Int. J. of Thermodynamics **ISSN 1301-9724**
Vol. 9 (No. 2), pp. 65-72, June 2006

Specific Exergy Costs and Revenues in a Two-Pressure Combined Cycle Plant

David Paulus
Technical University of Berlin
Institute for Energy Engineering
Marchstrasse 18
10587 Berlin, Germany
e-mail: d.paulus@iet.tu-berlin.de

Naroa Gonzales Zarraonandia
ESCP-EAP (European School of Management)
Arroyofresno 1
28035 Madrid, Spain

Abstract

Paulus and Tsatsaronis presented a method with which specific exergy *revenues* can be calculated, as opposed to specific exergy *costs*. In this paper, specific exergy revenues and costs are calculated for a hypothetical two-pressure combined cycle power plant. First, the plant-internal specific exergy revenues and associated exergoeconomic variables are calculated for the case when the product revenues are equal to the product costs. The exergoeconomic, revenue-based variables are then compared to those resulting from the traditional, cost-based methods. The good agreement of the exergoeconomic variables calculated by both methods provides evidence of the validity of the proposed auxiliary equations for calculating revenues. Then, a parametric study with varying product revenues is performed. The resulting exergoeconomic variables show that, for a fixed fuel input, increased capital investment is desired as the products become more valuable.

Keywords: Exergoeconomics, thermoeconomics, specific exergy revenue

1. Introduction

Exergoeconomics is traditionally employed to find the specific cost of exergy associated with flows within a system, as well as the final product costs. In order to do this, monetary balances are written for each component, along with the appropriate auxiliary equations. When the cost of fuel is known, the resulting system of equations allows for the finding of the desired specific exergy costs, both within and at the boundaries of the system. One methodology for finding these auxiliary equations has been formulated by Lazzaretto and Tsatsaronis (1996, 1997, 1999). Valero and coworkers (1993) have presented the structural theory of thermoeconomics, which yields an essentially equivalent set of equations (Erlach, 1998).

These costs can be used to calculate certain exergoeconomic variables, such as the f-factor. These variables are useful in the optimization of an energy system, when the goal is to minimize the total cost for a fixed output with the fuel and capital investment as the independent variables (see, for example, Bejan et al., 1996).

There are times, however, when instead of a specific exergy cost, it is desirable to find the specific revenue associated with the exergy flows of a system, and to calculate the other exergoeconomic variables therewith. Although the term “revenue” was not used by them, Reistad and Gaggioli recognized this concept (1980). For example, consider a company purchasing a gas turbine-based cogeneration system that will replace all of their steam production and supplant some of their electricity purchases. A given gas turbine has essentially a fixed-fuel input at full load. At full load, capital costs are traded against an increased electric output. In this example, the revenue associated with the electric power is the amount of

---

*Author to whom correspondence should be addressed purchased electricity that has been replaced, multiplied by its price to the company.

As when calculating costs, monetary balances form part of the necessary set of equations to determine the revenues. However, the set of auxiliary equations will differ from that used for calculating costs, and the price of the products replaces the cost of the fuel as a boundary condition. Paulus and Tsatsaronis (2004, 2006) developed a methodology for determining the auxiliary equations for finding specific exergy revenues, as well as explaining the fundamental difference between specific exergy costs and revenues, and recommending when the latter should be used.

The purpose of this paper is to further examine the methodology given by Paulus and Tsatsaronis. A comparison is made between exergoeconomic variables (cost rates of exergy destruction and f-factors) when calculated with costs and revenues for a hypothetical two-pressure combined cycle power plant (CCPP). When calculating specific exergy revenues, the specific revenue associated with electric power was set equal to its average cost. For this case, it was expected that the exergoeconomic variables should be in relatively good (but not perfect) agreement when calculated from either revenue or cost data. This was expected because all profit (outside the investors' profit implicit in the revenue-required method of assigning capital cost) is thus removed from the system. It will be shown that, for most components, exergoeconomic variables calculated by both means have satisfactory agreement; the deviations will be elaborated upon.

One case where revenues are recommended for calculating exergoeconomic variables in lieu of costs is for the optimization of a system with a fixed fuel input. In this case, increased efficiency results in greater product revenue flow. In the optimization, capital costs are traded against the total product revenue flow. Therefore, components of the same system should show increased cost rates of exergy destruction with increasing product prices (specific revenue). The cost rate of exergy destruction here approximates the lost sales (lost product revenue) due to the exergy destruction in the component. As the cost rates of exergy destruction increase, the f-factors, which show the ratio of capital cost to total cost, decrease. A parametric study with varying product prices (revenues) has been performed on the sample CCPP, and it will be shown that the cost rates of exergy destruction and the f-factors behave as expected with varying product revenues.

2. The Auxiliary Equation Rules

Costs

The following two rules for formulating the auxiliary equations are valid when it is desired to find the specific costs of exergy associated with flows:

F-Principle: The total cost associated with the removal of exergy must be equal to the cost at which the removed exergy was supplied to the same stream in upstream components (Lazzaretto and Tsatsaronis, 1997).

P-Principle: Each exergy unit is supplied to any stream associated with the product at the same average cost (Lazzaretto and Tsatsaronis, 1997).

Revenues

The following two rules for formulating the auxiliary equations are valid when it is desired to find the specific revenues associated with exergy flows:

F-Principle (for revenues): Each exergy unit, of any type of exergy, which is supplied by any fuel stream to a device, has the same specific revenue associated with it (Paulus and Tsatsaronis, 2004).

P-Principle (for revenues): The revenue associated with a unit of exergy, supplied to a stream, is the same as the revenue of a unit of exergy removed from the same stream in a downstream component (Paulus and Tsatsaronis, 2004).

3. The Example System

Description

The example system is a natural gas-fired, two-pressure CCPP, modeled in GateCycle. A system diagram is at the end of this article (*Figure 2*); the exergy flows are given in

The specific cost of the exergy of the natural gas is 5.539 €/GJ. The specific cost associated with both the intake air and the cooling water is zero. (The calculated exergy flow of this air is non-zero because a standard model (Szargut et al., 1988) was used for chemical exergy, and the air was modeled with a chemical composition other than the reference state employed by the standard model.) The three remaining boundary conditions are given by setting the cost of electric power to the pumps equal to the average cost of power from the plant. For the calculation of revenues, there are again twenty balances and fourteen auxiliary equations; six boundary conditions are required. For the first calculation of specific revenues and exergoeconomic variables, the specific revenue associated with electric power was set equal to the average cost of the power:

$$r_{el} = \frac{c_{32}\dot{E}_{32} + \sum_j \dot{Z}_j}{\dot{W}_{el,net}} = 1.706\,\text{€/MJ} \qquad (1)$$

Streams 8 and 33 are waste streams; they have zero revenue. Also, the revenue flow associated with the air at the gas turbine was set equal to zero.

TABLE . TABLE II shows the capital costs for each component.

Table . This table shows also the relevant rule used to formulate each auxiliary equation.

Boundary Conditions

TABLE II shows capital costs. TABLE IV shows the fourteen auxiliary equations, which are used in conjunction with monetary balances on each component for the calculation of specific exergy costs. With forty unknown specific exergy costs, six boundary conditions are necessary to solve the resulting set of equations.

The specific cost of the exergy of the natural gas is 5.539 €/GJ. The specific cost associated with both the intake air and the cooling water is zero. (The calculated exergy flow of this air is non-zero because a standard model (Szargut et al., 1988) was used for chemical exergy, and the air was modeled with a chemical composition other than the reference state employed by the standard model.) The three remaining boundary conditions are given by setting the cost of electric power to the pumps equal to the average cost of power from the plant. For the calculation of revenues, there are again twenty balances and fourteen auxiliary equations; six boundary conditions are required. For the first calculation of specific revenues and exergoeconomic variables, the specific revenue associated with electric power was set equal to the average cost of the power:

$$r_{el} = \frac{c_{32}\dot{E}_{32} + \sum_j \dot{Z}_j}{\dot{W}_{el,net}} = 1.706\,\text{€/MJ} \qquad (1)$$

Streams 8 and 33 are waste streams; they have zero revenue. Also, the revenue flow associated with the air at the gas turbine was set equal to zero.

TABLE I. EXERGY FLOWS.

Stream	Exergy Flow [MW]	Stream	Exergy Flow [MW]
1	138.90	21	18.33
2	128.13	22	0.81
3	112.08	23	0.84
4	66.53	24	6.12
5	53.86	25	0.87
6	53.02	26	6.81
7	30.75	27	6.91
8	21.67	28	2.23
9	60.21	29	4.67
10	45.96	30	4.89
11	59.38	31	0.78
12	51.62	32	500.23
13	14.56	33	11.03
14	59.70	34	8.24
15	79.87	$\dot{W}_{el,GT1}$	151.79
16	0.35	$\dot{W}_{el,ST1}$	13.11
17	21.41	$\dot{W}_{el,ST2}$	54.91
18	1.21	$\dot{W}_{el,PUMP1}$	0.04
19	20.20	$\dot{W}_{el,PUMP2}$	0.10
20	20.90	$\dot{W}_{el,PUMP3}$	0.24

Fuel, Product and Efficiency Definitions

The definitions for the exergetic fuel and product are per Lazzaretto and Tsatsaronis (1996, 1997, 1999) and are shown in TABLE III. These definitions are independent of whether specific costs or revenues are being calculated.

Auxiliary Equations

The auxiliary equations used for calculating both specific costs and revenues are given in

TABLE II. COMPONENTS, CAPITAL COSTS AND MONETARY BALANCES.

Device	Capital Cost[1] [€/hr]	Device	Capital Cost [€/hr]
CND1	16.2	PUMP2	6.0
DA1	1.6	PUMP3	12.3
ECON1	38.7	SP1	0
ECON2	42.6	SP2	0
EVAP1	125.3	SP3	0
EVAP2	258.8	SPHT1	38.9
GT1	1877.	SPHT2	64.7
M1	0	SPHT3	7.8
M2	0	ST1	296.6
PUMP1	2.6	ST2	712.6

For the parametric study, revenues and exergoeconomic values were additionally calculated at one half, three halves and twice the average cost of electric power:

---

[1] The capital costs associated with piping have been included with those of the primary components. Therefore, the capital costs of mixers and splitters are zero.

$$r_{el} = \left(0.5, 1.0, 1.5, 2.0\right) \cdot 1.706\,€/\mathrm{MJ} \qquad (2)$$

TABLE III. EXERGETIC FUEL AND PRODUCT OF COMPONENTS.

Device	$\dot{E}_F$	$\dot{E}_P$
CND1	$\dot{E}_{21} - \dot{E}_{22}$	$\dot{E}_{33} - \dot{E}_{34}$
DA1	$\dot{m}_{25}\left(e_{25} - e_{26}\right)$	$\dot{m}_{24}\left(e_{26} - e_{24}\right)$
ECON1	$\dot{E}_{4} - \dot{E}_{5}$	$\dot{E}_{13} - \dot{E}_{30}$
ECON2	$\dot{E}_{7} - \dot{E}_{8}$	$\dot{E}_{24} - \dot{E}_{23}$
EVAP1	$\dot{E}_{3} - \dot{E}_{4}$	$\dot{E}_{12} - \dot{E}_{13}$
EVAP2	$\dot{E}_{6} - \dot{E}_{7}$	$\dot{E}_{17} - \dot{E}_{28}$
GT1	$\dot{E}_{32}$	$\dot{W}_{el,\mathrm{GT1}} + \left(\dot{E}_{1} - \dot{E}_{31}\right)$
PUMP1	$\dot{W}_{el,\mathrm{PUMP1}}$	$\dot{E}_{23} - \dot{E}_{22}$
PUMP2	$\dot{W}_{el,\mathrm{PUMP2}}$	$\dot{E}_{27} - \dot{E}_{26}$
PUMP3	$\dot{W}_{el,\mathrm{PUMP3}}$	$\dot{E}_{30} - \dot{E}_{29}$
SPHT1	$\dot{E}_{1} - \dot{E}_{2}$	$\dot{E}_{9} - \dot{E}_{12}$
SPHT2	$\dot{E}_{2} - \dot{E}_{3}$	$\dot{E}_{11} - \dot{E}_{10}$
SPHT3	$\dot{E}_{5} - \dot{E}_{6}$	$\dot{E}_{20} - \dot{E}_{19}$
ST1	$\dot{E}_{9} - \dot{E}_{11}$	$\dot{W}_{el,\mathrm{ST1}}$
ST2	$\dot{E}_{15} - \dot{E}_{21}$	$\dot{W}_{el,\mathrm{ST2}}$

Specific Costs (Revenues) Associated with the Exergetic Fuel or Product, Costs of Exergy Destruction and f-Factors

The specific cost of the exergetic fuel (or product) is found by dividing the cost flow associated with the fuel (or product) by its exergy flow. For example, for the heat exchanger SPHT1:

$$c_{F,\mathrm{SPHT1}} = \frac{\dot{C}_1 - \dot{C}_2}{\dot{E}_1 - \dot{E}_2} = \frac{c_1\dot{E}_1 - c_2\dot{E}_2}{\dot{E}_1 - \dot{E}_2} \qquad (3)$$

$$c_{P,\mathrm{SPHT1}} = \frac{\dot{C}_9 - \dot{C}_{12}}{\dot{E}_9 - \dot{E}_{12}} = \frac{c_9\dot{E}_9 - c_{12}\dot{E}_{12}}{\dot{E}_9 - \dot{E}_{12}} \qquad (4)$$

The same equations are used to calculate the specific revenue of the fuel or product, with “ $\dot{R}$ ” substituted for “ $\dot{C}$ ” and “*r*” for “*c*”.

When working with costs, the cost rate of exergy destruction is defined with (Bejan et al., 1996):

$$\dot{C}_{D,i} = c_{F,i}\dot{E}_{D,i} \qquad (5)$$

Alternatively, when working with revenues, the cost rate of exergy destruction is defined with [5]:

$$\dot{C}_{D,i} = r_{P,i}\dot{E}_{D,i} \qquad (6)$$

Instead of approximating the additional cost to the system, Equation approximates the lost revenue to the plant due to the exergy destruction in component *i*.

TABLE IV. AUXILIARY EQUATIONS.

Device	Cost. Aux. Eq.		Revenue Aux. Eq.	
CND1	F	$c_{21}=c_{22}$	P	$r_{24}=r_{33}$
DA1	-	-	P	$r_{24}=r_{26}$
ECON1	F	$c_4=c_5$	P	$r_{30}=r_{13}$
ECON2	F	$c_7=c_8$	P	$r_{23}=r_{24}$
EVAP1	F	$c_3=c_4$	P	$r_{13}=r_{12}$
EVAP2	F	$c_6=c_7$	P	$r_{28}=r_{17}$
GT1	P	$c_1=c_{el,\mathrm{GT1}}$	-	-
M1	-	-	F	$r_{11}=r_{16}$
M2	-	-	F	$r_{14}=r_{20}$
PUMP1	-	-	P	$r_{22}=r_{23}$
PUMP2	-	-	P	$r_{26}=r_{27}$
PUMP3	-	-	P	$r_{29}=r_{30}$
SP1	F	$c_{18}=c_{16}$	-	-
SP2	F	$c_{17}=c_{18}$	-	-
SP3	F	$c_{27}=c_{28}$	-	-
SPHT1	F	$c_1=c_2$	P	$r_{10}=r_{11}$
SPHT2	F	$c_2=c_3$	P	$r_{12}=r_9$
SPHT3	F	$c_5=c_6$	P	$r_{19}=r_{20}$
ST1	F	$c_9=c_{10}$	-	-
ST2	F	$c_{15}=c_{21}$	-	-

The f-factor represents the ratio of the capital cost of a component to its total cost, the sum of capital cost and the cost of exergy destruction, as defined in Equations (5) and (6).

$$f_i = \frac{\dot{Z}_i}{\dot{Z}_j + \dot{C}_{D,i}} \qquad (7)$$

4. Results

Specific Costs and Revenues

The resulting specific costs and revenues associated with the exergy flows are reported in Table . (The revenues reported therein are for the case of the revenue associated with electricity set equal to its average cost.)

Exergoeconomic Variables

The costs of exergy destruction in each component, as well as the component's f-factor, are reported in Table . These values are shown as calculated from (1) the specific exergy costs and (2) the specific exergy revenue when calculated with the revenue associated with electricity set equal to its average cost.

Both methods of calculating the costs of exergy destruction and the f-factors for the steam turbines show excellent agreement. (The difference in the cost of exergy destruction is less than ten percent for both turbines; the difference in the f-factor is less than two percent.) The values for the heat exchangers differ more, with the cost of exergy destruction averaging about eighteen percent higher than the corresponding revenue; the resultant f-factors average fourteen percent higher.

TABLE V. SPECIFIC COSTS AND REVENUES WITH $r_{el}=c_{el,avg}$.

Stream	c [€/GJ]	r [€/GJ]
1	11.33	5.125
2	11.33	5.012
3	11.33	4.788
4	11.33	3.370
5	11.33	2.680
6	11.33	2.642
7	11.33	1.209
8	11.33	0.000
9	15.69	9.369
10	15.69	9.201
11	15.50	9.201
12	15.73	9.369
13	17.93	9.369
14	15.52	9.204
15	16.14	9.288
16	17.37	9.201
17	17.37	9.114
18	17.37	7.605
19	17.37	9.204
20	17.35	9.204
21	16.14	0.1652
22	16.14	9.286
23	17.08	9.286
24	21.09	9.286
25	17.37	6.966
26	21.20	9.286
27	21.38	9.286
28	21.38	9.114
29	21.38	9.369
30	21.85	9.369
31	0.00	0.000
32	5.539	5.557
33[2]	26.03	0.000
34	0.00	0.000
$\dot{W}_{el,GT1}$	11.33	17.06
$\dot{W}_{el,ST1}$	23.34	17.06
$\dot{W}_{el,ST2}$	21.70	17.06
$\dot{W}_{el,PUMP1}$	14.61	-12.60
$\dot{W}_{el,PUMP2}$	14.61	-8.098
$\dot{W}_{el,PUMP3}$	14.61	-5.737

While the values for the steam turbines and heat exchangers are reasonably close, there is substantial deviation in the exergy destruction cost and the f-factor of the gas turbine.

Parametric Study

Table shows the variation of the f-factor (as calculated with $\dot{C}_{D,i} = r_{P,i}\dot{E}_{D,i}$) with varying product revenue. For all components, the f-factor declines as the product revenue increases.

TABLE VI. EXERGOECONOMIC VARIABLES AS CALCULATED FROM SPECIFIC COSTS AND REVENUES WITH $r_{el}=c_{el,avg}$.

Device	C_D (from c_F) [€/hr]	f (from c_F)	C_D (from r_P) [€/hr]	f (from r_P)
DA1	8.9	0.152	4.7	0.254
ECON1	122.2	0.240	101.1	0.277
ECON2	155.0	0.216	127.1	0.251
EVAP1	346.2	0.266	286.4	0.304
EVAP2	126.1	0.672	101.5	0.718
GT1	4178.5	0.310	8567.5	0.180
PUMP1	0.4	0.867	0.3	0.911
PUMP2	0.5	0.923	0.3	0.950
PUMP3	1.3	0.902	0.9	0.935
SPHT1	88.9	0.304	73.5	0.346
SPHT2	106.9	0.377	86.8	0.427
SPHT3	6.0	0.567	4.8	0.617
ST1	64.6	0.821	70.2	0.809
ST2	385.5	0.649	407.5	0.636

TABLE VII. VARIATION OF THE F-FACTOR WITH VARYING PRODUCT PRICE.

f-factor

---

[2] The condenser was not treated as a dissipative component in this paper.

Device	$r_{el}=$ $0.5\cdot c_{el,avg}$	$r_{el}=$ $1.0\cdot c_{el,avg}$	$r_{el}=$ $1.5\cdot c_{el,avg}$	$r_{el}=$ $2.0\cdot c_{el,avg}$
DA1	0.503	0.254	0.169	0.127
ECON1	0.542	0.277	0.186	0.140
ECON2	0.500	0.251	0.168	0.126
EVAP1	0.575	0.304	0.207	0.157
EVAP2	0.876	0.718	0.609	0.528
GT1	0.336	0.180	0.123	0.093
PUMP1	0.968	0.911	0.860	0.815
PUMP2	0.983	0.950	0.919	0.890
PUMP3	0.978	0.935	0.896	0.860
SPHT1	0.621	0.346	0.240	0.184
SPHT2	0.673	0.427	0.313	0.247
SPHT3	0.817	0.617	0.496	0.414
ST1	0.894	0.809	0.738	0.679
ST2	0.778	0.636	0.538	0.467

5. Discussion

Exergoeconomic Variables

In the calculation of the specific costs and revenues, the combustion gas turbine was treated as a single component, as it is typically purchased as such. Therefore, it is not possible to calculate the specific exergy costs (or revenues) of the streams internal to the gas turbine. With this treatment of the gas turbine, there are two choices for auxiliary equations.

In the auxiliary equations used to calculate the specific exergy costs, the gas turbine was assumed to have two products, and the P-rule yields $c_1=c_{el,GT1}$. This results in the proportional assignment of the gas turbine's capital costs to both the power output and the gas turbine's exhaust gas. (Note that this is not strictly consistent with the SPECO approach. However, the results of this approach are slightly closer to the results when the gas turbine *is* broken into components.)

An alternative is to assume the gas turbine to have one product, electric power, in strict compliance with the SPECO approach. With this assumption, all of the gas turbine's capital costs are assigned to the electricity, and the F-rule yields $c_1=c_{32}$. In order to clarify why the f-factors of heat exchangers were consistently somewhat higher when calculated based on revenue data rather than cost data, the f-factors were recalculated. In this recalculation, the f-factors were calculated based on cost data with the assumption that the gas turbine had a single product.

When the f-factors of the heat exchangers, as calculated from revenue data, were compared to those from the recalculation, it was found that those calculated from revenue data were now somewhat lower than those calculated from cost data. That is, the f-factors of the heat exchangers, when calculated from revenue data, fell between the two sets of those calculated from costs. This is shown graphically in *Figure 1*. The lower calculated cost of exergy at Stream 1 reduces the calculated costs of exergy destruction in the heat exchangers. This reduction results in higher calculated f-factors. (Not shown on the graph is the deaerator. Its f-factor, as calculated from revenue data, also falls between the f-factors from the two sets of cost data.)

If it were possible to split the combustion gas turbine into its components, the resulting specific exergy costs would fall between those calculated assuming (1) the gas turbine has one product and (2) the gas turbine has two products. This is because, when the gas turbine is split into components: (1) the generator's capital costs would be assigned entirely to the electric power, (2) the capital costs of the compressor and combustion chamber would be assigned proportionally to the exhaust gas and the electric power and (3) the expander's capital costs would be assigned directly to mechanical power; some of these costs (approximately half) flow back to the compressor, while the remainder are assigned to the electric power. As the *majority* of the capital costs would be assigned proportionally, the results would be expected to be closer to those from the assumption of two products. Because not *all* of the capital costs are assigned proportionally, the results must lie between those of the assumptions of one product and two products. Thus, if the gas turbine could be split into components, the authors would expect the f-factors calculated from both revenues and costs to match very closely.

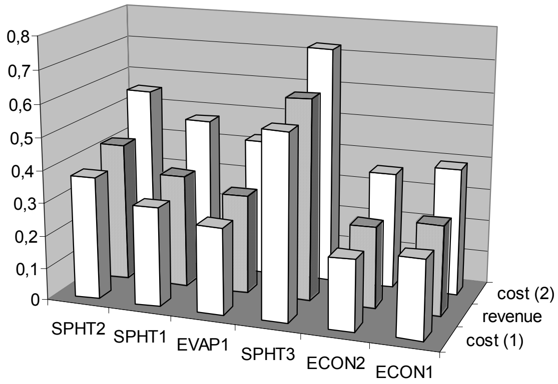

Figure 1. f - factors of the heat exchangers[3].

Calculations by the authors, estimating the internal parameters of the gas turbine, and estimating the capital costs as being equally split between the compressor, combustion chamber, turbine and generator, showed agreement in the

---

[3] The set with the shaded bars was calculated from revenue data. The set cost (1) was calculated from cost data with $c_1=c_{el,GT1}$ and the set cost (2) with $c_1=c_{32}$.

f-factors of these components within ten percent for all components except the combustion chamber (which had an f-factor of 0.15 and 0.092 calculated from costs and revenues, respectively).

This discussion reiterates that in the absence of a detailed cost breakdown of a subassembly of an energy system, even a rudimentary estimate of this breakdown may improve the accuracy of exergoeconomic calculations.

Parametric Study

The f-factor, representing the ratio of capital cost to total cost (capital cost and the cost of exergy destruction), is a tool useful in the iterative optimization of an energy system (Bejan et al., 1996). A very high f-factor is a sign that a reduction in efficiency should be accepted in order to reduce capital costs, and a very low value is a sign that additional capital should be invested in order to reduce exergy destruction. When calculated from cost data, the f-factor is in no way affected by the product price.

There are times, however, when it is desirable to have an f-factor that is influenced by price (the specific revenue associated with the product). Consider as an example a cogeneration system being designed for a company currently producing its own steam but purchasing all needed electricity. Assume that the plant will not completely meet the company's electric demand. Then, the specific revenue associated with the electricity is equal to the current purchase price of electricity for the company. Logically, if the fuel input to the plant is fixed (as it would be, for example, if the plant were fired by a gas turbine), the higher the purchase price of electricity, the more capital should be invested in the plant.

The results from the parametric study show that the f-factor, when calculated from revenue data, is strongly influenced by the product's specific revenue. As the specific revenue increases, the f-factors decrease, suggesting that more capital should be invested in each component. This is in agreement with logic and the expected behavior, and such behavior is nonexistent when the f-factors are calculated from cost data.

The authors suggest that when fuel input is fixed, exergoeconomic variables calculated from revenue data should be employed for any analysis.

6. Conclusion

Validity of the Auxiliary Equations for the Calculation of Specific Exergy Revenues

The generally good agreement between (1) the cost of exergy destruction in components and (2) the components' f-factors when calculated based on (a) costs and (b) revenues (the latter calculated with the revenue of electricity set to its average cost of production) provides evidence that the auxiliary equations for calculating the specific costs associated with exergy streams, as proposed by Paulus and Tsatsaronis [5], are valid. Although some discrepancies were initially noted, these were definitively attributed to the lumping of the individual components of the gas turbine.

Applicability of Revenues to Exergoeconomic Analysis

An exergoeconomic analysis in which specific exergy costs are used to calculate the exergoeconomic variables is unable to take into account product price information. For the case of a fixed system output, this is of no account to optimization. Minimizing product costs suffices as an optimization goal.

However, the design of some systems (including any system based on a commercially available combustion gas turbine) has the constraint of fixed fuel input. Then, capital costs are traded against additional output. In some cases (such as that of an additional power plant for a utility), minimizing the average costs likely suffices as an optimization goal. However, in other cases, such as the one where a proposed plant will offset the purchase of a currently commercially purchased commodity, it does not. In these latter cases, the economically optimal design of a plant will be strongly influenced by product price. Here, methods that take into account this price are necessary. The specific revenues associated with exergy flows should then be used to calculate exergoeconomic variables. This paper demonstrated that the use of revenues for these calculations provides price feedback to the exergoeconomic variables.

Acknowledgement

The comments from Professor George Tsatsaronis were greatly appreciated.

References

Bejan, A., Tsatsaronis, G. & Moran, M., 1996, *Thermal Design and Optimization*, John Wiley and Sons, New York, Ch. 8.

Erlach, B., 1998, "Comparison of Thermoeconomic Methodologies: Structural Theory, AVCO and LIFO, Application to a Combined Cycle", Department of Mechanical Engineering, University of Zaragoza, Zaragoza, Spain.

Lazzaretto, A. & Tsatsaronis, G., 1996, "A General Process-Based Methodology for Exergy Costing", *1996 Proceedings of the ASME*

Advanced Energy Systems Division, AES-Vol. 36, ASME, New York, pp. 413-428.

Lazzaretto, A. & Tsatsaronis, G., 1997, "On the Quest for Objective Equations in Exergy Costing", *1997 Proceedings of the ASME Advanced Energy Systems Division*, AES-Vol. 37, ASME, New York, pp. 197-210.

Lazzaretto, A. & Tsatsaronis, G., 1999, "On the Calculation of Efficiencies and Costs in Thermal Systems", *1999 Proceedings of the ASME Advanced Energy Systems Division*, AES-Vol. 39, ASME, New York, pp. 421-430.

Paulus, D. M. Jr. & Tsatsaronis, G., 2004, "Auxiliary Equations for the Determination of Specific Exergy Revenues", *Proceedings of the 17th International Conference on Efficiency, Costs, Optimization, Simulation and Environmental Impact of Energy Systems, ECOS '04*, R. Rivero et al., ed., Guanajuato, México, pp. 561-572.

Paulus, D. M. Jr. & Tsatsaronis, G., "Auxiliary Equations for the Determination of Specific Exergy Revenues", 2006, *Energy, the International Journal* (Article in press, corrected proofs available online as of April 16, 2006).

Reistad, G. M. & Gaggioli, R. A., 1978, "Available Energy Costing", *Thermodynamics: Second Law Analysis*, R. A. Gaggioli, ed., American Chemical Society, Washington, D.C.

Szargut, J., Morris D. R. & Steward, F. R., 1988, *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, Hemisphere, New York, p. 297.

Valero, A., Serra, L., & Lozano, M. A., 1993, "Structural Theory of Thermoeconomics", *International Symposium on Thermodynamics and the Design, Analysis and Improvement of Energy Systems*, ASME Book No. H00874, H. J. Richter, ed., New Orleans, pp. 189-198.

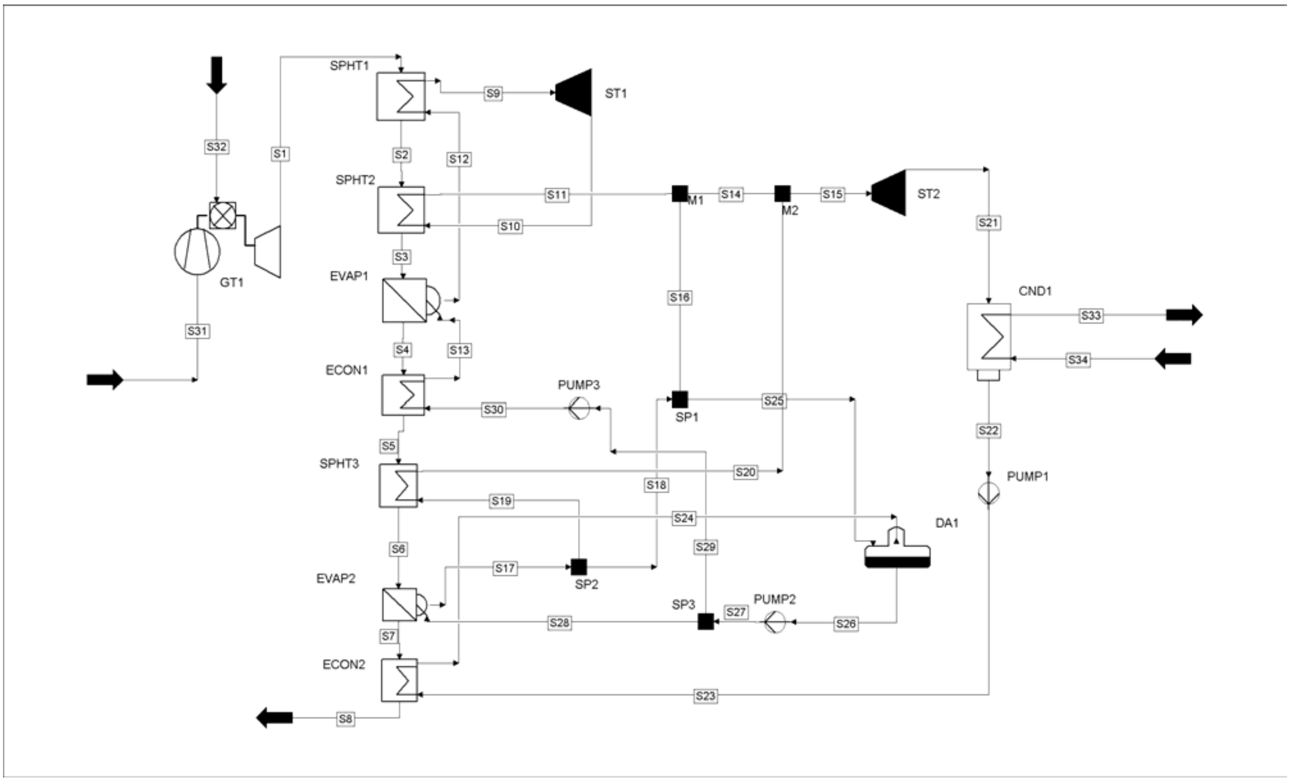

Figure 2. CCPP Flowchart.