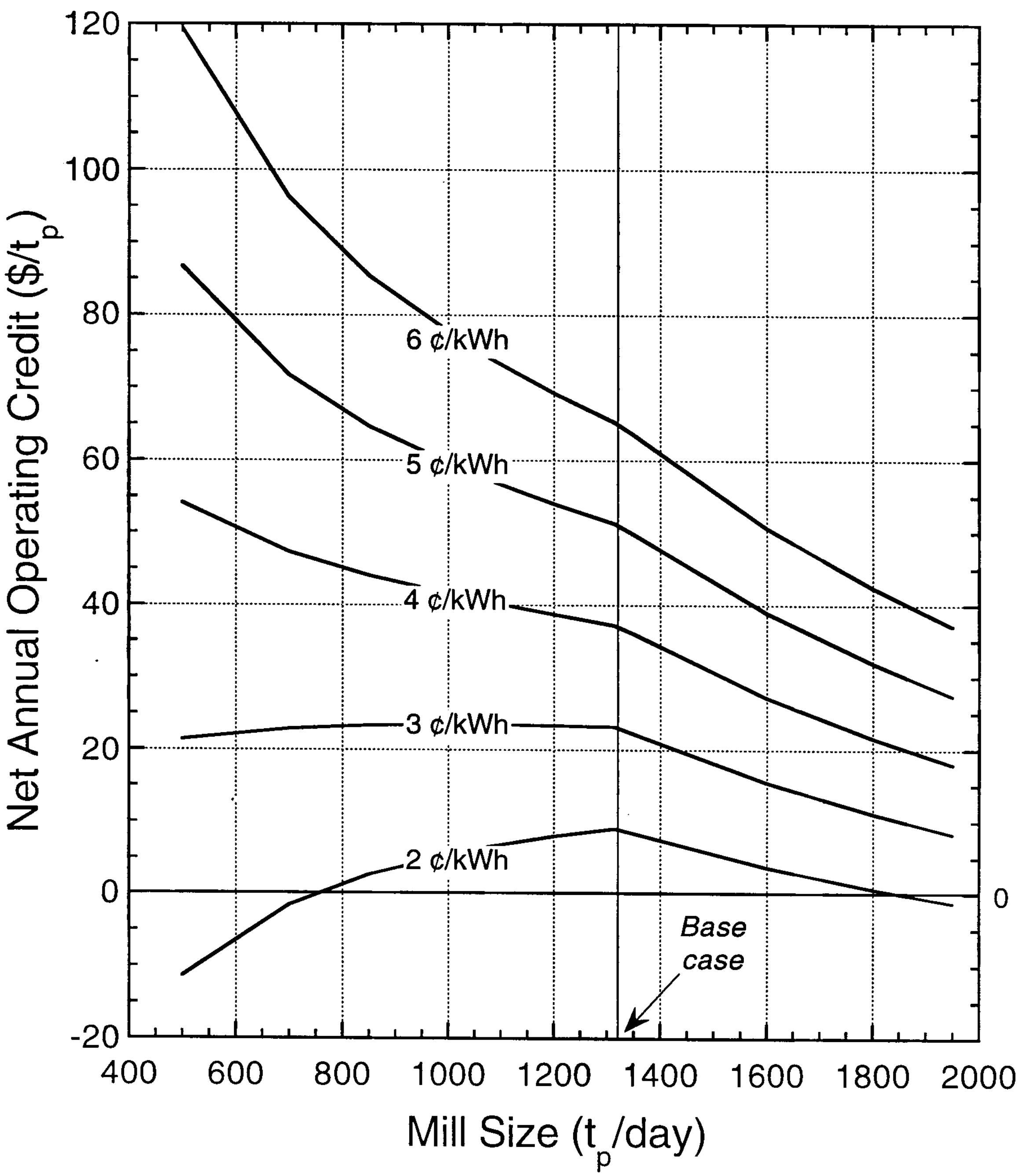

Fig. 12. Net annual operating credit per tonne of pulp produced with a BLGCC powerhouse vs. a Tomlinson powerhouse. The net annual operating credits shown in Fig. 11 are divided by annual pulp production (assuming 8000 hr/yr) to give the results shown here.