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Thermoeconomic cost allocation in simple trigeneration systems including thermal energy storage

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Abstract

The present paper tackles the issue of allocating economic costs in trigeneration systems including thermal energy storage (TES) for buildings of the residential-commercial sector. As energy systems become more and more complex (multiple resources, products and technologies; joint production; TES) the issue of the appropriate way to allocate the cost of the resources consumed arises. This is important because the way in which allocation is made directly affects the prices of the products obtained and, thus, the consumers' behaviour. Thermoeconomics has been used to explain the cost formation process in complex energy systems. In this paper, two issues in thermoeconomics that have not been deeply studied are addressed: (i) the joint production of energy services in dynamic energy systems; and (ii) the incorporation of TES. A thermoeconomic analysis of a simple trigeneration system including TES was performed and the hourly unit costs of the internal flows and final products were obtained for a day of the year. The cost allocation proposal considered that the cogenerated products must share the benefits of the joint production. Regarding the TES, the interconnection between charging and discharging periods was explored, allowing the discharged energy flow to be traced back to its production period.

Keywords: cost allocation, thermal energy storage, thermoeconomics, trigeneration.

1 Introduction

Over the last decades, our society has been facing the challenge of improving quality of life while lowering environmental impacts in an economical and efficient manner. As energy consumption is an essential factor for the development of society, a transition towards advanced, innovative, and efficient energy conversion systems becomes imperative. In this respect, polygeneration systems stand out as compelling alternatives to conventional energy systems. Owing to an appropriate energy integration between the constituting devices, polygeneration systems can achieve higher energy efficiency, lower primary energy consumption, lower unit cost of the final products, and lower environmental burdens relative to conventional energy systems [1-4].

Polygeneration can be defined as the combined production of two or more energy services from a common resource. Cogeneration, or Combined Heat and Power (CHP), is the simplest form of polygeneration, and generally refers to the joint production of electricity (and/or mechanical energy) and heat from a common resource. The joint production takes place in the cogeneration module, composed of a prime mover (e.g. reciprocating internal combustion engine, gas turbine, microturbine, fuel cell), which converts the chemical energy of the fuel into shaft power, an alternator, which converts the shaft power into electricity, and a heat recovery system. A typical extension of cogeneration is trigeneration, also known as Combined Cooling, Heating and Power (CCHP), which usually refers to the combined production of electricity, heat, and cooling. Trigeneration systems are basically composed of a thermally activated technology (TAT), such as an absorption chiller, and/or a mechanical chiller coupled to the cogeneration module. Nevertheless, many alternative devices may be incorporated in various existing configuration modes [5-8].

In the European Union (EU), buildings account for 40% of total energy consumption [9], which suggests a great potential for energy savings. In this regard, the EU Directive 2010/31/EU [9] on the energy performance of buildings recognizes advanced energy systems, such as cogeneration, as key elements in improving the energy efficiency of buildings. The design of polygeneration systems for building applications requires two fundamental issues to be addressed [10, 11], i.e. the synthesis of the plant configuration (installed devices and capacities) and the operational planning (strategy concerning the operational state of the devices, energy flow rates, purchase/selling of electricity, etc.). For existing plants, the operational planning is the only concern. However, finding the best solution for new plants is more complex owing to the wide variety of devices commercially available, the variability of energy demands (hourly and monthly), and the fluctuations in energy prices. A common approach to this problem is the single-objective model aimed at fulfilling an objective function (e.g. economic cost, environmental burden, thermodynamic efficiency) that is to be minimized or maximized [12]. The reviews by [13, 14] describe the characteristics of the optimization methods for polygeneration systems presented in recent publications, indicating the time scale, the objective function, and the solution method employed.

The design procedure for building applications must provide energy systems that are flexible, efficient, and reliable. To this end, the incorporation of thermal energy storage (TES) ensures energy security, reduces operation costs, enhances overall system performance, and allows for a reduction in the installed capacity of the devices. According to [15, 16], TES is particularly beneficial in energy systems characterized by: (i) time-varying energy prices, (ii) low-grade waste heat production, and (iii) intermittent renewable energy sources. The benefits of the inclusion of TES in cogeneration and trigeneration systems has been demonstrated by several works [17-24].

Thermoeconomics combines thermodynamic principles with economic analysis aiming at revealing opportunities of energy and cost savings in the analysis, diagnosis, and optimization of energy conversion systems that are not available through conventional methods [25-26]. The objective of thermoeconomics is to explain the cost formation process throughout the system, from the resources consumed to the final products obtained [25]. The fundamental problem of cost allocation can be formulated as follows [26]: Given a system whose limits have been defined and a level of aggregation that specifies the constituting subsystems, how to obtain the cost of all flows becoming interrelated in such structure.

As energy systems become more and more complex (e.g. multiple fuels, multiple products, multiple technologies, joint production, process integration, energy storage), the problem of the appropriate way to distribute the resources consumed to the internal flows and final products of the system increases. The way in which allocation is made is important because it directly affects the prices of the final products obtained and thus the final consumers' behavior and policy makers' decisions. Widespread acceptance of polygeneration systems in building applications requires that consumers [27,28]: (i) be offered cheaper energy services prices relative to other alternatives available in the market, and (ii) be given informative indications on the rational, economic and environmentally friendly consumption of energy services.

In polygeneration systems, common resources are consumed to produce different products and there is no way, based on pertinent facts, to identify the share of resources consumed associated with each product flow. The allocation of costs in joint production is thus always arbitrary [29-32]. In this regard, numerous methodologies have been proposed [29,33-39], e.g. energy method, exergy method, power bonus method, fuel chargeable to power (FCP) method, benefit distribution method, market-based prices method. However, no consensus has been reached as to a universally accepted approach. An appropriate allocation criterion should: (i) allow all products to remain competitive and profitable relative to their alternatives in the market [29,30], (ii) consider the context in which joint production takes place, as well as value judgements [40], and (iii) be evaluated on a case-by-case basis, so that there is no approach suitable for every situation [41]. Ultimately, the decision on the allocation method must be made in accordance with the objectives of the analysis.

Although thermoeconomic analysis has been traditionally used for the allocation of economic and energy (exergy) resources, there is no limitation to the incorporation of environmental loads or impacts, such as CO_2 emissions and other pollutants [27,39,42,43]. Allocation is also an important issue in Life Cycle Assessment (LCA) studies, as addressed by several works [44-46].

Despite the vast number of studies on thermoeconomic cost allocation in energy systems, most of them have focused on large industrial systems, characterized by steady or quasi-steady operation, often isolated from the economic environment, and owned by individual parties. Energy systems in building applications fundamentally differ from the industry's in aspects such as: (i) consumer behavior (the variability of energy demands of the consumer center requires that devices operate at partial load), (ii) economic environment (the energy system is generally inserted in an economic market that dictates the energy prices), and (iii) ownership (multiple decision makers must reach an agreement in commonly operated systems, e.g. a trigeneration system supplying energy services for a multi-family building complex). Therefore, further development and refinement of allocation methodologies is required [28,47].

The incorporation of TES in energy conversion systems increases the difficulty of cost allocation as it decouples production of energy services from consumption [48,49]. In a previous paper [50], we have studied the optimal operation of a simple trigeneration system including TES. It was demonstrated how the operation of the system in an hourly period may be affected by the operation at different hourly periods and how the system can take advantage of the different operation conditions (e.g. available resources, energy prices, operation levels) at different hours to achieve more interesting results in accordance with the objective function.

The purpose of this paper is to discuss the issue of the appropriate way to allocate economic costs in trigeneration systems including TES for the building sector. This work intends to contribute by proposing cost allocation approaches to two issues in thermoeconomics that have not been deeply studied in the context of building applications: (i) the joint production of energy services in dynamic energy systems, and (ii) the incorporation of TES. The methodology proposed herein aims at a fair cost-and-benefit apportionment of the joint production costs to the energy products. In this way, the benefits of the more efficient (and complex) production are distributed between all energy products, promoting the acceptance of polygeneration systems in the society.

Taking the work developed in Ref. [50] as the starting point, a thermoeconomic analysis of a simple trigeneration system including TES is carried out, obtaining the unit costs of all internal flows and final products of the system for a day of the year. It must be emphasized that only operation costs are considered in this analysis. A detailed account on the definition of the productive structure is made, unraveling the various existing productive trajectories that connect the resources consumed to the final products obtained and focusing on the objective of a fair cost-and-benefit apportionment of the joint production costs. As stated in the title of the paper, the trigeneration system and the example developed herein are simple, but they allow for interesting analyses and conceptual interpretations. In this way, this methodological-oriented paper demonstrates the development and the application of the cost allocation proposals.

This paper is structured as follows: Section 2 describes the simple trigeneration system including TES and the reference system analyzed in this paper, as well as the mathematical model and the optimal operation of the trigeneration system for a day of the year that brings the minimum energy cost. Section 3 explains the thermoeconomic cost allocation proposal developed herein, including the definition of the productive structure (considerations for the joint production of energy services, the disaggregation of energy flows and devices, and the incorporation of TES) and the cost allocation equations. Section 4 presents the unit costs of the internal flows and final products obtained. Finally, Section 5 draws the conclusions of this work.

2 The simple trigeneration system including TES

This paper is a follow-up to a previous study [50] in which the optimal operation of a simple trigeneration system including TES has been analyzed. Based on the information provided in Ref. [50], the following subsections describe: (i) the simple trigeneration system including TES analyzed herein, as well as the energy demands of the consumer center that it must attend and the energy resources prices, (ii) the optimization model that minimizes the daily operation cost, and (iii) the optimal operation of the system for a day of the year. Additionally, the reference system considered in this work is defined in the last subsection.

2.1 System description

The simple trigeneration system analyzed herein is depicted in Fig. 1. The system is composed of a cogeneration module CM, an auxiliary boiler AB, a single-effect absorption chiller AC, a mechanical chiller EC, and a TES unit TS (used to store chilled water). The trigeneration system was designed to attend the electricity E_d, heating Q_d, and cooling R_d demands of a consumer center (e.g. multi-family building). It is considered that the system is interconnected with the electric grid, so purchase E_p and sale E_s of electricity are possible. The CM consumes natural gas F_c and produces cogenerated electricity W_c and heat Q_c. Part of the cogenerated electricity W_c can be sold to the grid E_s. The part that is not sold W_{cc}, along with the electricity purchased from the grid E_p, is used to attend the electricity demand E_d and/or drive the EC E_r. The AB consumes fuel-oil F_a and produces conventional heat Q_a. Part of the cogenerated heat can be wasted into the environment Q_{cl}. The part that is not wasted Q_{cc}, along with Q_a, is used to attend the heating demand Q_d and/or drive the AC Q_r. The cooling produced by the AC R_q and EC R_e are used to cover the cooling demand R_d and/or charge the TS. The TS can be either charging R_{in} or discharging R_{out} in each hourly period; energy losses R_s are proportional to the stored energy S_r and to the TS energy loss factor τ_{TS}. All system devices can be operated at partial or full load with constant performance factors. Table 1 presents the technical parameters and capacity limits of the system's devices.

It is important to emphasize the reasons for including a TES unit for cooling and not for heat (or both): First, the cooling demand presents higher variations throughout the day than the heating demand. Secondly, the aim of this paper is to demonstrate the proposed cost allocation methodology; the inclusion of two or more TES units would hinder the clarity of the analysis.

The simple trigeneration system interacts with the economic environment through the purchase of natural gas F_c, fuel-oil F_a, and electricity E_p, as well as through the sale of cogenerated electricity E_s. The energy prices are given in Table 2. Moreover, it was considered that no cost was associated with the dissipation of cogenerated heat to the environment $rq_{cl} = 0$ €/kWh.

The energy demands E_d, Q_d, and R_d of the consumer center for a day of the year are described by 24 consecutive periods of 1-hour duration and are given in Table 3. As can be seen, E_d is required all through the day, Q_d is required at hours 1 and 7 to 24, and R_d is only required between hours 14 and 22.

Given the various resources available and devices that constitute the simple trigeneration system, it becomes evident that many alternative production routes can be identified to supply the energy demands of the consumer center. For instance, the heating demand Q_d can be covered by useful cogenerated heat Q_{cc} from the CM consuming natural gas F_c at price p_{fc} and/or with conventional heat Q_a from the AB consuming fuel-oil F_a at price p_{fa}. Mathematical models based on linear programming (LP) are generally used to obtain a rational operational strategy, which is always linked to an objective function (e.g. minimize the operation cost, minimize the environmental loads). A rational, complete, and exact operational strategy constitutes essential data when addressing the cost allocation issue in energy systems.

2.2 Optimization model

A LP model was developed to obtain the hourly operational strategy of the simple trigeneration system for a day of the year. The objective function, expressed by Eq. (1), minimizes the daily operation cost DC, which corresponds to the sum of the hourly operation cost $HC(h)$ for the 24 periods h ($NP = 24$) of 1-hour duration ($NHP = 1$) that comprise the day.

$$Min\ DC = NHP \cdot \sum_{h=1}^{NP} HC(h) \quad (1)$$

For each hourly period *h*, *HC(h)* includes the costs of purchasing electricity, natural gas, and fuel-oil, the cost associated with heat dissipation, and the income from selling cogenerated electricity to the electric grid, as expresses Eq. (2):

$$HC(h) = p_{ep}(h) \cdot E_p(h) + p_{fc}(h) \cdot F_c(h) + p_{fa}(h) \cdot F_a(h) + rq_{cl}(h) \cdot Q_{cl}(h) - p_{es}(h) \cdot E_s(h) \quad (2)$$

The objective function is subject to equipment constraints (capacity limits and production restrictions) and balance equations. For detailed information about the optimization model the reader is referred to [50].

Regarding the TS, it is worth noting that the energy losses in each hourly period $R_s(h)$ are equal to the stored energy at the end of the previous period $S_{rf}(h\text{-}1)$ multiplied by the TS energy loss factor τ_{TS}:

$$R_s(h) = \tau_{TS} \cdot S_{rf}(h-1) \quad (3)$$

Moreover, given the daily regularity of the energy demands, it was considered that the TS must return to its initial state after a daily cycle; in this way, the energy stored at the end of the day $S_{rf}(24)$ must be equal to the energy stored at the beginning of the day $S_{ri}(1)$. Because of the continuous operation of the TS, it follows that the energy stored at the beginning of an hourly period $S_{ri}(h)$ must be equal to the energy stored at the end of the previous period $S_{rf}(h\text{-}1)$.

2.3 Optimal operation of the simple trigeneration system

The optimization model was solved using the software LINGO [51]. A daily operation cost *DC* of 660.8 €/day was obtained, from which: (i) 600 €/day is due to the purchase of natural gas F_c for the CM; (ii) 115.6 €/day corresponds to the purchase of electricity from the grid E_p; (iii) 8.6 €/day is due to the purchase of fuel-oil F_a for the AB; and (iv) 63.3 €/day is the income generated by the selling of cogenerated electricity E_s.

The energy flows of the optimal operation are presented in Table 3, in which E_{grid} represents the net electricity exchanged with the electric grid (negative values mean sale E_s and positive values mean purchase E_p), and R_{TS} indicates whether the TS is charging (positive values, R_{in}) or discharging (negative values, R_{out}).

The cogeneration module CM operates at full load all through the day (daily load factor of 100%), consuming 24,000 kWh/day of natural gas F_c and simultaneously producing 8400 kWh/day of cogenerated electricity W_c and 9600 kWh/day of cogenerated heat Q_c. In the morning (hours 1 to 8) and in the night (hours 23 and 24), the system sells 791.2 kWh/day of surplus cogenerated electricity E_s, which represents 9.4% of the total electricity produced W_c. On the other hand, from hours 9 to 13 and 17 to 22, the system must purchase 1155.5 kWh/day of electricity E_p, which represents 13.2% of the total electricity consumed (E_d + E_r). Regarding the heat production in the CM, no cogenerated heat is wasted into the environment (Q_{cl} = 0 kWh/day). Additionally, the available cogenerated heat Q_{cc} represents 96.6% of the total heat consumed by the system (Q_d + Q_r). The remaining 3.4% (342.4 kWh/day) is supplied by the AB (daily load factor of 4%), which operates marginally to cover peak heat demands (e.g. hours 10, 11, and 20).

Even though the consumer center only requires cooling between hours 14 and 22, its production also takes place at previous hours to charge the TS. Considering the cooling produced by the system, 56.9% (2401.5 kWh/day) is produced in the AC (daily load factor of 40%) and 43.1% (1821.5 kWh/day) is produced in the EC (daily load factor 30%). As can be seen from Table 3, cooling R_e is produced in the EC at hours 8 and 14 to 22. It is interesting to note the different electricity sources available for the EC at different hours: on the one hand, at hours 8 and 14 to 16 the system is not purchasing electricity (E_p = 0 kWh), so all cooling R_e is produced with cogenerated electricity W_{cc}; on the other hand, at hours 17 to 22, cooling R_e is produced with both purchased E_p and cogenerated W_{cc} electricity flows. In the case of the AC, cooling R_q is produced at hours 1 to 9, 12, 13, 15 to 18, and 22 to 24. Although there is no physical limitation to the use of cogenerated Q_{cc} and/or conventional Q_a heat flows, it can be seen from Table 3 that in the optimal operation the AB is never used to supply heat to drive the AC, which means that all R_q is produced with cogenerated heat Q_{cc}.

Charging of the TS takes place for 13 hours, beginning at hour 23 of the previous day until hour 9 and continuing at hours 12 and 13 until the TS is fully charged with 2000 kWh. Discharging takes place for 6 hours, beginning at hour 14 along with the cooling demand R_d, until hour 19. Considering the daily demand R_d, 48.8% of it is supplied by the TS, meaning that it was produced at different previous hours. By the end of the discharging period the TS is fully discharged and remains this way until hour 23, when the charging cycle begins again. Following from the explanation provided in the previous paragraph, it is also interesting to note the different types of cooling stored: hour 8 is characterized by production of both R_q (with cogenerated heat Q_{cc}) and R_e (with cogenerated electricity W_{cc}); the rest of the charging hours are characterized by exclusive production of R_q (with cogenerated heat Q_{cc}).

2.4 Reference system

The reference system considered in this work corresponds to the separate conventional production of energy services, as depicted in Fig. 2. In this way, considering the same energy resources prices and technical parameters of the devices as for the simple trigeneration system: (i) the electricity demand E_d is covered by purchase from the electric grid, (ii) the heating demand Q_d is covered by the auxiliary boiler AB consuming fuel-oil F_a, and (iii) the cooling demand R_d is covered by the mechanical chiller EC consuming electricity purchased from the grid E_p.

Therefore, the energy services production costs in the reference system are: (i) electricity: purchase price from the electric grid $(cW)_{ref} = p_{ep}$ = 0.100 €/kWh, (ii) heat: production cost in the AB consuming fuel-oil $(cQ)_{ref} = p_{fa}/\eta_{AB}$ = 0.025 €/kWh, and (iii) cooling: production cost in the EC with electricity purchased from the grid $(cR)_{ref} = p_{ep}/COP_e$ = 0.020 €/kWh.

3 Thermoeconomic cost allocation

Cost accounting tackles the problem of allocating the costs of the resources consumed to the internal flows and final products of the system. The difficulty of cost allocation increases when different products are obtained from common resources, as is the case with polygeneration systems. The way in which allocation is made is important because it will directly affect the results obtained.

Obtaining unit costs of internal flows and final products is a cornerstone of several thermoeconomic methodologies that have been presented in the literature [52]. Lozano et al. [34] applied three different approaches to determine the unit costs of the internal flows and final products of a simple trigeneration system: (i) analysis of marginal costs corresponding to the optimal operation; (ii) valuation of products according to their market prices; and (iii) internal cost calculation. From the various results obtained for each approach, it was concluded that there is no general rule to decide which approach is the best, as it depends on the objectives of the analysis.

The fundamental difference between marginal and unit (or average) costs is that marginal costs are a derivative and correspond to the cost of producing an additional unit of a flow, while unit costs are ratios and represent the unit (or average) production cost of a flow, calculated by dividing the total cost by the total quantity produced.

Marginal costs give valuable insight into the operation of the system, explaining how and why the system operates given a change in external circumstances (e.g. increase in the consumer center's energy demand). On the downside, marginal costs are generally not appropriate to explain the actual production of the system [50,52,53], apart from not being conservative [34,50]. In Ref. [50], the authors have used marginal costs to explain the optimal operation of the simple trigeneration system described in Section 2 and the role of the TES unit in achieving the optimal operation.

By contrast, unit costs provide valuable information to explain the way the system is operating. Based on the cost conservation principle, the total cost of the resources exchanged with the economic environment must be equal to the total cost of the products obtained. Considering the daily operation cost DC from Eq. (1), the following expression holds true:

$$DC = \sum_h \sum_i c_i(h) \cdot R_i(h) = \sum_h \sum_j c_j(h) \cdot P_j(h) \tag{4}$$

in which $c_i(h)$ and $R_i(h)$ are, respectively, the unit cost and the energy flow of the resource i exchanged with the economic environment at the hourly period h; and $c_j(h)$ and $P_j(h)$ are, respectively, the unit cost and the energy flow of the product obtained j at the hourly period h.

In the present analysis, the energy resources are natural gas, fuel-oil, and electricity purchased from the electric grid, and the energy products are the electricity sold to the electric grid and the energy demands of the consumer center (electricity, heating, and cooling). Provided that all energy flows R_i and P_j in each hourly period h are known, as well as the unit costs of the resources c_i, the aim is to objectively determine the unit costs of the products c_j. In this regard, it is essential to connect the product flow that is being valued to the different resources consumed, so that each product flow receives its corresponding share of costs.

The productive structure is the tool that is generally used in thermoeconomics to unveil the distribution of resources to the internal flows and final products of an energy system. Identifying the appropriate productive structure is a crucial step when performing a thermoeconomic analysis [26-28]. Once the productive structure has been defined, the application of cost conservation balance to its elements allows for the determination of the unit costs of product flows, unveiling the cost formation process.

The following subsections describe: (i) the definition of the productive structure and the issues faced in the process; and (ii) the cost allocation proposals for the system analyzed herein.

3.1 Definition of the productive structure

Fig. 1 shows the physical structure of the simple trigeneration system including TES. The physical structure depicts the devices that constitute the system and the energy flows that connect the devices with each other and the system with its boundaries (economic environment and consumer center). The productive structure, on the other hand, consists of defining the main product (or the productive purpose) of each device with the aim of allocating the resources consumed throughout the plant. Thus, the productive structure is not necessarily equal to the physical structure and many possible configurations can be obtained depending on the objective of the analysis; clearly, different costs of the final products are obtained for different productive structures. This underlines the importance of appropriately defining the productive structure of the energy conversion system, so that the results obtained are in accordance with the objective of the analysis.

The internal flows and final products of the productive structure must be expressed in terms of an extensive magnitude, e.g. mass, volume, energy or exergy content, number of moles. In this work, the productive structure is composed of energy flows and, thus, the associated unit costs are expressed in terms of energy. The reason for expressing the unit costs in terms of energy is that this is the most typical billing mechanism perceived by the final consumers (final consumers pay for their energy resources per unit of energy consumed), which are the ones that will ultimately make the decision on whether to consume energy service from the trigeneration system.

The joint production of energy services that takes place in polygeneration systems is achieved through appropriate energy integration of the production processes [1,2]. Such a high level of integration hinders the determination of a logical distribution of the resources consumed towards the cogenerated products. The true purpose of this work is to achieve a fair cost-and-benefit apportionment of the joint production costs to the energy services produced. This requires: (i) the definition of a productive structure with the highest possible disaggregation level, so as to connect the resources consumed to the final products obtained through the various existing productive trajectories [26], and (ii) the definition of fair allocation criteria, so as not to favor or prioritize any resource/product [29,32,35].

Thus, it becomes clear that to connect the resources consumed by the simple trigeneration system to its internal flows and final products one must tackle the issues of: (i) the joint production of electricity and heat that takes place in the cogeneration module; (ii) the disaggregation of energy flows and devices; and (iii) the interconnection between charging and discharging periods due to the incorporation of a TES unit. These aspects are analyzed in detail in the following subsections.

3.1.1 Joint production in the cogeneration module

As described by Lozano et al. [27,28], the fundamental device of a cogeneration system is the cogeneration module CM, in which the joint production of electricity (and/or mechanical energy) and heat takes place. By incorporating a TAT, such as an absorption chiller AC, the cogenerated heat can be extended to cooling production. The combination CM+AC thus make the trigeneration subsystem.

In the present paper, it was proposed to expand this trigeneration subsystem to include a mechanical chiller EC, so that cogenerated electricity can also be used to produce cooling. In this way, both CM products can contribute to cooling production. The combination CM+AC+EC thus forms the trigeneration subsystem considered in the productive structure, as depicted in Fig. 3.

In the trigeneration subsystem analyzed herein, the CM consumes natural gas F_c to produce cogenerated electricity W_c and cogenerated heat Q_c. The cogenerated electricity W_c can be: (i) sold to the electric grid E_s; (ii) used in the EC to produce cooling R_{ce}; and (iii) used to cover the electricity demand W_{cd}. In the case of the cogenerated heat Q_c, there are three possible destinations: (i) attend the heat demand Q_{cd}; (ii) produce cooling in the AC R_{cq}; and (iii) be dissipated to the environment Q_{cl}. As mentioned earlier, the purchase price of natural gas p_{fc} and the price of the electricity sold to the grid p_{es} are defined by the market; also, heat dissipation can occur with no associated cost (rq_{cl} = 0 €/kWh). Therefore, the four cogenerated products to which costs should be allocated are W_{cd}, Q_{cd}, R_{ce}, and R_{cq}.

3.1.2 Productive structure

When it comes to precisely allocating resources to internal flows and final products, defining the productive structure requires the highest possible disaggregation level of physical flows and devices. This is done so that the productive structure reflects the various productive trajectories which, in an integrated energy system, connect the resources consumed to the final products obtained. Avoiding the disaggregation by combining devices and/or processes only hides the problem and, thus, is not recommended.

Supporting the production of the trigeneration subsystem are the auxiliary boiler and the electric grid. So, when the cogeneration module CM and the auxiliary boiler AB are both in operation, there are two heat sources available to drive the absorption chiller AC and to attend the heat demand Q_d. Analogously, when the CM is operating and the system is purchasing electricity from the grid E_p, there are two electricity sources available to drive the mechanical chiller EC and to attend the electricity demand E_d. Therefore, in accordance with Lozano et al. [27,28], the AC and the EC can each be divided into two virtual devices; in this way, each virtual device will consume energy from its specific source.

The productive structure obtained is depicted in Fig. 4, which includes the trigeneration subsystem defined in Section 3.1.1 (enclosed in the gray box), the conceptual division of the absorption chiller AC and mechanical chiller EC, and the corresponding virtual flows.

As an imposing limitation to the definition of the productive structure, it must be possible to evaluate all flows of the productive structure unequivocally in relation to the state of the plant as defined by the physical structure [26]. The relations that define the virtual flows in the productive structure are explained in the following paragraphs.

The absorption chiller AC is divided into two virtual devices: ACc, which consumes cogenerated heat Q_{cr} and produces cogenerated absorption cooling R_{cq}, and ACa, which consumes conventional heat Q_{ar} and produces conventional absorption cooling R_{aq}. Both virtual heat flows compose the Q_r in Fig. 1, so that

$$Q_r(h) = Q_{cr}(h) + Q_{ar}(h) \tag{5}$$

The mechanical chiller EC is divided into two virtual devices: ECc, which consumes cogenerated electricity W_{cr} and produces cogenerated mechanical cooling R_{ce}, and ECp, which consumes purchased electricity E_{pr} and produces auxiliary cooling R_{pe}. Both virtual electricity flows compose the E_r in Fig. 1, so that

$$E_r(h) = W_{cr}(h) + E_{pr}(h) \tag{6}$$

Despite the inclusion of additional virtual flows and/or devices in the productive structure, in each hourly period the same amount of energy resources (natural gas, fuel oil and purchase/sale of electricity from/to the grid) is consumed to attend the energy services (electricity, heating and cooling demands) as in the physical structure's optimal operation described in Section 2. With these aspects “fixed”, there are various ways in which the disaggregation of internal flows can take place without affecting the operation state of the plant. Therefore, the energy flows distribution in distributors Q2, Q3, E2 and E3 are inevitably arbitrary.

In accordance with the core objective of this study, which is to promote a fair cost-and-benefit apportionment of costs in the trigeneration system, it is proposed to distribute the cogenerated heat Q_{cc}, the conventional heat Q_a, the cogenerated electricity W_{cc} and the purchased electricity E_p in distributors Q2, Q3, E2 and E3, respectively, in a way that: (i) no energy resource is prioritized in the production of energy services, and (ii) no energy service is prioritized in the use of energy resources. As a result, no energy service gets favored with a lower cost due to an also arbitrary decision to prioritize its production with the consumption of a cheaper energy resource.

Two parameters are defined for the distribution of heat and electricity, respectively: (i) δ_1 expresses the share of heat that covers the heat demand in proportion to the total heat demanded (Eq. (7)); and (ii) δ_2 expresses the share of electricity that attends the electricity demand in proportion to the total electricity demanded (Eq. (8)).

$$\delta_1(h) = Q_d(h)/(Q_d(h) + Q_r(h)) \tag{7}$$

$$\delta_2(h) = E_d(h)/(E_d(h) + E_r(h)) \tag{8}$$

The available cogenerated heat Q_{cc} and the conventional heat Q_a are distributed between the consumer center and the AC as follows:

$$Q_{cd}(h) = \delta_1(h) \cdot Q_{cc}(h) \tag{9}$$

$$Q_{cr}(h) = \left(1 - \delta_1(h)\right) \cdot Q_{cc}(h) \tag{10}$$

$$Q_{ad}(h) = \delta_1(h) \cdot Q_a(h) \tag{11}$$

$$Q_{ar}(h) = \left(1 - \delta_1(h)\right) \cdot Q_a(h) \tag{12}$$

The cogenerated electricity W_{cc} and the purchased electricity E_p are distributed between the consumer center and the EC as follows:

$$W_{cd}(h) = \delta_2(h) \cdot W_{cc}(h) \tag{13}$$

$$W_{cr}(h) = \left(1 - \delta_2(h)\right) \cdot W_{cc}(h) \tag{14}$$

$$E_{pd}(h) = \delta_2(h) \cdot E_p(h) \tag{15}$$

$$E_{pr}(h) = \left(1 - \delta_2(h)\right) \cdot E_p(h) \tag{16}$$

The cooling produced from cogenerated heat R_{cq} and the cooling produced from conventional heat R_{aq} are determined as follows:

$$R_{cq}(h) = COP_q \cdot Q_{cr}(h) \tag{17}$$

$$R_{aq}(h) = COP_q \cdot Q_{ar}(h) \tag{18}$$

The cooling produced from cogenerated electricity R_{ce} and the cooling produced from purchased electricity R_{pe} are

$$R_{ce}(h) = COP_e \cdot W_{cr}(h) \tag{19}$$

$$R_{pe}(h) = COP_e \cdot E_{pr}(h) \tag{20}$$

The cooling produced by the absorption chillers R_q and by the mechanical chillers R_e compose the total cooling produced in the hourly period R_{pro} (Eq. (21)). Part of R_{pro} can be charged to the TS R_{in}; the part that is not charged is the cooling produced and consumed in the hourly period R_{pi} (Eq. (22)). In this way, the charged cooling R_{in} in an hourly period has the same characteristics as the cooling produced at that time. In turn, the discharge R_{out} will depend on the charged cooling of previous hourly periods. This connection between charging and discharging periods is implicit in the productive structure defined herein and is explored in the following section.

$$R_{pro}(h) = R_q(h) + R_e(h) \tag{21}$$

$$R_{pi}(h) = R_{pro}(h) - R_{in}(h) \tag{22}$$

The virtual flows and the distribution parameters previously defined were calculated and are given in Table 4.

3.1.3 Interconnection between hourly periods through the TS

The hourly operation of an energy system can be described in terms of the operational state of the devices (full load, partial load, off), production rates, resource consumption, etc. For a system that does not include energy storage, the hourly operation periods are always independent from each other. However, the incorporation of energy storage allows energy service production to be decoupled from consumption, so that the operation of the system in an hourly period may be affected by others; now, the hourly operation periods cannot be assessed individually, but as a whole.

This is particularly relevant for the cost allocation problem involving energy storage because connecting the resources consumed to the internal flows and final products requires analyzing the temporal connection between charging and discharging hourly periods. Therefore, the presence of the energy storage unit incorporates a new dimension to the cost allocation problem, as it becomes necessary to know not only the amount of energy that must be charged and discharged in each hourly period, but also the origin period of the discharged energy. By doing so, the resources consumed to produce the charged flow can be forwarded to the discharging periods and to the final products.

In the case of the simple trigeneration system analyzed in this paper, the optimal operation model provides the amount of energy that must be charged R_{in} or discharged R_{out} in each hourly period. In order to lift the veil on how the stored energy is distributed between the hourly periods, a charging and discharging network was considered, as shown in Fig. 5. The network is composed of nodes and pairs. Source nodes (circles) receive the charged energy R_{in} and distribute it to the sink nodes (rhombs), from which the discharged energy R_{out} leaves. Between the source and the sink nodes, there are intermediate nodes (squares) at the beginning of each hourly period from which energy losses r_s are deduced. The charged energy flows from source to sink nodes through pairs called *IN*, when they leave the source node, and called *OUT*, when they enter the sink node.

The charging and discharging network in Fig. 5 can be represented in algebraic form as follows: The discharged energy $R_{out}(h)$ in period *h* is equal to the sum of all pairs *OUT(z,h)* that originate in previous periods *z* and arrive in period *h* (Eq. (23)). The charged energy $R_{in}(z)$ in period *z* may be divided into pairs *IN(z,h)* that originate in period *z* and are directed to discharging periods *h* (Eq. (24)). Energy losses $r_s(z,h,k)$ are evaluated along the path *(z,h)* at the beginning of each hourly period *k* according to Eq. (25), for $k > z$, or Eq. (26), for $k < z$. It holds true that for the path *(z,h)* the charged energy pair *IN(z,h)* is equal to the discharged pair *OUT(z,h)* plus the energy losses $r_s(z,h,k)$ along the path (Eq. (27)).

$$R_{out}(h) = \sum_{z \neq h} OUT(z,h) \tag{23}$$

$$R_{in}(z) = \sum_{h \neq z} IN(z,h) \tag{24}$$

$$r_s(z,h,k) = IN(z,h) \cdot \tau_{TS} \cdot (1-\tau_{TS})^{(k-z-1)}, \text{ for } k > z \tag{25}$$

$$r_s(z,h,k) = IN(z,h) \cdot \tau_{TS} \cdot (1-\tau_{TS})^{(k-z-1+NP)}, \text{ for } k < z \tag{26}$$

$$IN(z,h) = OUT(z,h) + \sum_{k \neq z} r_s(z,h,k) \tag{27}$$

These equations can be either included in the optimization model or solved separately. It must be noted that: (i) solving the equation set does not change the optimal operation of the system; and (ii) the feasible solution obtained is not unique, as numerous combinations of paths *(z,h)* may exist to fulfill the charging and discharging requirements. In order to guarantee a unique feasible solution, the first in first out (FIFO) method was imposed, which determines that the first unit of energy to be charged must be the first unit of energy to be discharged.

Solving the equation set with R_{in} and R_{out} from the optimal operation of the system as input data yields the energy flows that compose the charging and discharging network. In the case analyzed herein, the interconnection between hourly periods through the TES unit TS is presented in Fig. 6. An example of interpretation of the results is provided as follows: The energy charged at hour 3 $R_{in}(3)$ = 250 kWh is directed to hours 14 (*IN(3,14)* = 40.56 kWh) and 15 (*IN(3,15)* = 209.44 kWh). The discharged energy at hour 15 $R_{out}(15)$ = 410.64 kWh proceeds from hours 3 (*OUT(3,15)* = 185.64 kWh), 4 (*OUT(4,15)* = 223.83 kWh), and 5 (*OUT(5,15)* = 1.16 kWh).

3.2 Cost allocation

The cost conservation principle applied to the elements in the productive structure allows the cost formation process to be transparent throughout the system, from the resources consumed to the final products obtained. The unit energy costs of the internal flows and final products are thus obtained, representing the amount of resources that must be consumed to produce one unit of the flow. The unit cost name of the flows in the productive structure of Fig. 4 is obtained by adding the letter *c* at the beginning of the energy flow name.

The first and foremost requirement to performing cost allocation is the knowledge of the operational state of the system, which means that all energy flows in each hourly period must be known. For the trigeneration system analyzed herein, the energy flows are provided in Table 3 and Table 4. The market-based prices of the electricity, natural gas, and fuel-oil are also known and shown in Table 2.

The cost conservation principle is applied to all junctions (rhombs), distributors (circles), and devices of the productive structure, allowing the following cost balance equations to be formulated:

Junctions:

E4: $$cW_{cd}(h) \cdot W_{cd}(h) + cE_{pd}(h) \cdot E_{pd}(h) - cE_{d}(h) \cdot E_{d}(h) = 0 \quad (28)$$

Q4: $$cQ_{cd}(h) \cdot Q_{cd}(h) + cQ_{ad}(h) \cdot Q_{ad}(h) - cQ_{d}(h) \cdot Q_{d}(h) = 0 \quad (29)$$

R1: $$cR_{aq}(h) \cdot R_{aq}(h) + cR_{cq}(h) \cdot R_{cq}(h) - cR_{q}(h) \cdot R_{q}(h) = 0 \quad (30)$$

R2: $$cR_{ce}(h) \cdot R_{ce}(h) + cR_{pe}(h) \cdot R_{pe}(h) - cR_{e}(h) \cdot R_{e}(h) = 0 \quad (31)$$

R3: $$cR_{q}(h) \cdot R_{q}(h) + cR_{e}(h) \cdot R_{e}(h) - cR_{pro}(h) \cdot R_{pro}(h) = 0 \quad (32)$$

R5: $$cR_{pi}(h) \cdot R_{pi}(h) + cR_{out}(h) \cdot R_{out}(h) - cR_{d}(h) \cdot R_{d}(h) = 0 \quad (33)$$

Considering that the unit costs of the entering flows are known, the unit cost of the junction's product is directly obtained from the cost balance equation.

Distributors:

E3: $$p_{ep} \cdot E_{p}(h) - cE_{pr}(h) \cdot E_{pr}(h) - cE_{pd}(h) \cdot E_{pd}(h) = 0 \quad (34)$$

Q3: $$cQ_{a}(h) \cdot Q_{a}(h) - cQ_{ar}(h) \cdot Q_{ar}(h) - cQ_{ad}(h) \cdot Q_{ad}(h) = 0 \quad (35)$$

R4: $$cR_{pro}(h) \cdot R_{pro}(h) - cR_{in}(h) \cdot R_{in}(h) - cR_{pi}(h) \cdot R_{pi}(h) = 0 \quad (36)$$

For the distributors, a generally accepted accounting principle, which states that the unit costs of the products from the same line are equal, is applied. The following auxiliary equations are thus obtained:

$$cE_{pr}(h) = cE_{pd}(h) \quad (37)$$

$$cQ_{ar}(h) = cQ_{ad}(h) \quad (38)$$

$$cR_{pi}(h) = cR_{in}(h) \quad (39)$$

Devices:

AB: $$p_{fa} \cdot F_{a}(h) - cQ_{a}(h) \cdot Q_{a}(h) = 0 \quad (40)$$

ACa: $$cQ_{ar}(h) \cdot Q_{ar}(h) - cR_{aq}(h) \cdot R_{aq}(h) = 0 \quad (41)$$

ECp: $$cE_{pr}(h) \cdot E_{pr}(h) - cR_{pe}(h) \cdot R_{pe}(h) = 0 \quad (42)$$

The AB, ACa and ECp have only one product. In this case, the unit cost of the product is directly obtained from the cost balance equation, provided the unit costs of the consumed flows are known. The ACc and ECc also have only one product, but because they are inserted in the trigeneration subsystem the unit costs of their products are calculated differently, as will be explained below.

As already mentioned, the trigeneration subsystem and the TES unit TS impose some issues to the cost allocation problem that have not been deeply studied in thermoeconomics so far, namely (i) the joint production of energy services in dynamic trigeneration systems; and (ii) the incorporation of a TES unit. These aspects are analyzed in detail in the next paragraphs.

(i) Joint production in the trigeneration subsystem:

The cost balance equation associated with the trigeneration subsystem is expressed by Eq. (43):

Tri-Sub: $$p_{fc} \cdot F_c(h) - p_{es} \cdot E_s(h) + rq_{cl} \cdot Q_{cl}(h) - cW_{cd}(h) \cdot W_{cd}(h) - cQ_{cd}(h) \cdot Q_{cd}(h) - cR_{cq}(h) \cdot R_{cq}(h) - cR_{ce}(h) \cdot R_{ce}(h) = 0 \quad (43)$$

No cost was attributed to the dissipation of cogenerated heat Q_{cl} to the ambient (rq_{cl} = 0 €/kWh). Considering that the resources consumed by the trigeneration subsystem must be allocated to its useful cogenerated products (W_{cd}, Q_{cd}, R_{cq}, R_{ce}) three auxiliary equations are needed to determine their unit costs (cW_{cd}, cQ_{cd}, cR_{cq}, cR_{ce}).

In accordance with the objective of promoting widespread acceptance of polygeneration systems in society through a fair cost-and-benefit apportionment of joint production costs, it was proposed to apply the same discount d to all products of the trigeneration subsystem with respect to a reference cost of the corresponding energy services production. In previous papers [27,28,34], the authors have applied the discount method in similar thermoeconomic analyses of trigeneration systems.

$$d = 1 - cW_{cd}(h)/(cW)_{ref} = 1 - cQ_{cd}(h)/(cQ)_{ref} = 1 - cR_{cq}(h)/(cR)_{ref} = 1 - cR_{ce}(h)/(cR)_{ref} \quad (44)$$

According to [29,31], the discount method, or benefit distribution method, is practicable for allocating variable costs because it results in sharing the benefits of joint production among all cogenerated products. Moreover, based on the cost allocation decision guide given in [32,40], the benefit distribution method can be justified under the fairness or equity criterion, which establishes that when several parties participate in a joint production process, an allocation procedure that satisfies all of them is required.

In the present analysis, the final consumers are the owners of the trigeneration system and thus all of them must receive the benefits of the joint production, which should be translated as lower unit costs of energy services relative to the conventional separate production cost. Therefore, the reference costs considered herein correspond to the energy services production cost of the reference system, as presented in Section 2.4. The three auxiliary equations are thus obtained from Eq. (44):

$$cW_{cd}(h)/(cW)_{ref} = cQ_{cd}(h)/(cQ)_{ref} \quad (45)$$

$$cW_{cd}(h)/(cW)_{ref} = cR_{cq}(h)/(cR)_{ref} \quad (46)$$

$$cW_{cd}(h)/(cW)_{ref} = cR_{ce}(h)/(cR)_{ref} \quad (47)$$

(ii) Incorporation of a TES unit:

The cost allocation in the TS follows from the methodology developed in Section 0, which considers the interconnection between hourly periods through the TS as a charging and discharging network.

As expresses Eq. (39), the unit cost of the charged cooling cR_{in} is equal to the unit cost of the cooling produced cR_{pi} in the hourly period. This reflects the fact that the energy stored in the TS may have different unit costs according to the hourly period in which it was produced. Considering that the penalty for energy wasting in the TS must be allocated to its useful products, no cost was allocated to the energy losses R_s (cR_s = 0 €/kWh). The unit cost of the discharged cooling cR_{out} was obtained by tracing the discharged flow back to its origin periods, as expresses Eq. (48).

$$cR_{out}(h) \cdot R_{out}(h) = \sum_{z \neq h} cR_{in}(z) \cdot IN(z,h) \quad (48)$$

4 Results and discussion

The results obtained from the application of the cost allocation approach proposed in Section 3.2 to the simple trigeneration system are analyzed in subsection 4.1. Subsection 4.2 discusses the assessment of exergy-based unit costs.

4.1 Application of the proposed cost allocation approach

The hourly unit costs of the internal flows and final products of the simple trigeneration system were obtained by solving the linear equation system proposed in Section 3.2 using the software EES (Engineering Equation Solver) [54]. The allocation proposal allowed to distribute the operation cost between the internal flows and final products of the system in each hourly period. The main unit costs obtained are presented in Table 5.

Fig. 7 presents the hourly unit costs obtained for the final products of the trigeneration system and their respective reference costs (separate production costs defined in the previous Section). As can be seen, the hourly cE_d, cQ_d, and cR_d were always lower than their respective reference costs. The daily cE_d, cQ_d, and cR_d were 38%, 41%, and 36% cheaper than $(cW)_{ref}$, $(cQ)_{ref}$, and $(cR)_{ref}$, respectively.

The knowledge of the operational state of the system in each hourly period provides valuable insight into the unit cost analysis. For instance, the increase in the cE_d from hours 9 to 13 and 17 to 22 is due to the purchase of electricity that takes place in those hours; in the case of the heat production, the cQ_d is higher at hours 10 and 20 because the share of conventional heat Q_a in the total heat produced increases; the cR_d increases from hour 17 to 21 as increases the share of cooling produced with purchased electricity R_{pe}. The cost formation process thus becomes evident, reflecting how the fluctuations in prices and quantities of resources consumed influence the unit costs of the internal flows and final products.

Regarding the trigeneration subsystem, its operation cost (consumption of natural gas) and revenues (sale of cogenerated electricity to the grid) were allocated to the cogenerated products in an equitable manner. Fig. 8 presents the hourly unit costs of the cogenerated products, and their respective reference costs. It was verified that the unit costs of the cogenerated products were always lower than the associated reference costs; the discount *d* being, on average, about 44%.

It is worth noting that even though the trigeneration subsystem has four cogenerated products (W_{cd}, Q_{cd}, R_{cq}, and R_{ce}), it does not mean that all four are produced in the same hourly period. For example, at hours 8, 15 to 18, and 22 the four cogenerated products are produced, whereas at hours 2 to 6, 10, and 11 only two cogenerated products are produced. This affects the unit costs obtained, as the operation cost and benefits will be distributed between two, three, or four products. As can be seen from Fig. 8, when both R_{cq} and R_{ce} are produced, their unit costs are the same; this follows from the application of the discount *d* (Eq. (44)), which considered the same reference cost $(cR)_{ref}$ to both types of cooling produced.

The unit cost of the discharged energy cR_{out} in each hourly period was determined from the interconnection between hourly periods through the TS. By knowing the origin periods of the discharged energy and the unit costs of the charged energy in those periods, the cR_{out} could be assessed. Similar to Fig. 6, Fig. 9 shows the unit costs of the charged cR_{in} and discharged cR_{out} cooling, and of the associated pairs *cIN* and *cOUT*.

As can be seen from Fig. 9, the unit costs of the discharged energy cR_{out} were always lower than the reference cost of cooling $(cR)_{ref}$, about 37% on average. Also, the unit cost of the discharged energy *cOUT* was always greater than that of the corresponding *cIN*. This is due to the energy losses along the path, which increase with the storage time. Therefore, the longer the storage time, the higher the increase in *cOUT* relative to *cIN*, which can also be interpreted as the penalty over *cOUT* due to energy wasting. For example, the energy discharged at hour 14 has been stored for, on average, 13 hourly periods, which implies an average penalty of 14% over the unit cost of the corresponding charged energy; on the other hand, the energy discharged at hour 19 has been stored for, on average, 6 hourly periods, which implies an average penalty of 6%.

4.2 Exergy-based unit costs

Exergy is recognizably the most applied magnitude in thermoeconomic studies found in the academic literature. However, the discussion about what is the most appropriate base in which unit costs should be expressed (e.g. energy or exergy) is secondary to this study because whenever an unambiguous relation between two extensive magnitudes X and Y can be established, the unit costs base change from one to another is obvious: $c_y = c_x \cdot X/Y$. When exergy flows are considered, the Carnot factor related to the temperature level of the heating and cooling loads must be defined. Therefore, the cost allocation methodology proposed herein can be solved regardless of energy- or exergy-based approach and the same equivalent results would be obtained. This is demonstrated in this subsection.

First, the energy flows of the productive structure must be converted to exergy. In the case of the electricity, its exergy content is equal to its energy content.

The exergy content Ex of heating can be obtained by multiplying its energy content En by the Carnot factor:

$$\frac{Ex}{En} \equiv 1 - \frac{T_0}{T_H} = 1 - \frac{297}{360} = 0.1750 \tag{49}$$

where, T_0 is the reference ambient temperature (297 K) and T_H is the average temperature for the heat (360 K).

The exergy content Ex of cooling can be obtained by dividing its energy content En by the Carnot cycle COP:

$$\frac{Ex}{En} \equiv \frac{T_0}{T_C} - 1 = \frac{297}{280} - 1 = 0.0607 \tag{50}$$

where, T_C is the average temperature for the cooling (280 K).

The exergy content of the natural gas can be obtained by multiplying its energy content F_c by 1.0352, which corresponds to the ratio of its specific exergy 39,330 kJ/kg to its LHV (lower heating value) 37,991 kJ/kg. In the case of the fuel-oil its exergy content can be obtained by multiplying its energy content F_a by 1.0616 (specific exergy 46,149 kJ/kg and LHV 43,472 kJ/kg).

Secondly, the exergy-based prices of the energy resources consumed can be obtained by dividing the energy-based prices from Table 2 (electricity purchase p_{ep}, electricity sale p_{es}, natural gas p_{fc} and fuel-oil p_{fa}) by the corresponding factor from the previous paragraph; in the case of the electricity, the exergy-based price is equal to the energy-based one.

The reference costs considered in this work (Section 2.4), related to the separate production of energy services, can also be assessed in terms of exergy by dividing the energy-based reference cost by the corresponding factor from Eq. 49 and 50:

- Energy-based unit cost of the electricity 0.100 €/kWh → Exergy-based unit cost of the electricity 0.100 €/kWh
- Energy-based unit cost of the heat 0.025 €/kWh → Exergy-based unit cost of the heat 0.1429 €/kWh
- Energy-based unit cost of the cooling 0.020 €/kWh → Exergy-based unit cost of the cooling 0.3294 €/kWh

Finally, the thermoeconomic model has been solved using the software EES [54], obtaining the hourly exergy unit costs of the internal flows and final products of the trigeneration system. The aggregated daily values of the energy and exergy flows and unit costs of the final products of the trigeneration system are presented in Table 6. Analogously, Table 7 compares the energy and exergy flows and unit costs of the trigeneration subsystem products.

As can be seen, the final products, as well as the trigeneration subsystem products, present lower exergy-based unit costs than the corresponding exergy-based reference costs. The discount d of the cogenerated products being, on average, about 44%. Thus, it becomes clear that considering the base change from energy- to exergy-based unit costs, the results obtained are the same. This highlights the core issue approached in this work, which is not to discuss the base in which unit costs should be expressed (e.g. energy or exergy), but rather to propose fair criteria for the distribution of joint production costs among the final consumers.

5 Conclusions

The present paper has addressed the issue of allocating economic costs in simple trigeneration systems including TES for buildings of the residential-commercial sector. Appropriately defining the allocation method is important because the way in which allocation is made directly affects the unit costs of the final products obtained and, thus, they can inform and influence the consumers' behavior.

The purpose of this paper was to address two issues in thermoeconomics that have not been deeply studied so far: (i) the joint production of energy services in dynamic energy systems; and (ii) the incorporation of TES. This study is a follow-up to a previous paper [50], in which the optimal operation and the corresponding marginal costs of a simple trigeneration system including TES were obtained and analyzed. Taking the operational state of the system from Ref. [50] as a starting point, the thermoeconomic analysis of the simple trigeneration system was performed, obtaining the hourly unit costs of all internal flows and final products for a day of the year.

The allocation proposal considered that the final products must share the benefits and inefficiencies of the combined production of energy services; this means that the income from selling electricity to the grid as well as the penalties of energy wasting (dissipated cogenerated heat and energy losses in the TS) must be attributed to the internal flows and final products. As originally proposed by Lozano et al. [27,28,34], allocation in joint production was made by applying a discount to the cogenerated products relative to a reference cost (in this case, the separate production cost). By decoupling energy service production from consumption, the TES allows the system to take advantage of the different operation conditions (e.g. available resources, energy prices, operation levels) of other hourly periods to achieve more interesting results in accordance with the objective of the analysis. Therefore, the presence of the TES unit adds a new dimension to the cost allocation problem, as it becomes necessary to know not only the device in which production takes place but also the hourly period. The cost allocation proposal explored the interconnection between hourly periods through the TES by considering a charging and discharging network. In this way, it was possible to trace the discharged energy flow back to its production period and, thus, connect the resources consumed to internal flows and final products. By knowing the unit cost of the charged energy, it was possible to determine exactly the unit cost of the discharged energy.

The unit costs of the final products obtained were cheaper than the corresponding reference costs. In this way, the cost allocation proposal allowed the benefits of the trigeneration system to be distributed in a fair and equitable manner between the products of the system, promoting economic competitiveness and acceptability of consumers.

It must be emphasized that this work was intended as a methodological-oriented paper aimed at presenting and discussing cost allocation proposals in trigeneration systems that promote a fair cost-and-benefit apportionment of the joint production costs to the products obtained. Also, only operation costs have been considered. As stated in the title of the paper, the trigeneration system and the example developed herein are simple. Increasing the complexity of the model would not provide more relevant conclusions and would hide, to some extent, the clarity of the analysis.

The application of the cost allocation methodology to a concrete scenario must take into consideration the following factors: (i) the size of the equipment/plant: economies of scale, technical parameters, energy prices varying as a function of the amount of energy resources consumed; (ii) the place in which the system is installed: economic policies and subsidies for the installation of cogeneration units, permission or not to sell the electricity produced to the electric grid, and (iii) the duration of the analysis: time span (years, seasons, months, days) and temporal resolution (daily, hourly, minute basis). These aspects have been addressed in a previous paper [55], in which the thermoeconomic analysis of a trigeneration system including TES and renewable energy sources is developed; the analysis is carried out for the period of one year divided into 12 representative days, obtaining the energy, capital and total unit costs of the internal flows and final products of the system on an hourly, monthly and annual basis. Furthermore, the paper discusses the issue of the appropriate way to allocate the capital costs of the devices, with particular focus on the TES unit.

Finally, the allocation proposal developed herein focused on the distribution of economic costs, however the same methodology could also be used for the allocation of other resources, such as CO_2 emissions.

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7 References

[1] L. M. Serra, M. A. Lozano, J. Ramos, A. V. Ensinas, S. A. Nebra. Polygeneration and efficient use of natural resources. Energy, vol. 34, pp. 575-586, 2009.

[2] P. Mancarella. MES (multi-energy systems): An overview of concepts and evaluation models. Energy, vol. 65, pp. 1-17, 2014.

[3] A. Rong, R. Lahdelma. Role of polygeneration in sustainable energy system development challenges and opportunities from optimization viewpoints. Renew. Sustain. Energy Rev., vol. 53, pp. 363-372, 2016.

[4] V. Andiappan. State-of-the-art review of mathematical optimisation approaches for synthesis of energy systems. Process Integration Optimization Sustainability. Published Online 13 August 2017. (doi:10.1007/s41660-017-0013-2).

[5] N. Petchers. Combined heating, cooling & power handbook: technologies & applications. Marcel Dekker, 2003.

[6] D. W. Wu, R. Z. Wang. Combined cooling, heating and power: A review. Prog. Energy Combust. Sci., vol. 32, pp. 459-495, 2006.

[7] M. Liu, Y. Shi, F. Fang. Combined cooling, heating and power systems: A survey. Renew. Sustain. Energy Rev., vol. 35, pp. 1-22, 2014.

[8] J. Deng, R. Z. Wang, G. Y. Han. A review of thermally activated cooling technologies for combined cooling, heating and power systems. Prog. Energy Combust. Sci., vol. 37, pp. 172-203, 2011.

[9] EU. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast). Off. J. Eur. Union, pp. 13-35, 2010.

[10] M. A. Lozano, J. C. Ramos, M. Carvalho, L. M. Serra. Structure optimization of energy supply systems in tertiary sector buildings. Energy and Buildings, vol. 41, pp. 1063-1075, 2009.

[11] R. Yokoyama, Y. Shinano, S. Taniguchi, M. Ohkura, T. Wakui. Optimization of energy supply systems by MILP branch and bound method in consideration of hierarchical relationship between design and operation. Energy Convers. Manag., vol. 92, pp. 92-104, 2015.

[12] G. Chicco, P. Mancarella. Distributed multi-generation: A comprehensive view. Renew. Sustain. Energy Rev., vol. 13, pp. 535-551, 2009.

[13] A. N. Ünal, S. Ercan, G. Kayakutlu. Optimisation studies on tri-generation: A review. Int. J. Energy Res., vol. 39, pp. 1311-1334, 2015.

[14] A. Rong, Y. Su. Polygeneration systems in buildings: A survey on optimization approaches. Energy and Buildings, vol. 151, pp. 439-454, 2017.

[15] A. Arteconi, N. J. Hewitt, F. Polonara. State of the art of thermal storage for demand-side management. Applied Energy, vol. 93, pp. 371-389, 2012.

[16] G. Li, X. Zheng. Thermal energy storage system integration forms for a sustainable future. Renew. Sustain. Energy Rev., vol. 62, pp. 736-757, 2016.

[17] D. Haeseldonckx, L. Peeters, L. Helsen, W. D'haeseleer. The impact of thermal storage on the operational behaviour of residential CHP facilities and the overall CO_2 emissions. Renew. Sustain. Energy Rev., vol. 11, pp. 1227-1243, 2007.

[18] M. A. Lozano, J. C. Ramos, L. M. Serra. Cost optimization of the design of CHCP systems under legal constraints. Energy, vol. 35, pp. 794- 805, 2010.

[19] D. Buoro, M. Casisi, A. de Nardi, P. Pinamonti, M. Reini. Multicriteria optimization of a distributed energy supply system for an industrial area. Energy, vol. 58, pp. 128-137, 2013.

[20] M. Rivarolo, A. Greco, A. F. Massardo. Thermo-economic optimization of the impact of renewable generators on poly-generation smart-grids including hot thermal storage. Energy Convers. Manag., vol. 65, pp. 75-83, 2013.

[21] T. Capuder, P. Mancarella. Techno-economic and environmental modelling and optimization of flexible distributed multi-generation options. Energy, vol. 71, pp. 516-533, 2014.

[22] W. Liu, G. Chen, B. Yan, Z. Zhou, H. Du, J. Zuo. Hourly operation strategy of a CCHP system with GSHP and thermal energy storage (TES) under variable loads: A case study. Energy and Buildings, vol. 93, pp. 143-153, 2015.

[23] T. Wakui, H. Kawayoshi, R. Yokoyama. Optimal structural design of residential power and heat supply devices in consideration of operational and capital recovery constraints. Applied Energy, vol. 163, pp. 118-133, 2016.

[24] D. Olsthoorn, F. Haghighat, P. A. Mirzaei. Integration of storage and renewable energy into district heating systems: A review of modelling and optimization. Solar Energy, vol. 136, pp. 49-64, 2016.

[25] R. A. Gaggioli. Second law analysis for process and energy engineering. In Efficiency and Costing, ACS Symposium Series, vol. 235, pp. 3-50, 1983.

[26] M. A. Lozano, A. Valero. Theory of the exergetic cost. Energy, vol. 18, pp. 939-960, 1993.

[27] M. A. Lozano, M. Carvalho, L. M. Serra. Tackling environmental impacts in simple trigeneration systems operating under variable conditions. Int. J. Life Cycle Assess., vol. 19, pp. 1087-1098, 2014.

[28] M. A. Lozano, M. Carvalho, L. M. Serra. Allocation of economic costs in trigeneration systems at variable load conditions. Energy and Buildings, vol. 43, pp. 2869-2881, 2011.

[29] C. Gochenour. Regulation of heat and electricity produced in combined heat and power plants. World Bank working paper 27201, Oct. 2003.

[30] A. L. Thomas. The allocation problem in financial accounting theory. American Accounting Association, 1969.

[31] R. S. Kaplan, A. A. Atkinson. Advanced management accounting. Prentice-Hall, 2nd ed., 1989.

[32] C. T. Horngren, G. Foster, S. M. Datar, M. V. Rajan, C. M. Ittner. Cost accounting: A managerial emphasis. Pearson, 13th ed., 2009

[33] S. A. da Gama, S. A. Nebra. Cost attribution methodologies in cogeneration systems. Energy Convers. Manag., vol. 40, pp. 1587-1597, 1999.

[34] M. A. Lozano, M. Carvalho, J. C. Ramos, L. M. Serra. Thermoeconomic analysis of simple trigeneration systems. Int. J. of Thermodynamics, vol. 12, pp. 147-153, 2009.

[35] E. S. Amundsen, P. Andersen, F. Jensen. Testing for cross-subsidisation in the combined heat and power generation sector: A comparison of three tests. Energy Economics, vol. 33, pp. 750-757, 2011.

[36] A. C. Overland, B. A. Sandoff. Joint cost allocation and cogeneration. Proc. from 14th Int. Symp. Dist. Heat. Cool., pp. 267-281, 2014.

[37] H. Li, Q. Sun, Q. Zhang, F. Wallin. A review of the pricing mechanisms for district heating systems. Renew. Sustain. Energy Rev., vol. 42, pp. 56-65, 2015.

[38] T. Tereshchenko, N. Nord. Uncertainty of the allocation factors of heat and electricity production of combined cycle power plant. Appl. Therm. Eng., vol. 76, pp. 410-422, 2015.

[39] H. Holmberg, M. Tuomaala, T. Haikonen, P. Ahtila. Allocation of fuel costs and CO_2-emissions to heat and power in an industrial CHP plant: Case integrated pulp and paper mill. Applied Energy, vol. 93, pp. 614–623, 2012.

[40] R. Frischknecht. Allocation in life cycle inventory analysis for joint production. Int. J. Life Cycle Assess., vol. 5, pp. 85-95, 2000.

[41] F. Ardente, M. Cellura. Economic allocation in life cycle assessment: the state of the art and discussion of examples. J. Ind. Ecol., vol. 16, pp. 387-398, 2012.

[42] A. González, J. M. Sala, I. Flores, L. M. López. Application of thermoeconomics to the allocation of environmental loads in the life cycle assessment of cogeneration plants. Energy, vol. 28, pp. 557-574, 2003.

[43] J. A. da Silva, J. J. Santos, M. Carvalho, S. de Oliveira. On the thermoeconomic and LCA methods for waste and fuel allocation in multiproduct systems. Energy, vol. 127, pp. 775-785, 2017.

[44] A. Azapagic, R. Clift. Allocation of environmental burdens in multiple-function systems. J. Clean. Prod., vol. 7, pp. 101-119, 1999.

[45] A. T. Ubando, A. B. Culaba, K. B. Aviso, R. R. Tan. Simultaneous carbon footprint allocation and design of trigeneration plants using fuzzy fractional programming. Clean Techn Environ Policy, vol. 15, pp. 823-832, 2013.

[46] G. P. Beretta, P. Iora, A. F. Ghoniem. Allocating resources and products in multi-hybrid multi-cogeneration: What fractions of heat and power are renewable in hybrid fossil-solar CHP?. Energy, vol. 78, pp. 587-603, 2014.

[47] A. Piacentino, F. Cardona. On thermoeconomics of energy systems at variable load conditions: Integrated optimization of plant design and operation. Energy Convers. Manag., vol. 48, pp. 2341-2355, 2007.

[48] M. A. Lozano, A. Anastasia, L. M. Serra, V. Verda. Thermoeconomic cost analysis of central solar heating plants combined with seasonal storage. ASME Paper No. IMECE2010-40549, pp. 643-653, 2010.

[49] M. A. Lozano, C. Mancini, L. M. Serra, V. Verda. Exergy and thermoeconomic analysis of a solar air heating plant. ASME Paper No. ESDA2014-20152, 12 pages, 2014.

[50] E. A. Pina, M. A. Lozano, L. M. Serra. Optimal operation and marginal costs in simple trigeneration systems including thermal energy storage. Energy, vol. 135, pp. 788-798, 2017.

[51] L. Schrage. Optimization modeling with LINGO. Lindo Systems, 1999.

[52] M. A. Lozano, M. Carvalho, L. M. Serra. Operational strategy and marginal costs in simple trigeneration systems. Energy, vol. 34, pp. 2001-2008, 2009.

[53] C.W. Hui. Determining marginal values of intermediate materials and utilities using a site model. Computers and Chemical Engineering, vol. 24, pp. 1023-1029, 2000.

[54] EES. Engineering Equation Solver. F-Chart Software, 2017.

[55] E. A. Pina, M. A. Lozano, L. M. Serra. Thermoeconomic Cost Allocation in Trigeneration Systems Including Renewable Energy Sources and Thermal Energy Storage. ECOS 2017 – International Conference on Efficiency, Cost, Optimisation, Simulation and Environmental Impact of Energy Systems, July 2-6, San Diego, USA.

Nomenclature	
AB	auxiliary boiler
AC	single-effect absorption chiller
ACa	virtual absorption chiller that consumes heat from the auxiliary boiler
ACc	virtual absorption chiller that consumes heat from the cogeneration module
c	unit cost of the flow (letter c is added to the name of energy flow) (€/kWh)
CM	cogeneration module
COP_e	COP of mechanical chiller
COP_q	COP of single-effect absorption chiller
DC	daily operation cost (€/day)
EC	mechanical chiller
EC_c	virtual mechanical chiller that consumes electricity from the cogeneration module
EC_p	virtual mechanical chiller that consumes electricity from the grid
E_d	electricity demand (kWh)
E_{grid}	net electricity exchanged with the electric grid, purchase is positive, selling is negative (kWh)
E_p	electricity purchased from the grid (kWh)
E_{pd}	purchased electricity that attends the electricity demand (kWh)
E_{pr}	purchased electricity that drives the mechanical chiller (kWh)
E_r	electricity consumed by the mechanical chiller (kWh)
E_s	electricity sold to the grid (kWh)
F_a	fuel-oil consumed by the auxiliary boiler (kWh)
F_c	natural gas consumed by the cogeneration module (kWh)
HC	hourly operation cost (€/h)
IN	energy flow that leaves the source node (kWh)
NHP	number of hours per period
NP	number of periods in the day
OUT	energy flow that enters the sink node (kWh)
p_{ep}	purchase price of electricity (€/kWh)
p_{es}	selling price of electricity (€/kWh)
p_{fa}	purchase price of fuel-oil (€/kWh)
p_{fc}	purchase price of natural gas (€/kWh)
Q_a	conventional heat produced by the auxiliary boiler (kWh)
Q_{ad}	conventional heat that covers the heat demand (kWh)
Q_{ar}	conventional heat that drives the absorption chiller (kWh)
Q_c	cogenerated heat produced by the cogeneration module (kWh)
Q_{cc}	cogenerated heat that is not dissipated (kWh)
Q_{cd}	cogenerated heat produced by the trigeneration subsystem (kWh)
Q_{cl}	dissipated cogenerated heat (kWh)
Q_{cr}	cogenerated heat that drives the absorption chiller (kWh)
Q_d	heating demand (kWh)
Q_{max}	maximum capacity of auxiliary boiler (kWh)
Q_r	heat consumed by the single-effect absorption chiller (kWh)
R_{aq}	cooling produced by the absorption chiller with conventional heat (kWh)

R_{ce}	cogenerated cooling produced by the mechanical chiller in the trigeneration subsystem (€/kWh)
R_{cq}	cogenerated cooling produced by the single-effect absorption chiller in the trigeneration subsystem (kWh)
R_d	cooling demand (kWh)
R_e	cooling produced by the mechanical chiller (kWh)
$R_{e,max}$	maximum capacity of mechanical chiller (kWh)
R_{in}	charged energy (kWh)
R_{out}	discharged energy (kWh)
R_{pe}	cooling produced by the mechanical chiller with purchased electricity (kWh)
R_{pi}	cooling produced and consumed in the hourly period (kWh)
R_{pro}	total cooling produced in the hourly period (kWh)
R_q	cooling produced by the single-effect absorption chiller (kWh)
$R_{q,max}$	maximum capacity of single-effect absorption chiller (kWh)
rq_{cl}	unit cost of dissipated cogenerated heat (€/kWh)
R_s	energy losses (kWh)
r_s	energy losses in each hourly period along a path (kWh)
R_{TS}	cooling exchanged with the thermal energy storage unit, charge is positive, discharge is negative (kWh)
S_{rf}	stored energy at the end of hourly period (kWh)
S_{ri}	stored energy at the beginning of hourly period (kWh)
TS	thermal energy storage unit
V_{max}	maximum capacity of thermal energy storage unit (kWh)
W_c	cogenerated electricity produced by the cogeneration module (kWh)
W_{cc}	cogenerated electricity that is not sold (kWh)
W_{cd}	cogenerated electricity produced by the trigeneration subsystem (kWh)
W_{cr}	cogenerated electricity that drives the mechanical chiller (kWh)
W_{max}	maximum electricity capacity of cogeneration module (kWh)
$(cQ)_{ref}$	reference cost considered for heat (€/kWh)
$(cR)_{ref}$	reference cost considered for cooling (€/kWh)
$(cW)_{ref}$	reference cost considered for electricity (€/kWh)
Greek letters	
α_q	thermal efficiency of cogeneration module
α_w	electrical efficiency of cogeneration module
δ_1	share of heat that covers the heat demand in proportion to the total heat demanded
δ_2	share of electricity that attends the electricity demand in proportion to the total electricity demanded
η_q	thermal efficiency of auxiliary boiler
τ_{TS}	energy loss factor of the thermal energy storage unit (h-1)
Acronyms	
CCHP	combined cooling, heating and power
CHP	combined heat and power
COP	coefficient of performance
EES	Engineering Equation Solver
EU	European Union
FIFO	first in first out
LCA	life cycle assessment

LHV	lower heating value
LP	linear programming
TAT	thermally activated technology
TES	thermal energy storage

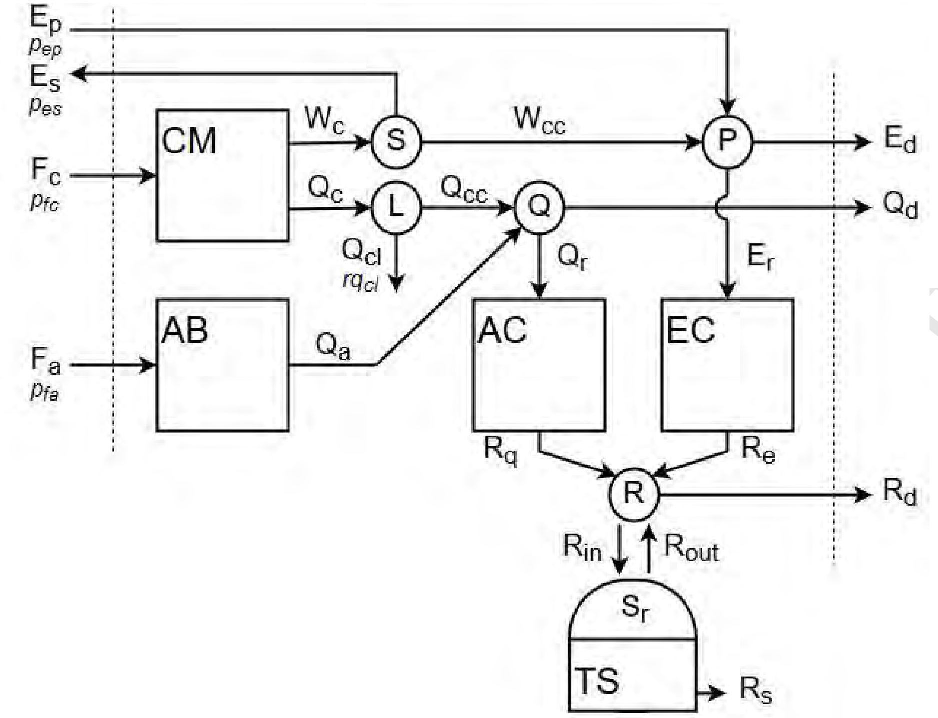


Fig. 1: Simple trigeneration system including TES

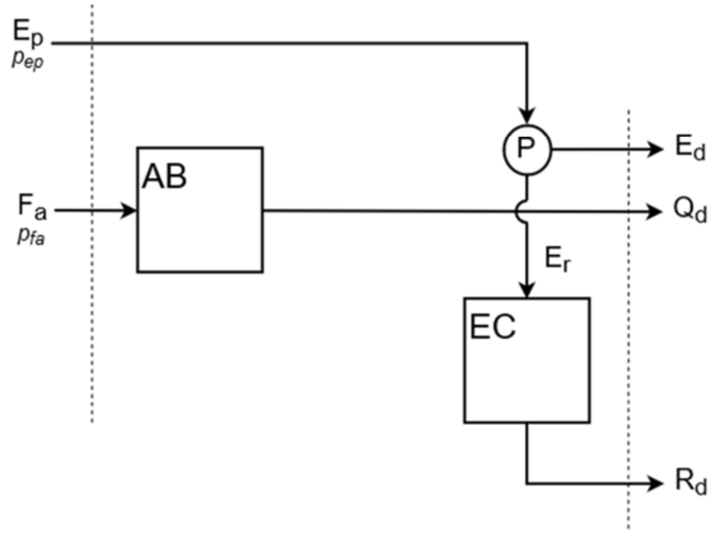


Fig. 2: Reference system

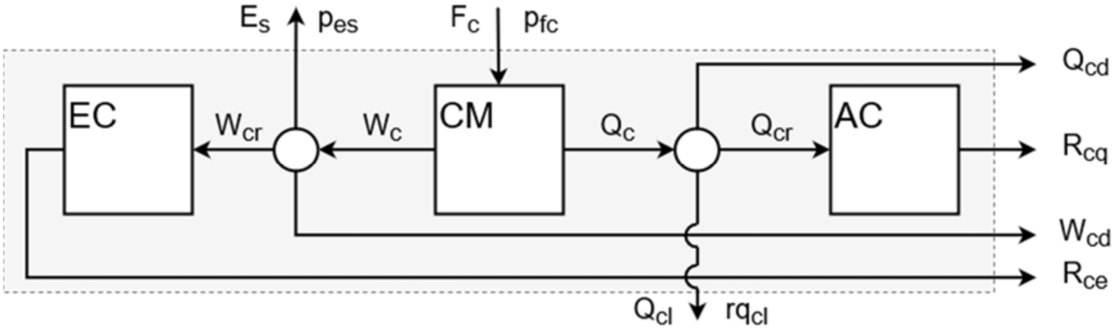


Fig. 3: Trigeneration subsystem

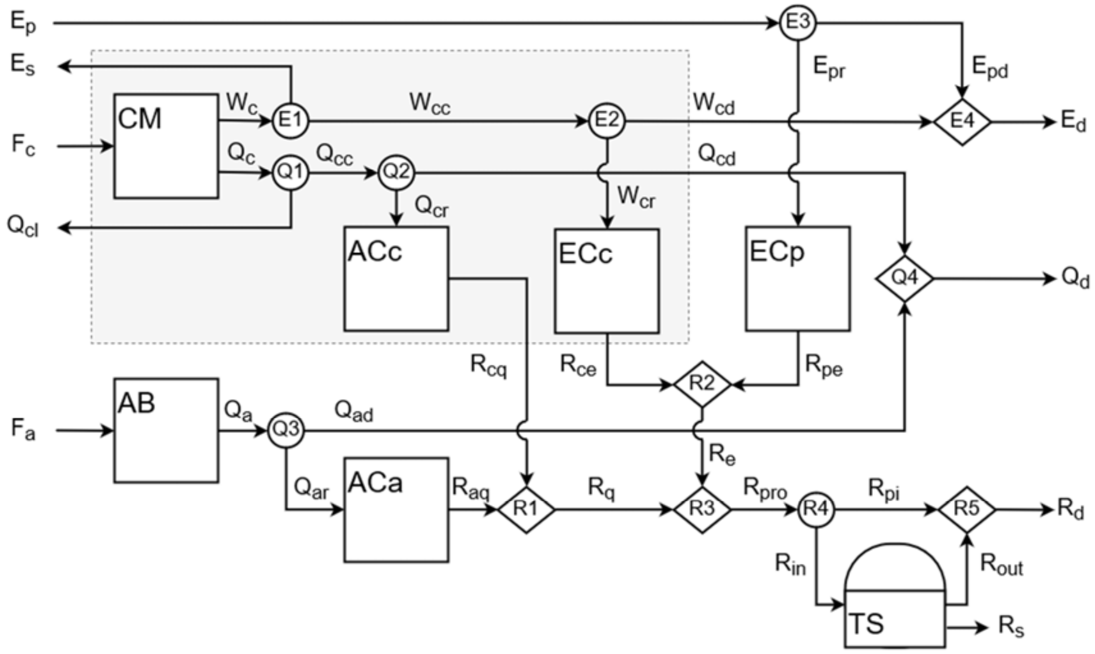


Fig. 4: Productive structure of the simple trigeneration system

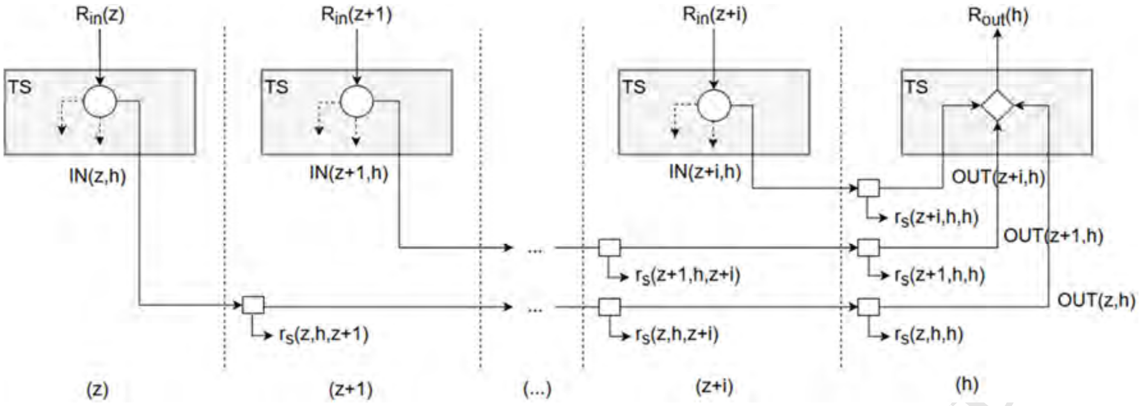
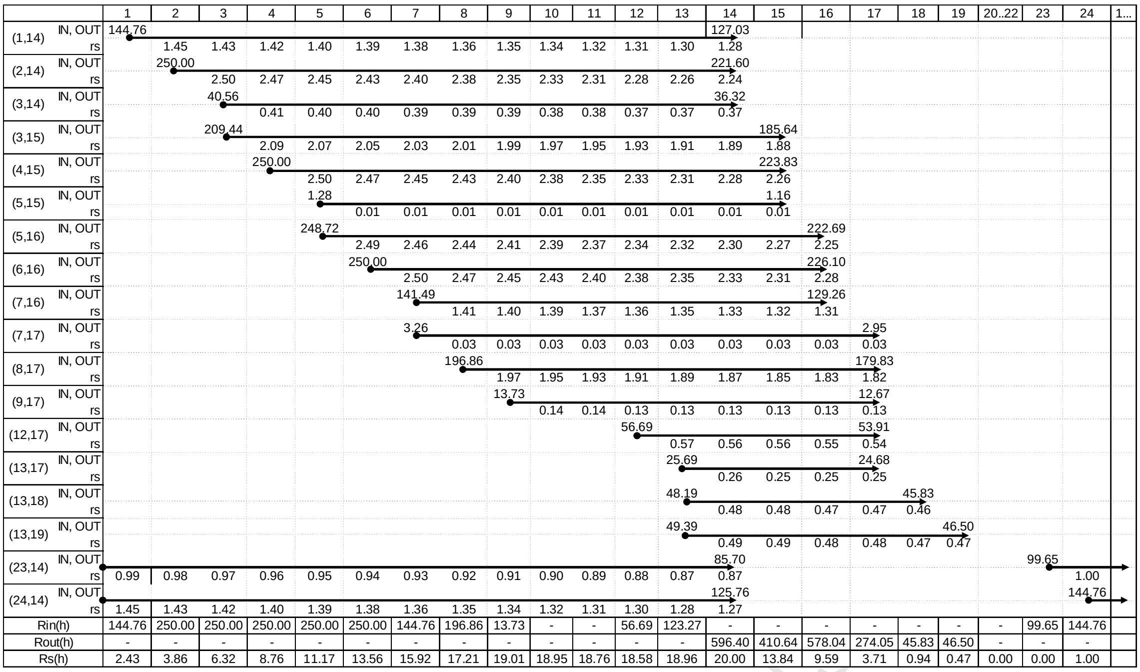


Fig. 5: Charging and discharging network



		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20..22	23	24	1...
(1,14)	IN, OUT	144.76													127.03									
	rs		1.45	1.43	1.42	1.40	1.39	1.38	1.36	1.35	1.34	1.32	1.31	1.30	1.28									
(2,14)	IN, OUT		250.00												221.60									
	rs			2.50	2.47	2.45	2.43	2.40	2.38	2.35	2.33	2.31	2.28	2.26	2.24									
(3,14)	IN, OUT			40.56											36.32									
	rs				0.41	0.40	0.40	0.39	0.39	0.39	0.38	0.38	0.37	0.37	0.37									
(3,15)	IN, OUT			209.44												185.64								
	rs				2.09	2.07	2.05	2.03	2.01	1.99	1.97	1.95	1.93	1.91	1.89	1.88								
(4,15)	IN, OUT				250.00											223.83								
	rs					2.50	2.47	2.45	2.43	2.40	2.38	2.35	2.33	2.31	2.28	2.26								
(5,15)	IN, OUT					1.28										1.16								
	rs						0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01								
(5,16)	IN, OUT					248.72											222.69							
	rs						2.49	2.46	2.44	2.41	2.39	2.37	2.34	2.32	2.30	2.27	2.25							
(6,16)	IN, OUT						250.00										226.10							
	rs							2.50	2.47	2.45	2.43	2.40	2.38	2.35	2.33	2.31	2.28							
(7,16)	IN, OUT							141.49									129.26							
	rs								1.41	1.40	1.39	1.37	1.36	1.35	1.33	1.32	1.31							
(7,17)	IN, OUT							3.26										2.95						
	rs								0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03						
(8,17)	IN, OUT								196.86									179.83						
	rs									1.97	1.95	1.93	1.91	1.89	1.87	1.85	1.83	1.82						
(9,17)	IN, OUT									13.73								12.67						
	rs										0.14	0.14	0.13	0.13	0.13	0.13	0.13	0.13						
(12,17)	IN, OUT												56.69					53.91						
	rs													0.57	0.56	0.56	0.55	0.54						
(13,17)	IN, OUT													25.69				24.68						
	rs														0.26	0.25	0.25	0.25						
(13,18)	IN, OUT													48.19					45.83					
	rs														0.48	0.48	0.47	0.47	0.46					
(13,19)	IN, OUT													49.39						46.50				
	rs														0.49	0.49	0.48	0.48	0.47	0.47				
(23,14)	IN, OUT														85.70							99.65		
	rs	0.99	0.98	0.97	0.96	0.95	0.94	0.93	0.92	0.91	0.90	0.89	0.88	0.87	0.87								1.00	
(24,14)	IN, OUT														125.76								144.76	
	rs	1.45	1.43	1.42	1.40	1.39	1.38	1.36	1.35	1.34	1.32	1.31	1.30	1.28	1.27									
Rin(h)		144.76	250.00	250.00	250.00	250.00	250.00	144.76	196.86	13.73	-	-	56.69	123.27	-	-	-	-	-	-	-	99.65	144.76	
Rout(h)		-	-	-	-	-	-	-	-	-	-	-	-	-	596.40	410.64	578.04	274.05	45.83	46.50	-	-	-	
Rs(h)		2.43	3.86	6.32	8.76	11.17	13.56	15.92	17.21	19.01	18.95	18.76	18.58	18.96	20.00	13.84	9.59	3.71	0.94	0.47	0.00	0.00	1.00	

Fig. 6: Interconnection between charging and discharging periods through the TS – energy flows

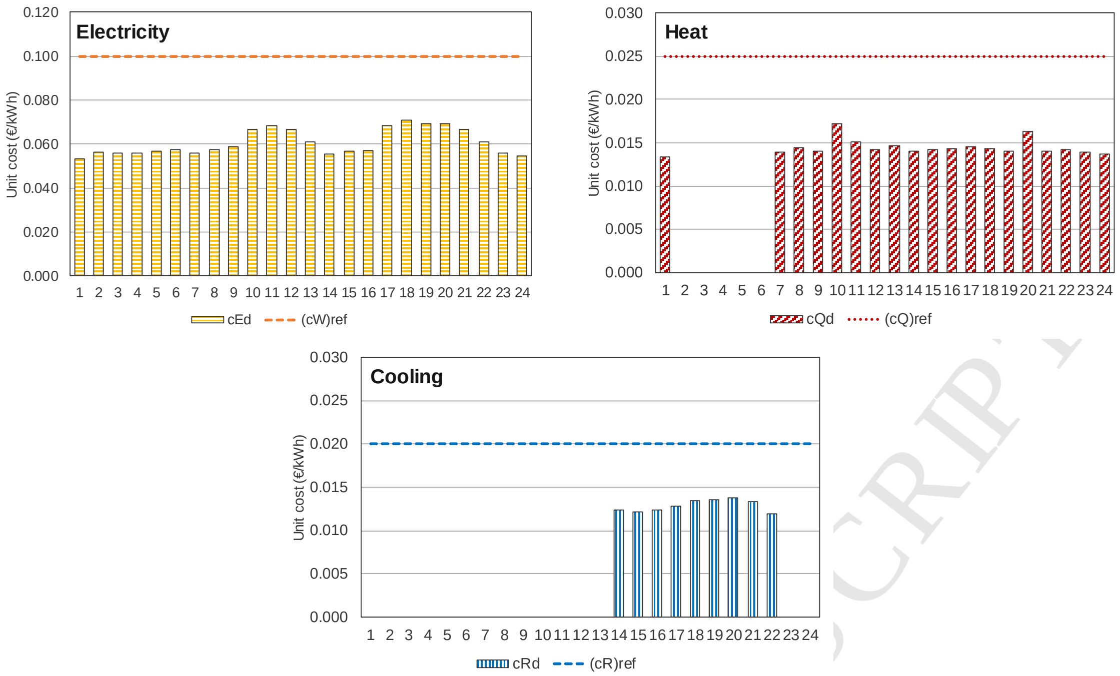


Fig. 7: Hourly unit costs of the final products of the simple trigeneration system and reference costs

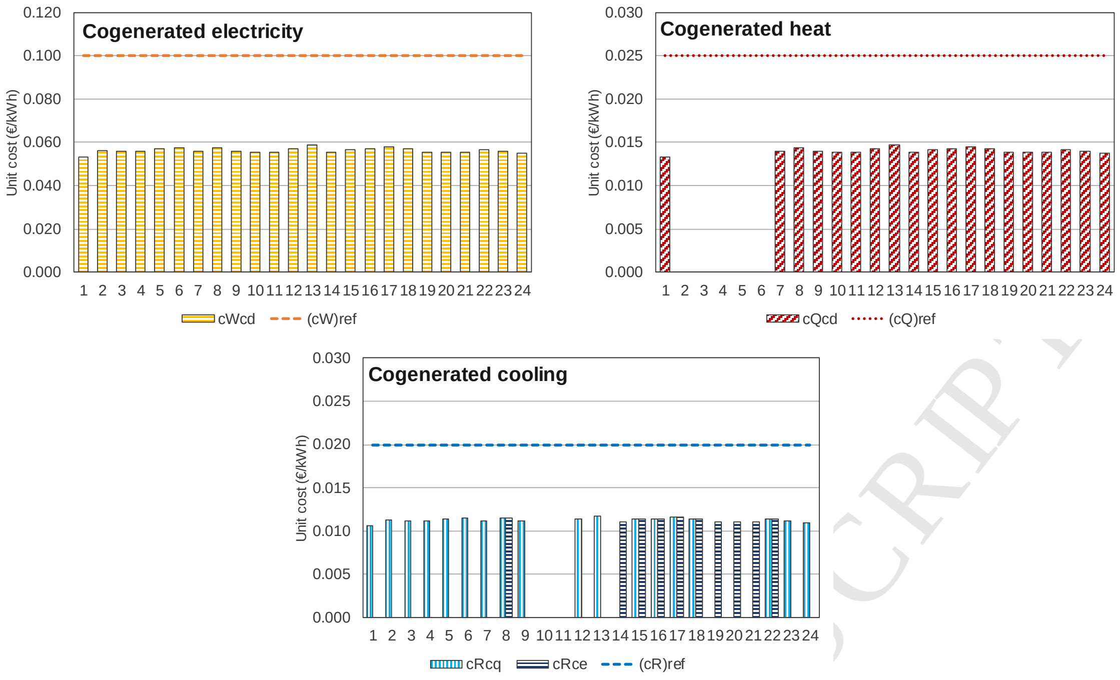


Fig. 8: Hourly unit costs of the cogenerated products and reference costs

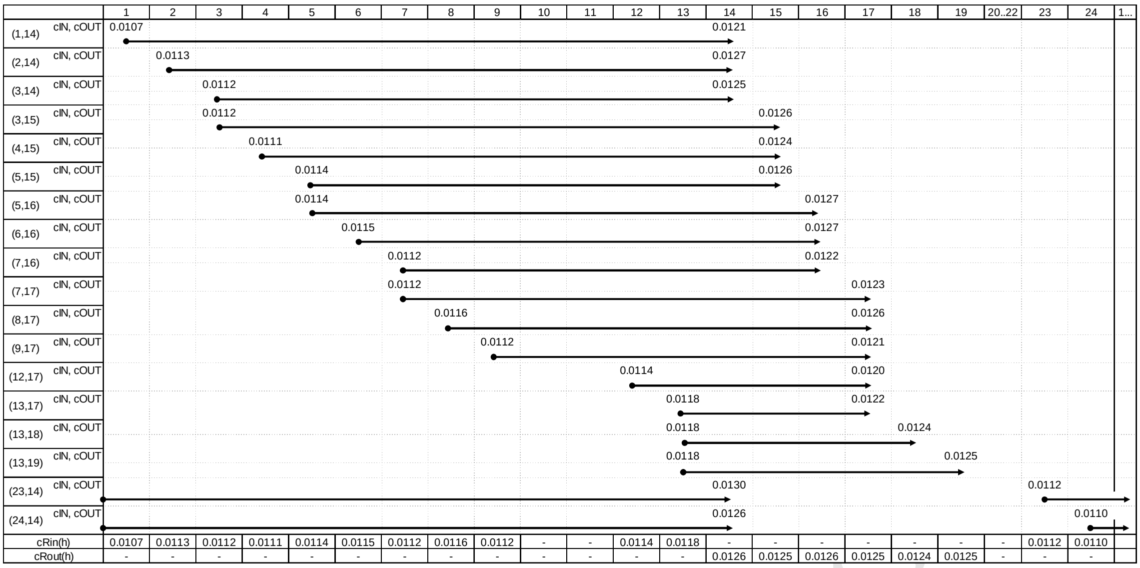


Fig. 9: Interconnection between charging and discharging periods through the TS – unit costs (€/kWh)

Table 1: Technical parameters and capacity limits of the trigeneration system's devices

Device	Technical parameters	Capacity limits
Cogeneration Module (CM)	$\alpha_w = W_c/F_c = 0.35$ $\alpha_q = Q_c/F_c = 0.40$	$W_{max} = 350$ kW
Auxiliary Boiler (AB)	$\eta_q = Q_a/F_a = 0.80$	$Q_{max} = 400$ kW
Absorption Chiller (AC)	$COP_q = 0.625$	$R_{q,max} = 250$ kW
Electric Chiller (EC)	$COP_e = 5$	$R_{e,max} = 250$ kW
Thermal Energy Storage (TS)	$\tau_{TS} = 0.01$ h^{-1}	$V_{max} = 2000$ kWh

Table 2: Energy prices, in €/kWh

Purchased electricity	Sold electricity	Natural gas	Fuel-oil
$p_{ep} = 0.100$	$p_{es} = 0.080$	$p_{fc} = 0.025$	$p_{fa} = 0.020$

Table 3: Optimal operation of the system. Energy flows in kWh and *HC* in €

Hour	E_d	Q_d	R_d	E_{grid}	F_c	W_c	W_{cc}	Q_c	Q_{cc}	Q_{cl}	F_a	Q_a	Q_r	R_q	E_r	R_e	R_{TS}	R_s	S_{rf}	HC
1	253.6	168.4	0.0	-96.4	1000	350	253.6	400	400	0	0.0	0.0	231.6	144.8	0.0	0.0	144.8	2.4	385.7	17.3
2	247.0	0.0	0.0	-103.0	1000	350	247.0	400	400	0	0.0	0.0	400.0	250.0	0.0	0.0	250.0	3.9	631.9	16.8
3	241.7	0.0	0.0	-108.3	1000	350	241.7	400	400	0	0.0	0.0	400.0	250.0	0.0	0.0	250.0	6.3	875.6	16.3
4	237.7	0.0	0.0	-112.3	1000	350	237.7	400	400	0	0.0	0.0	400.0	250.0	0.0	0.0	250.0	8.8	1116.8	16.0
5	253.6	0.0	0.0	-96.4	1000	350	253.6	400	400	0	0.0	0.0	400.0	250.0	0.0	0.0	250.0	11.2	1355.6	17.3
6	262.9	0.0	0.0	-87.1	1000	350	262.9	400	400	0	0.0	0.0	400.0	250.0	0.0	0.0	250.0	13.6	1592.1	18.0
7	286.8	168.4	0.0	-63.2	1000	350	286.8	400	400	0	0.0	0.0	231.6	144.8	0.0	0.0	144.8	15.9	1720.9	19.9
8	324.0	244.0	0.0	-6.1	1000	350	343.9	400	400	0	0.0	0.0	156.0	97.5	19.9	99.4	196.9	17.2	1900.6	24.5
9	377.1	378.0	0.0	27.1	1000	350	350.0	400	400	0	0.0	0.0	22.0	13.7	0.0	0.0	13.7	19.0	1895.3	27.7
10	468.7	570.5	0.0	118.7	1000	350	350.0	400	400	0	213.1	170.5	0.0	0.0	0.0	0.0	0.0	19.0	1876.3	41.1
11	494.0	446.8	0.0	144.0	1000	350	350.0	400	400	0	58.5	46.8	0.0	0.0	0.0	0.0	0.0	18.8	1857.6	40.6
12	454.1	309.3	0.0	104.1	1000	350	350.0	400	400	0	0.0	0.0	90.7	56.7	0.0	0.0	56.7	18.6	1895.7	35.4
13	369.1	202.8	0.0	19.1	1000	350	350.0	400	400	0	0.0	0.0	197.2	123.3	0.0	0.0	123.3	19.0	2000.0	26.9
14	325.3	405.5	719.8	0.0	1000	350	350.0	400	400	0	6.9	5.5	0.0	0.0	24.7	123.4	-596.4	20.0	1383.6	25.1
15	313.4	319.6	644.0	0.0	1000	350	350.0	400	400	0	0.0	0.0	80.4	50.2	36.6	183.2	-410.6	13.8	959.1	25.0
16	338.6	299.0	698.2	0.0	1000	350	350.0	400	400	0	0.0	0.0	101.0	63.1	11.4	57.0	-578.0	9.6	371.5	25.0
17	414.3	240.6	614.4	112.4	1000	350	350.0	400	400	0	0.0	0.0	159.4	99.7	48.1	240.7	-274.0	3.7	93.7	36.2
18	468.7	299.0	359.0	168.7	1000	350	350.0	400	400	0	0.0	0.0	101.0	63.1	50.0	250.0	-45.8	0.9	47.0	41.9
19	452.8	405.5	296.5	152.8	1000	350	350.0	400	400	0	6.9	5.5	0.0	0.0	50.0	250.0	-46.5	0.5	0.0	40.4
20	455.5	508.6	243.3	154.1	1000	350	350.0	400	400	0	135.8	108.6	0.0	0.0	48.7	243.3	0.0	0.0	0.0	43.1
21	418.3	405.5	247.9	117.8	1000	350	350.0	400	400	0	6.9	5.5	0.0	0.0	49.6	247.9	0.0	0.0	0.0	36.9
22	361.2	319.6	177.0	36.5	1000	350	350.0	400	400	0	0.0	0.0	80.4	50.2	25.3	126.7	0.0	0.0	0.0	28.7
23	308.1	240.6	0.0	-41.9	1000	350	308.1	400	400	0	0.0	0.0	159.4	99.7	0.0	0.0	99.7	0.0	99.7	21.6
24	273.5	168.4	0.0	-76.5	1000	350	273.5	400	400	0	0.0	0.0	231.6	144.8	0.0	0.0	144.8	1.0	243.4	18.9
Day	8400.0	6100.0	4000.0	364.3	24,000	8400	7608.8	9600	9600	0	428.0	342.4	3842.4	2401.5	364.3	1821.5	223.0	223.0	22,302.0	660.8

Table 4: Virtual flows of the productive structure and distribution parameters. Energy flows in kWh

Hour	W_{cd}	W_{cr}	E_{pd}	E_{pr}	Q_{cd}	Q_{cr}	Q_{ad}	Q_{ar}	R_{ce}	R_{pe}	R_{cq}	R_{aq}	R_{pro}	R_{pi}	δ_1	δ_2
1	253.6	0.0	0.0	0.0	168.4	231.6	0.0	0.0	0.0	0.0	144.8	0.0	144.8	0.0	0.42	1.00
2	247.0	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	250.0	0.0	250.0	0.0	0.00	1.00
3	241.7	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	250.0	0.0	250.0	0.0	0.00	1.00
4	237.7	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	250.0	0.0	250.0	0.0	0.00	1.00
5	253.6	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	250.0	0.0	250.0	0.0	0.00	1.00
6	262.9	0.0	0.0	0.0	0.0	400.0	0.0	0.0	0.0	0.0	250.0	0.0	250.0	0.0	0.00	1.00
7	286.8	0.0	0.0	0.0	168.4	231.6	0.0	0.0	0.0	0.0	144.8	0.0	144.8	0.0	0.42	1.00
8	324.0	19.9	0.0	0.0	244.0	156.0	0.0	0.0	99.4	0.0	97.5	0.0	196.9	0.0	0.61	0.94
9	350.0	0.0	27.1	0.0	378.0	22.0	0.0	0.0	0.0	0.0	13.7	0.0	13.7	0.0	0.95	1.00
10	350.0	0.0	118.7	0.0	400.0	0.0	170.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	1.00
11	350.0	0.0	144.0	0.0	400.0	0.0	46.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.00	1.00
12	350.0	0.0	104.1	0.0	309.3	90.7	0.0	0.0	0.0	0.0	56.7	0.0	56.7	0.0	0.77	1.00
13	350.0	0.0	19.1	0.0	202.8	197.2	0.0	0.0	0.0	0.0	123.3	0.0	123.3	0.0	0.51	1.00
14	325.3	24.7	0.0	0.0	400.0	0.0	5.5	0.0	123.4	0.0	0.0	0.0	123.4	123.4	1.00	0.93
15	313.4	36.6	0.0	0.0	319.6	80.4	0.0	0.0	183.2	0.0	50.2	0.0	233.4	233.4	0.80	0.90
16	338.6	11.4	0.0	0.0	299.0	101.0	0.0	0.0	57.0	0.0	63.1	0.0	120.1	120.1	0.75	0.97
17	313.6	36.4	100.7	11.7	240.6	159.4	0.0	0.0	182.2	58.5	99.7	0.0	340.4	340.4	0.60	0.90
18	316.3	33.7	152.5	16.3	299.0	101.0	0.0	0.0	168.7	81.3	63.1	0.0	313.1	313.1	0.75	0.90
19	315.2	34.8	137.6	15.2	400.0	0.0	5.5	0.0	174.0	76.0	0.0	0.0	250.0	250.0	1.00	0.90
20	316.2	33.8	139.2	14.9	400.0	0.0	108.6	0.0	168.9	74.4	0.0	0.0	243.3	243.3	1.00	0.90
21	312.9	37.1	105.4	12.5	400.0	0.0	5.5	0.0	185.4	62.4	0.0	0.0	247.9	247.9	1.00	0.89
22	327.0	23.0	34.1	2.4	319.6	80.4	0.0	0.0	114.8	12.0	50.2	0.0	177.0	177.0	0.80	0.93
23	308.1	0.0	0.0	0.0	240.6	159.4	0.0	0.0	0.0	0.0	99.7	0.0	99.7	0.0	0.60	1.00
24	273.5	0.0	0.0	0.0	168.4	231.6	0.0	0.0	0.0	0.0	144.8	0.0	144.8	0.0	0.42	1.00
Day	7317.4	291.4	1082.6	72.9	5757.6	3842.4	342.4	0.0	1456.9	364.6	2401.5	0.0	4223.0	2048.5	0.61	0.96

Table 5: Hourly unit costs of selected internal flows and final products of the trigeneration system, in €/kWh

h	Final products			Trigeneration subsystem products				Other internal flows								Stored energy
	cE_d	cQ_d	cR_d	cW_{cd}	cQ_{cd}	cR_{cg}	cR_{ce}	cQ_a	cE_{pr}	cR_{pe}	cR_e	cR_g	cR_{pro}	cR_{in}	cR_{out}	cS_{rf}
1	0.0533	0.0133	-	0.0533	0.0133	0.0107	-	-	-	-	-	0.0107	0.0107	0.0107	-	0.0110
2	0.0564	-	-	0.0564	-	0.0113	-	-	-	-	-	0.0113	0.0113	0.0113	-	0.0112
3	0.0560	-	-	0.0560	-	0.0112	-	-	-	-	-	0.0112	0.0112	0.0112	-	0.0113
4	0.0557	-	-	0.0557	-	0.0111	-	-	-	-	-	0.0111	0.0111	0.0111	-	0.0113
5	0.0569	-	-	0.0569	-	0.0114	-	-	-	-	-	0.0114	0.0114	0.0114	-	0.0114
6	0.0576	-	-	0.0576	-	0.0115	-	-	-	-	-	0.0115	0.0115	0.0115	-	0.0115
7	0.0557	0.0139	-	0.0557	0.0139	0.0112	-	-	-	-	-	0.0112	0.0112	0.0112	-	0.0116
8	0.0578	0.0144	-	0.0578	0.0144	0.0116	0.0116	-	-	-	0.0116	0.0116	0.0116	0.0116	-	0.0117
9	0.0591	0.0140	-	0.0559	0.0140	0.0112	-	-	-	-	-	0.0112	0.0112	0.0112	-	0.0118
10	0.0668	0.0172	-	0.0556	0.0139	-	-	0.0250	-	-	-	-	-	-	-	0.0120
11	0.0685	0.0151	-	0.0556	0.0139	-	-	0.0250	-	-	-	-	-	-	-	0.0121
12	0.0669	0.0143	-	0.0570	0.0143	0.0114	-	-	-	-	-	0.0114	0.0114	0.0114	-	0.0122
13	0.0609	0.0147	-	0.0588	0.0147	0.0118	-	-	-	-	-	0.0118	0.0118	0.0118	-	0.0123
14	0.0556	0.0140	0.0124	0.0556	0.0139	-	0.0111	0.0250	-	-	0.0111	-	0.0111	-	0.0126	0.0123
15	0.0568	0.0142	0.0121	0.0568	0.0142	0.0114	0.0114	-	-	-	0.0114	0.0114	0.0114	-	0.0125	0.0124
16	0.0572	0.0143	0.0124	0.0572	0.0143	0.0114	0.0114	-	-	-	0.0114	0.0114	0.0114	-	0.0126	0.0123
17	0.0683	0.0145	0.0128	0.0581	0.0145	0.0116	0.0116	-	0.1000	0.0200	0.0137	0.0116	0.0131	-	0.0125	0.0122
18	0.0711	0.0143	0.0135	0.0572	0.0143	0.0114	0.0114	-	0.1000	0.0200	0.0142	0.0114	0.0137	-	0.0124	0.0124
19	0.0691	0.0140	0.0136	0.0556	0.0139	-	0.0111	0.0250	0.1000	0.0200	0.0138	-	0.0138	-	0.0125	-
20	0.0691	0.0163	0.0138	0.0556	0.0139	-	0.0111	0.0250	0.1000	0.0200	0.0138	-	0.0138	-	-	-
21	0.0668	0.0140	0.0134	0.0556	0.0139	-	0.0111	0.0250	0.1000	0.0200	0.0134	-	0.0134	-	-	-
22	0.0609	0.0142	0.0120	0.0568	0.0142	0.0114	0.0114	-	0.1000	0.0200	0.0122	0.0114	0.0120	-	-	-
23	0.0558	0.0139	-	0.0558	0.0139	0.0112	-	-	-	-	-	0.0112	0.0112	0.0112	-	0.0112
24	0.0548	0.0137	-	0.0548	0.0137	0.0110	-	-	-	-	-	0.0110	0.0110	0.0110	-	0.0111
Day	0.0620	0.0147	0.0127	0.0563	0.0141	0.0113	0.0113	0.0250	0.1000	0.0200	0.0130	0.0113	0.0120	0.0113	0.0126	0.0118

Table 6: Daily energy and exergy flows and unit costs of the final products

Final products	Energy, kWh	Unit energy cost, €/kWh	Exergy, kWh	Unit exergy cost, €/kWh
E_d	8400.0	0.0620	8400.0	0.0620
Q_d	6100.0	0.0147	1067.5	0.0838
R_d	4000.0	0.0127	242.9	0.2095

Table 7: Daily energy and exergy flows and unit costs of the trigeneration subsystem products

Trigeneration subsystem products	Energy, kWh	Unit energy cost, €/kWh	Exergy, kWh	Unit exergy cost, €/kWh
W_{cd}	7317.4	0.0563	7317.4	0.0563
Q_{cd}	5757.6	0.0141	1007.6	0.0803
R_{cq}	2401.5	0.0113	145.8	0.1859
R_{ce}	1456.9	0.0113	88.5	0.1862

Highlights

- Cost allocation of joint production in a dynamic trigeneration system is addressed
- A novel cost allocation approach for thermal energy storage is proposed
- The interconnection between charging and discharging hourly periods is explored
- The cost of discharged energy was traced back to its origin period
- The hourly unit costs of the internal flows and final products are obtained