

Biomass cogeneration plants integrated into poultry slaughterhouses for reducing industry costs with energy

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ABSTRACT. A technical and economic feasibility analysis was performed concerning biomass cogeneration to supply the thermal and electricity demands of poultry slaughterhouses. The analysis considers measured data referring to the annual energy consumption from an existing industry as well as the characteristics of equipment available in the Brazilian market. The cogeneration plant is equipped with a water tube steam generator and a condensing-extraction steam turbine in a Rankine cycle. Four different configurations were evaluated, including impulse and reaction turbines at two steam pressure/temperature levels (43 bar / 450 °C and 68 bar / 520 °C). A steady state full load operation is considered at cogeneration mode on the weekdays and at Rankine power plant mode on the weekends, when there is no process steam consumption. The technical analysis pointed out the reaction turbine at 68 bar / 520 °C as the best alternative, leading to the highest overall efficiency. In addition, this plant configuration showed economic advantages represented by an Internal Rate of Return (IRR) of 21%, a Net Present Value (NPV) of US\$ 10.93 million, and a payback time of 6 years, enabling a reduction on the industrial cost with energy in the slaughterhouse to 19 US\$/ton of product (-30% in comparison to the base case). Finally, the calculated LCOE of 73 US\$/MWh was lower than the current price of the electricity in the market, indicating potential economic feasibility of the proposed concept.

Keywords: biomass cogeneration plants; poultry slaughterhouses; renewable energy; wood chips.

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Introduction

The meat industries require a large amount of process steam and electricity to drive motors, compressors, conveyors and lighting (Bueno, Rossi, Souza, Teruel, & Bueno, 2015; Feliciano, Rodrigues, Gonçalves, Santos, & Leite, 2014; Nunes, Silva, Andrade, & Gaspar, 2016; Ramírez, Patel, & Blok, 2006; Rocha, Bajay, & Gorla, 2010). In Brazil, wood chips of Eucalyptus or Pinus are used in low pressure saturated steam generators, while the electricity is imported from local distributors or from the open electricity market. Although in Brazil the cogeneration technology is consolidated, its use in the meat industries still does not occur; therefore, this is the motivation of this work.

Cogeneration power plants have been widely used in the world for industrial, commercial and district heating or cooling applications, using any liquid, gaseous or solid fuels, as well as industrial process waste gases. Typical prime movers are steam turbines, gas turbines, reciprocating engines and combined cycles. By using cogeneration plants, the industry revenues could be increased by exporting surplus electricity to the local grid (Alves, Ponce, Silva, & Ensinas, 2015). In addition, the industry expenses with electricity, heating and cooling can be reduced. For example, Silva, Higa and Silva (2019) identified the opportunity of reducing the costs with energy by up to 72% in a payback period of 24 months in a soluble coffee industry in Brazil, by integrating a cogeneration plant equipped with a condensing-extraction steam turbine and an ammonia-water absorption cooling system.

Previous works have been reported focusing on cogeneration applied to the meat industry. As examples, Bianchi, Cherubini, De Pascale, Peretto and Elmegaard (2006) proposed the use of poultry industry wastes' energy content to run an indirectly fired gas turbine cogeneration plant application. Huang et al. (2015) presented a technical and economic analysis of producing biochar and generating electricity and heat from poultry litter. Compton, Willis, Rezaie and Humes (2018) presented several energy saving measures (including

Superheated steam is produced in the steam generator and is directed to the steam turbine (1). Part of steam mass flow is extracted at (2) and directed to a desuperheater (5) where it is mixed with liquid water (17). Then, the saturated steam (7) is directed to the process, while condensate is returned to the deaerator (9). The remaining steam mass flow in the turbine is expanded until the condenser (3), where condensation occurs by the action of the cooling water (18). The condensate is then pumped to the deaerator (12), while cooling water returns to the cooling tower (19). The steam extraction feeds the process demand and the steam (11) required by deaerator. Make-up water (10) is used to supply the losses in the plant. From the deaerator, feedwater is directed to the boiler (15).

The plant can be operated in cogeneration mode when there is poultry processing and in Rankine power plant mode when there is no process steam consumption. The continuous operation of the plant despite the process steam demand is possible by selling surplus electric energy to the Brazilian open or regulated markets.

Thermodynamic modelling

The thermodynamic performance of steam cycle was calculated by a component-wise modelling based on the first law and mass conservation equations followed by a simulation using the software EES®.

Steam generator

The performance of the steam generator is evaluated according to the energy balance described in Equation 1,

$$\eta_{sg} LHV \dot{m}_b = \dot{m}_{sh} h_{sh} - \dot{m}_{fw} h_{fw} \quad (1)$$

where η_{sg} is the thermal efficiency of the steam generator; h_{sh} and h_{fw} [kJ kg⁻¹] are the specific enthalpy of superheated steam and feedwater, respectively; \dot{m}_{sh} and \dot{m}_{fw} [kg s⁻¹] are the superheated steam and feedwater mass flows; \dot{m}_b [kg s⁻¹] is the biomass consumption and LHV [kJ kg⁻¹] the biomass low heat value.

Steam turbine

The net power output of a turbine stage is calculated according to Equation 2,

$$\dot{W}_{st} = \eta_{st,mec} \eta_{st,el} \dot{m} (h_{in} - h_{out}) \quad (2)$$

where $\dot{m} (h_{in} - h_{out})$ is the energy output of the expanded steam [kW], $\eta_{st,mec}$ is the efficiency of mechanical system (bearing, coupling, and heat loss) and $\eta_{st,el}$ is the electrical efficiency of the generator.

The output enthalpy of the exhaust steam is achieved considering the isentropic efficiency, $\eta_{st,iso}$, of the turbine stage – Equation 3 (Shlyakhin, 2005),

$$\eta_{st,iso} = \frac{(h_{in} - h_{out})}{(h_{in} - h_{out,s})} \quad (3)$$

where the subscript s denotes the output state for the isentropic process.

Deaerator

As it can be seen in Figure 1, the proposed cogeneration plant is equipped with a deaerator system to remove dissolved gases from the circuit to protect the plant from corrosion. Deaerator is modeled in this work considering Equation 4 (Borgnakke & Sonntag, 2019).

$$\sum_{i=1}^M \dot{m}_{in,i} h_{in,i} = \sum_{j=1}^N \dot{m}_{out,j} h_{out,j} \quad (4)$$

Pumps

The auxiliary electricity power required for a pump operation, \dot{W}_p [kW], is modelled according to Equation 5,

$$\dot{W}_p = \frac{\dot{m} (h_{in} - h_{out})}{\eta_{p,mec} \eta_{p,el}} \quad (5)$$

where $\dot{m} (h_{in} - h_{out})$ represents the energy gain of the pumped fluid [kW], $\eta_{p,mec}$ is the efficiency of mechanical system (bearing, coupling, and heat loss), and $\eta_{p,el}$ is the efficiency of the electric motor.

The output enthalpy of pumped fluid is achieved considering the isentropic efficiency of pump, $\eta_{p,iso}$, as it is stated by Equation 6 (Borgnakke & Sonntag, 2019).

$$\eta_{p,iso} = \frac{(h_{out,s} - h_{in})}{(h_{out} - h_{in})} \quad (6)$$

Condenser and cooling tower

It is considered that the cogeneration plant is equipped with a condenser and cooling tower system (see Figure 1). The condenser and the cooling tower are designed for the maximum turbine exhaust steam mass flow. The temperatures involved in condenser and cooling tower systems operation are indicated in Figure 2.

The energy balance in the condenser is performed to calculate the cooling water mass flow demand, \dot{m}_{cw} [kg s^{-1}], as stated by Equation (7),

$$\dot{m}_s (h_{s,in} - h_{s,out}) + \dot{m}_{cw} (h_{cw,in} - h_{cw,out}) = 0 \quad (7)$$

where \dot{m}_s [kg s^{-1}] is the turbine exhaust steam mass flow, $h_{s,in}$ and $h_{s,out}$ [kJ kg^{-1}] are the inlet and outlet steam enthalpies, and $h_{cw,in}$ and $h_{cw,out}$ [kJ kg^{-1}] are the inlet and outlet cooling water enthalpies.

The cooling tower uses atmospheric air in countercurrent with the cooling water to reduce its temperature. Equation 8 represents the energy balance in the tower,

$$\dot{m}_a (h_{a,d,in} + h_{a,w,in} \omega_{a,in}) - \dot{m}_a (h_{a,d,out} + h_{a,w,out} \omega_{a,out}) = \dot{m}_{cw} (h_{cw,in} - h_{cw,out}) \quad (8)$$

where \dot{m}_a [kg s^{-1}] is the air mass flow, $\omega_{a,in}$ and $\omega_{a,out}$ [kg kg^{-1} – kilogram of water per kilogram of dry air] are the absolute humidity of air at the inlet and outlet of the tower, $h_{a,d,in}$ and $h_{a,d,out}$ [kJ kg^{-1}] are the inlet and outlet enthalpies of dry air, and $h_{a,w,in}$ and $h_{a,w,out}$ [kJ kg^{-1}] are the inlet and outlet enthalpies of air moisture content.

Equation 9 is used to determine the mass flow rate of make-up water for losses by evaporation and by dragging of droplets and purges. The make-up water mass flow is normally around 2 to 5% of the total flow (Lora & Nascimento, 2004). Droplet drag and purge losses are considered to be 1.3% of the mass flow rate of cooling water.

$$\dot{m}_a (\omega_{in} - \omega_{out}) + \dot{m}_{cw} 1,013 = \dot{m}_{rep} \quad (9)$$

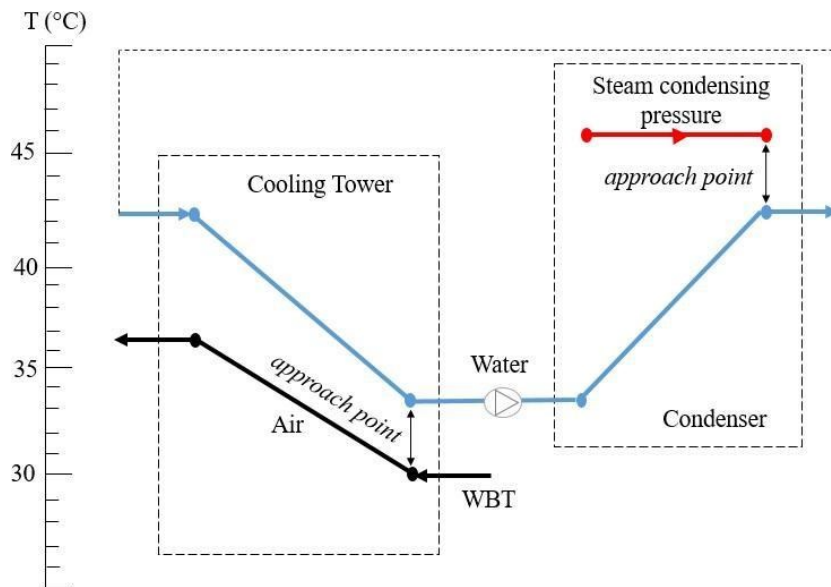


Figure 2. Condenser and cooling tower operation scheme. Adapted from Lora and Nascimento (2004).

Process heat demand

In this work the process heat demand, \dot{Q}_p [kW], is calculated according to Equation 10,

$$\dot{Q}_p = \dot{m}_p h_{lh} \quad (10)$$

where \dot{m}_p [kg s^{-1}] process steam mass flow (Figure 1, point 7) and h_{lh} [kJ kg^{-1}] the steam latent heat.

Plant thermal efficiency

The thermal efficiency of cogeneration plant, η_p [%], is calculated according to Equation 11,

$$\eta_p = 100 \frac{(\dot{W}_{st} + \dot{Q}_p - \dot{W}_p)}{(\dot{m}_b LHV)} \quad (11)$$

where \dot{W}_{st} [kW] is the steam turbine power output, \dot{W}_p [kW] is the power consumption of the pumps, \dot{m}_b [kg s⁻¹] is the biomass mass flow, LHV [kJ kg⁻¹] is the lower heating value of fuel and \dot{Q}_p [kW] is the process heat demand.

Calculation of the energy forestry area demand

The forest area to be chopped annually, A_s [ha], to meet the biomass demand of power plant is calculated according to Equation 12 by considering a mean annual volume increment of energy forest plantation, MAI [m³ ha-yea⁻¹] (Matthews, Jenkiws, Mackie, & Dick, 2016),

$$A_s MAI \Delta t \frac{\rho}{1000} = BD \quad (12)$$

where BD [t year⁻¹] represents the power plant annual biomass demand, ρ [kg m⁻³] is the biomass density and Δt [years] represents the forest plantation age.

If n subfields with area A_s with a difference of one-year of age each are managed simultaneously, the total forest plantation area, A_f [ha], to provide the power plant biomass demand can be calculated according to Equation 13,

$$A_f = A_s n \quad (13)$$

Economic analysis

The economic feasibility of cogeneration plants is evaluated by calculating the Levelized Cost of Electricity ($LCOE$ [US\$ MWh⁻¹]), the Net Present Value (NPV [US\$]), the Internal Rate of Return (IRR [%]), the discounted payback period (DPP [years]) of investments (Short, Packey, & Holt, 2005) and the slaughterhouse industrial cost with energy. The exchange rate considered was 1 US\$ to 3.43 R\$, average value from January to June of 2018.

The $LCOE$ [US\$ MWh⁻¹] is calculated according to Equation 14,

$$LCOE = \frac{\sum_{t=0}^n (CAPEX_t + OPEX_t + C_t - HC_t)(1+r)^{-t}}{\sum_{t=1}^n (EL_t)(1+r)^{-t}} \quad (14)$$

where $CAPEX_t$ [US\$] is the investment cost, $OPEX_t$ [US\$ year⁻¹] represents the annual operation and maintenance costs, C_t [US\$ year⁻¹] the annual expenditures related to fuel purchasing, HC_t [US\$/year] the avoided annual cost related to process steam generation (heat credit), EL_t [MWh year⁻¹] the produced electricity, r [%] the discount rate, t [years] the time and lt [years] the plant lifetime. In order to calculate the heat credit HC_t , the cost of process steam produced by cogeneration plants is considered equal to the Levelized Cost of Heat (LCOH) of base case conventional saturated steam boiler, as indicated by International Energy Agency and Nuclear Energy Agency (2015).

The calculation of NPV [US\$] was performed according to Equation 15.

$$NPV = \sum_{t=0}^{lt} \frac{(CAPEX_t + OPEX_t + C_t - HC_t)}{(1+r)^t} \quad (15)$$

The discounted payback period, DPP [years], was calculated based on the time in which the sum of cash flows equals zero, by considering the change in the money value over time.

In case of $LCOE$ [US\$ MWh⁻¹], NPV [US\$] and DPP [years] the parameter r [%] is considered equal to the Minimum Acceptable Rate of Return (MARR), which is a decision parameter that represents the minimum that the investor proposes to earn when performing an investment.

The IRR [%] was calculated by Equation 16.

$$0 = \sum_{t=0}^{lt} \frac{(CAPEX_t + OPEX_t + C_t - HC_t)}{(1+IRR)^t} \quad (16)$$

Finally, the industrial costs with thermal energy ICT [US\$ t⁻¹] and electricity ICE [US\$ t⁻¹] were calculated according to Equations 17 and 18, respectively,

$$ICT = \frac{LCOH_{HCO}}{FPO} \quad (17)$$

$$ICE = \frac{LCOE_{ECO}}{FPO} \quad (18)$$

where HCO [MWh/year] is the annual slaughterhouse thermal energy consumption, ECO [MWh year⁻¹] is the annual slaughterhouse electricity consumption and FPO [ton/year] the annual final product plant output.

Analysis of an existing poultry slaughterhouse plant

Base case scenario description

The concept here proposed is applied to an existing typical poultry slaughterhouse plant located in the state of Parana, Brazil. The plant has the capacity to slaughter 500 thousand poultres per day and is operated from Mondays to Fridays (24h day⁻¹), with Saturdays and Sundays reserved for scheduled maintenance services.

Data related to process operation was collected in the plant, including final product output, electricity bills, electricity and steam mass flow demands, biomass consumption, etc. A sample of the collected data is presented in the Appendix A, while Appendix B presents the energy consumption and demand charges applied locally by the distributor during the period when this work was developed.

During the year of 2017, the final product output was 312.2 thousand tons. Regarding electricity consumption, it was 66,962 MWh at an average price of 111 US\$ MWh⁻¹ (with peak electricity demand limited to 12 MW).

The process steam consumption was on average equal to 14 t h⁻¹ (at 10 bar) during operation days (16 t h⁻¹ peak). The low-pressure steam generator was fueled with eucalyptus chips purchased at an average price of 45.19 US\$ t⁻¹. In 2017 the biomass consumption was 19,833 tons, leading to the annual Levelized Cost of Heat (LCOH) of 21.87 US\$/MWh.

In this regard, the industrial costs with thermal energy ICT and electricity ICE were 3.35 US\$ ton⁻¹ and 23.89 US\$ ton⁻¹, respectively, leading to the total of 27.24 US\$ ton⁻¹.

Cogeneration plant design

The plant design was performed considering the parameters presented in Table 1. The plant capacity was set to 12 MW, while steam extraction (Figure 1, point 2) mass flow was calculated to feed the process saturated steam demand (limited to 16 t h⁻¹, 10 bar, x=1) and deaerator. The plant is operated at constant power output in the cogeneration mode during the weekdays and in the Rankine mode on weekends or holidays. In both operation modes, electricity surplus is delivered to the grid.

Table 1. Assumptions considered for power plant design.

Parameter	Adopted value	Unit
Plant electricity output capacity	12	MW
Process steam mass flow (at 10 bar, x=1)	16	t h ⁻¹
Condensing pressure	0.105	Bar
Cooling tower inlet and outlet air properties	30 (70% RH) / 35 (100% RH)	°C
Steam generator efficiency ^a	86	%
Steam used directly in process ^b	50	%
LHV of Eucalyptus at 36% moisture content) ^c	10,366	kJ kg ⁻¹
Eletromechanical efficiency of turbogenerator ^a	96	%
Isentropic efficiency of pumps ^a	78	%
Eletromechanical efficiency of pumps ^a	96	%
Plant availability factor	0.92	%

^a Data provided by equipment manufacturers; ^b Measured; ^c Data provided by the poultry slaughterhouse plant.

Four plant configurations are compared, involving two pressure and superheated steam temperature levels (43 bar / 450°C and 68 bar / 520°C), as well as the use of impulse or reaction turbines. The configurations are: SG1/ST1 (boiler 43 bar / 450°C – impulse turbine), SG1/ST2 (boiler 43 bar / 450°C – reaction turbine), SG2/ST1 (boiler 68 bar and 520°C – impulse turbine) and SG2/ST2 (68 bar and 520°C boiler – reaction turbine). These configurations were selected to represent an important range of commercially available solutions in the Brazilian market. Technical data and the Capital Expenditure (CAPEX) for steam generators and steam turbines are presented in Tables 2 and 3.

Table 2. Technical and economic data of steam generators (equipment manufacturer data).

Equipment	Steam mass flow capacity (t h ⁻¹)	Pressure (bar)	Temperature (°C)	CAPEX ^a (10 ³ US\$)
SG1	60	43	450	7,684
	72	43	450	8,694
SG2	60	68	520	8,112
	72	68	520	9,162

^aQuoted CAPEX.**Table 3.** Technical and economic data of steam turbines (equipment manufacturer data).

Equipment	Expansion type	Isentropic efficiency	Pressure (bar)	Temperature (°C)	CAPEX ^a (10 ³ US\$)
ST1	Impulse	0.725 ^b ; 0.673 ^c	43	450	3,120
			68	520	3,265
ST2	Reaction	0.883 ^b ; 0.785 ^c	43	450	3,484
			68	520	3,644

^a Quoted CAPEX; ^b Point 1 to 2 (Figure 1); ^c Point 2 to 3 (Figure 1).

The calculation of Eucalyptus plantation area, A_f [ha] (Equation 13), was performed considering the mean annual volume increment $MAI=30 \text{ m}^3 \text{ ha}^{-1} \text{ year}^{-1}$ (Elli, Sentelhas, Freitas, Carneiro, & Alvares, 2019), the management of $n = 8$ sub-fields aged up to eight years, and the biomass density $\rho=700 \text{ kg m}^{-3}$ (Alves, Oliveira, & Carrasco, 2017).

Additional parameters considered for economic analysis are presented in Table 4.

Table 4. Additional parameters adopted for economic analysis.

Parameter	Adopted value	Unit
Cooling tower system CAPEX ^a	204	10 ³ US\$
Water treatment system CAPEX ^a	146	10 ³ US\$
Water treatment cost ^a	0.73	US\$ m ⁻³
Annual plant operation labor cost ^b	251	10 ³ US\$ year ⁻¹
Annual plant maintenance cost ^a	110	10 ³ US\$ year ⁻¹
Biomass cost ^c	45	US\$ t ⁻¹
Heat credit	22	US\$ MWh ⁻¹
Surplus electricity selling price ^d	58	US\$ MWh ⁻¹
Plant lifetime	25	Year
MARR	10	%

^a Data provided by equipment manufacturers; ^b Data from the National Employment Site (SINE) and based on the personnel needed to operate the plant; ^c Average local biomass price; ^d Auction electricity contract price for biomass power plants in 2018.

Results and discussion

In Table 5, the results for design point operation of proposed concepts are presented. The SG2/ST2 configuration showed the highest thermal efficiency values, equal to 40.2 and 27.2% for the cogeneration and Rankine operation modes. In this regard, the SG2/ST2 configuration had the lowest biomass consumption, equal to 18.0 t h⁻¹ during the week and 15.1 t h⁻¹ at the end of the week. In the same way, this configuration led to the lowest cooling tower water consumption, equal to 45.0 t h⁻¹ and 44.6 t h⁻¹ for the cogeneration and Rankine operation modes. The best results of the SG2/ST2 are due to higher grade superheated steam and the higher isentropic efficiency of ST2 reaction turbine. It is also interesting to observe in Table 5, the great increment of plant efficiency when, for the same superheated steam parameters, a reaction turbine (with higher isentropic efficiency) is considered in place of an impulse model. This is further discussed in sequence considering the economic analysis figures.

Table 5. Results for design point operation of proposed concepts.

Parameter	SG1/ST1		SG1/ST2		SG2/ST1		SG2/ST2	
Operation mode	Cogen.	Rankine	Cogen.	Rankine	Cogen.	Rankine	Cogen.	Rankine
Steam flow (t h ⁻¹)	72.1	62.1	63.5	53.5	62.6	53.8	55.2	46.4
Fuel demand (t h ⁻¹)	22.5	19.3	19.8	16.6	20.4	17.5	18.0	15.1
Plant thermal efficiency (%)	32.2	21.4	36.6	24.9	35.4	23.5	40.2	27.2
Make-up water (t h ⁻¹)	64.9	63.1	52.9	51.2	55.8	55.2	45.0	44.6

The process diagrams related to the design point SG2/ST2 plant operation in cogeneration and Rankine modes are presented in Figures 3 and 4, respectively. As it can be observed, the superheated steam mass flow is reduced when there is no process heat consumption and additional mass flow is expanded to the last stages of turbine. This provides the part load operation of steam generator (84% load), which might not lead to significant impact on equipment performance. Moreover, during the process operation days, 41% of steam mass flow is extracted at point 2 at 10 bar, while 59% is expanded up to condensation pressure. On weekends, on the other hand, 13% of steam mass flow is extracted at point 2 at 10 bar, while 87% is expanded up to condensation pressure. These figures might be considered when specifying the steam turbine.

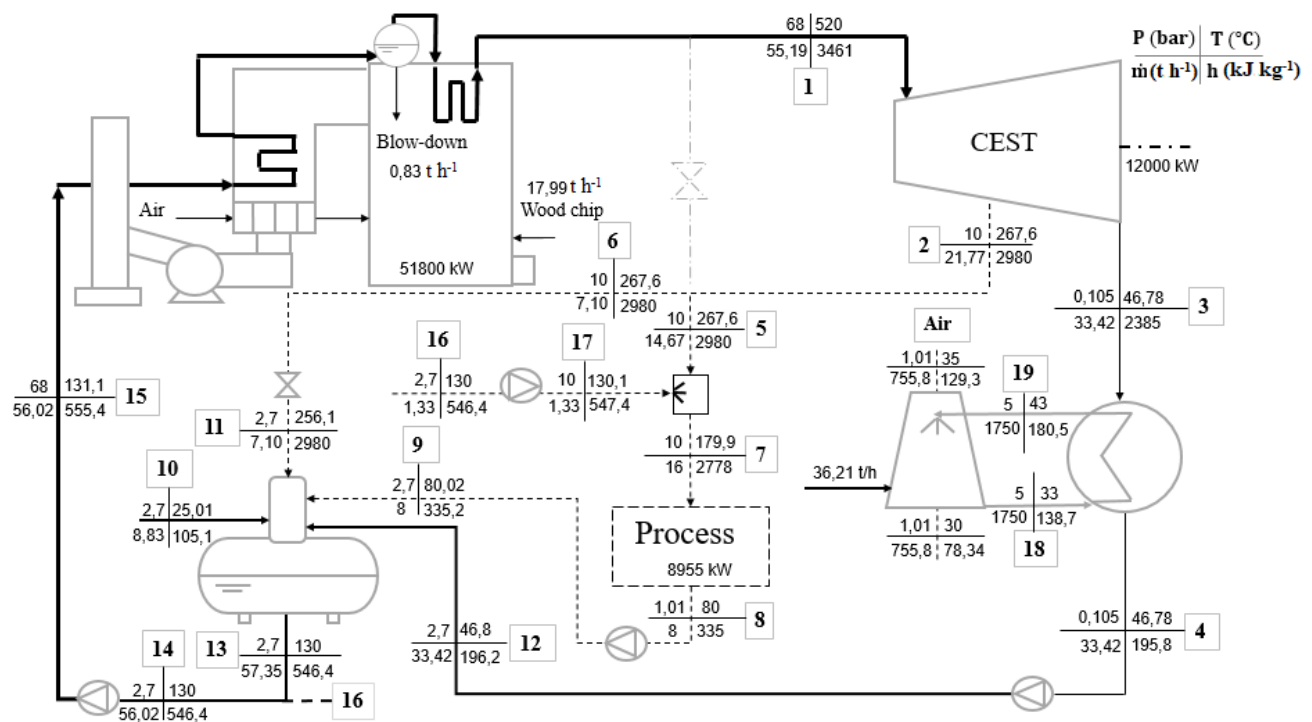


Figure 3. Design point SG2/ST2 plant operation in cogeneration mode (working days).

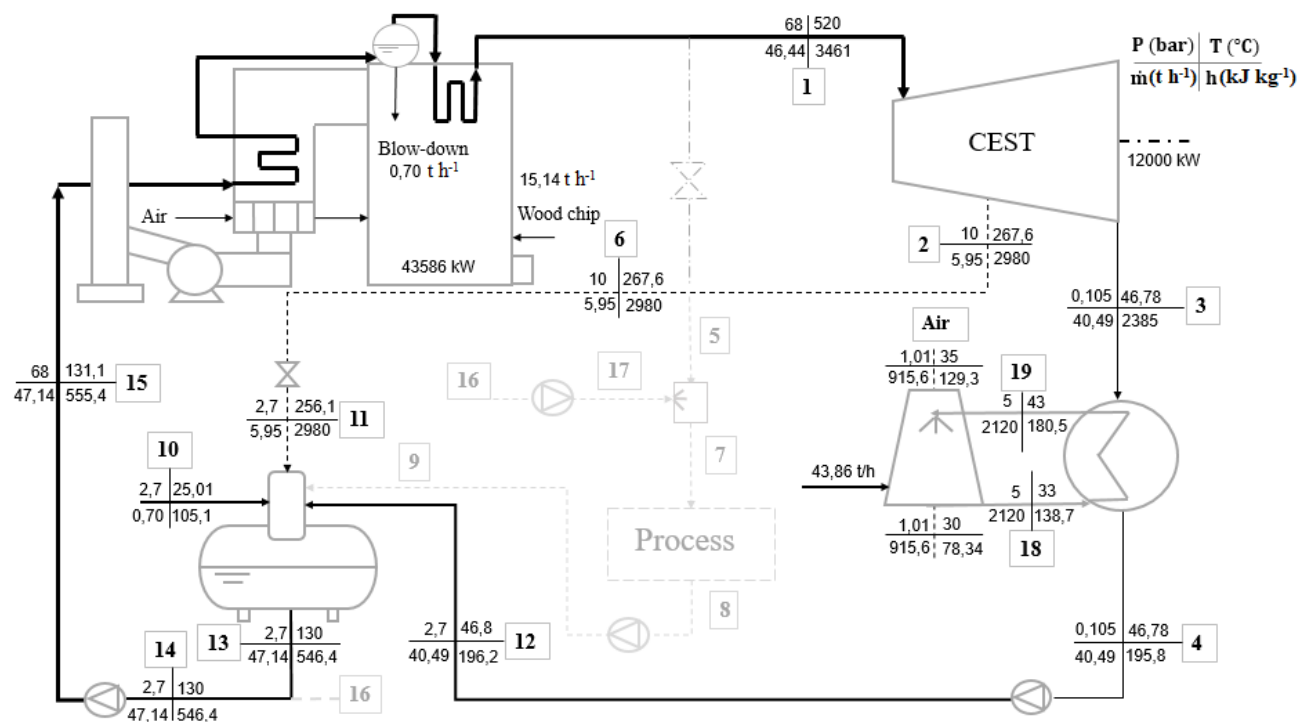


Figure 4. Design point SG2/ST2 plant operation in Rankine mode (weekends).

The results for the annual operation of plants are presented in Table 6.

Table 6. Results for annual operation of proposed concepts.

Parameter	SG1/ST1	SG1/ST2	SG2/ST1	SG2/ST2
Electricity output (MWh year ⁻¹)	96,480	96,480	96,480	96,480
Electricity exported to the grid (MWh year ⁻¹)	29,517	29,517	29,517	29,517
Process thermal energy output (MWh year ⁻¹)	51,430	51,430	51,430	51,430
Plant efficiency (%)	29.6	33.8	32.6	37.2
Biomass consumption (t year ⁻¹)	173,262	151,761	157,481	138,093
Land area demanded for biomass crop, A_{la} [ha]	8,251	7,227	7,499	6,576
Make-up water consumption (t year ⁻¹)	517,397	421,606	447,472	361,024

As it can be seen, the concept SG2/ST2 presented the highest thermal efficiency due to the higher grade of superheated steam and the higher isentropic efficiency of reaction turbine. This led to reduced annual biomass and make-up water consumption. Furthermore, the reduced biomass consumption translates into less land area demanded for the biomass crop. Under the base case scenario where process steam is generated in a low-pressure boiler, the land area demand calculated according to Equations 12 and 13 is estimated at 944 ha, while in the case of SG2/ST2, it might be expanded to 6,576 ha (~7x more land area demand). In this regard, land area availability is an important aspect to be considered when proposing to supply the heat and electricity demands of poultry industries.

Results related to the economic analysis are presented in Table 7.

Table 7. Costs related to proposed concepts.

Parameter	SG1/ST1	SG1/ST2	SG2/ST1	SG2/ST2
CAPEX (10 ³ US\$)	12,163	12,528	12,777	12,106
OPEX ^a (10 ³ US\$ year ⁻¹)	738	668	687	624
Fuel (10 ³ US\$ year ⁻¹)	7,830	6,858	7,117	6,240
Avoided costs (10 ³ US\$ year ⁻¹)	9,389	9,389	9,389	9,389
Revenues (10 ³ US\$ year ⁻¹)	1,712	1,712	1,712	1,712
Expenses (10 ³ US\$ year ⁻¹)	10,267	9,225	9,503	8,564
Cash flow (10 ³ US\$ year ⁻¹)	834	1,875	1,598	2,537

^a OPEX: Operational Expenditures.

The Capital Expenditures (CAPEX) include the investment cost of the steam generator, steam turbine, cooling tower and water treatment system. As it can be seen, no significant CAPEX variation between the concepts is observed. In case of SG2/TG2, despite the use of higher pressure/temperature steam parameters and reaction turbine type, the improved thermal efficiency of plant led to the specification of a cheaper reduced capacity steam generator. The Operational Expenditures (OPEX) include the annual operating and maintenance costs, consisting of labor, water treatment and equipment maintenance costs. Expenditure on the purchase of biomass is calculated considering the annual fuel consumption of each concept and the local biomass cost (45.19 US\$ t⁻¹). Regarding the avoided costs, they consist of the amount that would be paid for the electricity and for producing steam if base case system was used, while the revenue is related to the sale of surplus electricity to the grid. In turn, the annual expenses are calculated considering the cost of fuel, OPEX and costs related to electricity demand contract and electricity consumption. The demand contract is necessary to guarantee the supply of electricity in case the cogeneration plant is offline (See Appendix B). Moreover, the electricity consumption refers to the value consumed during the shutdown of the cogeneration plant for maintenance.

Regarding the economic analysis, the SG1/ST1 configuration presented negative NPV, that is, during the useful life of the plant the return is lower than the investment. On the other hand, the SG1/ST2, SG2/ST1 and SG2/ST2 configurations had positive NPV; therefore, the initial investment was paid and yielded 4.49, 1.72, and US\$ 10.93 million, respectively.

The IRR and the discounted payback DP are shown in Figure 5. When the NPV is positive, the IRR is higher than the minimum acceptable rate of return and the discounted payback is less than the plant lifetime. In contrast, for a negative NPV, the IRR is lower than the minimum acceptable rate of return and the discounted payback is longer than the plant lifetime. The SG2/ST2 configuration presented positive NPV of US\$ 10.93 million, IRR of 20.77% (which is higher than the 10% minimum acceptable rate of return) and discounted payback of six years.

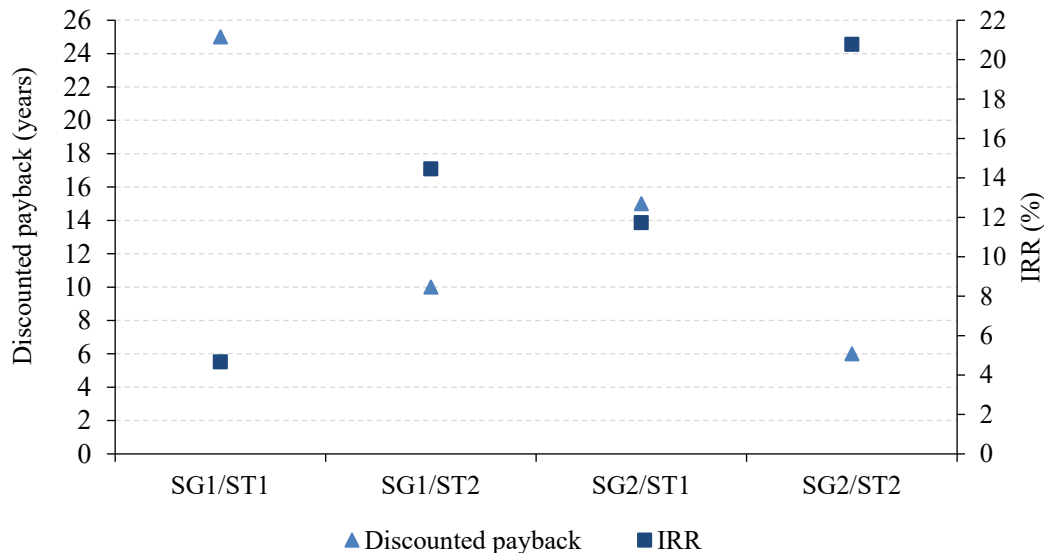


Figure 5. Discounted payback time and Internal Rate of Return (IRR) of investments for the proposed concepts.

The LCOE versus plant thermal efficiency for the proposed concepts are presented in Figure 6. As it can be seen, the SG2/ST2 plant presented the best operating conditions, both for the efficiency of 37.2% and for the LCOE of 73 US\$ MWh⁻¹. In all cases, nevertheless, the obtained LCOE results were higher than the 58 US\$/MWh paid for surplus electricity. In fact, the feasibility of plants was determined by the avoided costs related to electricity purchasing and steam generation under the base case layout.

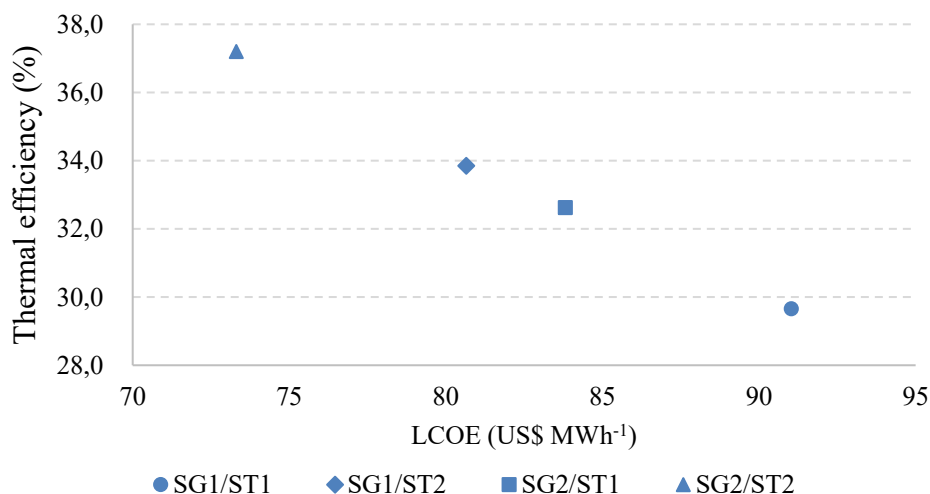


Figure 6. LCOE versus plant thermal efficiency for proposed concepts.

In summary, it was possible to identify that the most feasible layout was based on the use of higher steam parameters and reaction turbine. This is in accordance with the trend observed in the Brazilian market of biomass power plants, where improved steam parameters are being implemented today – see Figure 7. Furthermore, regarding the influence of superheated steam parameters and turbine expansion type on the economic figures, it was possible to identify, for the scenarios here studied, that upgrading the plant

configuration to a reaction turbine (SG1/ST1 to SG1/ST2) tented to be more profitable than upgrading steam parameters (SG1/ST1 to SG2/ST1). This is an important result that might be considered during the conceptual engineering phase, when designers must choose the most feasible solution.

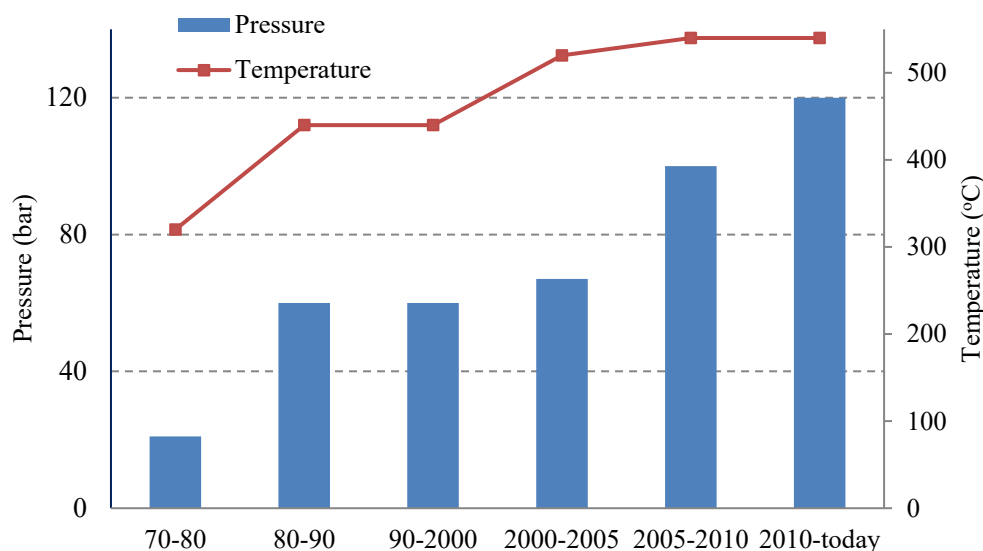


Figure 7. Typical superheated steam parameters of biomass steam generators delivered in the Brazilian market along the time.
Sources: <https://bitlybr.com/43ntHexd>.

Finally, the industrial costs with thermal energy ICT [US\$ ton⁻¹] and electricity ICE [US\$ ton⁻¹] for the base case and cogeneration equipped plants are presented in Figure 8. In case of SG2/ST2 scenario, the industrial cost with energy is reduced to 19 US\$ ton⁻¹, i.e. 30% lower when compared to the base case, indicating potential economic feasibility of the proposed concept.

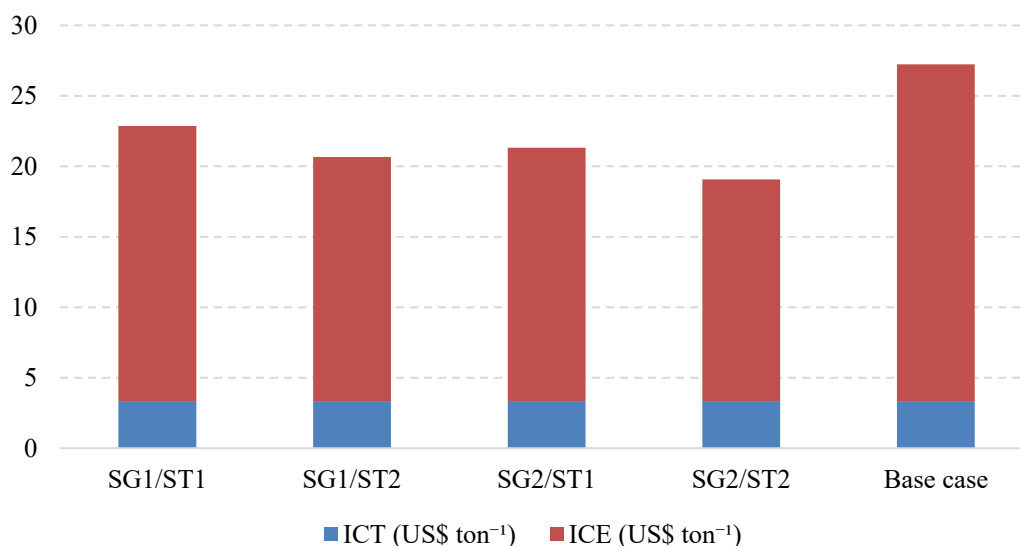


Figure 8. Industrial costs with thermal energy ICT and electricity ICE for base case (reference plant) and cogeneration equipped slaughterhouse.

Conclusion

The results obtained in this work indicate the technical and economic feasibility of cogeneration plants to meet the thermal and electrical energy demands of poultry slaughterhouses, which represent an important sector of the Brazilian agribusiness. In general, the improvement of superheated steam parameters and the use of reaction steam turbines lead to a higher thermal efficiency of the plants, reduced energy forest plantation area for the production of woodchips, and greater economic attractiveness. The results

demonstrated the possibility of reducing industrial energy costs by up to 30%, indicating the economic potential of the proposed concept.

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Appendix A

The hourly electricity and process steam demands for one selected day are presented in Figures A1 and A2, respectively. As it can be seen, the demand profiles are nearly stable along the day.

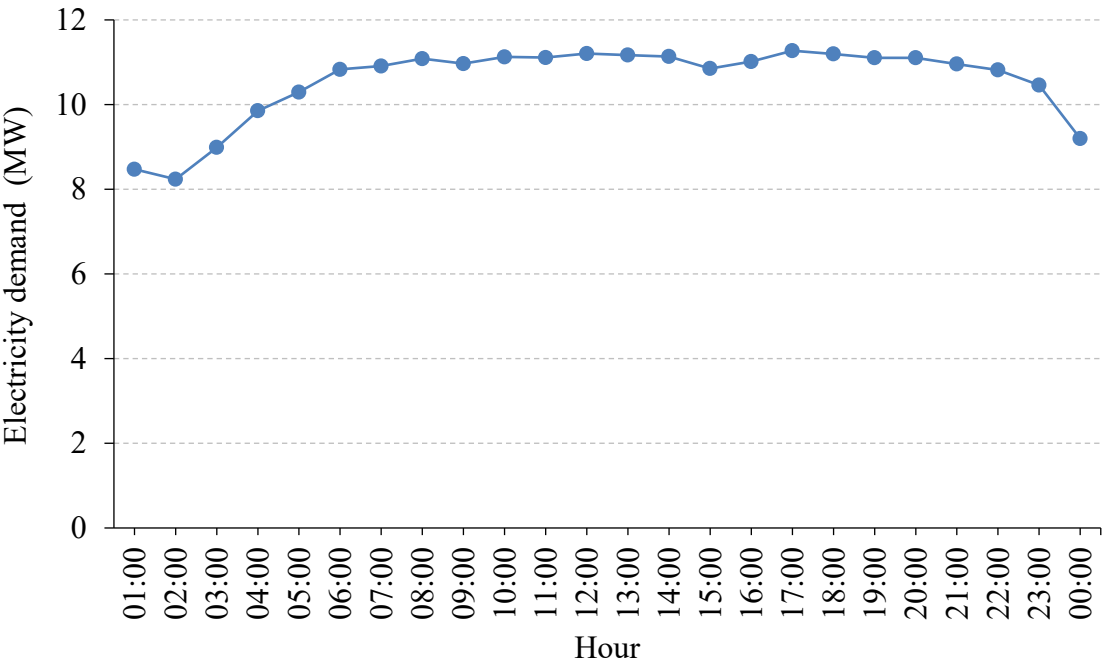


Figure A1. Poultry slaughterhouse average hourly electricity demand.

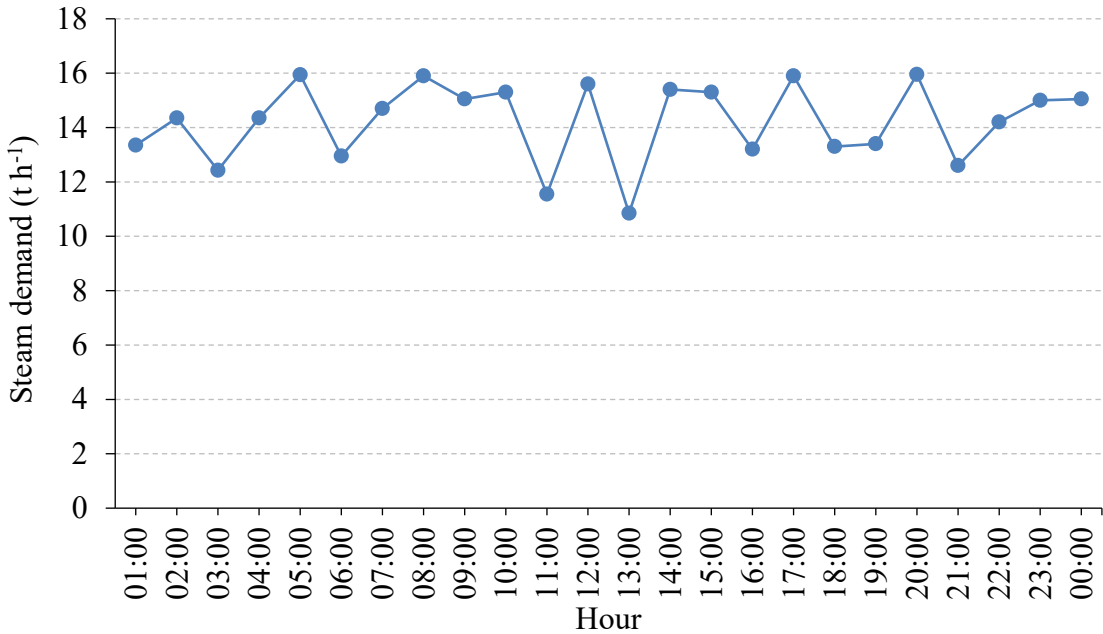


Figure A2. Poultry slaughterhouse average hourly process steam demand.

Appendix B

The energy consumption and demand charges applied to the studied poultry slaughterhouse are presented in Table B1. The contract with the electricity distributor is considered to guarantee the electricity supply to the slaughterhouse even when the cogeneration plant is off.

Table B1. Energy and demand charges applied locally by the electricity distributor to the studied poultry slaughterhouse.

Parameter		Value	Unit
Demand charges	Peak hours ^a	4.13	US\$ kW ⁻¹
	Off-peak hours	1.72	US\$ kW ⁻¹
Distribution system usage charge		0.0091	US\$ kWh ⁻¹
Energy charges	Peak hours ^a	0.1064	US\$ kWh ⁻¹
	Off-peak hours	0.0696	US\$ kWh ⁻¹

^a 18 to 21h (19 to 22h at summertime) on working days (from Monday to Friday, except holydays). Source: <https://www.copel.com/>