Power Generation from Low Grade Industrial Waste Heat

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***Abstract*—The objective of this study is to investigate the economic viability of non-conventional power cycles such as Kalina Cycle System 11 (KCS-11) and Organic Rankine Cycle (ORC) to convert waste heat of aluminum smelters into electricity. A comparison between both technologies is carried out using a model that combines market economic parameters and energy performances obtained from the thermodynamic analysis. Indicator such as specific cost of power generation has been determined for different capital cost scenarios. Additionally, a sensitivity analysis is conducted to determine the effect of governing parameters on the economics. The results show that KCS-11 performances are superior to those obtained with ORCs under the same operating conditions. The overall efficiency based on the energy content of the thermal effluent is in the range of 2.4% to 8.5% depending on the heat source temperature. In addition, results reveal that a specific net power output of 16kW per ton of aluminum annual production is technically achievable and a specific cost of power generation around 6 ¢/kWh appears to be feasible.**

***Index Terms*—waste heat recovery, power cycles, economic assessment**

I. Introduction

The industry activities result in large quantities of waste heat of various grades being discharged directly to the atmosphere. Due to arising energy costs and environmental constraints the industry shows an interest to study the possibility to capture waste heat to use it within plant facilities or sell it to external consumers for other applications. For instance, the captured heat can be used for power generation, compressed air production, process heat and space/water heating or cooling. If the recovered heat is used for power generation, it will enhance the process efficiency by increasing the amount of useful energy output per unit of energy input while substantially reducing greenhouse gas emissions. The generated power avoids purchasing extra electricity to increase the production. Hence, it is necessary to investigate the possibility to convert this low grade waste heat to usable high voltage electricity using non-conventional power cycles.

A review of the literature revealed that research on low grade heat source for power generation has received a lot of attention namely for solar, geothermal and Combined Heat & Power (CHP) applications [1]-[3]. A thorough review of the various applications is presented in reference [4]. Among the conversion systems investigated, the Kalina cycle is being considered the most promising solution for low grade waste heat recovery. A comparison between Kalina and ORC performance for low temperature applications is conducted in references [5]-[7] by performing thermodynamic analysis. However, only few studies examine the economic performances of such systems. The work in reference [8] provides a brief cost analysis as well as the environmental benefits using a Kalina cycle. A more detailed economic analysis has been reported by [9]. Their results show that the theoretical efficiency and cost/production ratio are much better for Kalina cycle.

The purpose of this study is to investigate the technical and economic feasibility of implementing non-conventional systems based on ORCs and the KCS-11 to harness low-grade waste heat embodied in top-gas exiting electrolytic cells in primary aluminum plants. An evaluation of potential costs and benefits of this application is discussed along with a sensitivity analysis to identify the parameter that heavily impacts the profitability.

II. Waste Heat Characterization

Aluminum smelters are made up of one or many clusters of electrolytic cells connected in series. The cells are covered by a hood and are maintained at a slightly negative pressure to avoid any contamination of the workplace with the process top-gas. A system of exhaust of process top-gas is connected to one or more gas treatment center (scrubbers) where large mass flow rate are treated prior to their release into the atmosphere. An illustration of connection duct is shown in Fig. 1. The gas treatment center is used to recycle HF gas into the process by injecting alumina and also to capture contaminant matters.

Primary aluminum industry possesses various waste heat sources with potential of further exploitation to maximize energy recovery via non conventional power cycles. This study focuses on the electrolytic cells where approximately 50% of the electricity input dissipates in the form of heat: about 70% of this waste heat is lost to the environment through sidewalls, hood; collector bars, bottom and deck; the remaining waste heat (30%) is lost through the top-gas as illustrated in Fig. 2.

Manuscript received June 13, 2015; revised December 29, 2015.

doi: 10.18178/ijoee.4.1.42-47

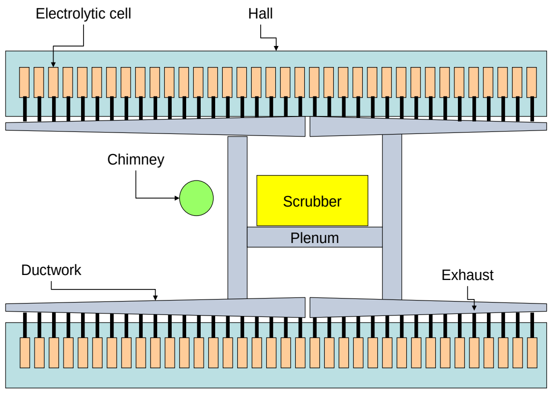

Figure 1. Illustration of a primary aluminum plant configuration.

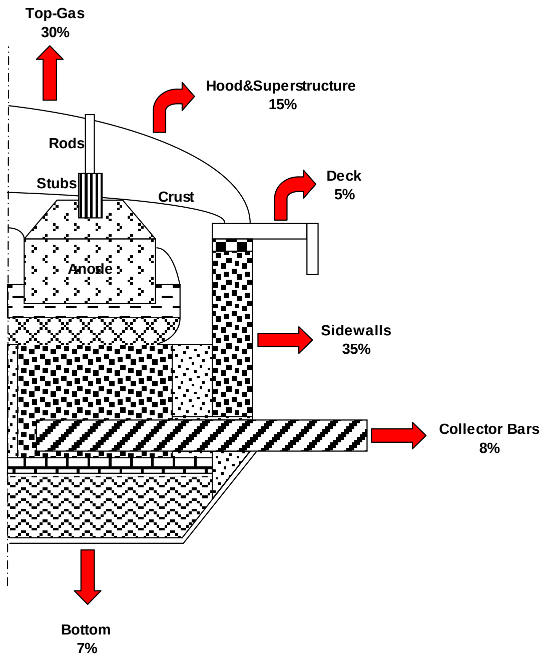

Figure 2. Schematic representation of energy losses breakdown in an electrolytic cell.

This waste heat can be significant in even the most efficiently designed plant. But given that the electrolysis process is temperature sensitive, heat capturing from the sidewalls could be technically risky and compromising for the process. Therefore, the study emphasizes on the waste heat embodied in process top-gas which has been estimated to approximately 700GWh/yr for a typical plant of 250,000 tons of aluminum production per year using the following assumptions:

- Mass flow rate of exit gas: 2.4×10^6 Nm^3/hr
- Temperature of top-gas stream: 100 ℃ above the ambient temperature
- Availability of waste heat source: 100%
- The physical properties of process top-gas are approximated by those of air.

III. Thermodynamic Analysis

The purpose of the thermodynamic analysis is to identify the most efficient option for the application under investigation. Therefore, parametric analyses on both cycles (Fig. 3 and Fig. 4) have been performed to study the impact of the governing parameters (working fluid, mass flow rate, heat source and sink temperatures etc.) on the performance of the system. A commercial software "Chemcad" is used for this purpose. Among the results generated by simulation, only those relative to the most efficient ORCs have been used to compare their overall performances to Kalina cycle.

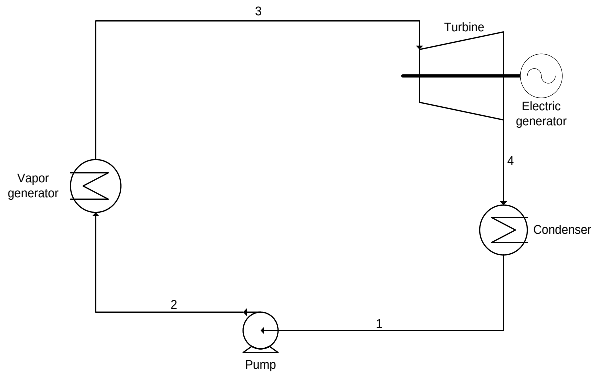

Figure 3. Schematic representation of basic ORC.

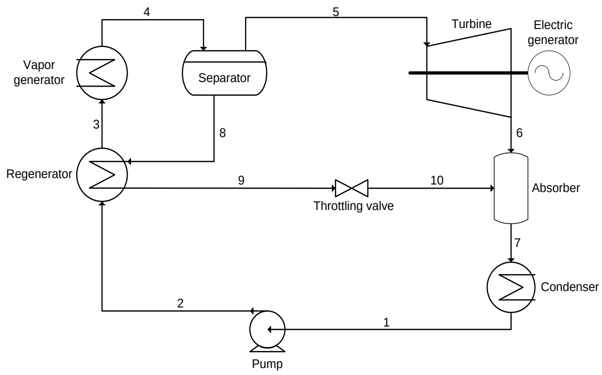

Figure 4. Schematic representation of KCS-11.

The thermodynamic efficiency of any power cycle is usually defined as follows:

$$\eta = \frac{\dot{w}_{turbine} - \dot{w}_{pump}}{\dot{q}_{generator}} = \frac{\dot{w}^{net}_{turbine}}{\dot{q}_{generator}} \tag{1}$$

However, the above definition introduces a bias when different technologies are being compared. Indeed, the denominator is not constant and varies depending on the performance of the cycle under consideration. Hence, it is necessary to introduce the overall efficiency based on the energy content of the waste heat source in order to compare fairly the different technologies on the same basis [10]. Thus, the overall efficiency of the system is defined by the following equation:

$$\eta_{overall} = \eta_{el} \cdot \eta_{th} = \frac{\dot{w}_{turbine} - \dot{w}_{pump}}{\dot{q}_{stream}} = \frac{\dot{w}^{net}_{turbine}}{\dot{q}_{stream}} \tag{2}$$

where η_{el} is the electric efficiency and η_{th} is the heat transfer efficiency of the vapor generator.

The net power output and the energy recovered are results of simulations performed on the cycle. The energy content $\dot{q}_{stream}$ of the waste heat source is given by the following expression:

$$\dot{q}_{stream} = \dot{m}_{top-gas} C_p T_{cell} = \alpha_{top-gas} \dot{m}_{stream} C_p T_{cell} \quad (3)$$

where:

$\alpha_{top\text{-}gas}$: Percentage of top-gas in the diluted process stream (%)

$\dot{m}$: Top-gas mass flow rate (kg/s)

C_p: Top-gas specific heat capacity (kJ/kg. ℃)

T_{cell}: Electrolytic cell temperature (℃)

The energy content has been estimated for a process stream volumetric flow of 2.4×10^6 Nm^3/hr by assuming that the process stream contains roughly 90% of air at the ambient temperature T_{amb} and the remainder being top-gas exiting the electrolytic cell at a temperature T_{cell} fixed to 960℃. Thus, a $\alpha_{top\text{-}gas}$ set to 10% and the physical properties of air are used in equation (3): It is interesting to mention that with a percentage of 10%, calculations with (4) revealed that the temperature of the process stream is typically 100℃ above the ambient temperature in the range of operating temperature conditions.

$$T_{stream} = \frac{\dot{m}_{air} T_{amb} + \dot{m}_{top-gas} T_{cell}}{\dot{m}_{stream}} \quad (4)$$

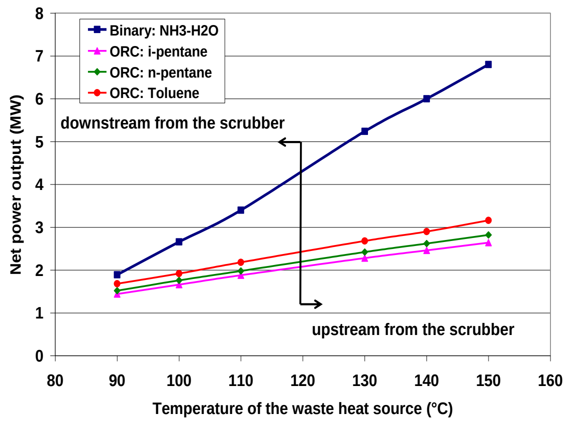

Figure 5. Net power output of KCS-11 versus ORC.

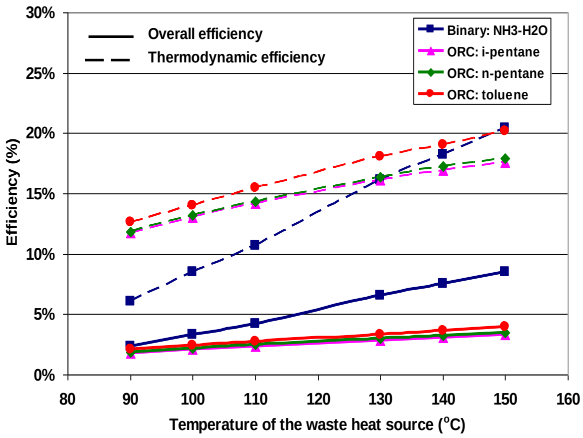

Figure 6. Overall efficiency of KCS-11 vs. ORC.

From the various results obtained from simulations of ORCs for different working fluid, only those using iso-pentane, n-pentene and toluene are compared with Kalina cycle as displayed in Fig. 5 and Fig. 6. These figures illustrate respectively the net power output, the overall efficiency for the ORCs and Kalina KCS-11 as a function of the temperature of the process top-gas released with a flow rate of 2.4×10^6 Nm^3/hr. The temperature of the cold source (condenser) is set to 25℃ and the mass flow rate of the working fluid in all cases is fixed to 50 tons/hr.

It is shown that under the same conditions, the Kalina cycle is superior namely for higher temperature of the top-gas: both the net power output and the overall efficiency are roughly 10% to 60% higher in the case of the Kalina KCS-11 compared to the best case of ORC where toluene is used as a working fluid.

For example at a temperature of 150℃, the net power output obtained with a KCS-11 is 6.8MW ($\eta_{overall}$=8.5%) while it is only 3.16MW ($\eta_{overall}$=3.9%) with the ORC using toluene.

Concerning the thermodynamic efficiency, results show that the KCS-11 performs better than the ORC for higher temperatures. The threshold temperature is 120℃ in the case of i-pentane and n-pentene while it is 150℃ for toluene.

The difference can be explained by the fact that for the Kalina cycle, there is a better temperature matching between the waste heat stream and the working fluid due to the temperature glide of binary fluids during evaporation as mentioned earlier. Thus, the heat transfer in vapour generator is enhanced and consequently its thermal efficiency is improved.

Concerning the ORCs, the constant temperature evaporation process of pure single fluids is the reason of the relatively low thermal efficiency obtained. In this case the temperature difference between streams is large. The thermal efficiency in the vapor generator of the Kalina cycle is around 40% compared to 15÷20% for the ORCs.

IV. Economic Assessment

A tool for economic assessment of waste heat recovery has been developed. It is based on the combination of economic parameters and technical parameters to calculate the Net Present Worth (NPW) and the Annual Payment (ANP) for the technologies under investigation. The technical parameters such as the net power output and the waste heat captured by the system are the outputs of the thermodynamic analysis.

A. Economic Analysis

The economic viability of implementing a waste heat to power system on the top-gas of an aluminum smelting plant depends on the following parameters:

- Size of the plant
- Temperature of top-gas
- Capital cost of the system
- Avoided cost of energy (purchased energy tariff)
- System's operation cost
- Maintenance cost (O&M cost)
- Major replacement cost
- Discount rate or cost of capital

The economic assessment is based on a cash flow approach covering 15 years (system's lifetime) beginning from the date of investment. The cash flow calculations include the costs (capital cost, operation cost, maintenance cost and major replacement cost) and returns (energy cost savings) from the potential investment.

The total cost (C_{TOT}) regroups capital cost (C_C), operation cost (C_O) maintenance cost (C_M) and the cost of major replacements of the system's components (C_R). It is given by the following expression:

$$C_{TOT} = C_C + C_O + C_M + C_R \tag{5}$$

The C_O cost regroups essentially the cost the energy related to the electric consumption of the pump, blower etc. but does not include the labor cost. The maintenance cost of the system is fixed to 0.5, 1.0 cents per kilowatt-hour (¢/kWh) of electricity generated with a Kalina KCS-11 and ORC respectively. The cost of the pump's electric consumption is calculated using the annual consumption of the feed pump and the following electricity rates:

- Demand charges: 11.85$/kW
- Energy charges: 0.0274$/kWh.

The economic indicator used in this study is the specific generation cost obtained by dividing the annuity over the system's annual power generation.

The system's economic viability to the customer is generally determined by comparing the ANP with the utility cost of delivered electricity and the difference represents the total annual money savings. The Annual Payments or annuities (ANP) are calculated as follows:

$$ANP = NPW \cdot \left[\frac{i \cdot (1+i)^n}{(1+i)^n - 1} \right] \tag{6}$$

NPW is the net present value, *i* is the market discount rate and *n* is the covered period.

Essentially, if the difference between the system operating costs and avoided electricity is large enough relative to the investment required to meet the customer's investment-return criteria, the project will go forward. Nevertheless, in this particular situation the customer has essentially three different options to manage the electricity generated onsite:

- Reduce the amount of purchased electricity from the grid
- Sell the electricity to the local electric utility
- Increase the aluminum production

The detailed analysis of the economics under these different scenarios has not been carried out in the present study. However, a more universal economic indicator will be determined in subsequent section. It is believed that this indicator will help the decision makers to gauge the profitability of the application under the above mentioned scenarios.

The following assumptions have been adopted to conduct the economic analysis. It is worth mentioning that escalation, debt and tax assumptions are not considered in the present study.

- Capital cost: 2500$/kW for Kalina and 3000$/kW for ORCs.
- Maintenance cost: 0.5 ¢/kWh$_e$ for Kalina and 1.0 ¢/kWh$_e$ for ORCs
- Major replacement cost: 30% of the capital cost; recurrent at 5 years interval
- Operation cost (energy cost of auxiliary): 4.5 ¢/kWh
- Market discount rate: 10%
- Availability of the system: 96% the equivalent of approximately 8400 hours per year.
- System's lifetime: 15 years

It should be noted that, the capital cost of 3000$/kW represents the ORC specific system's cost based on its implementation history. Concerning the Kalina cycle, a capital cost of 2500$/kW has been adopted since there is a lack of data on this relatively new technology. However, the capital cost for a Kalina cycle is expected to be less than that of a ORC cycle in terms of installed capacity ($/kW) according to the licensing company of Kalina cycle. Indeed, the Husavik geothermal power plant is the only application with published record. The specific cost of the 2MW plant is approximately 1500$/kW which probably does not include the cost of drilling representing 30% to 40% of the total cost. Hence, it is more conservative to fix it at 2500$/kW for Kalina application in smelters' considering the characteristics of the Husavik plant: high potential of the heat source (water at 125 ℃) and the sink (water at 4 ℃).

The cost breakdown for ORC and Kalina cycle are illustrated respectively in Fig. 7 and Fig. 8. It is important to mention that for the same source of waste heat the Kalina cycle produces 12.5% more electricity with 9.4% less expenditure compared to the best ORC using toluene as a working fluid. Hence, the superiority of the Kalina cycle from the technical and economic perspectives is reaffirmed.

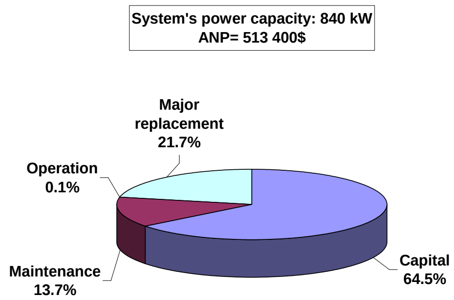

Figure 7. Annuity cost breakdown for ORC.

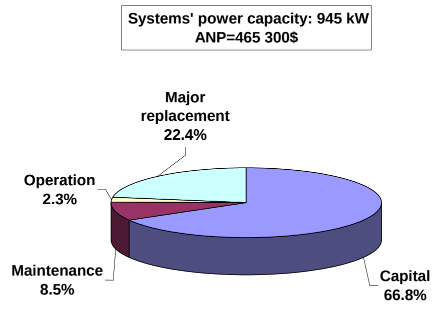

Figure 8. Annuity cost breakdown for Kalina cycle.

B. Sensitivity Analysis

The aim of the sensitivity analysis is to examine the effect of the variability of economic and technical parameters on the profitability of waste heat recovery systems. One at a time, each of the parameters is changed by a fixed percentage, and the simulation is run with this new input. The relative change in the annuity was used as the gauge for sensitivity.

The results are presented in the form of bar graph to illustrate the effect of each parameter on the annuity obtained by fixing all the parameter to their mean values except for the parameter under investigation. This effect is obtained by the deviation of the mean values of the variable parameters by ±25%. This procedure is repeated for each parameter separately. Notice that the mean annuity is obtained by fixing all the parameters at their mean values given in the precedent section.

Fig. 9 and Fig. 10 allow to evaluate the impact of all the parameters on the mean annuity and to identify the most influent ones for ORC and Kalina cycle respectively. On the other hand, they represent an interesting source of information for the range of changes of the mean annuity under variable parameters.

Indeed, the bar graph reveals that the capital cost is the most important economic parameter seeing that it has the most influence on the annuity. If the mean purchase cost is reduced by 25%, the mean annuity decreases for both cycles by a maximum of 22% approximately.

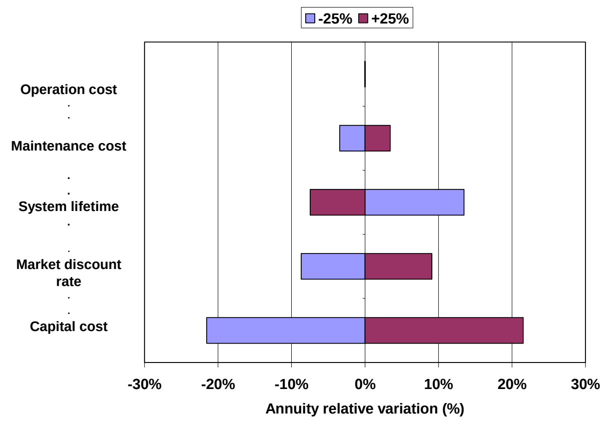

Figure 9. Effect of governing parameters on the annuity for ORC.

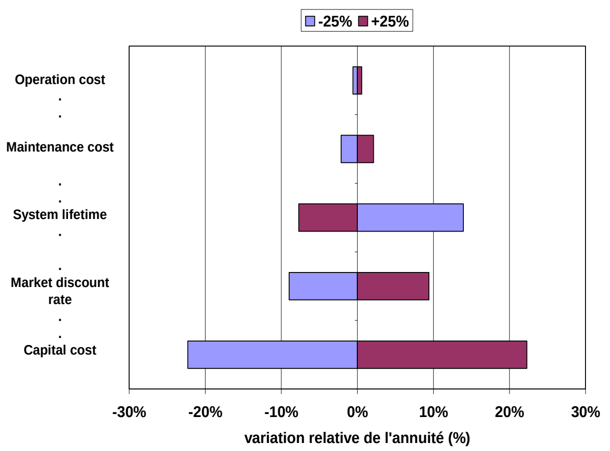

Figure 10. Effect of governing parameters on the annuity for Kalina cycle.

It should be noted that the impact is linear. Hence, a 25% augmentation of this parameter yields to an increase of the mean annuity by the same percentage (symmetrical distribution). The other economic parameters (market discount rate, system lifetime, maintenance cost and operation cost) have much less influence on the mean annuity than the precedent one especially the operation and maintenance cost.

C. *Profitability Indicator*

As mentioned earlier, the economic indicator used in this study is represented by the specific cost of power generation. It is obtained by dividing the annual electric generation of the system (an output of the thermodynamic analysis) by the corresponding annuity (an output of the economic analysis). Fig. 11 illustrates the specific cost of electricity generation using ORCs and Kalina cycle. The results presented are obtained by fixing all the parameters to their mean values except for the capital cost which has been varied to obtain the following scenarios:

- Realistic scenario: 2500$/kW for Kalina and 3000$/kW for ORCs
- Optimistic scenario: realistic capital cost reduced by 25%
- Pessimistic scenario realistic capital cost increased by 25%

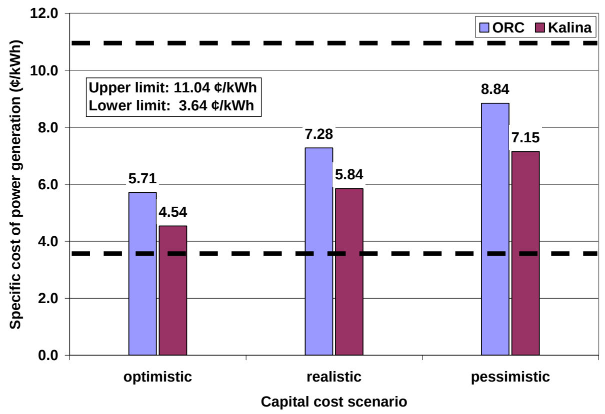

Figure 11. Comparison of specific cost of power generation using ORC versus Kalina.

The two straight lines represent the maximum and the minimum of electricity generation corresponding respectively to the most optimistic and the worst pessimistic scenarios from the economic point of view. In other words, the upper limit is obtained under conditions where all the costs (capital, maintenance etc.) and the market discount rate are low while the system's lifetime is high. In this case the electricity generation is at its minimum and reaches 3.64 ¢/kWh$_e$. In the opposite case, the upper limit is at 11.04 ¢/kWh$_e$.

It is observed that the specific electricity generation is approximately 20% less important when using a Kalina cycle regardless the specific capital cost. This can be explained by the fact that the economic indicator in question is linearly dependent on ratio of the annuity and the power generation. In the case of ORCs, the power generation cost is high because the corresponding annuity is more important and the power generation is inferior compared to the Kalina cycle. This makes Kalina technology more attractive as mentioned before.

The preliminary internal economic analysis indicates that for a roughly 1MW facility with a total plant cost approaching $2.5 million and an anticipated 15 year life-cycle; the low operation and maintenance costs for a plant of this nature would produce energy at a break-even cost under the bar of 6 ¢/kWh$_e$. This means of harnessing the vast source contained in top-gas via the Kalina cycle is an economically viable application and possesses a great potential to dramatically contribute to energy savings to meet the government mandates for energy and emission reductions as well as the aluminum industry goal to reduce its energy consumption.

V. Conclusion

The above results successfully demonstrated the superiority of Kalina cycle performance has been successfully demonstrated. The analysis indicates that the overall efficiency is in the range of 2.4% to 8.5% depending on the location of such a heat recovery system. In addition, thermodynamic simulations reveal that a specific net power output of 16kW per ton of aluminum annual production is technically achievable and a cost of power around 6 ¢/kWh appears to be feasible with current technology. Thus, integrating this technology represents an interesting option in the short term as it can cost effectively increase power generation capacity without adding greenhouse gas emissions.

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