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ECONOMIC OPTIMIZATION OF A POLYGENERATION SYSTEM FOR A MILK PROCESSING PLANT

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Abstract. *The food and beverage industry presents the highest rate of electricity consumption in the industrial sector and dairy processing is considered one of the most energy-intensive sectors within the food industry. Dairy industries are good candidates for polygeneration systems because of their high energy demands and also their need for reliable and flexible energy supply systems. The optimal configuration of polygeneration systems is a complex problem because of the wide variety of available energy conversion technologies, fuel sources, and fluctuations in tariffs and energy demands. This study optimizes a polygeneration system for a dairy industry located in João Pessoa, Northeast Brazil. The energy demands are heat (steam and hot water), electricity, and chiller water. The solution of a mixed integer linear programming model that incorporated local economic conditions determined the optimal configuration and operation of the energy system throughout an entire representative year. The objective function focuses on the minimization of annual costs. The optimal economic solution includes natural gas and diesel cogeneration modules, a natural gas boiler, and a mechanical chiller. Although the optimal system presented higher capital costs, the total annual costs were 25.38% lower than the reference system.*

Keywords: *Dairy, energy, food industry, mixed integer linear programming, synthesis.*

1. INTRODUCTION

The industrial sector consumes more energy than any other sector, corresponding to 54% of the global energy consumption (PABLO-ROMERO; SÁNCHEZ-BRAZA; EXPÓSITO, 2019). In Brazil, the industrial sector accounted for 37.5% of the electricity consumed in 2018 (BRASIL, 2019a). Within the industrial sector, the food and beverage industry presents the highest rate of electricity consumption and dairy processing is considered one of the most energy intensive sectors within the food industry (Ladha-Sabur et al., 2019). Brazil was the fourth largest milk producer in 2017 (BRASIL, 2019b). Dairy industries require different types of processes depending on the final products (milk, cheese, butter, etc.). According to Xu and Flapper (2009), the energy demands for fluid-milk processing plants usually include electricity (for transportation, storage, and separation) and thermal energy (for pasteurization and cleaning).

Dairy industries are good candidates for polygeneration systems because of their high energy demands and also their need for reliable and flexible energy supply systems. Polygeneration is the simultaneous production of two or more energy services or products that, using process integration schemes to achieve the maximum thermodynamic efficiency (CARVALHO; LOZANO; SERRA, 2012). Polygeneration systems can combine different types of fuels and technologies. The energy sources can include fossil fuels (natural gas, coal, and diesel) as well as renewable energy sources, such as biogas, solar, biomass, etc. Some of the technologies widely used in this type of systems are gas turbines, internal combustion engines, fuel cells, boilers, and chillers. The proper selection of technologies must take into account the type of fuels available, the application, and related costs (ANGRISANI; ROSELLI; SASSO, 2012).

The optimal configuration of polygeneration systems is a complex problem because of the wide variety of available energy conversion technologies, fuel sources, and fluctuations in tariffs and energy demand (PINA *et al*., 2020). Due to a large number of variables involved, Mixed Integer Linear Programming (MILP) is widely applied to the synthesis of polygeneration systems (PINTO; SERRA; LÁZARO, 2020) as it establishes the optimal design of the many acceptable designs available with respect to the objective function (RAO, 2009). As stated in Sioshansi and Conejo (2017), MILP is a particular case of linear optimization problems where some or all of the decision variables are limited to admit integer values.

The optimization of polygeneration systems has been investigated for different applications, such as the mining, residential, and tertiary sectors. Pina (2019) proposed a polygeneration system for a multi-family building in Zaragoza, Spain, that required electricity, heating (domestic hot water and space heating) and cooling (chilled water). The author developed a MILP model to establish the optimal configuration of the system and the operation strategy for the year. Carvalho *et al.* (2019) implemented a multiobjective optimization of a polygeneration system to be installed in a hospital located in João Pessoa/PB, to satisfy the demands for electricity, hot water, steam, and cooling. The mathematical model considered economic and environmental objective functions. Romero *et al.* (2020) applied the MILP to search for cost-effective energy supply solutions for a remote off-grid underground mine located in Canada. Diesel imports, wind energy and hydrogen (as a storage solution for wind energy) were the utilities available to meet the demands for electricity, heat, and cooling.

This study optimizes a polygeneration system for a dairy industry located in João Pessoa/PB. To this end, MILP-based optimization was utilized to determine the optimal configuration and operation strategy, considering the minimization of the total annual costs of the energy supply system.

2. MATERIALS AND METHODS

2.1 Energy demands

The study object is a milk processing plant located in João Pessoa (Paraíba state, Northeast Brazil). The industry operates 16 h/day on weekdays and 8 h/day on weekend days, and produces 47,872,734 millions of milk annually. The energy demands were based on Tomasula *et al.* (2013), Brasil (2020), and Lawder (2012), established in hourly periods considering two representative days (one weekday and one weekend day) for each month over a year, totaling 576 hourly periods. The annual energy demands of the plant are electricity 4903.70 MWh, steam 0.37 MWh, hot water 0.86 MWh, and chilled water 203.50 MWh. The demands are related to process utility requirements such as pasteurization, standardization, cleaning, and non-process requirements (e.g., office space conditioning and building lighting). Table 1 depicts the daily demands for each representative day of the year.

Table 1. Daily demands for each representative day

Month/ Representative day	No. of days	Electricity	Steam	Chilled Water	Hot Water
		kWh/day			
Jan. / wday	22	16,949.69	1.27	703.40	2.99
Jan. / wend	8	8474.84	0.63	351.70	1.49
Feb. / wday	20	17,887.10	1.34	742.30	3.15
Feb. / wend	8	8943.55	0.67	371.15	1.58
Mar. / wday	20	19,999.52	1.49	829.96	3.52
Mar. / wend	10	9999.76	0.75	414.98	1.76
Apr. / wday	21	18,261.85	1.36	757.85	3.22
Apr. / wend	7	9130.93	0.68	378.92	1.61
May / wday	22	16,772.22	1.25	696.03	2.95
May / wend	8	8386.11	0.63	348.02	1.48
Jun. / wday	20	15,261.87	1.14	633.35	2.69
Jun. / wend	10	7630.94	0.57	316.68	1.34
Jul. / wday	23	13,276.26	1.00	550.95	2.34
Jul. / wend	8	6638.13	0.50	275.48	1.17
Aug. / wday	22	13,747.29	1.03	570.50	2.42
Aug. / wend	9	6873.64	0.51	285.25	1.21
Sep. / wday	21	14,282.60	1.07	592.71	2.52
Sep. / wend	8	7141.30	0.53	296.36	1.26
Oct. / wday	23	15,602.14	1.16	647.47	2.75
Oct. / wend	7	7801.07	0.58	323.74	1.37
Nov. / wday	20	16,071.87	1.20	666.97	2.83
Nov. / wend	8	8035.94	0.60	333.48	1.42
Dec. / wday	21	15,281.57	1.14	634.17	2.69
Dec. / wend	9	7640.79	0.57	317.09	1.35
		MWh/year			
Year	355	4903.70	0.37	203.50	0.86

Figure 1 and 2 show, respectively, the hourly energy demands of a weekday and weekend day in March, which is the month with highest rate of energy consumption.

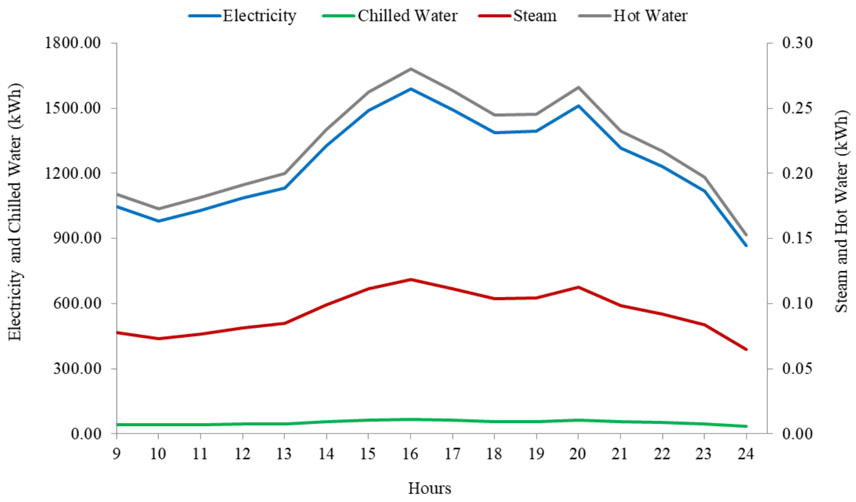

Figure 1. Hourly energy demands of a weekday in March.

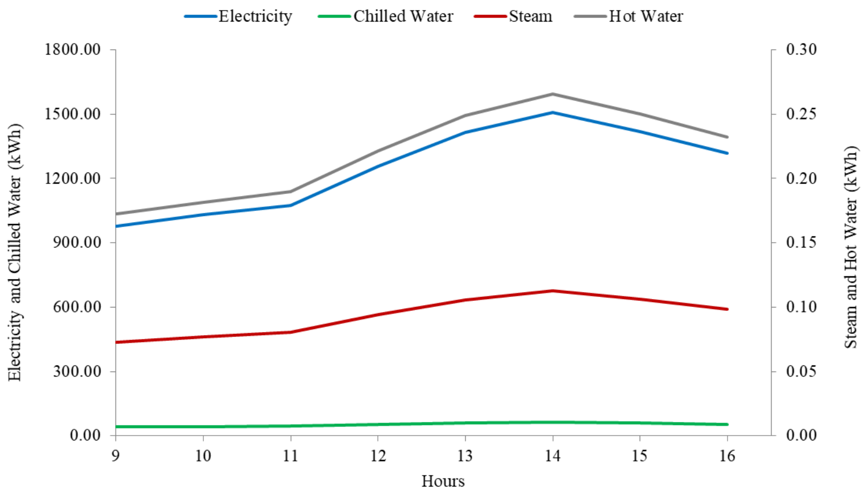

Figure 2. Hourly energy demands of a weekend day in March.

2.2 Superstructure

Based on the energy demands, a superstructure was built to represent all the possible processes and connections of the energy supply system, thus incorporating all features that could be part of an optimal solution. The optimization model will determine the best combination of technologies and connections within the superstructure. A detailed survey of technologies was carried out, leading to the selection of commercially available equipment. Technical specifications and acquisition costs were obtained directly with suppliers and manufacturers. Energy balances were developed for each piece of equipment to establish the interconnections between utilities and energy conversions.

The superstructure of the energy supply system for the milk processing plant is shown in Fig. 3. The available utilities were natural gas, biomass, diesel, electricity, hot water, steam, chilled water, cooling water, and ambient air. The energy conversion technologies selected include gas turbine with a cogeneration module, gas and diesel engines with cogeneration module, gas and biomass steam boilers, steam and hot water heat exchangers, double-effect steam absorption chiller (VA), single effect hot water absorption chiller (WC), mechanical chiller, and cooling tower. D, P, and W correspond to demand, purchase, and waste, respectively.

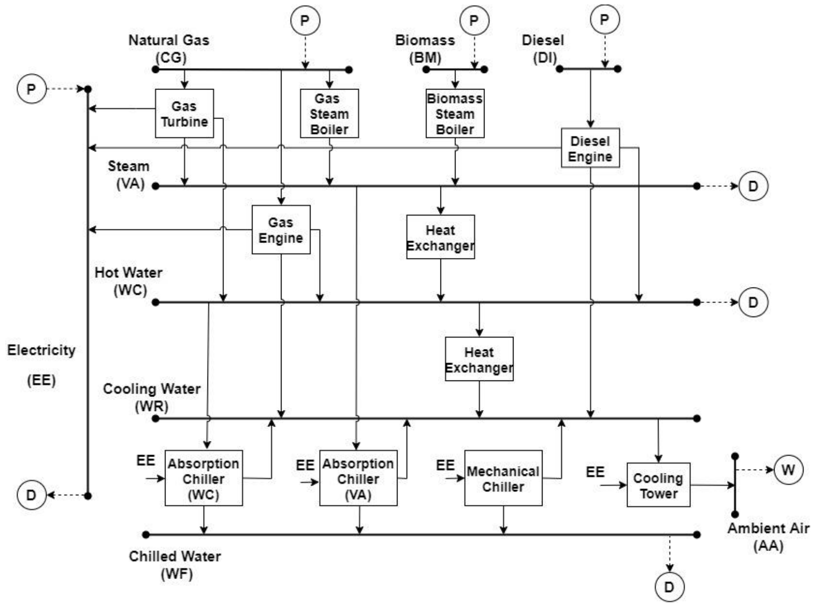

Figure 3. Superstructure of the polygeneration system.

The superstructure allows the purchase of diesel, natural gas, biomass, and electricity from the grid. The fuel tariffs were acquired directly from local companies and secondary sources (PBGAS, 2020; DELGADO *et al.*, 2018; PROCON-PB, 2020; ENERGISA, 2020). The tariffs considered were: natural gas 220 R$/MWh, biomass 78 R$/MWh, and diesel 347 R$/MWh. The electricity tariff has an hourly differentiation, according to the time of use: for on-peak hours (from 5:30 pm to 8:30 pm) the tariff is 1870 R$/MWh, whereas for off-peak hours the tariff is 263 R$/MWh.

Table 2 displays the costs, nominal power, and production coefficients of the equipment selected for the superstructure. The production coefficient is normalized to the main energy service supplied by the equipment (coefficient 1). A positive coefficient indicates a utility that is being produced, while a negative coefficient indicates the consumption of a utility. HX refers to heat exchanger. To account for maintenance and operation expenses, a monetary cost per unit of produced energy (R$/MWh) was considered for each equipment within the superstructure, according to Carvalho, Romero e Millar (2014) and Romero (2016).

Table 2. Equipment data and matrix of production coefficients.

Equipment				**Utility**								
Technology	**Cost (10^3 R$)**	**Nominal Power (MW)**	**O&M Cost (R$/MWh)**	**EE**	**VA**	**WF**	**CG**	**DI**	**BM**	**WC**	**WR**	**AA**
Gas turbine	9096.00	1.21	15.00	1	1.92		-4.13			0.53		
Gas engine	463.00	0.41	15.00	1			-2.66			1.10	0.45	
Diesel engine	227.00	0.36	15.00	1				-2.73		0.67	0.65	
Gas steam boiler	49.30	0.22	2.00		1		-1.22					
Biomass steam boiler	56.52	0.32	8.00		1				-1.18			
SE absorption chiller	539.70	0.49	10.00	-0.01		1				-1.32	2.26	
DE absorption chiller	465.20	0.46	10.00	-0.01	-0.77	1					1.69	
Mechanical Chiller	217.40	0.27	4.00	-0.23		1					1.22	
Cooling tower	42.09	0.74	10.00	-0.01							-1.00	1
Steam HX	8.90	0.40	2.00		-1.10					1		
Hot water HX	7.40	0.40	2.00							-1.10	1	

2.3 Mathematical model

The MILP optimization model aims to minimize the total annual cost necessary to satisfy the energy demands of the milk processing plant. The model includes three types of variables: binary, integer, and continuous. Binary and integer variables are used for the selection of technologies and the determination of the number of components installed, respectively, and continuous variables represent energy and economic flows. The operational limits of the system are implemented in the algorithm as constraints, which are production and capacity restrictions and balance equations. The MILP model was solved in Lingo 18, a commercial software package for solving optimization problems (LINDO SYSTEMS, 2018).

The objective function to be minimized is the total annual costs (Equation 1), constituted by fixed (Equation 2) and variable costs (Equation 3). The fixed cost encompasses capital and installations costs, while the variable cost includes the purchase of fuels and electricity from the grid.

$$Min\ C_{total} = C_{fix} + C_{var} \tag{1}$$

$$C_{fix} = frc \cdot (1 + fci) \cdot \sum_i NE(i) \cdot CE(i) \tag{2}$$

$$C_{var} = \sum_d \sum_h p(d,h) \cdot t(d,h) \tag{3}$$

In Eq. (2), NE(i) and CE(i) are, respectively, the number of pieces of equipment installed and the acquisition cost of each component for technology i, with the capital recovery factor (fcr) and indirect costs factor (fci). In Eq. (3), t(d, h) corresponds to the annual operational hours, while p(d, h) is the hourly energy charge as shown in Eq. (4).

$$p(d,h) = V_e(d,h) \cdot c_e(d,h) + V_g \cdot c_g(d,h) + V_d \cdot c_d(d,h) + V_b \cdot c_b(d,h) \tag{4}$$

Where c_e, c_g, c_d and c_b refer to the purchase of electricity, natural gas, diesel, and biomass, respectively, in the period (d,h). V_e, V_g, V_d and V_b are the tariffs in R$/MWh for electricity, natural gas, diesel and biomass, respectively.

The fci factor represents the indirect costs such as staff, legal expenses, contracts, etc., and it was considered to be 15% of the total equipment costs. The capital recovery factor, Eq. (5), refers to the amortization of the system's investments, i.e., the annual payment with the interest rate iyr and the lifetime of equipment nyr. An interest rate of 10% per year and equipment lifetime of 15 years were considered, resulting in fcr = 0,13.

$$fcr = \frac{iyr \cdot (1 + iyr)^{nyr}}{(1 + iyr)^{nyr} - 1} \tag{5}$$

The possibilities of interaction between the energy supply system and the economic market are represented by a binary matrix (0 = no, 1 = yes) shown in Tab. 3. The indicators INDPUR, INDDEM, and INDWAS are, respectively, the purchase, demand, and waste for each utility j.

Table 3. Matrix of system interactions

Utility (j)	INDPUR	INDDEM	INDWAS
Natural gas	1	0	0
Steam	0	1	0
Hot water	0	1	0
Cooling water	0	0	0
Ambient air	0	0	1
Chilled water	0	1	0
Electricity	1	1	0
Diesel	1	0	0
Biomass	1	0	0

For each type of technology *i* the installed power is shown in Eq. (6), where $P_{nom}(i)$ is the nominal power of the equipment.

$$PIN(i) = NE(i) \cdot P_{nom}(i) \tag{6}$$

The operation of the system is subject to capacity limits, production constraints, and balance equations. The production capacity (PRODT), of the set of technologies i in the period (d, h), is restricted to the installed capacity of the equipment:

$$PRODT(d,h,i) \leq PIN(i) \tag{7}$$

Equation (8) shows the production constraint, where X is the energy flow of the utility j produced or consumed by the technology i and K is the absolute value of the production coefficients of Table 3.

$$X(i,j,d,h) = K(i,j) \cdot PRODT(d,h,i) \tag{8}$$

Also, the system has to satisfy the following energy balance equations:

$$Prod(j,d,h) - Cons(j,d,h) + C(j,d,h) - D(j,d,h) - P(j,d,h) = 0 \tag{9}$$

$$Prod(j,d,h) = \sum_i X(i,j,d,h) \cdot YTUP(i,j), \text{ com } YTUP(i,j) \in \{0,1\} \tag{10}$$

$$Cons(j,d,h) = \sum_i X(i,j,d,h) \cdot YTUC(i,j), \text{ com } YTUC(i,j) \in \{0,1\} \tag{11}$$

$$C(j,d,h) \leq INDPUR(j) \cdot (Cons(j,d,h) + D(j,d,h)), \text{ com } INDPUR(j) \in \{0,1\} \tag{12}$$

$$P(j,d,h) \leq INDWAS(j) \cdot Prod(j,d,h), \text{ com } INDWAS(j) \in \{0,1\} \tag{13}$$

$$D(j,d,h) \leq INDDEM(j) \cdot (Prod(j,d,h) + C(j,d,h)), \text{ com } INDDEM(j) \in \{0,1\} \tag{14}$$

Where, Prod(j,d,h) and Cons(j,d,h) represent the internal flows of utility production and consumption, respectively. C(j,d,h), P(j,d,h) and D(j,d,h) are, respectively, the purchase, waste and demand of utility j on a given day d and hour h. These coefficients represent the utility interchange between the polygeneration system and the environment. YTUP(i,j) is 1 when the production coefficient (Tab. 2) is positive, that is when the technology i produces the utility j. YTUC(i,j) is 1 when the production coefficient is negative, that is, the technology i consumes the utility j.

3. RESULTS

The optimization results are presented for two systems. The first is the reference system, which the optimization model does not allow the use of cogeneration and renewable energy. Only traditional technologies, such as gas steam boiler, heat exchangers, mechanical chiller, and cooling tower were taken into account. The second system considers all the feasible combinations of technologies within the superstructure (free optimization). Table 4 shows the economic optimization results.

In the optimization solver, the free optimization problem had a total of 74,115 restrictions and 104,653 variables, being 1750 integer variables. The model performed a total of 148,852 iterations. For the reference system, the problem presented 74,115 restrictions and 104,647 variables, of which 1744 are integers.

Table 4. Optimization results

	Optimal System	Reference System
System Composition	No. of pieces of equipment (Installed Power)	
Gas turbine	-	-
Gas engine	2 (820 kW)	-
Diesel engine	1 (360 kW)	-
Gas steam boiler	1 (220 kW)	1 (220 kW)
Biomass steam boiler	-	-
SE absorption chiller	-	-
DE absorption chiller	-	-
Mechanical chiller	1 (270 kW)	1 (270 kW)
Steam heat exchanger	1 (400 kW)	1 (400 kW)
Hot water heat exchanger	3 (1200 kW)	-
Cooling tower	3 (2220 kW)	1 (740 kW)
	Annual Energy Flows (MWh/year)	
Imported electricity	4193	4953
Purchase of natural gas	1671	2
Purchase of diesel	392	-

Cogenerated useful heat	71	-
	Annual Costs (R$/year)	
Imported electricity	1,308,143	2,729,401
Purchase of natural gas	367,600	353
Purchase of diesel	136,072	-
Maintenance and operations	27,207	3301
Annual equipment costs	235,772	47,495
Initial investment in equipment	**R$ 1,813,631**	**R$ 365,344**
Total annual cost	**R$ 2,074,793 / year**	**R$ 2,780,550 / year**

The reference system is based on the purchase of electricity from the local grid to meet all the demand for electricity and chilled water (produced by mechanical chiller). A natural gas boiler is installed to attend the steam demand, and a portion of that steam goes through a heat exchanger, producing hot water to satisfy the demand.

In the optimal solution, a combination of natural gas and diesel generators plus the purchase of electricity from the local grid meet the demand of electricity as well as the chilled water demand (produced by mechanical chiller). As the same operational strategy of the reference system, a natural gas boiler generates steam. The recovery of exhaust gas heat from the generators produces hot water.

Although the optimal system presented a high initial investment in equipment, it showed a reduction of 25.38% in the total annual cost when compared to the reference system. The higher annual cost of the reference system is due to the purchase of electricity from the grid during on-peak hours at the cost of 1870 R$/MWh. On the other hand, the optimal system imported the electricity from the grid on off-peak hours, and during on-peak hours the diesel and natural gas cogeneration modules were used to meet the electricity demand. For the optimal system, the amortization cost of the initial investment in equipment is R$ 235,772 annually.

4. FINAL REMARKS

The study presented herein optimized a polygeneration system to be installed in a milk processing plant. The optimization model focused on the minimization of total annual costs and employed commercially available equipment. The study case was a dairy industry with a production capacity of 47,872,734 million of milk annually located in João Pessoa/PB.

The optimal system applied a combination of diesel and natural gas generators with the purchase of electricity from the grid to satisfy the electricity and chilled water demand. The generators are used only during on-peak hours when the electricity tariff is much higher, and applying this operational strategy the optimal system showed a reduction of 25,38% in the annual cost. Thus, the result indicates that electricity consumption from the local grid is economically advantageous only on off-peak hours. Also, the optimal system takes advantage of cogeneration to produce hot water in order to attend the cleaning needs of the plant. Both systems, the optimal and reference, apply a natural gas boiler to produce steam.

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6. REFERENCES

Alberto, R., 2016. *Optimal design and control of mine site energy supply systems*. Ph.D. thesis, Laurentian University, Sudbury, Canada.

Angrisani, G., Roselli, C. and Sasso, M., 2012. “Distributed microtrigeneration systems”. *Progress in Energy and Combustion Science*, Vol. 38, pp. 502-521.

Brasil 2019a. Empresa de Pesquisa Energética. “Balanço Energético Nacional 2019: Ano base 2018”. Rio de Janeiro: EPE.

Brasil 2019b. Empresa Brasileira de Pesquisa Agropecuária. “Anuário Leite 2019”. Juiz de Fora: EMBRAPA Gado de Leite.

Brasil, 2020. Instituto Brasileiro de Geografia e Estatística. “Indicadores IBGE: Estatística da Produção Pecuária”. IBGE.

Carvalho, M., Lozano, M.A. and Serra, L.M., 2012. "Multicriteria synthesis of trigeneration systems considering economic and environmental aspects". *Applied Energy*, Vol. 91, pp. 245-254.

Carvalho, M.; Romero, A.; Millar, D., 2014. "Biomassa e energia solar térmica na síntese e otimização de um sistema de poligeração". In: *V Congresso Brasileiro de Energia Solar*. Recife, Brazil.

Delgado, D. B. M.; Carvalho, M.; Júnior, L. M. C.; Chacartegui, R., 2018. "Analysis of biomass-fired boilers in a polygeneration system for a hospital". *Frontiers in Management Research*, Vol. 2.

ENERGISA, 2020. Grupo Energisa. 14 Sep. 2020 <https://www.energisa.com.br>

Ladha-Sabur, A., Bakalis, S., Fryer, P.J. and Lopez-Quiroga, E., 2019. Mapping energy consumption in food manufacturing. Trends in Food Science & Technology, 86, pp.270-280.

Lawder, J. H., 2012. *Análise Energética e Econômica em uma Agroindústria de Laticínios*. Masters dissertation, Universidade Estadual do Oeste do Paraná, Cascavel, Brasil.

Lindo Systems, 2018. "LINGO: The Modeling Language and Optimizer". Illinois: Lindo Systems.

Pablo-Romero, M. P.; Sánchez-Braza, A.; Expósito, A., 2019. "Industry level production functions and energy use in 12 EU countries". *Journal of Cleaner Production*, Vol. 212, p. 880-892.

PBGÁS, 2020. "Tarifas". Companhia Paraibana de Gás. 14 Sep. 2020 < http://www.pbgas.com.br/?page_id=1477 >

Pina, E. A., 2019. *Thermoeconomic and environmental synthesis and optimization of polygeneration systems supported with renewable energies and thermal energy storage applied to the residential-commercial sector*. Ph.D. thesis, Universidad de Zaragoza, Zaragoza, Spain.

Pina, E.A., Lozano, M.A., Ramos, J.C. and Serra, L.M., 2020. "Tackling thermal integration in the synthesis of polygeneration systems for buildings". *Applied Energy*, Vol. 269, pp. 115-115.

Pinto, E.S., Serra, L.M. and Lázaro, A., 2020. "Evaluation of methods to select representative days for the optimization of polygeneration systems". *Renewable Energy*, Vol. 151, pp. 488-502.

PROCON-PB, 2020. "Pesquisas PROCON". Proteção e Defesa do Consumidor do Estado da Paraíba. 14 Sep. 2020 < https://procon.pb.gov.br/pesquisas>

Rao, S.S., 2009. *Engineering Optimization: Theory and Practice.* John Wiley & Sons, New Jersey, 4th edition.

Sioshansi, R. and Conejo, A.J., 2017. *Optimization in Engineering: Models and Algorithms*. Springer, Cham.

Tomasula, P.M., Yee, W.C.F., Mcaloon, A.J., Nutter, D.W., Bonnaillie, L.M., 2013. "Computer simulation of energy use, greenhouse gas emissions, and process economics of the fluid milk process". *Journal of Dairy Science*, Vol. 96, pp. 3350-3368.

Xu, T. and Flapper, J, 2009. "Energy use and implications for efficiency strategies in global fluid-milk processing industry". *Energy Policy*, Vol. 37, pp. 5334-5341.

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