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MULTI-OBJECTIVE OPTIMIZATION OF ORC CYCLES OPERATION FOR WASTE HEAT RECOVERY IN STEEL-MAKING INDUSTRY.

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Abstract. *This study evaluates the application of an organic Rankine cycle for the generation of electricity by recovering the low-temperature residual heat of a steel-making industry. High demand for electricity marks Siderurgic applications. The disposal of residual heat in these activities is a concern both financially and from the environmental point of view. This study will evaluate the multiobjective optimization of the operating parameters of an ORC cycle using R245fa working fluid for the low-temperature residual heat recovery of a process of the ThyssenKrupp Steel Company of the Atlantic Steel Company (TKCSA). The thermal source evaluated corresponds to the waste gases from the company's Thermoelectric Power Plant. The operation of the plant is modeled with the ASPEN-HYSYS® software v.8.6 according to the actual process conditions. The objective functions of interest in the optimization process were to maximize the net power of the ORC cycle and to minimize the area of the heat exchangers. The operation variables of the cycle: Pinch point, superheat, vapor pressure, condensation temperature and effectiveness of the heat exchangers are selected as input conditions for the combination of the parameters in the multiobjective simulation. In this analysis, the optimal results of the use of the ORC cycle would allow the generation of net power above 2100 kW. The operation parameters that provides greater economic viability occurs for the generation of 1633 kW of net power.*
Keywords: *Organic Rankine Cycle, Waste heat recovery, Steel Industry*

1. INTRODUCTION

Global energy demand has grown steadily in the last decades, and in parallel, awareness of the limitation of fossil fuel resources. However, we are currently experiencing a period of alignment of global public policies concerning the mitigation of environmental problems. These factors accentuate the search for more efficient, environmentally and economically efficient industrial processes and energy generation methods.

Steelmaking is one of the great pillars of Brazilian industry, with a strong presence both in the intern market and in Brazil's exports. Their great economic importance and their resulting environmental impacts often make them the target of discussion mainly for public policies. These policies relate to environmental constraints and also to industrial growth (BAJAY, 2009). High demand for electricity marks Siderurgic applications. According to United Nations, (2015) energy is the dominant contributor to climate change, accounting for around 60 percent of total global greenhouse gas emissions.

Most industrial activities reject about 50 percent of all the heat generated in their production processes (CARCASCI; FERRARO; MILIOTTI, 2014). Results from a study conducted in the USA showed that the potential for energy generation using the residual heat of industrial processes in the country is higher than the total electricity produced by renewable sources (US DEPARTMENT OF ENERGY, 2008).

Residual heat sources in the range of 200° C to 400° C can be easily found in the steel industry. Waste heat recovery is an excellent opportunity for improvement in energy efficiency using an organic Rankine cycle (ORC) as clean and renewable energy.

Organic Rankine cycle is an alternative technology for efficient conversion of low and medium temperatures for electricity generation at small and microscale. This technology allows the use of energy resources with smaller systems and high economic performance. The working fluids in an ORC cycle present boiling points and latent heat of vaporization inferior to that of water, allowing evaporation to lower temperatures. These technical features provide better utilization of low-quality energy sources, allowing efficient use of energy resources. (GOTELIP, 2015)

Cement industry can generate about 20% of the total electric energy consumed by the plant through the exhaust gases and the cooling air during the production process. Disposal of waste heat is a concern not only from a financial point of view but also from an environmental point of view. The disposal of carbon dioxide in the atmosphere is one of the most significantly responsible for global warming and intensification of the greenhouse effect (VESCOVO, 2009)

2. TECHINICAL DESCRIPTION

In this study will be evaluated the multiobjective optimization of the operating parameters of an ORC cycle for the low-temperature residual heat recovery of a process of the ThyssenKrupp Steel Company of the Atlantic Steel Company (TKCSA).

The thermal source evaluated in this study were the waste gases from the Thermoelectric Power Plant (TPP), after the recovery of heat from the combined cycle. The thermoelectric plant operates in a combined cycle composed of two gas turbines, which exhaust gases are recovered in recovery boilers for the steam generation used in a Conventional Rankine system. The fuel used in the turbine is the blast furnace gas of the industry itself. The representation of the facilities of the thermal plant that operates in the plant is shown in Figure 1.

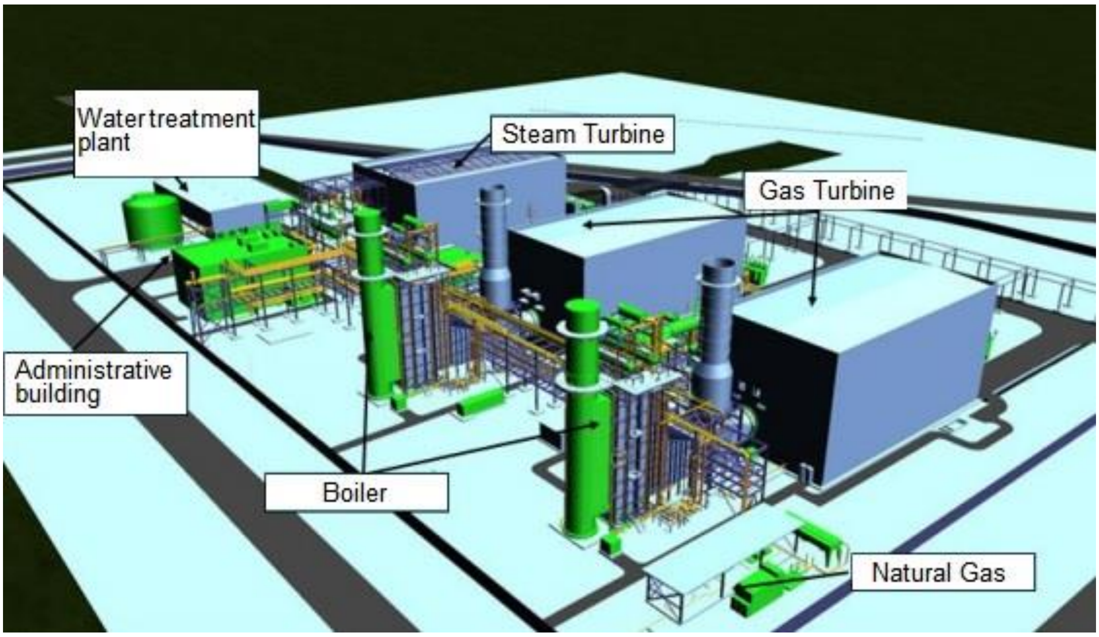

Figure 1. Schematic representation of the Thermoelectric Power Plant.

The operation of the TPP allows the company to generate 490 MW of electrical power, of which 255 MW is used in the steel mill's processes, and the remaining 235 MW is sold in the National Interconnected System. The purpose of this study is to evaluate the use of the ORC cycle to increase the electric power generation in the TPP, recovering the thermal energy the residual gas of the plant, discarded in the atmosphere after the combined cycle.

2.1 ORGANIC RANINE CYCLE

The generation of electric energy using heat recovery is a well-established form of energy conversion, whose most exploited thermodynamic cycle is the conventional Rankine cycle. However, the use of heat sources below 400 ° C makes it impossible to use the conventional Rankine cycle due to its low efficiency under these conditions, considerably increasing generation costs.

The organic Rankine cycle (ORC) is a more efficient technology alternative for conversion of low and medium temperatures for small and micro-scale electricity generation. This technology allows the use of energy resources, counting on smaller systems and with high economic performance.

The ORC has the same operating principle as the conventional cycle, consisting of its main components: a pump, evaporator, turbine, and condenser. The differential between the cycles is the working fluid used, where the conventional Rankine cycle operates using water and the ORC uses hydrocarbons or refrigerant fluids, which gives it, differentiated characteristics.

Working fluids in an ORC cycle have a low boiling point and a latent heat of vaporization below that of the water, allowing evaporation at lower temperatures, which allows better utilization of the heat supplied by the hot source, and shows its use for the use of sources of low and medium temperatures.

The operation of the ORC cycle is described in Figure 2, and can be represented as:

1-2: Compression of the liquid performed by the pump.
2-3: Receiving heat.
3-4: Receiving vaporization heat at pressure P2.
4-5: Receiving heat from the superheater.

5-6: Expansion in the turbine with the production of work.
6-1: Heat rejection in the condenser.

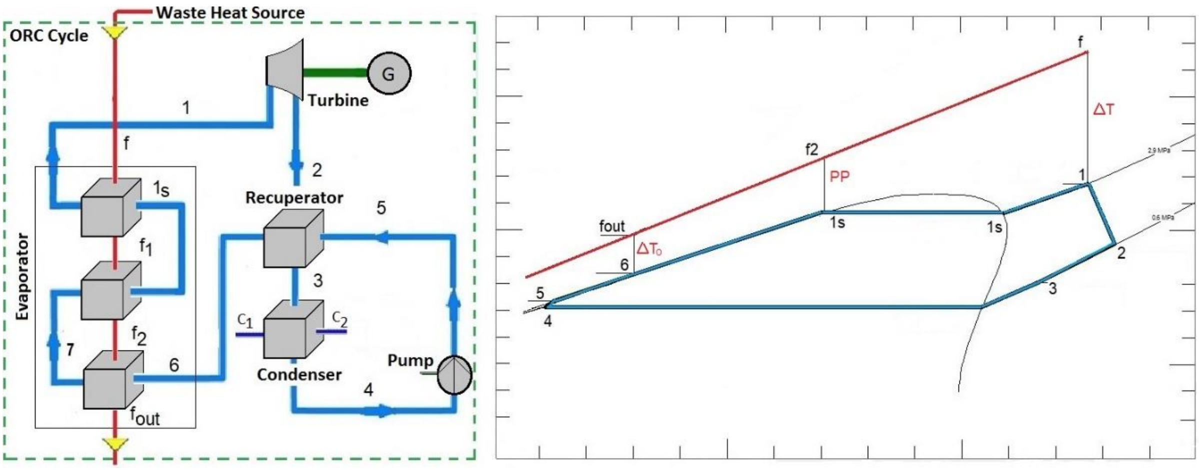

Figure 2 ORC diagram (GOTELIP et al., 2018).

3. METHODOLOGY

3.1 Thermodynamic Modeling of the ORC Cycle

The properties of the working fluids, operating parameters and the configuration of the thermal system have a fundamental role in the thermodynamic efficiency and economic viability of the ORC cycle. A computational tool was developed in MATLAB® to determine the mass and energy balance of the cycle operation, allowing the evaluation of the thermodynamic properties of the working fluids and the thermal source. The model in question uses the cubic state equations of REFPROP 9.1® software as its subroutine as well as its fluid library. In this way, it is possible to carry out the performance analysis of the operation of the ORC cycle. The full model is described in (GOTELIP et al., 2018).

The mass and energy balance are applied to each component of the cycle. For a control volume in a steady state, the situation of the mass in its interior and its borders does not change with the time; one has the energy balance the formulation:

$$\dot{Q}_{vc} - \dot{W}_{vc} + \sum_{e} \dot{m}_e \left(h_e + \frac{V_e^2}{2} + g z_e \right) - \sum_{s} \dot{m}_s \left(h_s + \frac{V_s^2}{2} + g z_s \right) = 0 \tag{1}$$

In the thermodynamic modeling of the cycle the following simplifications were assumed:

- The operating cycle occurs under steady state;
- The variation of potential energy and kinetic energy of the working fluid throughout the cycle is disregarded;
- Heat losses to the environment in pipes, turbine, pump and heat exchangers are disregarded;
- Detailed calculations of pressure losses and heat transfer in the evaporator, recuperator, and condenser are ignored as they depend heavily on materials and design details of heat exchangers (adiabatic process);
- Heat exchangers operate with countercurrent flow;
- The isentropic efficiencies of the turbine and the pump are constant (ηb = ηt = 80%);
- The working fluid at the condenser outlet is a saturated liquid;

3.2 Thermodynamic modeling of the thermal source

The processes of the Thermoelectric Power Plant (UTE) evaluated in this study were simulated using ASPEN-HYSYS® software v.8.6. The model of PRSV state equations was used to calculate the physical and thermodynamic properties, according to the composition of the actual gas flows of the operation. The composition of the process waste gases and their operating conditions are described in Table 1 and Table 2 respectively. The full plant is described by (JÚNIOR, 2017).

Table 1 Composition of the heat source. (VIEIRA, 2015)

Substance	Mass Fraction
Oxygen	0.1273
Nitrogen	0.5953
Water	0.0124
Carbon dioxide	0.2650

Table 2 Heat Source Data (ALSTOM, 2007).

Properties	Value
Temperature (°C)	142.0
Pressure(kPa)	101.3
Mass flow (kg/s)	311.0

3.3 Economic analysis

The design of a new thermal system will require an appropriate economic evaluation. Thus, investments, taxes, operating and maintenance costs must be established to analyze the feasibility of the project.

However, the purchase costs of each equipment (PEC) that compose the cycle are estimated through non-linear mathematical correlations, generally in function of the area required for evaporators, heat exchangers and capacitors, and electric power generated or consumed in the case of turbines and pumps, as can be seen in (TALJAN et al., 2012; TOFFOLO et al., 2014). Costs of heat exchangers (evaporator, recuperator, and condenser), turbine and pump can be estimated using the mathematical correlations, Equations 2-7, presented in (ANVARI; TAGHAVIFAR; PARVISHI, 2017).

$$PEC_{Eva} = 309.143 \cdot (A_{Eva}) + 231.915 \quad (2)$$
$$PEC_{Turb} = 6000 \cdot (\dot{W}_{ST}^{0.7}) \quad (3)$$
$$PEC_{Cond} = 1773 \cdot (\dot{m}_{steam}) \quad (4)$$
$$PEC_{Reg} = 0.322 \cdot (30.000 + 0.75 \cdot A^{0.8}) \quad (5)$$
$$PEC_{Pump} = 3540 \cdot (\dot{W}_{P}^{0.7}) \quad (6)$$
$$PEC_{total} = PEC_{Eva} + PEC_{Turb} + PEC_{Cond} + PEC_{Reg} + PEC_{Pump} \quad (7)$$

The economic appraisal methodology generally involves a set of techniques that provide decision criteria to the investor to determine the economic and financial viability of one or more investments considering a given opportunity cost. These decision parameters will be determined in this study from the analysis of the Net Present Value (NPV). The economic analysis addressed in this study is described in (SOTOMONTE, 2015).

The purpose of NPV is to evaluate regarding present value the impact of future events related to a specific investment, i.e., it is the monetary equivalence for the present instant of the future cash flows, discounted to the minimum rate of attractiveness, being expressed by equation:

$$NPV = -I + \sum_{t=1}^{n} \frac{CF_t}{(i+1)^t} \quad (8)$$

CF= Cash flow in period t.
I= Initial investment.
i= Comparative interest rate.

There are three possibilities for the NPV of investment: 1) Values above zero indicating that the investment is economically attractive, that is, the present value of the cash inflows is higher than the present value of the cash outflows. 2) Values equal to zero indicate that the investment is neutral since the present value of the inflows and outflows are equivalent. 3) Values below zero indicate that the investment is not economically attractive. In this order of ideas, it is clear that the higher the NPV, the more attractive the investment (SOTOMONTE, 2015).

3.4 Multiobjective optimization

Multiobjective optimization is performed using the developed computational tool, integrated with the commercial software ModeFrontier®, which is modeled by the NSGA-II optimization algorithm. The objective functions of interest for this study were defined as maximizing the net power of the ORC cycle and maximizing the NPV of the investment. The evaluation of the results is based on a series of constraints, implicit in the thermodynamic model, that penalize the solutions in order to remove the thermodynamically inconsistent results.

The pinch, superheat, vapor pressure, condensation temperature (ORC cycle) and heat exchanger effectiveness variables are selected as input conditions for the combination of parameters in multiobjective simulation. The determination of these variables has a direct influence on the performance of the cycle.

In this initial analysis, we considered the optimization of ORC cycle operating parameters by evaluating only R245fa as working fluid. The R245fa is commonly used in consolidated operations of ORC systems, in addition to having significant security features, low levels of ODP.

In this study, the Pareto methodology was used to determine the ideal results of the operation of ORC cycles for the generation of electric power through the recovery of residual heat from the processes of the steel industry. The Pareto Optimum, presented in PARETO (1896), provides a precise meaning for "ideal equilibrium curve," allowing a definition of optimization for a multiobjective problem.

4. RESULTS

In Figure 3 is presented the result of the multiobjective optimization of the application of the ORC cycle for residual heat recovery of the Thermoelectric Power Plant processes. In this analysis, different operating parameters of the ORC cycle were evaluated using R245fa fluid. The optimization aims to maximize the power generated in the ORC cycle and maximize the NPV. The highest power obtained by the ORC cycle was 2100 [kW].

It is observed that the distribution of the results has a parabolic behavior. The increase of the power generated in the ORC cycle promotes an increase of the NPV up to a maximum point, from which this value decreases according to the increase of power, due to the associated increase of equipment costs.

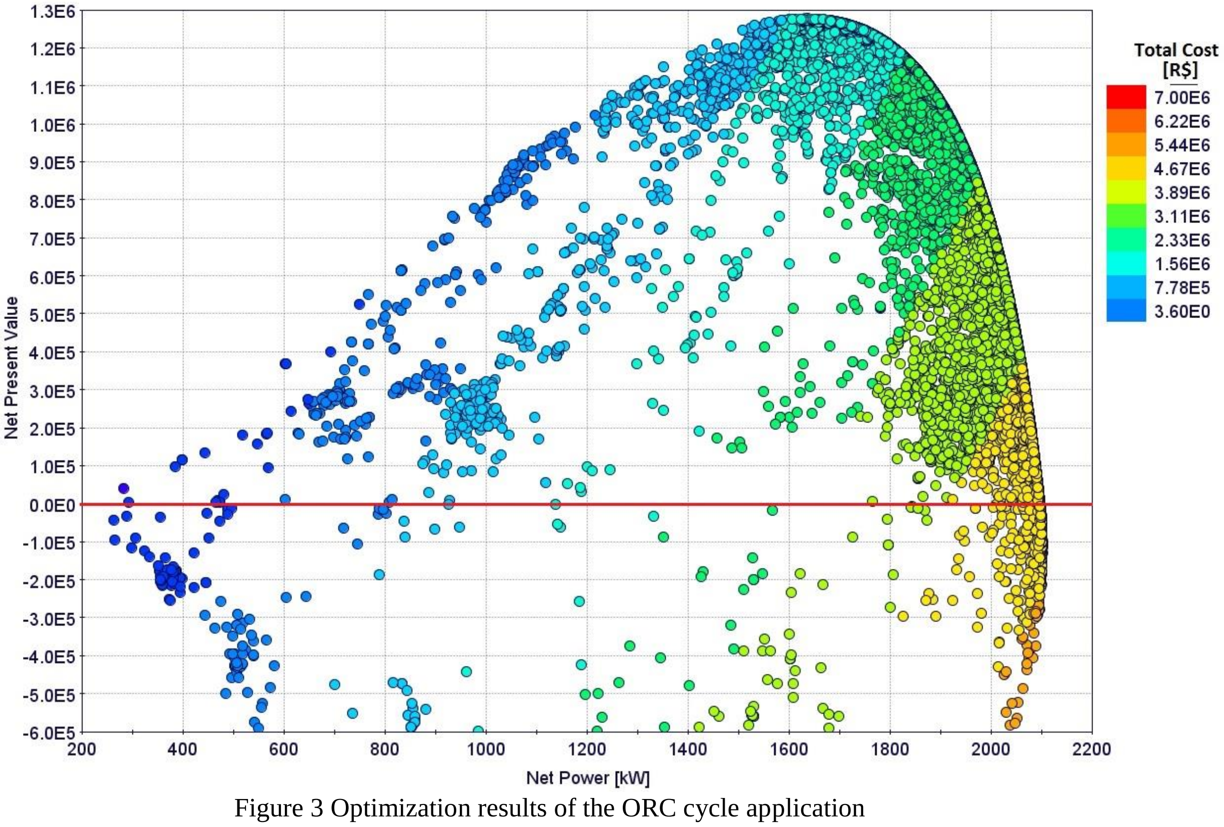

Figure 3 Optimization results of the ORC cycle application

In Figure 4 it can be observed that the increase of the power generated by the cycle requires a larger area of the equipment of heat exchange, directly connected to the increase of the total cost of the cycle. From the results evaluated, on average the evaporator is responsible for 67% of the total area of heat exchange required by the cycle, followed by the condenser with 33%. Since it is a source of low temperature, none of the cases of the optimization results was favorable for the use of the ORC cycle heat exchanger.

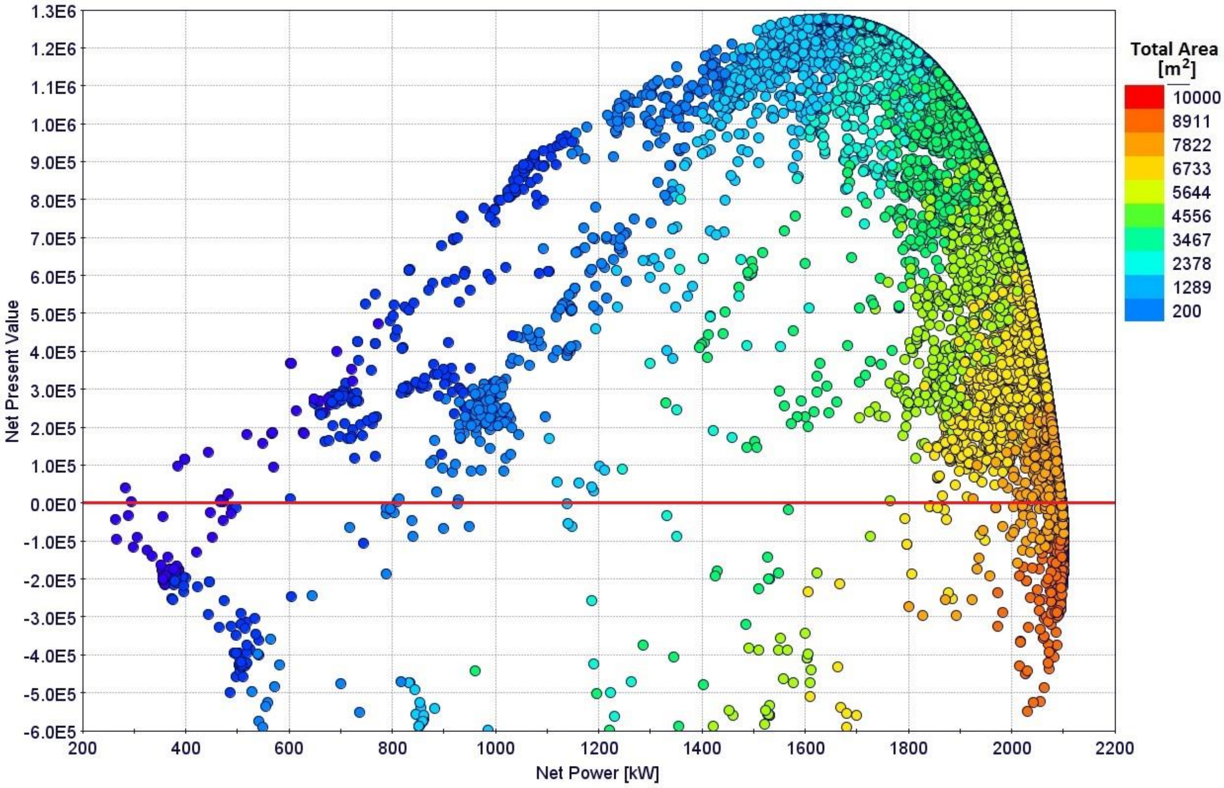

Figure 4 Analysis of the area in the results of the ORC cycle.

In the Figure 5 the Pareto frontier of the multiobjective optimization is shown. This analysis presents the results of higher NPV for each net power generated. The highest value of NPV is 1,277e6, associated with the generation of 1633 [kW] of net power. For this condition, the total cost of installing the ORC cycle was R $ 2,911,717.00. The costs of the project are divided between direct costs R $ 786,950.00, indirect costs R $ 393,475 and costs of equipment purchase R $ 1,967,376.00. The turbine represents the largest share of equipment purchase costs of 57.5%, followed by the evaporator and condenser 31.9% and 7% respectively, followed by pump costs of 3.6%.

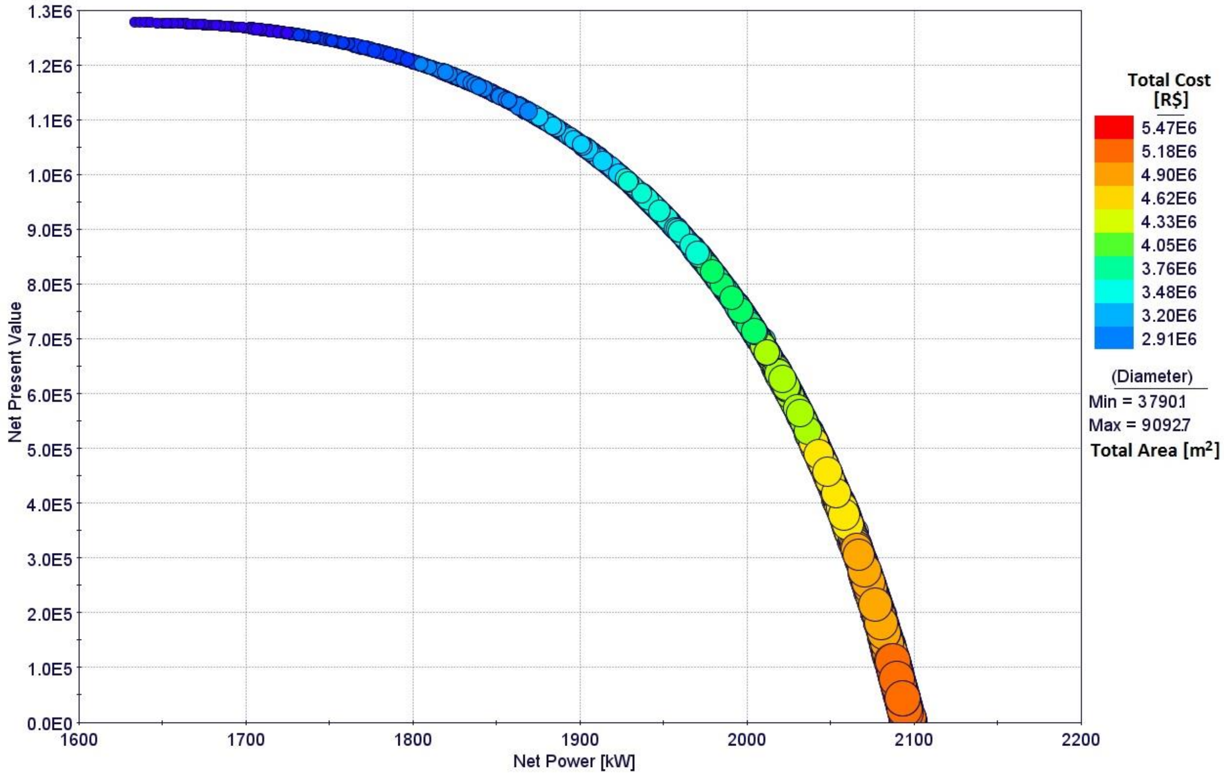

Figure 5 Pareto frontier of optimization results.

5. CONCLUSIONS

The present study allowed the evaluation of the recovery of residual heat from processes of a steel industry in Brazil for the generation of electric power using ORC cycles. Through the computational tool developed, it is possible to evaluate different operating conditions of the proposed cycles and the heat source, determining the optimum operating conditions.

The use of ORC cycles for residual heat recovery in a steel industry is favorable, allowing, in a clean and safe way, an increase of the electricity demand of the process besides the greater efficiency of the plant.

Optimizing the ORC cycle for plant heat recovery reveals a potential application of the technology, providing the generation of up to 2100 kW of net power. The primary objective of any investment is that it is economically viable. Due to this, an economic analysis is essential for decision-making. This analysis revealed that the operation parameters that provides greater economic viability occurs for the generation of 1633 kW of net power. The generation of higher powers from this point increases equipment costs, reducing the feasibility of system deployment.

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