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Thermoeconomic Analysis of Simple Trigeneration Systems*

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Abstract

Trigeneration is the combined production of heating, cooling and power from the same source of energy. In this paper, the operation of a simple trigeneration system is analyzed. The system is interconnected to the electric utility grid, both to receive electricity and to deliver surplus electricity. For any given demand required by the users, a great number of operating conditions are possible. The operational mode with the lowest variable cost is obtained through a linear programming model. Three different approaches to determine the costs of internal flows and final products of the simple trigeneration systems are presented: marginal costs corresponding to optimal operation, costs obtained when production costs are distributed to the final products according to their market prices, and internal costs corresponding to a thermoeconomic analysis of the operation mode of the system. As expected, the costs obtained with the approaches mentioned are different and it can be concluded that there are no general rules to decide which approach is best: it depends on the issue under investigation.

Keywords: *CHCP, Linear Programming, Optimization, Thermoeconomics, Trigeneration.*

1. Introduction

Over a long period of time, cogeneration has been contributing significantly and cost-effectively to economic competitiveness, environmental friendliness and security of energy supply for the industrial sector (Horlock, 1987; EDUCOGEN, 2001). To expand the benefits of cogeneration to the buildings sector, the EU Cogeneration Directive (European Union, 2004) explicitly refers to the Buildings Directive (European Union, 2003) which establishes that for new buildings with a total usable space area over 1000 m^2, the technical, environmental and economic feasibility of alternative energy systems, such as cogeneration, must be considered and taken into account before construction starts.

Starting from the same source of energy – for example, natural gas – cogeneration (CHP) provides heating and power that can meet energy needs of large commercial buildings and city districts. Combining cogeneration with heat-driven absorption chillers, the heat demand can be extended into the summer months to match cooling loads. This is of particular interest for Mediterranean countries (TRIGEMED, 2003).

Trigeneration (CHCP) systems constitute of a variety of technologies (Lindenberg et al., 2000; Chicco and Mancarella, 2006; Li et al., 2006; Wu and Wang, 2006). Two fundamental issues should be addressed in the design of trigeneration plants for buildings (Yokoyama et al., 1994; Serra et al., 2008), the synthesis of the plant configuration (number and capacity of equipment for each type of technology employed) and the operational planning (strategy concerning operational state of the equipment, energy flow rates, purchase/selling of electricity, etc.). For new plants these issues are not independent, but for existing plants the operational strategy is the only concern.

For the sake of clarity, this paper only deals with the analysis of the operation of simple trigeneration systems. As shown in Figure 1, a simple trigeneration system consists of: i) a cogeneration module which includes the prime mover (gas turbine, reciprocating engine, etc.) converting the fuel energy to shaft power, an alternator which transforms mechanical to electric power, and a heat recovery system, ii) an absorption chiller, that converts heat into cold water, and sometimes: iii) an auxiliary boiler, iv) an electric driven chiller.

In a competitive energy market scenario, profitability of the operation of simple trigeneration systems depends on the capacity and performance of the installed technologies, fuel and electricity prices (subject to high variability and volatility). There are also great daily and seasonal variations of quantities demanded of energy services in buildings. For a given demand several operating conditions are possible. To minimize variable cost a continuously adjusting of operating conditions is required in reaction to changing demands and market conditions.

In management, cost accounting is the process of tracking, recording and analyzing costs associated with the products or activities of a plant. Managers use cost accounting to support decision making to reduce a company's costs and improve its profitability. In energy systems with several products such as trigeneration plants, it is often critical to know how much of the costs should be attributed to each product (El-Sayed and Gaggioli, 1989). Appropriate cost assessment criteria are essential to promote rational and efficient energy services production and consumption.

In this paper the thermoeconomic analysis of simple trigeneration systems is accomplished based on three different approaches for cost assessment: i) analysis of marginal costs, ii) valuation of products applying market prices, and iii) internal cost calculation. The different costs obtained with different approaches were analyzed along with their specific applications, which depend on the issue to be solved.

The optimal operation of the simple trigeneration system was obtained using a linear programming model and unit costs of internal flows and final products for all three approaches were calculated and compared.

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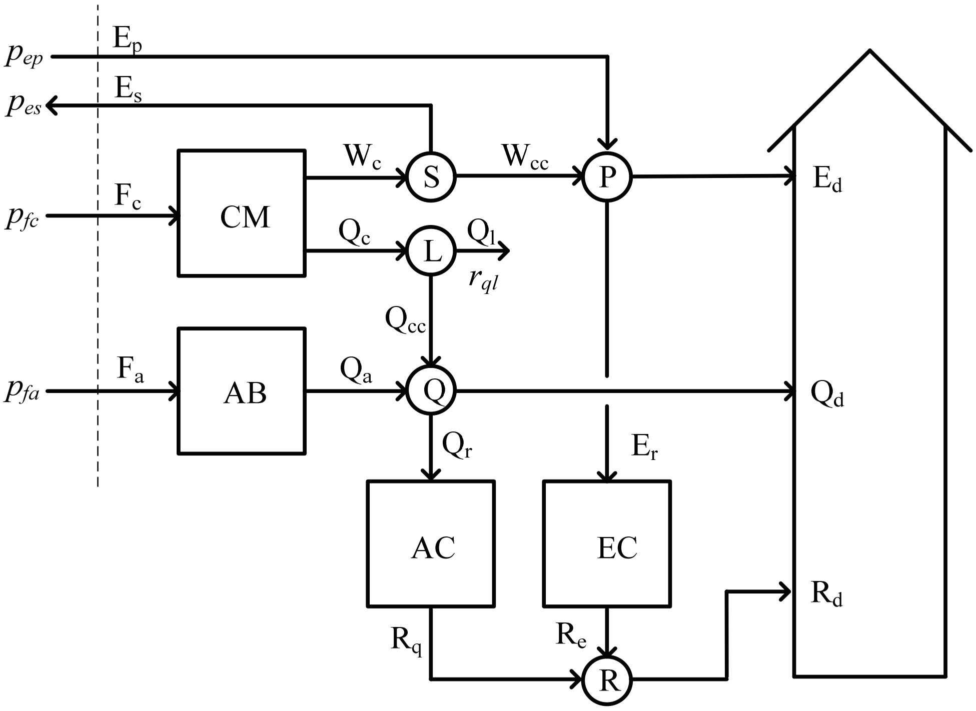

Figure 1. Schematic Diagram of the Simple Trigeneration System.

2. Trigeneration System

2.1 Functional Aspects

The purpose of the trigeneration system shown in Figure 1 is to attend the demand of different energy services (electricity, E_d; heating, Q_d; and cooling, R_d) of a consumer center. The trigeneration system consists of the following productive units: a cogeneration module CM (providing heat, Q_c, and work, W_c), an auxiliary boiler AB (providing heat, Q_a), an absorption chiller AC (providing cooling, R_q, and driven by heat, Q_r) and a vapor compression chiller EC (providing cooling, R_e, and driven by electricity, E_r).

Demands will always be met either by the trigeneration system productive units or with the help of purchased electricity from the electric grid (E_p). There is also the possibility of selling electricity (E_s) to the market. A fraction (Q_l) of the cogenerated heat could be wasted. Wasted heat permits the operation of the cogeneration module to match the demand of the consumer center or to realize profits by selling surplus electricity produced to the market. The consumer has the freedom to decide how the system operates to minimize costs.

Table 1. Technical Parameters.

Unit	Efficiency coefficient	Nominal capacity [kW]
CM	$\alpha_w \equiv W_c/F_c = 0.35$ $\alpha_q \equiv Q_c/F_c = 0.40$	$W_{c\ nom} = 350$
AB	$\eta_q \equiv Q_a/F_a = 0.80$	$Q_{a\ nom} = 400$
AC	$COP_q \equiv R_q/Q_r = 0.625$	$R_{q\ nom} = 250$
EC	$COP_e \equiv R_e/E_r = 5.0$	$R_{e\ nom} = 250$

2.2 Technical Aspects

Table 1 shows the technical data of the trigeneration system productive units. All of the units can operate either at part load or full load, assuming constant values of efficiency coefficients.

2.3 Economical Aspects

Fuel and electricity were the only significant variable costs considered, and cogenerated heat could be wasted without cost, i.e., $r_{ql} = 0$. Table 2 summarizes the prices of energy flows interchanged with the market.

Table 2. Energy Prices [€/kWh].

p_{ep}	p_{es}	p_{fc}	p_{fa}
0.100	0.080	0.025	0.020

3. Optimal Operation

Optimal operation for the simple trigeneration system is obtained by solving a linear programming model. The model was solved using the LINGO modelling language and optimizer (LINDO Systems, 2007), a commercial software package for solving optimization problems. The objective function to be minimized in the linear model is the operation variable cost [€/h]:

$$CH = p_{fc} \cdot F_c + p_{fa} \cdot F_a + p_{ep} \cdot E_p - p_{es} \cdot E_s + r_{ql} \cdot Q_l \quad (1)$$

subject to the following constraints:

Capacity limits

CM: $W_c \leq W_{c\ nom}$ (2)

AB: $Q_a \leq Q_{a\ nom}$ (3)

AC: $R_q \leq R_{q\ nom}$ (4)

EC: $R_e \leq R_{e\ nom}$ (5)

Production restrictions

CMw: $\alpha_w \cdot F_c - W_c = 0$ (6)

CMq: $\alpha_q \cdot F_c - Q_c = 0$ (7)

AB: $\eta_q \cdot F_a - Q_a = 0$ (8)

AC: $COP_q \cdot Q_r - R_q = 0$ (9)

EC: $COP_e \cdot E_r - R_e = 0$ (10)

Balance equations

S: $W_c - W_{cc} - E_s = 0$ (11)

P: $W_{cc} + E_p - E_d - E_r = 0$ (12)

L: $Q_c - Q_{cc} - Q_l = 0$ (13)

Q: $Q_{cc} + Q_a - Q_d - Q_r = 0$ (14)

R: $R_q + R_e - R_d = 0$ (15)

Demand constraints (Example C1)

ED: $E_d = 400$ kW (16)

QD: $Q_d = 400$ kW (17)

RD: $R_d = 400$ kW (18)

Given the energy demands to be satisfied, LINGO determines the feasible operation state with minimum variable cost.

The group of operation states can be classified in 9 different operation modes, considering the values of purchased electricity (E_p), sold electricity (E_s), auxiliary heat (Q_a) and waste heat (Q_l). These operation modes are shown in Table 3.

Summary of the results (flows and hourly costs) for optimal operation states corresponding to operation modes C_1, C_3, C_7 and C_9 are shown in Table 4.

4. Thermoeconomic Analysis

Thermoeconomics launches an intensive analysis dose on the design and operation concepts of energy conversion systems for the purpose of revealing opportunities of energy and cost savings (El-Sayed, 2003). Thermoeconomic methods are powerful tools for the analysis (Tsatsaronis and Winhold, 1985; Lozano and Valero, 1993b), diagnosis (Lozano et al., 1994; Arena and Borchiellini, 1999) and optimization (von Spakovsky and Evans, 1990b; Lozano et al., 1996) of energy conversion systems.

According to Gaggioli (1983) the objectives of thermoeconomic cost accounting are: 1) to determine the actual cost of products, 2) to provide a rational basis for pricing products, 3) to provide a means of controlling expenditures, and 4) to form a basis for operating decisions and the evaluation thereof.

In this paper, thermoeconomic cost accounting of simple trigeneration systems is accomplished based on three different approaches: i) analysis of marginal costs, ii) valuation of products applying market prices, and iii) internal costs calculation.

The analysis of thermoeconomic costs was carried out for example C1 in Tables 3 and 4. The demands of the three energy services (electricity, heating and cooling) are equal to 400 kW. The energy flows corresponding to the operation with minimum variable cost are shown in Figure 2. The variable cost is CH = 41 €/h.

Table 3. Operation Modes.

	$E_p > 0$, $E_s = 0$	$E_p = 0$, $E_s = 0$	$E_p = 0$, $E_s > 0$
$Q_a > 0$, $Q_l = 0$	**C_1**	C_4	**C_7**
$Q_a = 0$, $Q_l = 0$	C_2	C_5	C_8
$Q_a = 0$, $Q_l > 0$	**C_3**	C_6	**C_9**

Table 4. Optimal Operation (Examples).

		C1	C3	C7	C9
E_d	kW	400	400	200	200
Q_d	kW	400	100	600	100
R_d	kW	400	100	100	100
E_p	kW	100	50	0	0
E_s	kW	0	0	130	150
F_c	kW	1000	1000	1000	1000
F_a	kW	300	0	250	0
W_c	kW	350	350	350	350
Q_c	kW	400	400	400	400
W_{cc}	kW	350	350	220	200
E_r	kW	50	0	20	0
Q_l	kW	0	140	0	140
Q_{cc}	kW	400	260	400	260
Q_a	kW	240	0	200	0
Q_r	kW	240	160	0	160
R_q	kW	150	100	0	100
R_e	kW	250	0	100	0
CH	€/h	41.00	30.00	19.60	13.00

4.1 Marginal Costs

The LINGO solution report for the model presented in the previous section also gives a dual price figure for each constraint.

The dual price can be interpreted as the amount by which the objective function would increase as the right-hand side, or constant term, of the constraints is increased by one unit. In the model all constraints refer to energy flows. If a constraint expresses the produced quantity of a flow, then its dual price can be interpreted as the marginal cost of this flow.

Table 5 shows the results provided by LINGO for the marginal costs (λ) corresponding to the final products (dual prices of demand constraints). The marginal cost of internal flows can also be obtained from the dual prices corresponding to the other constraints (See Figure 3).

Table 5. Marginal Cost of Final Products.

$\lambda(E_d)$	0.100	€/kWh
$\lambda(Q_d)$	0.025	€/kWh
$\lambda(R_d)$	0.040	€/kWh

Dual prices and marginal costs are important for two reasons: 1) to identify which operation constraint could be changed to improve the solution, and 2) to react automatically when external operational circumstances change. Marginal costs, in particular, have important information for design and operation optimization of energy systems (Ranade and Robert, 1987; Frangopoulos, 1987; von Spakovsky and Evans, 1990a; Hui, 2000; Quelhas et al., 2006).

Figure 3 explains graphically the meaning of the marginal costs obtained for the final products in example C1; i.e., how the components of the plant must be operated in order to produce an additional unit of the final products. For example, if an additional unit of electricity is necessary, it will be purchased directly from the electric grid at the price of purchased electricity (p_{ep}). The marginal cost both of Q_d and Q_r is the unit cost of producing heat Q_a in the boiler (p_{fa}/η_q). Finally, the marginal cost of R_d is the unit cost of producing cooling in the absorption chiller driven by heat produced in the boiler [$(p_{fa}/\eta_q)/COP_q$].

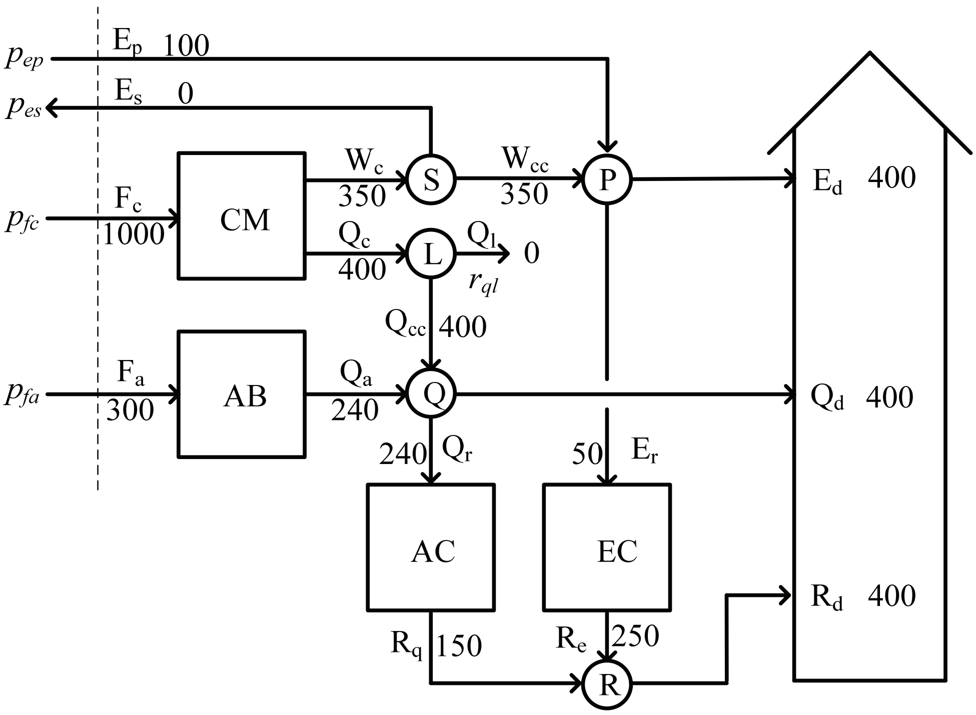

Figure 2. Energy flows.

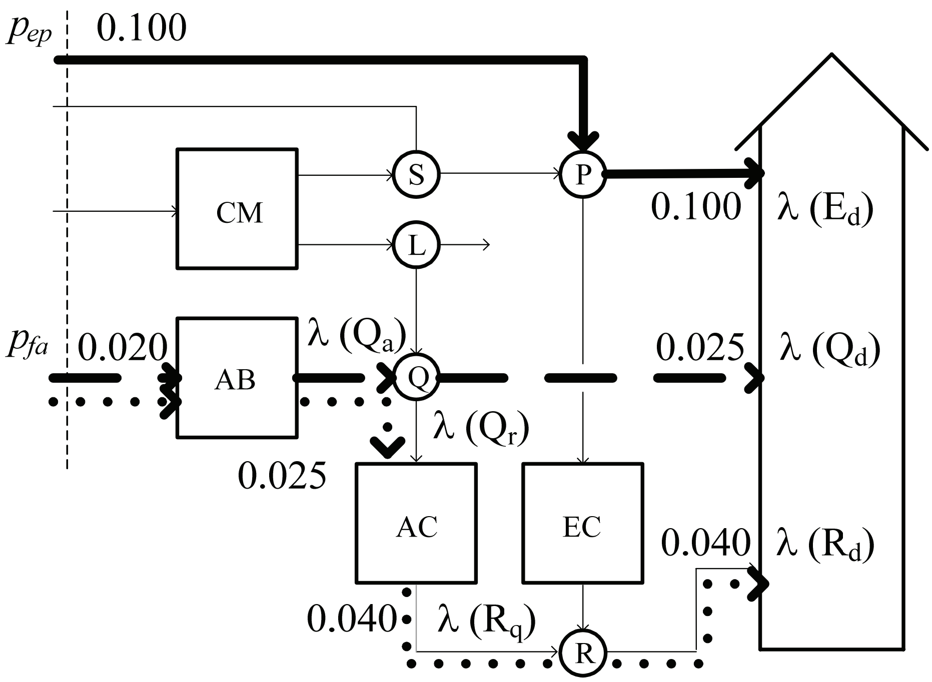

Figure 3. Marginal Costs.

4.2 Valuation Based on Market Prices

When an external reference is imposed on value products, for example market prices π (see Table 6), the average costs of products β will be assigned based on that reference.

Table 6. Market Prices [€/kWh].

π_e	π_q	π_r
0.100	0.030	0.050

The hourly cost to obtain the final products of the trigeneration system when considering reference prices is

$$CH_{ref} = \pi_e \cdot E_d + \pi_q \cdot Q_d + \pi_r \cdot R_d \quad (19)$$

In a trigeneration system properly designed and operated, there will be cost savings in production when compared to the same quantity of products obtained at market prices. As a consequence, the discount *d* defined as:

$$d \equiv (CH_{ref} - CH)/CH_{ref} = 1 - CH/\ CH_{ref} \quad (20)$$

will be positive. A fair criterion to distribute CH among the final product consumers is that all of them receive the discount derived from the combined production, i.e., the following unit cost will be assigned to the products:

$$\beta(i) = \pi_i\,(1 - d) \quad (21)$$

Production costs CH are thereby distributed to final products according to the economic value of those products.

Table 7 displays the costs, obtained for the final products of the simple trigeneration system operating in example C1, which are different from the marginal costs shown in Table 5.

Table 7. Cost of Final Products.

CH	41.00	€/h
CHref	72.00	€/h
d	0.4306	-
$\beta(E_d)$	0.0569	€/kWh
$\beta(Q_d)$	0.0171	€/kWh
$\beta(R_d)$	0.0285	€/kWh

Note that costs based on market prices are always conservative

$$CH = \beta(E_d)\cdot E_d + \beta(Q_d)\cdot Q_d + \beta(R_d)\cdot R_d \quad (22)$$

but marginal costs, in general, are not:

$$CH \neq \lambda(E_d)\cdot E_d + \lambda(Q_d)\cdot Q_d + \lambda\,(R_d)\cdot R_d \quad (23)$$

4.3 Internal Costs

In energy systems, resources are used up to provide certain qualities to the internal flows until the desired final products are obtained. Thermoeconomic analysis allows the cost formation process to be transparent throughout the system, from energy resources to final products. Obtaining unit costs of internal flows and products of energy systems is a cornerstone of several thermoeconomic approaches that have been presented in the literature (Tsatsaronis and Winhold, 1985; El-Sayed and Gaggioli, 1989; Lozano and Valero, 1993a; Serra et al., 1995; Lazzaretto and Tsatsaronis, 2006).

The conservation of costs, as a first principle, is common to all thermoeconomic approaches (all costs from resources consumed in a production unit must be charged to its useful products). Cost balances are explicitly formulated and external resources used in the production process are valued at the prices at which they were purchased. Applying the condition of cost conservation to the trigeneration system studied, the following equations are obtained:

CM: $\quad p_{fc}\cdot F_c = c_{wc}\cdot W_c + c_{qc}\cdot Q_c \quad (24)$

AB: $\quad p_{fa}\cdot F_a = c_{qa}\cdot Q_a \quad (25)$

AC: $\quad c_{qr}\cdot Q_r = c_{rq}\cdot R_q \quad (26)$

EC: $\quad c_{er}\cdot E_r = c_{re}\cdot R_e \quad (27)$

S: $\quad c_{wc}\cdot W_c = c_{wcc}\cdot W_{cc} + p_{es}\cdot E_s \quad (28)$

P: $\quad c_{wcc}\cdot W_{cc} + p_{ep}\cdot E_p = c_{er}\cdot E_r + c_{ed}\cdot E_d \quad (29)$

L: $\quad c_{qc}\cdot Q_c + r_{ql}\cdot Q_l = c_{qcc}\cdot Q_{cc} \quad (30)$

Q: $\quad c_{qcc}\cdot Q_{cc} + c_{qa}\cdot Q_a = c_{qr}\cdot Q_r + c_{qd}\cdot Q_d \quad (31)$

R: $\quad c_{rq}\cdot R_q + c_{re}\cdot R_e = c_{rd}\cdot R_d \quad (32)$

Considering that the operating state of the plant is known, then all energy flows, market prices for fuel and electricity (see Table 2 for p_{fc}, p_{fa}, p_{ep}, p_{es}) and the unit price entailing waste heat (here it was considered that $r_{ql} = 0$) are also known; consequently, there are 12 unit costs of internal flows and final products to be calculated: c_{wc}, c_{wcc}, c_{er}, c_{ed}, c_{qc}, c_{qcc}, c_{qa}, c_{qr}, c_{qd}, c_{rq}, c_{re}, and c_{rd}. As the system is described using 9 equations with 12 variables, 3 auxiliary equations are needed.

The development of generally applicable rules for the formulation of auxiliary costing equations has been a subject of discussion among the different thermoeconomic approaches. An accepted rule, either explicitly or implicitly, is that the unit cost of several flows obtained from a homogeneous flow is the same. Applying this rule to the branching points (**P** and **Q** in Figure 1), two more auxiliary equations are obtained:

P: $\quad c_{er} = c_{ed} \quad (33)$

Q: $\quad c_{qr} = c_{qd} \quad (34)$

Note that this rule cannot be applied to branching points **S** and **L**. In **S,** the system is interacting with the economic environment and the cost of sold electricity, E_s, is set by its market price. In **L**, Q_l is the wasted heat that is not consumed and therefore no cost is assessed.

One more auxiliary costing equation is needed and it must define how production costs in the cogeneration module ($p_{fc}\cdot F_c$) should be attributed to its products: heat ($c_{qc}\cdot Q_c$) and work ($c_{wc}\cdot W_c$). Our thesis is that a rational distribution of costs toward the products (in order to promote rational and efficient energy services' production and consumption) must consider the nature of the optimal operation mode, which is clearly determined by the economic environment and the variable energy demands of the system. This implies that different operation modes, as shown in Table 3, require different auxiliary equations. In operation mode C_1 electricity is purchased ($E_p > 0$) at a price p_{ep} and the auxiliary boiler is required to produce heat ($Q_a > 0$) at a unit cost c_{qa}. It is proposed to assign unit costs to the products of the cogeneration module in proportion to the cost of its alternative production. Therefore, the auxiliary equation for operation mode C_1 is as follows:

C1: $\quad c_{wc} / p_{ep} = c_{qc} / c_{qa} \quad (35)$

Hence now there are 12 equations and 12 unknown unit costs. The unit costs shown in Figure 4 are obtained by solving the equation system (24)-(35).

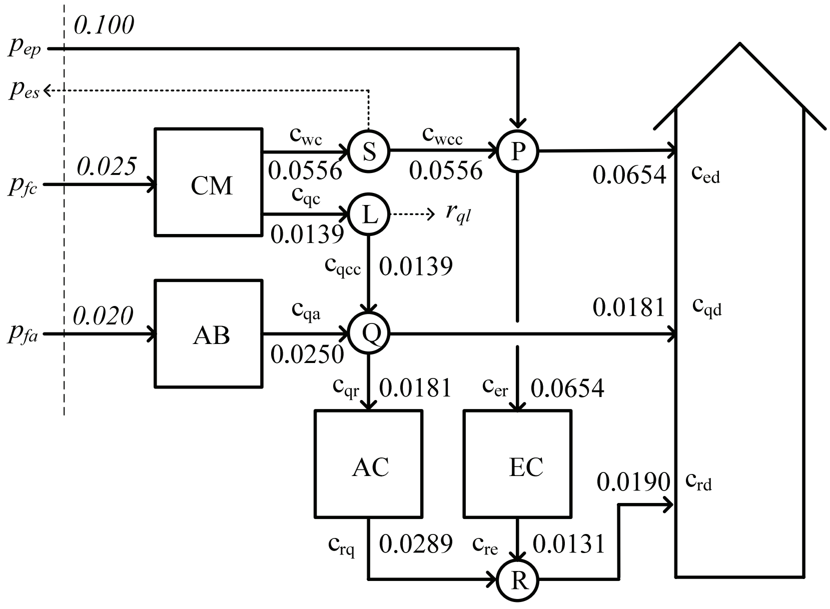

Figure 4. Internal Costs.

5. Conclusions

A thermoeconomic analysis of a simple trigeneration system was presented, considering different cost assessment methods.

One of the main issues encountered when calculating the costs of internal flows and products in trigeneration plants installed in buildings is the variation of energy services' demands. The minimal operation variable cost of the entire system was evaluated by a linear programming model. The model was applied to very different energy services' demands and the results show how different the operation modes for a simple trigeneration system can be. A greater sophistication of the optimization model, using non linear production restrictions and binary variables limiting both the minimum load of the productive units and the on/off status, would provide more precise results but, generally, these conclusions would still prevail.

For example, corresponding to the optimal operation mode with purchase of electricity and assistance of an auxiliary boiler, three different approaches to determine the costs of internal flows and final products of simple trigeneration systems were presented: marginal costs corresponding to optimal operation, costs obtained when production costs are distributed to the final products according to their market prices, and internal costs corresponding to a thermoeconomic analysis of the operation mode of the system.

The costs obtained with the approaches mentioned were different and it can be concluded that there are no general rules to decide which approach is best: it depends on the issue to be solved. The dual prices obtained in the optimization process were interpreted as marginal costs of internal flows and products and are useful to react automatically when external operational circumstances change, i.e. energy demand. Costs based on market prices are a fair criterion to distribute production costs among final product consumers, so that all of them receive the same discount from the market price. Internal costs permit the following of the cost formation process throughout the system, from the energy resources to final products.

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Nomenclature

c	Internal cost [€/kWh]
CH	Cost [€/h]
E_d	Demanded electricity [kW]
E_p	Purchased electricity [kW]
E_r	Work input to electric chiller [kW]
E_s	Sold electricity [kW]
F_a	Boiler fuel [kW]
F_c	Cogeneration module fuel [kW]
p_{fa}	Price of boiler fuel [€/kWh]
p_{fc}	Price of engine fuel [€/kWh]
p_{ep}	Price of purchased electricity [€/kWh]
p_{es}	Price of sold electricity [€/kWh]
Q_a	Heat from auxiliary boiler [kW]
Q_c	Cogenerated heat [kW]
Q_{cc}	Consumed cogenerated heat [kW]
Q_d	Demanded heat [kW]
Q_l	Waste heat [kW]
Q_r	Heat to absorption chiller [kW]
R_d	Cooling demand [kW]
R_e	Cooling from electric chiller [kW]
R_q	Cooling from absorption chiller [kW]
W_c	Cogenerated work [kW]
W_{cc}	Consumed cogenerated work [kW]
β	External cost [€/kWh]
λ	Marginal cost [€/kWh]
π_e	Market reference price for E_d [€/kWh]
π_q	Market reference price for Q_d [€/kWh]
π_r	Market reference price for R_d [€/kWh]

References

Arena, A.P., Borchiellini, R., 1999, "Application of different productive structures for thermoeconomic diagnosis of a combined cycle power plant", *Int. J. Therm. Sci.*, Vol. 38, pp. 601-612.

Chicco, G., Mancarella, P., 2006, "From Cogeneration to Trigeneration: Profitable Alternatives in a Competitive Market", *IEEE Transactions on Energy Conversion*, Vol. 21, pp. 265-272.

EDUCOGEN, 2001, *The European Education Tool on Energy-Efficiency through the Use of Cogeneration (Combined Heat and Power)*, SAVE Project, Survey Report available (www.cogeneurope.eu/projects/educogen.htm).

El-Sayed, Y.M., 2003, *The Thermoeconomics of Energy Conversions*, Pergamon.

El-Sayed, Y.M., Gaggioli, R.A., 1989, "A critical review of second law costing methods: Parts I and II", *ASME J. Energy Res. Technol.*, Vol. 111, pp. 1–15.

European Union, 2003, "Directive 2002/91/EC on the energy performance of buildings", *Official Journal of EC*, 4.1.2003, L1, 65-71.

European Union, 2004, "Directive 2004/8/CE on the promotion of cogeneration", *Official Journal of EU*, 21.2.2004, L52, 50-60.

Frangopoulos, C., 1987, "Thermoeconomic Functional Analysis and Optimization", *Energy*, Vol. 12, pp. 563-571.

Gaggioli, R.A., 1983, "Second Law Analysis for Process and Energy Engineering", In *Efficiency and Costing*, ACS Symposium Series 235, pp. 3-50.

Horlock, J.H., 1987, *Cogeneration-Combined Heat and Power (CHP): Thermodynamics and Economics*, Pergamon.

Hui, C.W., 2000. "Determining marginal values of intermediate materials and utilities using a site model", *Computers and Chemical Engineering*, Vol. 24, pp. 1023-1029.

Lazzaretto, A., Tsatsaronis, G., 2006, "SPECO: A systematic and general methodology for calculating efficiencies and costs in thermal systems", *Energy*, Vol. 31, pp. 1257-1286.

Li, H. et al., 2006, "Energy utilization evaluation of CCHP systems", *Energy and Buildings*, Vol. 38, pp. 253-257.

Lindenberg, D., Bruckner, T., Groscurth, H. M., Kümmel, R., 2000, "Optimization of solar district heating systems: seasonal storage, heat pumps, and cogeneration", *Energy*, Vol. 25, pp. 591-608.

LINDO Systems, 2007, *LINGO The modeling language and optimizer* (www.lindo.com).

Lozano, M.A., Valero, A., 1993a, "Theory of the exergetic cost", *Energy*, Vol. 18, pp. 939-960.

Lozano, M.A., Valero, A., 1993b, "Thermoeconomic Analysis of Gas Turbine Cogeneration Systems", In ASME Book H00874, pp. 311-320.

Lozano, M.A. et al., 1994, "Thermoeconomic Diagnosis of Energy Systems". In Proceedings of FLOWERS ´94, Florence, Italy, July 6-8, 1994, pp. 149-156.

Lozano, M.A., Valero, A., Serra, L., 1996, "Local Optimization of Energy Systems", In ASME Book G01022, pp. 241-250.

Quelhas, A.M., Gil, E., McCalley, J.D., 2006, "Nodal prices in an integrated energy system", *Int. J. Critical Infrastructures*, Vol. 2, No. 1, pp. 50-69.

Ranade, S.M., Robert, W.E., 1987, "Marginal Utility Cost Concept Helps Maximize Plant Efficiency", *Power*, July 1987, pp. 49-52.

Serra, L. et al., 1995, "On average and marginal costs in thermoeconomics", Proceedings of ECOS'95, Istanbul, Turkey, July 11-15, 1995, pp. 99-112.

Serra, L. et al., 2008, "Polygeneration and efficient use of natural resources", *Energy*, Vol. 34, pp. 575-586.

Tsatsaronis, G., Winhold, M., 1985, "Exergoeconomic Analysis and Evaluation of Energy-Conversion Plants", *Energy*, Vol. 10, pp. 69-80.

TRIGEMED, 2003, *Promotion of Trigeneration Technologies in the Tertiary Sector in Mediterranean Countries*, SAVE Project, Survey Report available (www.trigemed.com).

von Spakovsky, M.R., Evans, R.B., 1990a, "The foundations of engineering functional analysis", *Proceedings of FLOWERS ´90*, Florence, Italy, May 28-June 1, 1990, pp. 445-472.

von Spakovsky, M.R., Evans, R.B., 1990b, "The Design and Performance Optimization of Thermal Systems", *ASME J. Eng. Gas Turbines Power*, Vol. 112, pp. 86-93.

Yokoyama, R. et al., 1994, "Development of a General-Purpose Optimal Operational Planning System for Energy Supply Plants", *ASME J. Energy Res. Technol.*, Vol. 116, pp. 290-296.

Wu, D.W., Wang, R.Z., 2006, "Combined cooling, heating and power: A review", *Progress in Energy and Combustion Science*, Vol. 32, pp. 459-495.