Allocation of economic costs in trigeneration systems at variable load conditions

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Abstract:

This paper presents a thermoeconomic analysis of simple trigeneration systems interacting with the economic environment. One of the main difficulties in calculating the costs of internal flows and products in trigeneration plants within buildings is the continuous variation of energy supply services. Fuel prices and purchase/sale electricity tariffs could also vary. As a consequence there are different operation conditions that combine the possibility of buying or selling electricity and/or consuming heat from an auxiliary boiler - wasting the excess of cogenerated heat. The aim is to determine the energy and total costs of final energy services and internal flows for all possible operation conditions. A novel cost allocation method was proposed. The heat produced by cogeneration modules is disaggregated into three fractions: heat that meets the heat demand directly, heat utilized to drive the absorption chiller (producing cooling), and heat dissipated to the environment. Cost allocation to all cogeneration co-products is determined by means of the principle of avoided expenditures. The cost allocation proposal promoted rational and efficient energy services production and consumption, while also benefiting the consumers of the trigeneration system with a fair discount in comparison to the cost of obtaining the energy services separately by conventional systems.

Keywords:

Cogeneration, Cost assessment, Energy, Thermoeconomics, Trigeneration, Variable operation.

1. Introduction

As quality of life standards rise, the demand for comfort increases in parallel with a higher degree of environmental conscience. In general, meeting such comfort demands leads to greater consumption of energy services (for example, an increment in the use of air conditioning) , which is offset by environmental conscience regarding consumption of fossil fuels and its consequences, leading to a more rational use of energy. Polygeneration systems integrate appropriate energy processes for the combined production of two or more energy services and/or manufactured products, significantly increasing the efficient use of natural resources [1]. Presently, energy consumption of buildings in developed countries comprises 20-40% of total energy use and is greater than industry and transport figures in the European Union (EU) and USA [2]. European research projects [3-5] agree on the significant technical potential of implementing trigeneration in the residential and tertiary sector of countries in the Mediterranean area. In these countries, the need for heating is restricted to a few winter months, limiting the application of cogeneration systems. However, there is a significant need for cooling during the summer period. By combining cogeneration and heat-driven absorption chillers, the energy demand covered by cogeneration could be extended into the summer months to match cooling loads [6-7].

The enhanced fuel consumption efficiency is one of the main benefits of the production of three energy services (heat, cooling and electricity) from the same energy source in an optimized trigeneration system. This better use of fuel resources is important, as it is associated with economic savings and sparing of the environment with less fuel consumed and less pollution generated. In order to maximize these benefits, the optimal design of trigeneration plants for buildings needs to address two fundamental issues [8-12], including the synthesis of the plant configuration (e.g., number and capacity of equipment for each type of technology employed) and operational planning (e.g., strategy for operational state of the equipment, energy flow rates, purchase/selling of electricity, etc.). The variability of energy demands in buildings requires a design methodology that builds flexible utility systems which operate efficiently (thermodynamic target), capable of adjusting to different conditions (combinatorial challenge), and able to operate at a minimum economic cost. The reviews of Chicco and Mancarella [13] and Hinojosa et al. [14] summarize the characteristics of the optimization methods for polygeneration systems presented in recent journal publications, including the considered time scale, the objective function, and the solution method.

This article presents a thermoeconomic analysis of simple trigeneration systems. According to Gaggioli [15], the objective of thermoeconomics is to explain the cost formation process of internal flows and products of energy systems. The costs obtained with thermoeconomics can be used to diagnose the operation and control the production of existing plants, in addition to improving the processes and synthesis of new systems [16]. Several studies have been carried out on thermodynamics in cogeneration systems and how cost can be allocated based on different principles [17-22].

The growing significance of cost accounting in modern corporate economy has highlighted several problems that arise when joint costs are assigned, concerning managers, engineers, accountants, and economists [23]. Typically, there are common costs to the different products in polygeneration plants, and there is no way, based on pertinent facts, to determine the share of costs attributable to one or other product. Therefore the allocation of costs in polygeneration systems, as well as in any other multi-product system, is always arbitrary [22,24]. In strict economic terms, there is a considerable leeway to distribute common costs between the products. However, the allocation of cost must allow all co-products to be profitable and remain competitive for consumers when market and/or demand conditions vary, sharing the benefits without cross-subsidization.

In contrast with the operation of energy systems in industrial applications (characterized by steady energy demand profiles), in building applications the great number of components operating at unsteady conditions hinders the application of classical thermoeconomic cost accounting methodologies [25]. In Lozano et al. [26], three different approaches (with different applications) were used to determine the cost of internal flows and products in simple trigeneration systems, including i) analysis of marginal costs, ii) valuation of products applying market prices, and iii) internal costs calculation. Thermoeconomic analysis based on marginal production costs can be used to explain the best operational strategy as a function of market environment, operational capacity limits of the productive units, and demand of different energy services [27]. Costs based on market prices are a fair criterion to distribute production costs among final product consumers. Internal costs permit the following the cost formation process throughout the system, from the energy resources to final products [26]. A first attempt to study internal energy cost calculation in simple trigeneration systems under variable operations conditions was presented in ECOS 2009 [28]. The study emphasized the importance of selecting appropriate cost assessment criteria when a trigeneration system is operating in different modes due to demand and economic-market variations.

The current paper improves the cost assessment proposal for simple trigeneration systems, implementing the consideration for cogenerated cooling; furthermore, capital and maintenance costs are also considered. It is proved that the same cost assessment rules applied for energy costs are valid for thermoeconomic cost assessment (including energy, maintenance, and capital costs). The proposal will obtain product costs that are reasonable and in accordance with the design objective of the system of providing product costs inferior to those of separate production. The allocation proposal assumes that the consumers will receive credits (in the form of a discount) for what was saved as a result of an efficient production. This proposal not only will shed light on the cost formation process but will also help inform the consumers of trigeneration systems on the costs associated with the consumption of each energy service.

2. Trigeneration system

The purpose of a trigeneration system is to match the demands of different energy services (electricity, E_d; heating, Q_d; and cooling, R_d) of a consumer center. A trigeneration system basically consists of a cogeneration module and an absorption chiller. The cogeneration module (CM) includes a prime mover (gas turbine, reciprocating engine, etc.) to convert fuel energy to shaft power, an alternator to transform mechanical power to electrical power, and a heat recovery system. The absorption chiller (AC) can produce cooling from the recovered heat. Trigeneration plants become distinguishable by the different additional equipment incorporated [29]. The simple trigeneration system [26-28, 30] shown in Fig. 1, which we propose to analyze, also includes a mechanical chiller (EC) driven by electricity and one auxiliary boiler (AB).

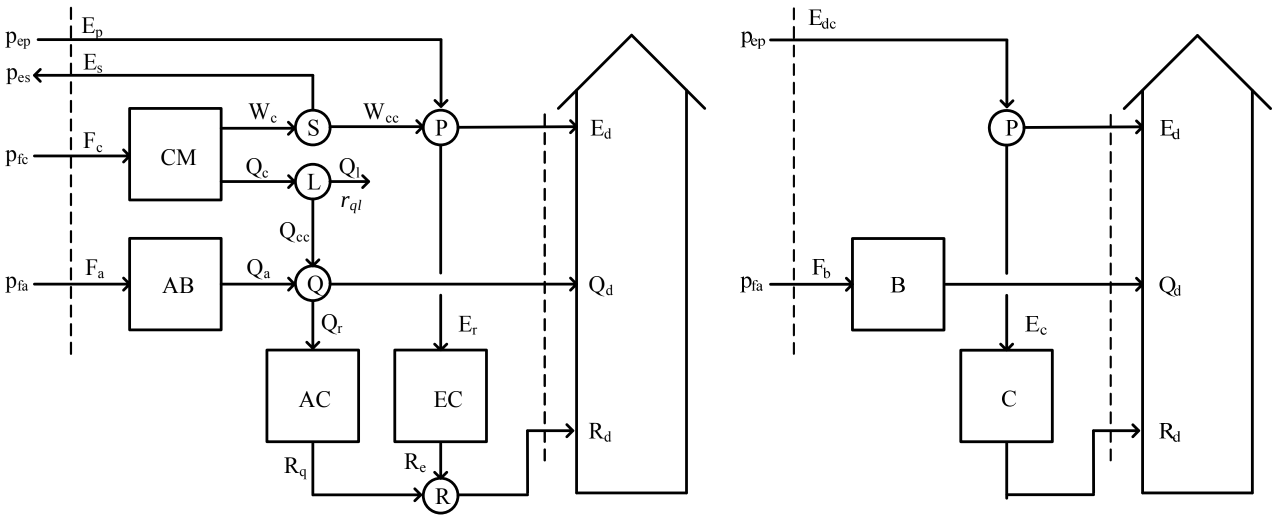

Fig. 1. Simple trigeneration system and reference plant

Table 1. Technical parameters and investment cost of equipment

Component	Efficiency coefficient	Investment zp (€/kW)	Trigeneration plant Capacity (kW)	Reference plant Capacity (kW)
Cogeneration Module	$\alpha_w \equiv W/F = 0.35$ $\alpha_q \equiv Q/F = 0.40$	750	$W_{CM\ nom} = 350$	-
Boiler	$\eta_q \equiv Q/F = 0.80$	50	$Q_{AB\ nom} = 400$	$Q_{B\ nom} = 800$
Absorption Chiller	$COP_q \equiv R/Q = 0.625$	150	$R_{AC\ nom} = 250$	-
Mechanical Chiller	$COP_e \equiv R/E = 5.0$	125	$R_{EC\ nom} = 250$	$R_{C\ nom} = 500$

Table 2. Energy prices (€/kWh)

p_{fc}	p_{fa}	p_{ep}	p_{es}	r_{ql}
0.025	0.020	0.100	0.080	0.000

Table 3. Energy demands of the consumer center during the year (8000 h/yr)

Energy flows	Demand 1 (2000 h/yr)	Demand 2 (2000 h/yr)	Demand 3 (2000 h/yr)	Demand 4 (2000 h/yr)
E_d (kW)	*400*	*400*	*200*	*200*
Q_d (kW)	*400*	*100*	*600*	*100*
R_d (kW)	*400*	*100*	*100*	*100*

Table 1 shows technical data (including the equipment investment cost) for the trigeneration system and a reference system consisting of a boiler and a mechanical chiller able to cover the heat and cooling demands of the consumer center (in this case the trigeneration system would not be installed). The nominal capacities of the boiler and mechanical chiller of the reference plant are the same as the maximum capacity of the trigeneration system to produce heat and cooling.

Table 2 presents the prices of the energy flows exchanged with the market. The prices of the different fuels consumed by the cogeneration module and the boiler are p_{fc} and p_{fa}, respectively.

The representative energy demands of the consumer center are shown in Table 3. Four different types of representative demands were considered to occur throughout the year. For the sake of simplicity in the analysis, it was assumed that each demand required 2000 hours per year, resulting in an annual operation of 8000 hours for the trigeneration system. The 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 at price p_{ep}). It is also possible that superfluous cogenerated electricity could be sold to the market (E_s at a price p_{es}) and/or a fraction of cogenerated heat could be wasted (Q_l with a cost r_{ql}). In this respect, there is freedom to decide how the system operates to minimize costs. The heat produced in the auxiliary boiler (Q_a) and the cogeneration module (Q_{cc}) can be used for covering either the heat demand of the consumer center (Q_d) and/or the heat required for driving the absorption chiller (Q_r). There is not any priority or technical limitation in this respect, i.e. the cogeneration module is able to provide, when required, heat to the consumer center and/or the absorption chiller indistinctly, and the same applies to the auxiliary boiler.

Table 4. Operation modes of the simple trigeneration system

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

In a competitive energy market scenario, the profitability of the operation of trigeneration systems depends on the capacity and performance of the installed technologies, fuel and electricity prices (in general subject to variability and volatility, although in this work have been considered constant values), and demanded quantities of energy services (with great daily and seasonal variation). The resulting feasible operation states can be classified into nine different operation modes based on the signs and values of purchased electricity (E_p), sold electricity (E_s), auxiliary heat (Q_a) and waste heat (Q_l).

For a given demand several operating conditions are possible. Considering that the technical characteristics of the equipment have already been selected (see Table1) then the optimal operation of the system in a specific moment in which the consumers have determined the demand of energy services (Table 3) is obtained minimizing the operation variable cost (in €/h).

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

The economic analysis considered that the only significant variable costs were electricity and fuel, and that cogenerated heat could be wasted without cost, *i.e.*, $r_{ql} = 0$. An explanation of the complete mathematical model, a linear programming model, has been presented in references [26-27]. Results were obtained by utilizing the computer application LINGO [31], which uses an algebraic language to formulate programming models and optimization algorithms to solve them. The minimum cost of satisfying the corresponding demands of the energy services of the consumer center is specific to each operation state, which exchanges energy flows at market prices and utilizes the productive capacity of the installed equipment. A summary of results (demand, flows, hourly energy costs and annual energy costs) corresponding to the optimal operation during a year are shown in Table 5. The four different optimum operation states correspond to a different operation mode (ExC_1: mode C_1, ExC_3: mode C_3, ExC_7: mode C_7, ExC_9: mode C_9).

In the case that the energy demands were covered by the reference system, the electricity would be purchased from the grid, the heat would be produced in the boiler and the cooling would be produced in the mechanical chiller. Thus, considering the technical data shown in Table 1 for the equipment of the reference system and the energy prices shown in Table 2, the energy flows and costs corresponding to matching the same annual demands (see Table 3) of the consumer center were obtained and are shown in Table 6.

Table 5. Energy flows and costs of the trigeneration system

Energy flows		**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**Year (kWh/yr)**
E_d	kW	*400*	*400*	*200*	*200*	*2 400 000*
Q_d	kW	*400*	*100*	*600*	*100*	*2 400 000*
R_d	kW	*400*	*100*	*100*	*100*	*1 400 000*
E_p	kW	**100**	**50**	0	0	300 000
E_s	kW	0	0	**130**	**150**	560 000
F_c	kW	1000	1000	1000	1000	8 000 000
F_a	kW	300	0	250	0	1 100 000
W_c	kW	350	350	350	350	**2 800 000**
Q_c	kW	400	400	400	400	3 200 000
W_{cc}	kW	350	350	220	200	2 240 000
E_r	kW	50	0	20	0	140 000
Q_l	kW	0	**140**	0	**140**	560 000
Q_{cc}	kW	400	260	400	260	2 640 000
Q_a	kW	**240**	0	**200**	0	**880 000**
Q_r	kW	240	160	0	160	1 120 000
R_q	kW	150	100	0	100	**700 000**
R_e	kW	250	0	100	0	**700 000**
Energy costs		**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**Year (€/yr)**
$p_{fc} \cdot F_c$	€/h	25.00	25.00	25.00	25.00	200 000
$p_{fa} \cdot F_a$	€/h	6.00	0.00	5.00	0.00	22 000
$p_{ep} \cdot E_p$	€/h	10.00	5.00	0.00	0.00	30 000
$p_{es} \cdot E_s$	€/h	(0.00)	(0.00)	(10.40)	(12.00)	(44 800)
HEC	**€/h**	**41.00**	**30.00**	**19.60**	**13.00**	AEC_{tri}=**207 200**

Table 6. Energy flows and costs of the reference plant

Energy flows		**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**Year (kWh/yr)**
E_{dc}	kW	480	420	220	220	2 680 000
F_b	kW	500	125	750	125	3 000 000
R_e	kW	400	100	100	100	1 400 000
Energy costs		**ExC$_1$**	**ExC$_3$**	**ExC$_7$**	**ExC$_9$**	**Year (€/yr)**
$p_{fa} \cdot F_b$	€/h	10.00	2.50	15.00	2.50	60 000
$p_{ep} \cdot E_{dc}$	€/h	48.00	42.00	22.00	22.00	268 000
HEC	**€/h**	**58.00**	**44.50**	**37.00**	**24.50**	AEC_{ref}=**328 000**

The annual energy cost savings (in €/yr) achieved with the trigeneration system are:

$$\Delta AEC = AEC_{ref} - AEC_{tri} = 328\,000 - 207\,200 = 120\,800 \text{ €/yr} \qquad (2)$$

The investment cost corresponding to the components of the trigeneration system (Table 1) is:

$$Z_{tri} = \sum_j Z_{tri\ j} = 750 \cdot W_{CM\ nom} + 50 \cdot Q_{AB\ nom} + 150 \cdot R_{AC\ nom} + 125 \cdot R_{EC\ nom} = 351\,250 \text{ €} \qquad (3)$$

In the case of the reference system, the investment cost of a system with the same installed power to produce heat and cooling as the trigeneration system, is (see Table 1):

$$Z_{ref} = \sum_j Z_{ref\ j} = 50 \cdot Q_{B\ nom} + 125 \cdot R_{C\ nom} = 102\,500 \text{ €} \qquad (4)$$

Therefore, installation of a trigeneration system requires an additional investment of:

$$\Delta Z = Z_{tri} - Z_{ref} = 351\,250 - 102\,500 = 248\,750 \text{ €/yr} \qquad (5)$$

Such additional investment ΔZ allows for significant annual savings in energy costs ΔAEC, resulting in a Payback period of approximately two years:

$$PB = \Delta Z / \Delta AEC = 2.06 \text{ yr} \qquad (6)$$

3. Thermoeconomic analysis

Thermoeconomics combines economic and thermodynamic analysis with the purpose of revealing opportunities of energy and cost savings when designing and operating energy conversion systems. Thermoeconomics was first developed during the 1960s and the name was coined by M. Tribus [32]. Thermoeconomics has been used to support the design, synthesis and operation of energy systems by providing crucial information not available through conventional methods [33-35]. Thermoeconomic provides powerful tools for the analysis [36-38], diagnosis [39-41] and optimization [42-44] of energy conversion systems.

Obtaining unit costs of internal flows and products of energy systems is a cornerstone of several thermoeconomic approaches [16-18, 45-47]. The issue of cost allocation emerges when there is a system producing different products. This is important since the manner in which cost allocation is made will not only affect the cost of the products but also the behavior of the consumers. Several proposals for cost allocation criteria in cogeneration systems have been made, but existing studies have mainly focused on energy systems in industrial applications, characterized by regular energy demand profiles, isolated from economic environments and with local consumption of products, including all cogenerated heat. This is not the case in buildings, where due to demand variability there is a great number of components operating in unsteady conditions. This makes difficult the application of existing methodologies [25], which if applied could provide non-valid results. Further development and refinement of these methodologies is required, as is explained in this paper.

Our thesis is that a rational distribution of costs to the products must consider the nature of the optimal operation mode [26-28], in order to promote rational and efficient energy services production and consumption. In the analyzed case, the operation mode has the feature of being clearly determined by the economic environment, with the possibility of buying/selling electricity from/to the grid, and by variable energy demands. Although this is a common situation in cogeneration and trigeneration systems for the residential-commercial sector, there is a lack of scientific literature on detailed thermoeconomic studies about the analysis and assessment of energy and total costs to the internal flows and final products in this type of systems. This paper discusses the fundamentals of thermoeconomics for energy systems with variable energy demands or operated at variable load in order to achieve a "most profitable operation".

Thus, the unit costs of the internal flows and final energy products of the trigeneration system are evaluated. This task requires the application of commonly accepted rules of all thermoeconomic analysis methodologies, such as: a) development of cost balances that allow for the cost assessment of the consumed resources towards the useful products of each component, and b) assignation of the same unit cost to the product flows (final or internally consumed) obtained from a homogeneous flow. Furthermore, it is also required to deal with new problems not deeply studied in thermoeconomic analysis, such as: c) an adequate capital cost assessment of the component to the internal flows and products considering the variable annual operation of the equipment and d) a fair cost-and-benefit apportionment of the combined production to the energy service products of the trigeneration system. A fair cost-and-benefit apportionment will contribute to the acceptance of the more complex but more efficient trigeneration systems by users, which is essential for the success of such systems when oriented to multiple users.

3.1. Capital costs

The apportioning of the capital cost of equipment towards internal flows and final products of a system is a well- known and solved problem in thermoeconomic analysis. However, this aspect has been usually analyzed in systems that are operating at steady state during the time period of the analysis, typically a year.

As previously mentioned, the trigeneration system under analysis presents the specific feature of experiencing highly variable operation conditions, with four different operation states where not all productive units operate throughout the year. Thus, in ExC_3 and ExC_9, the auxiliary boiler and the mechanical chiller do not operate and in ExC_7, the absorption chiller is shut down. When evaluating the costs of internal flows and final products of the system for each operation mode, the capital cost of non-operative equipment should not be assessed (there is no production); therefore, these units do not contribute towards the formation of the final products.

Considering the life time of the plant to be 15 years and an interest rate of 0.10 yr^{-1}, an annual capital recovery factor of 0.13 yr^{-1} was obtained. Annual maintenance and operating costs, different from energy costs, were considered to be 7% of the total investment cost. The factor fam = 0.20 yr^{-1} took into account both maintenance and capital recovery costs.

The annual total cost of the system, AC, including annual energy costs, AEC (Table 5), and annual capital costs, ACC (Table 1), in €/yr, is:

$$AC = AEC + ACC = 2000 \sum_{i=1,..,4} HEC_i + fam \sum_j Z_j \quad (7)$$

where 2000 h/yr is the operating time corresponding to each different demand. The investment cost in component j, in €, is:

$$Z_j = zp_j \cdot P_{nom\,j} \quad (8)$$

A relevant aspect to be discussed is the correct way to distribute the capital cost among the different demand periods. For components in steady operation, the capital cost is usually assigned to product flows by determining a "consumption of capital resources per hour", calculated by:

$$hZ_j = fam \cdot Z_j / TY_j \quad (9)$$

where TY_j are the annual operating hours of component j. Obviously, Eq. (9) cannot be used with components operating at variable loads because it implies that all TY_j annual operating hours of the jth component are assigned the same capital cost. In this case, when a component operates decreasing its production, i.e., operates increasingly at part load, then its cost per unit product would increase dramatically, which clearly does not make sense. Therefore, assuming a distribution of the investment cost of a component over its life cycle, we propose, in agreement with Piacentino and Cardona [48] the following expression for the capital cost per unit of product (€/kWh):

$$kZ_j = fam \cdot Z_j / PY_j \quad (10)$$

where PY_j is the annual production of component j. Thus, the capital cost assessed to each energy unit produced in the piece of equipment has the same value, without considering the dependence on the load factor. In those components with several useful products, PY_j corresponds to the main product, i.e., the electricity produced in the case of the cogeneration module.

Tables 7 and 8 show the capital costs and total hourly costs of the reference system, in which electricity is purchased from the grid, heat is produced in an auxiliary boiler, and cooling is produced in a mechanical chiller. In this case, the costs of the final energy products (electricity, heat and cooling) are constant and do not vary for the different operation periods:

$$(c_w)_{ref} = p_{ep} = 0.10000 \text{ €/kWh} \quad (11)$$

$$(c_q)_{ref} = p_{fa} / \eta_q + kZ_B = 0.02833 \text{ €/kWh} \quad (12)$$

$$(c_r)_{ref} = p_{ep} / COP_e + kZ_C = 0.02893 \text{ €/kWh} \quad (13)$$

This result is a consequence of considering constant values of the technical parameters of the equipment (Table 1) even for partial load operation, as well as of applying Eq. (10), i.e., assigning the same cost to all energy units produced.

Similarly, in the case of the trigeneration system, the average unit investment cost kZ_j of each component j expresses the investment cost per unit of product. Thus, for each operation period, the investment cost of the components that are in operation can be easily assessed by considering its production. Therefore, the assessment of the investment cost of the pieces of equipment is not uniform in time but proportional to production. Table 9 shows the capital costs for the different components of the trigeneration system.

Table 7. Capital costs and load factors of the reference system

Component J	Capacity kW	Investment €	Annual cost €/yr	Annual product kWh/year	Unit cost (kZ) €/kWh	Annual load %
B	800	40 000	8 000	2 400 000	0.00333	34.2
C	500	62 500	12 500	1 400 000	0.00893	32.0
Plant	-	102 500	20 500	-	-	-

Table 8. Total hourly cost of the reference system

Energy costs		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
$p_{fa}\cdot F_b$	€/h	10.00	2.50	15.00	2.50	60 000
$p_{ep}\cdot E_{dc}$	€/h	48.00	42.00	22.00	22.00	268 000
HEC	**€/h**	**41.00**	**30.00**	**19.60**	**13.00**	**328 000**
Capital costs		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
$kZ_B\cdot Q_d$	€/h	1.09	0.00	0.91	0.00	4000
$kZ_C\cdot R_d$	€/h	2.23	0.00	0.89	0.00	7500
HCC	**€/h**	**4.90**	**1.23**	**2.89**	**1.23**	**20 500**
Total cost		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
HC	**€/h**	**62.90**	**45.73**	**39.89**	**25.73**	**348 500**

Table 9. Capital costs and load factors of the trigeneration system

Component j	Capacity kW	Investment €	Annual cost €/yr	Annual product kWh/year	Unit cost (kZ) €/kWh	Annual load %
CM	350	262 500	52 500	2 800 000	0.01875	91.3
AB	400	20 000	4000	880 000	0.00455	25.1
AC	250	37 500	7500	700 000	0.01071	32.0
EC	250	31 250	6250	700 000	0.00893	32.0
Plant	-	351 250	70 250	-	-	-

Table 10. Total hourly cost of the trigeneration system

Energy costs		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
$p_{fc}\cdot F_c$	€/h	25.00	25.00	25.00	25.00	200 000
$p_{fa}\cdot F_a$	€/h	6.00	0.00	5.00	0.00	22 000
$p_{ep}\cdot E_p$	€/h	10.00	5.00	0.00	0.00	30 000
$p_{es}\cdot E_s$	€/h	(0.00)	(0.00)	(10.40)	(12.00)	(44 800)
HEC	**€/h**	**41.00**	**30.00**	**19.60**	**13.00**	**207 200**
Capital costs		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
$kZ_{CM}\cdot W_c$	€/h	6.56	6.56	6.56	6.56	52 500
$kZ_{AB}\cdot Q_a$	€/h	1.09	0.00	0.91	0.00	4000
$kZ_{AC}\cdot R_q$	€/h	1.61	1.07	0.00	1.07	7500
$kZ_{EB}\cdot R_e$	€/h	2.23	0.00	0.89	0.00	7500
HCC	**€/h**	**11.49**	**7.63**	**8.36**	**7.63**	**70 250**
Total cost		**ExC_1**	**ExC_3**	**ExC_7**	**ExC_9**	**Year (€/yr)**
HC	**€/h**	**52.49**	**37.63**	**27.96**	**20.63**	**277 450**

Values in Table 10 represent the hourly investment costs of the components assessed to each operation state. These values were obtained by multiplying the average unit investment cost, kZ, of each component (Table 9) by the production of the component in the operation state (Table 5). For example, the investment cost of the auxiliary boiler AB in the period ExC_1 was obtained by multiplying its average unit investment cost, 0.00455 €/kWh, by its production in ExC_1, 240 kW, and the obtained result 1.09 €/h is valid for the 2000 h/yr of operation of the system in state ExC_1.

3.2. Cost assessment in trigeneration systems

Trigeneration is the combined production of three different energy services –e.g. electricity, heat and cooling- using common resources. In the case of the simple trigeneration system considered in this paper (see Fig. 1), the conceptual trigeneration subsystem (core subsystem) is shown in Fig. 2.

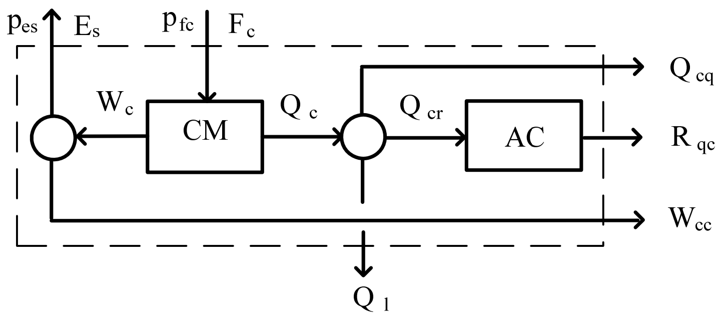

Fig. 2. Trigeneration subsystem

The trigeneration subsystem consists of a cogeneration module, producing power and heat, and an absorption chiller producing cooling from the heat released by the cogeneration module. In this subsystem, the combined production from common resources is achieved through thermal energy integration of the production processes. This integration impedes the establishment of a direct and unique logical relationship between the resources consumed and each product obtained. In other words, as a consequence of the thermal energy integration it is not possible to determine the amount of resources consumed in the production of each energy service. Thus, there are several options for apportioning the single fuel consumed, F_c, to the energy products obtained. A rational distribution of costs to the products in order to promote rational and efficient energy services production and consumption must consider the nature of the optimal operation mode of these systems [26-28, 30].

In the trigeneration subsystem, the power produced is distributed to the electricity sold to the grid, E_s, at the corresponding price p_{es} externally assessed (see Table 2), and to the electricity internally consumed or supplied to the consumer center, W_{cc}. In the case of heat, there are three possible destinations: 1) matching the heating demand, Q_{cq}, 2) production of cooling in the absorption chiller, R_{qc}, 3) release of heat to the environment, Q_l (only when profitable, allowing for cost minimization of the entire system). For the sake of simplicity, without a lack of generality in the analysis, this cost is considered to be null in this work, $r_{ql} = 0$. Therefore, W_{cc}, Q_{cq}, and R_{qc} are the three products co-generated, to which cost should be assessed.

In the simple trigeneration system there is also an auxiliary boiler and a mechanical chiller, assisting in the production of the trigeneration subsystem when required. This fact should also be considered when assessing the costs of internal flows and co-generated products. Thus, when the cogeneration module and the auxiliary boiler are both in operation, e.g. in operation period ExC_1, the share of the consumed co-generated heat, Q_{cc}, (i.e., $Q_c – Q_l$) that covers the heat demand of the consumer center, Q_{cq}, should be determined as well as the share used to obtain cooling in the absorption chiller, R_{qc} (see Fig. 3). The heat produced in the auxiliary boiler, Q_a, and in the cogeneration module, Q_{cc}, can be used to cover either the heat demand of the consumer center, Q_d, and/or the heat required to drive the absorption chiller, Q_r (Fig. 1). There is not any priority or technical limitation in this respect, i.e., the cogeneration module is able to provide, when required, heat to the consumer center and/or the absorption chiller indistinctly, and the same applies to the auxiliary boiler. Therefore when there is no preference the heat is distributed between the consumer center and the absorption chiller in proportion to the total heat demanded. The resulting productive structure is shown in Fig. 3, in which the absorption chiller is conceptually divided into two absorption chillers corresponding to the two different conceptual driving heats: the co-generated heat, Q_{cr}, and the heat produced in the auxiliary boiler, Q_{ar}. The heat driving the absorption chiller, Q_r in Fig. 1, consists of the addition of these two conceptual heat flows, i.e:

$$Q_r = Q_{cr} + Q_{ar} \quad (14)$$

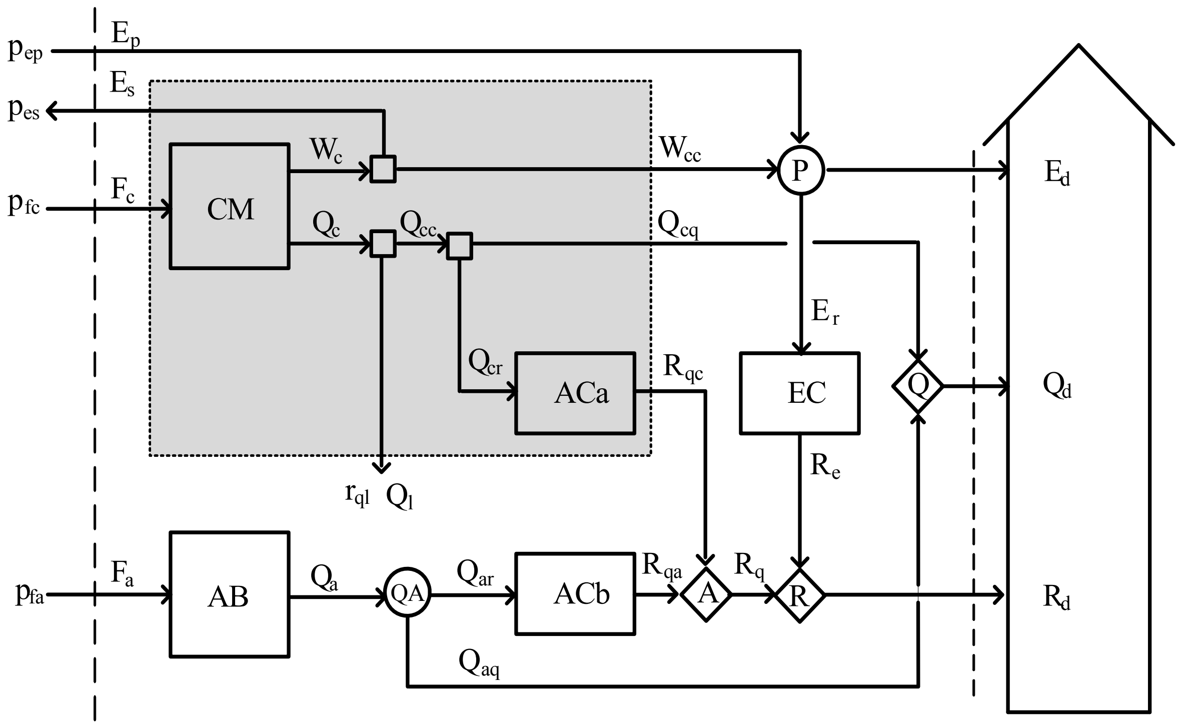

Fig. 3. Productive structure of the trigeneration system

In agreement with the previous premises, the heat is distributed between the consumer center and the absorption chiller in proportion to the total heat demanded, as well as in proportion to the heat produced in the cogeneration system and the auxiliary boiler. Thus, the next parameters are defined:

$$\beta = Q_d / (Q_d + Q_r) \quad (15)$$

$$\gamma = Q_{cc} / (Q_{cc} + Q_a) \quad (16)$$

The distribution of the cogenerated heat can be quantified as follows:

$$Q_{cq} = \beta \cdot Q_{cc} \quad (17)$$

$$Q_{cr} = (1 - \beta) \cdot Q_{cc} \quad (18)$$

The same applies for the distribution of the heat produced in the auxiliary boiler:

$$Q_{aq} = \beta \cdot Q_a \quad (19)$$

$$Q_{ar} = (1 - \beta) \cdot Q_a \quad (20)$$

The cooling produced in the absorption chiller with cogenerated heat is:

$$R_{qc} = \gamma \cdot R_q \quad (21)$$

and the cooling obtained from the heat produced in the auxiliary boiler is:

$$R_{qa} = (1 - \gamma) \cdot R_q \quad (22)$$

Once the nature of the co-production of the trigeneration system is determined and all relevant mass and energy flows have been identified and quantified, it is possible to assess rationally the costs to the co-products obtained. Energy integration allows for a more efficient and economic production of the energy services. Thus, there are operation periods in which part of the cogenerated heat is wasted –ExC_3 and ExC_9 in Table 5- and others in which part of the electricity produced is sold to the grid –ExC_7 and ExC_9. The trigeneration system operates in this way because it is economically profitable, yielding maximum economic benefits. Note that in operation period ExC_9, although the demand of the consumer center is low, it is profitable to operate the trigeneration system at full load even without using all produced heat, because the benefits of selling electricity compensate the waste of heat. Therefore, the benefits of selling electricity (E_s) and the costs associated to the waste of heat (Q_l) should be rationally assessed to the co-generated products. This means that all benefits and costs associated with the combined production should be assessed to the co-generated electricity, heat and cooling, and not only to one energy product. Lozano et al. [28] presented examples in which the benefits of selling electricity are mainly assessed to the electric power and the cost and penalties of wasting heat are mainly assessed to the cogenerated heat, obtaining inconsistent cost values.

Based on the principle of sharing costs among all consumers, fairly apportioning costs and benefits of the thermal energy integration, the same discount corresponding to the difference of the cost in the trigeneration system with respect to producing the same energy services in a reference system is applied to all products. The discount is evaluated as follows:

$$d = 1 - c_{wcc} / (c_w)_{ref} = 1 - c_{qcq} / (c_q)_{ref} = 1 - c_{rqc} / (c_r)_{ref} \qquad (23)$$

3.3. Application

The aforementioned concepts are applied in this section to the evaluation of the costs of internal flows and final products of the trigeneration system depicted in Figure 3.

The conservation of costs, as a basic principle, is common to all thermoeconomic approaches and states that 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 system of linear equations was obtained:

Components:

CM + ACa: $p_{fc}\cdot F_c - p_{es}\cdot E_s + r_{ql}\cdot Q_l + kz_{CM}\cdot W_c + kz_{ac}\cdot R_{qc} = c_{wcc}\cdot W_{cc} + c_{qcq}\cdot Q_{cq} + c_{rqc}\cdot R_{qc}$ (24)

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

ACb: $c_{qar}\cdot Q_{ar} + kz_{AC}\cdot R_{qa} = c_{rqa}\cdot R_{qa}$ (26)

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

Branching points (circles):

QA: $c_{qa}\cdot Q_a = c_{qar}\cdot Q_{ar} + c_{qaq}\cdot Q_{aq}$ (28)

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

Junctions (rhombus):

Q: $c_{qcq}\cdot Q_{cq} + c_{qaq}\cdot Q_{aq} = c_{qd}\cdot Q_d$ (30)

A: $c_{rqc}\cdot R_{qc} + c_{rqa}\cdot R_{qa} = c_{rq}\cdot R_q$ (31)

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

Considering that the operation state of the plant is known, then all energy flows (see Table 5), capital cost of components (see Table 9), 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 $r_{ql} = 0$). Consequently, there are 13 unit costs of internal flows and final products to be calculated: c_{wcc}, c_{qcq}, c_{rqc}, c_{qa}, c_{qar}, c_{qaq}, c_{rqa}, c_{rq}, c_{er}, c_{re}, c_{ed}, c_{qd}, and c_{rd}. Since the system is described using 9 equations with 13 unknowns, 4 auxiliary costing equations are needed.

In branching point **QA**, the heat produced in the auxiliary boiler is distributed, resulting in the following auxiliary equation:

QA: $c_{qar} = c_{qaq}$ (33)

In the case of branching point **P**, the consumed cogenerated electricity and the electricity purchased are combined and distributed without preferences, at the same unit cost, to meet the demand of the consumer center and the mechanical chiller, obtaining the following auxiliary cost equation:

P: $c_{er} = c_{ed}$ (34)

In branching points P and QA an accepted rule, either explicitly or implicitly, has been applied, that establishes that the unit cost of several flows of the final products and unit cost of internally consumed flows obtained from a homogeneous flow are the same.

Finally, two additional auxiliary equations remain to be defined. These auxiliary equations will allow for the appropriate assessment of the costs of the energy services co-produced in the trigeneration system, based on the nature of the optimal co-production of the trigeneration system explained in the previous section. In this respect, let us remember the premise that all costs (operation and capital) should be fairly allocated to the consumers of the energy services who are benefitting from the more efficient production in the trigeneration system with respect to a reference energy supply system, in which electricity is purchased from the grid, heat is produced in a conventional boiler and cooling is obtained from a conventional mechanical chiller (which is the most common technology for the single and separate production of cooling in households and residential sector). The benefits should be shared in an equitable form among all consumers. The auxiliary equations proposed are:

$$c_{qcq} / (c_q)_{ref} = c_{wcc} / (c_w)_{ref} \quad (35)$$

$$c_{rqc} / (c_r)_{ref} = c_{wcc} / (c_w)_{ref} \quad (36)$$

Based on these equations, production costs are distributed among the final consumers and all of them receive the same discount d (see Eq. 23). Note that the heat produced in the cogeneration module is valued using two different cost assessment equations corresponding to the two different uses of that heat. The heat used for matching the heat demand, Q_{dc}, receives the discount with respect to the production of heat in a conventional boiler, and the heat used for cooling, Q_{rc}, received the discount with respect to the conventional production of cooling in a mechanical chiller. Note that equations (30) and (31), which explain the distribution of the heat produced in the cogeneration module and auxiliary boiler, can be expressed as:

$$c_{qd} = c_{qcq} \cdot \gamma + c_{qaq} \cdot (1-\gamma) \quad (37)$$

$$c_{rq} = c_{rqc} \cdot \gamma + c_{rqa} \cdot (1-\gamma) \quad (38)$$

Table 11 shows the unit costs of internal flows and final products obtained by applying the assessment criteria proposed with equations (24 – 36), for the four different analyzed operation states. From the values shown in Table 11 it can be noted that the cost of the final products – c_{ed}, c_{qd} and c_{rd} – are lower than the costs of the purchased electricity $(c_w)_{ref} = 0.1$, the cost of heat produced in the auxiliary boiler $(c_q)_{ref} = 0.028$ and the cost of cooling produced in a mechanical chiller $(c_r)_{ref} = 0.029$. Therefore, the proposed cost assessment rules defined by equations (35 - 36) provides cost values consistent with the objective of equitable sharing the benefits among all the consumers, while also obtaining a clear economic benefit with respect to the conventional energy supply system. Note that costs shown in Table 11 are total costs, i.e., including the capital cost of equipment. A similar analysis can be performed considering only energy costs (Table 12). In this case, capital costs should not be considered, i.e., the terms kz_j should be removed from the cost balance for the pieces of equipment (equations 24-27), and the following reference costs should be considered in equations (35 and 36):

$(c_w)_{ref} = p_{ep} = 0.100$ €/kWh (39)

$(c_q)_{ref} = p_{fa} / \eta_q = 0.025$ €/kWh (40)

$(c_r)_{ref} = p_{ep} \cdot / COP_e = 0.020$ €/kWh (41)

Table 11. Unit costs of internal flows and final products of the analyzed trigeneration system

		ExC_1	ExC_3	ExC_7	ExC_9
E_d	kW	*400*	*400*	*200*	*200*
Q_d	kW	*400*	*100*	*600*	*100*
R_d	kW	*400*	*100*	*100*	*100*
γ		0.625	1	0.667	1
β		0.625	0.385	1	0.385
Q_{cq}	kW	250	100	400	100
Q_{cr}	kW	150	160	0	160
Q_{aq}	kW	150	0	200	0
Q_{ar}	kW	90	0	0	0
R_{qc}	kW	93.75	100	0	100
R_{qa}	kW	56.25	0	0	0
d		0.273	0.199	0.365	0.198
c_{wcc}	€/kWh	0.07270	0.08013	0.06349	0.08021
c_{qcq}	€/kWh	0.02060	0.02270	0.01799	0.02272
c_{rqc}	€/kWh	0.02103	0.02318	---------	0.02320
c_{qa}	€/kWh	0.02955	---------	0.02955	---------
c_{rqa}	€/kWh	0.05799	---------	0.05799	---------
c_{rq}	€/kWh	0.03489	0.02318	---------	0.02320
c_{re}	€/kWh	0.02468	--------	0.02163	--------
c_{ed}	€/kWh	0.07877	0.08261	0.06349	0.08021
c_{qd}	€/kWh	0.02395	0.02270	0.02184	0.02272
c_{rd}	€/kWh	0.02851	0.02318	0.02163	0.02320

Table 12. Unit energy costs of internal flows and final products of the trigeneration system

		ExC_1	ExC_3	ExC_7	ExC_9
d		0.420	0.367	0.544	0.469
c_{wcc}	€/kWh	0.05797	0.06329	0.04563	0.05306
c_{qcq}	€/kWh	0.01449	0.01582	0.01141	0.01327
c_{rqc}	€/kWh	0.01159	0.01266	-------	0.01061
c_{qa}	€/kWh	0.02500	-------	0.02500	-------
c_{rqa}	€/kWh	0.04000	-------	0.04000	-------
c_{rq}	€/kWh	0.02225	0.01266	-------	0.01061
c_{re}	€/kWh	0.01346	-------	0.00913	-------
c_{ed}	€/kWh	0.06731	0.06788	0.04563	0.05306
c_{qd}	€/kWh	0.01843	0.01582	0.01594	0.01327
c_{rd}	€/kWh	0.01676	0.01266	0.00913	0.01061

4. Conclusions

The overarching aim of this paper was to carry out a thermoeconomic analysis of trigeneration systems, specifically focusing on the residential-commercial sector. Such analysis has required to deal with new problems not deeply studied in previous thermoeconomic analysis studies, such as i) an adequate capital cost assessment of the components to the internal flows and products considering the variable annual operation of the equipment and ii) a fair cost-and-benefit apportionment of the combined production to the energy service products of trigeneration systems, submitted to great demands fluctuations and operating in different operation modes.

The issue of cost allocation emerges when there is a system producing different products. The manner in which cost allocation is made will not only affect the cost of the products but also the consumers. Existing studies on cost allocation in cogeneration have mainly focused on systems working at nominal load, isolated from the economic environments, and with local consumption of products (including all cogenerated heat). This paper deals with trigeneration systems in the residential-commercial sector, which combine the possibility of buying/selling electricity and/or consuming heat from an auxiliary boiler and also wasting excess cogenerated heat. The goal was to determine the energy and total costs of final energy services and internal flows for all possible operation conditions.

The application of basic thermodynamic rules is likely to be insufficient to solve this problem. In order to promote efficient energy services production and consumption, a rational distribution of cost to the products must consider the nature of the optimal operation mode, which is determined by the economic environment and the variable energy demands of the system. A fair cost and benefit apportionment will contribute to the acceptance of the more complex but more efficient trigeneration systems by the users, which is essential for the success of such systems oriented to multiple users. It was demonstrated how the benefits of trigeneration could be shared between consumers, and how costs were be allocated to improve competitiveness and affordability of energy services, and thus the consumers' acceptability.

Allocating costs based on the alternative supply of co-products was found to be a fair criterion to distribute production costs among final product consumers. The heat produced by cogeneration modules was disaggregated into three fractions: heat that meets the heat demand directly, heat utilized to drive the absorption chiller (producing cooling), and heat dissipated to the environment. Cost allocation was carried out by applying the principle of avoided expenditures. The cost allocation proposal promoted rational and efficient energy services production and consumption, while also benefiting the consumers of the trigeneration system with a fair discount in comparison to the cost of obtaining the energy services separately by conventional systems.

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