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# Environmental impact and cost allocations for a dual product heat pump

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ABSTRACT

Fair and reasonable cost allocation among the consumers of different energy services of a multiproduct system can contribute positively to wider acceptance of energy efficiency strategies and reduction of pollutant emissions. Cost allocation can be carried out by the application of thermoeconomic methodologies, which can unravel the cost formation process in complex energy systems. This work applies the UFS (Internal Energy – Flow Work – Entropy) thermoeconomic methodology to allocate costs and environmental impacts in a heat pump utilized for food dehydration and water production. The UFS method evaluates the main components of the heat pump individually, including the expansion valve. Exergy analysis is carried out to identify the components with highest exergy destruction. Economic analysis is carried out for monetary cost evaluation and Life Cycle Assessment calculated the carbon emissions associated with the products of the heat pump. Results revealed that the evaporator and condenser devices are responsible for more than half of the overall exergy destroyed and the overall system presented 1.07% exergy efficiency. The UFS method revealed that the cost of the system (US$ 698.2/month) and carbon emissions (151.5 kg $CO_2$-eq/month) should be allocated to the food dehydration and water production processes in a proportion of 51% and 49%, respectively.

## 1. Introduction

Energy and economic analyses of thermal systems are necessary to select and adequate technology that presents lower costs and environmental impacts while fulfilling an application. When evaluating multiproduct systems, economic analysis requires the definition of the productive costs associated with each product, and in this case Thermoeconomics is applied. The benefit of merging thermoeconomics and Life Cycle Assessment (LCA) is to increase rationality regarding the allocation of quantities (emissions, exergy, energy, monetary cost, consumption of given substance) in processes with two or more products. This improved rationality originates from unraveling the cost formation process (usually approached as a black box in LCA) by considering the subsystems and utilizing an allocation method based on the generation of entropy (exergy destruction) along the paths of the subsystems. As stated in Silva et al. [1], thermoeconomic methods can be adapted to any multiproduct step or process regardless whether the products are energy-related or not. A product of a productive process that generates more entropy will be more penalized than a product originated from a productive process that generates less entropy. This holds an environmental sense, as the generation of entropy is an absolute measurement of the reversibility of any process. As entropy generation is also inherent to any production process, thermoeconomic methods are general and suitable for the allocation of resources and waste in any process.

Exergy as well as emissions can be rationally allocated to the products of multi-product systems using thermoeconomics. Several researchers have been using thermoeconomic techniques to distribute pollutant emissions in cogeneration systems [2–6]. Silva et al. [7] applied thermoeconomics to allocate emissions and exergy in petroleum processing systems. Peiró [8] used thermoeconomics to allocate environmental impacts associated with the biodiesel production process. Santos [9], Santos et al. [10] and Silva et al. [1] have allocated $CO_2$-eq by coupling LCA and thermoeconomics in multi-product systems.

In recent years, several thermoeconomic methodologies have been developed. The Structural Theory of Thermoeconomics was proposed by Erlach, Serra, & Valero [11] as a standard and common mathematical formulation for all thermoeconomic methodologies employing thermoeconomic models that could be expressed by linear equations. Frangopoulos [12] presented the thermo-economic functional analysis and optimization. Kim [13] introduced the "wonergy" term, defined as an energy that can equally evaluate the worth of each product, resulting in a new thermoeconomic methodology for energy systems. The SPECO methodology was presented by Lazzaretto and Tsatsaronis [14], as a

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**Nomenclature**

| | |
|---|---|
| ABNT | Brazilian Association of Technical Standards |
| ANEEL | Brazilian National Electricity Agency |
| $b_{chem,w}$ | chemical exergy of water |
| $b_{f,i}$ | exergy component associated with work flow of flux i |
| $b_{phy,i}$ | physical exergy |
| $b_{s,i}$ | exergy component associated with entropy of flux i |
| $b_{total}$ | total specific exergy |
| $b_{u,a,i}$ | exergy component associated with internal energy of dry air of flux i |
| $b_{u,i}$ | exergy component associated with internal energy of flux i |
| $\dot{B}_F$ | exergy flux associated to work flow |
| $\dot{B}_{Qui}$ | chemical exergy flux |
| $\dot{B}_S$ | exergy flux associated to entropy |
| $\dot{B}_T$ | total exergy flux |
| $\dot{B}_U$ | exergy flux associated to internal energy |
| $c$ | monetary unit cost of the internal flows |
| $CO_2$-eq | Carbon Dioxide Equivalent |
| COND_AIR | control volume that involve the air flux in the condenser |
| COND_REF | control volume that involve the refrigerant flux in the condenser |
| COP | Coefficient of Performance |
| *CRF* | Capital Recovery Factor |
| EVAP_AIR | control volume that involve the air flux in the evaporator |
| EVAP_REF | control volume that involve the refrigerant flux in the evaporator |
| GSHP | Ground Source Heat Pump |
| $i$ | interest rate |
| IPCC | Intergovernmental Panel on Climate Change |
| H&S | enthalpy and entropy |
| $k$ | exergetic unit cost of internal flows |
| LCA | Life Cycle Assessment |
| $n_a$ | life cycle of equipment, in years |
| $n_h$ | annual operating time, in hours |
| Q_cond_air | heat flux received by the air in the condenser |
| Q_cond_env | heat flux transmitted from the condenser to environment |
| Q_cond_ref | heat flux rejected by the refrigerant in the condenser |
| Q_evap_air | heat flux rejected by the air in the evaporator |
| Q_evap_env | heat flux transmitted from the environment to evaporator |
| Q_evap_ref | heat flux received by the refrigerant in the evaporator |
| UFS | internal energy, flow work and entropy |
| $Y$ | generic internal productive flow |
| $Y_{a,0}$ | molar fraction of dry air in the mixture of humid air |
| $Y_{v,0}$ | molar fraction of humidity in the mixture of humid air |
| $Z$ | monetary cost per time |
| $Z_{ICblower}$ | estimated price for the blower |
| $\dot{Z}_T$ | cash flow associated to productive unit in dollars for second |
| $Z_{CI}$ | price of the productive unit |
| $\varphi$ | cost of maintenance and operation |
| λ | amount of emissions associate with obtaining one unit of exergy |

systematic and general methodology for calculating efficiencies and costs in thermal systems. The work of Lozano [15] addresses a thermoeconomic methodology for disaggregating the plant under analysis into productive and dissipative units. Santos et al. [16] opened the discussion about the procedure for negentropy[1] application in thermoeconomics, and Torres et al [17] presented the mathematical basis for the cost assessment and the formation process of residues.

The main benefit of the UFS (Internal Energy – Flow Work – Entropy) methodology in the evaluation of refrigeration systems is its capacity to disaggregate the expansion valve (which is a dissipative component) from the evaporator or condenser, by assigning a thermodynamic product to this component. This is accomplished by splitting the exergy flow rate into its components. Analysis of dissipative components, for which there is no thermodynamic product [14], such as valves and power plant condensers, has been a tough challenge for thermoeconomic approaches. According to Santos et al. [16], it is necessary to use, separately, the negentropy and enthalpy terms of physical exergy to address condenser devices in power plants. According to the H&S approach, the condenser is responsible for restoring the entropy level of the cycle. The use of negentropy and enthalpy terms are not sufficient to define a thermodynamic product for valves [18], and therefore Lourenço [19] presented the UFS methodology (U: Internal Energy; F: Flow work; S: Entropy), which disaggregated physical exergy into internal energy, work flow and negentropy.

For the specific case study considered herein, a heat pump utilized to dehydrate food (and consequently produce water), there is limited scientific literature on thermodynamic analysis. A broad review on the use of exergetic indicators in the food industry was published by Zisopoulos et al. [20], revealing a growing trend for exergy analysis with most of the applications targeting on drying processes due to the high-energy requirements involved in those processes. The study by Mortezapour et al. [21] focused on a hybrid photovoltaic–thermal solar dryer equipped with a heat pump system for saffron drying, determining the moisture content, thermal efficiency of the solar collector, electrical efficiency of the solar collector, specific moisture extraction rate, dryer efficiency, and solar fraction factors. Erbay and Hepbasli [22] carried out advanced exergy analysis of a heat pump drying system used in food drying, and Erbay and Hepbasli [23] applied conventional and advanced exergy analyses to evaluate the performance of a ground-source heat pump dryer used in food drying. The performance of a solar-ambient hybrid source heat pump drier for copra drying under hot-humid weather conditions was the focus of Mohanraj [24], while Yahya [25] studied the design and performance evaluation of a solar assisted heat pump dryer integrated with biomass furnace for red chilli. Exergoeconomic analysis of a gas engine driven heat pump drying system was performed by Gungor, Erbay & Hepbasli [26], based on experimental values using the Exergy, Cost, Energy and Mass (EXCEM) analysis method, applied to medicinal and aromatic plants.

Although the concepts of heat pumps and thermoeconomics are not novel, the number of papers centered exclusively on the aspect of thermoeconomic analysis of heat pump for food drying is very limited. Wall [27] presented the application of thermoeconomics to the optimization of a single-stage generic heat pump, revealing the advantages of applying the method of thermoeconomics to a heat pump process. A photovoltaic heat pump model was studied by Mastrullo and Renno [28] from energy, exergy and economic perspectives, with thermoeconomic analysis carried out in terms of exergy destruction rates and economic indexes. Exergoeconomic[2] analysis of plum drying in a heat pump conveyor dryer was studied by Hepbasli et al. [29], and an exergoeconomic analysis of a gas engine driven heat pump drying system was performed by Gungor, Erbay & Hepbasli [26], based on

[1] this magnitude allows quantifying the condenser product in a steam cycle plant, which was not possible before because the condenser is a dissipative component, whose product cannot be expressed in terms of exergy.

[2] Combination of exergy-based thermodynamic evaluations and economics. Thermoeconomics characterizes any combination of thermodynamics with economics, with a broader meaning, and therefore the term can be used instead of exergoeconomics (but not *vice versa*)[35].