TEST Engineering & Management

May – June 2020
ISSN: 0193-4120 Page No. 6118-6131

# Investigating Applications of Heat Recovery Systems in Aluminum Smelters in the UAE

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***Article Info***
***Volume 83***
***Page Number: 6118 - 6131***
***Publication Issue:***
***May - June 2020***

***Article History***
***Article Received:*** *19 November 2019*
***Revised:*** *27 January 2020*
***Accepted:*** *24 February 2020*
***Publication:*** *17 May 2020*

## Abstract

Around 80% of the world total energy consumption is mainly derived from fossil fuels including coal, oil and gas. The great dependency on these non-renewable resources contributes to the generation of greenhouse gases (GHGs) which derive the climate change. Since the development of renewable energies, the global renewable power capacity has reached 1,179 gigawatts according to IRENA and 75% reduction of GHGs could be achieved through using these sources. The United Arab Emirates is one of the largest energy consumers per capita, and about 20% of the country's total energy production is consumed by the aluminum industry. Around half of the energy input in the aluminum industry is lost as heat. The adoption of renewable energy sources and recovery of waste heat in aluminum industry would result in decreasing the overall cost, reducing greenhouse gas emissions and increasing the overall efficiency of the process. This paper presents a review and evaluation of waste heat-to-power conversion systems. The most appropriate system is selected based on the efficiency and the characteristics of the waste heat from the sidewalls of aluminum smelter. The integration of RE could be achieved through production and power modulation. The potential of heat waste recovered from the sidewall of a smelter cell, and its conversion into electricity is estimated. The resulting power efficiency improvement for the cells of a smelter operating with power modulation is estimated to reach 5.8%.

***Keywords:*** *Aluminum smelter, energy efficiency, heat engine, heat recovery, waste heat.*

## I.INTRODUCTION

Over the last decade, the fossil fuel stock of coal, oil and gas contributed to the generation of almost 80% of the world's energy [1]. Burning fossil fuels release huge amount of Greenhouse Gases (GHGs) making it the biggest contributor in driving climate change. In 2017, more than 36 billion metric tons of carbon dioxide were emitted through fossil fuel [2]. In recent years, the world energy consumption has risen, and concerns over climate change has compelled planners to reduce GHGs emissions by developing new energy conversion technology that produces electricity without harming the environment. The transition from fossil fuels toward clean energy systems has been going on since the development of renewable energy sources in the late 90s. Figure 1 below presents the world electricity production through various types of energy sources between 1985 and 2018.

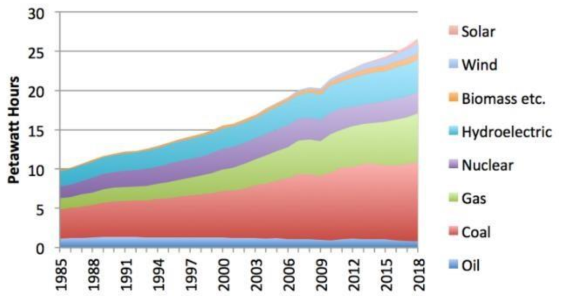


**Figure 1: World Electricity Production by type between 1985 and 2018 [3]**

The renewable energy is generated from natural resources such as water, wind, solar, biomass and geothermal sources. The continue falling cost, available know-how of renewables and governmental policy of reducing air pollution are driving the growth of adopting renewable energy rather than the continuous use of fossil fuels and according to IRENA, the global renewable power capacity has reached 1,179 Gigawatts in 2018 [4]. The adoption and implementation of renewables would gradually lead the world to achieve sustainability and meet energy demand of future generations. An estimated 75% reduction of GHGs according to IRENA could be achieved through adoption and use of renewable energy sources and electrification technologies [5].

The major sources of greenhouse gases include electricity, buildings, transportation, food waste, industry and agriculture. Industry as shown in Figure 2 is the second highest contributor to the emission of GHGs as the industrial processes include electricity use and chemical reaction emission.

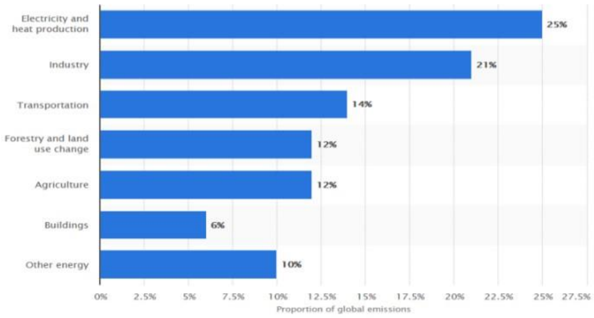


**Figure 2: Distribution of emissions of greenhouse gases by industry sector worldwide as of 2014 [6]**

Heavy industries such as steel, cement and aluminum are highly energy intensive, making them major source of global GHG emissions, therefore improving their efficiency is a matter of concern. During the industrial processes, many different greenhouse gases can be released which include $CO_2$, $CH_4$, $N_2O$, and perfluorocarbons (PFCs). Improving the industrial processes efficiency by adopting the best available technologies of renewable energy is the main opportunity for industries to reduce GHG emissions of burning fossil fuel.

The Aluminum industry accounts for 54% of the total industrial emissions [7]. The aluminum industrial heat waste accounts for more than 50% of the total energy input [8]. The industrial waste reduction and utilization are under process due to its important benefit on increasing efficiency and reducing pollution. The world is currently facing crucial choices to reach a sustainable future with safe climate. The Paris Agreement which is the first universal agreement on climate change was adopted in 2015 at the end of the United Nations Climate Change Conference (COP 21). The agreement aims to keep global warming below a 2°C increase by the end of the 21st century and conduct efforts to limit the temperature rise to 1.5°C only. The United Arab Emirates (UAE) was one of the first countries to ratify the Paris Agreement in September 2016 as the issue of climate change is one of its priority targets to maintain the country's sustainability and growth. The continued efforts of the world to facilitate the conversion of energy from fossil fuels to renewable sources have highlighted the importance of the reuse of industrial thermal waste to achieve sustainability.

The global energy waste has driven the demand for energy saving technologies which highlighted substantial interest in waste heat recovery systems which in turn lead to more energy efficient use. Interest in low grade heat recovery to generate electricity has grown in the past years. Number of solutions have been proposed and implemented in several industries to save energy and reduce GHG emissions.

The UAE owns large crude oil reserves around 8.2% of the world total oil reserves, which play critical role in meeting national energy demand [9]. The availability of energy directed the initial efforts to diversify the UAE's economy to focus on energy intensive industries including aluminum, steel, and cement. The intensive use of energy in industries, air cooling and desalination has made the UAE’s primary energy use per capita the seventh in the world, reaching around 346 GJ per person per year [10]. Moreover, the fossil fuel including oil and coal are losing their dominant position since the modern technology derived the use of renewable energy.

The UAE's superb geographic location provides an abundance of solar irradiation providing strong economic opportunity as the region experiences around 350 sunny days per year [11]. Moreover, the government aspires to use the nuclear power as a major source of non-hydrocarbon electricity generation to cover around quarter of the energy needs [11]. Other potential alternative energy sources considered as complements by the government are wind energy, geothermal power and waste to energy technology. All these sources together create high potential in reducing reliability on fossil fuels thus reducing carbon emissions and increasing renewable energy production. And just as the country's considerable oil reserves provided a

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catalyst for the current traditional energy revolution, its vast alternative resources especially solar energy and advanced technological development, are putting the region at the center of the new clean energy revolution. The global energy trend is shifting dramatically, and the UAE is at the forefront of this transition. The UAE's leadership has set a bold vision for the future of the nation that aims to make the country among the best in the world. As of 2010, H.H. Sheikh Mohammed bin Rashid Al Maktoum, Vice-President and Prime Minister of the UAE and Ruler of Dubai, launched the UAE Vision 2021. The national agenda of the vision covers six key sectors including sustainable environment and infrastructure. And as the nation grows and fulfills its ambitions, in 2007 the country introduced the UAE Energy Strategy 2050 with the aim of providing clean and affordable energy to reduce the total carbon emissions, maximize energy productivity to achieve economic growth and to build a sustainable future beyond oil [12]. The Energy strategy aims to balance between production and consumption of energy, reduce carbon footprint and diversify the energy mix. The UAE has been involved in several attempts to achieve the UAE Energy Plan 2050 which aims to reduce total greenhouse gas emissions up to 70% by establishing a national GHG emissions management system and modifying existing buildings with the addition of energy saving controls systems [13]. As shown in Figure 3, the energy mix will include 44 percent clean energy, 38 percent gas, 12 percent clean coal and 6 percent nuclear [13].The UAE is in the process of diversifying energy sources and strengthen their economic ties abroad, which are reflected by the establishment of many projects and initiatives in several emirates such as Masdar, Shams 1, Mohammed Bin Rashid Solar Park and many others.

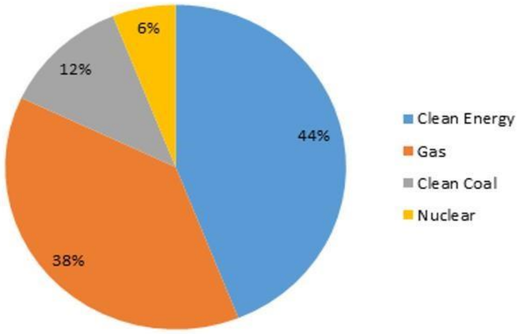


**Figure 3: Energy Mix Percentages in UAE by 2050**

## II.LITERATURE REVIEW

### *A.Aluminum*

Aluminum is the third most abundant mineral in the earth's crust, accounting for 8.32% [14]. However, due to its chemical reactivity it is always found as compound called bauxite, a mixture of aluminum oxides, iron oxides and clay. It typically possesses a range of favorable material properties including excellent electrical and thermal conductivity behavior, low recycling costs, low density, non-toxic and has excellent corrosion resistance making it attractive for many applications in various fields. The global demand of aluminum is expected to double in the next 15 years and around 40 to 50 new smelters will be needed to meet the new demand [15].

### *B.Aluminum Industry in the GCC Region*

The primary aluminum industry is an important manufacturing sector that the GCC relied on to develop their industrial sectors and economies. The aluminum journey in GCC region started with the establishment of Aluminum Bahrain (ALBA) in 1968, followed by Dubai Aluminum Company Limited (DUBAL) in 1975, Emirates Aluminum (EMAL) in Abu Dhabi and Qatar Aluminum Company Limited (Qatalum) in 2007. Through the years, as the demand for aluminum increased, the Gulf States became one of the global largest producers of aluminum with initial production capacity of 120 thousand metric tons in ALBA [16]. Although, the GCC region lacks large reserves of bauxite which is essential to produce aluminum, the availability of energy supported the continuous growth of this sector as this industry requires significant amount of energy in the form of electricity and heat at

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different grades. DUBAL, the company owned by the Government of Dubai started commercial production in 1981 with a capacity of 135 thousand metric tons per annum and through successive expansion, DUBAL smelter is considered as one of the largest modern smelters in the world [16]. On the other hand, EMAL a joint venture between Mubadala Development company and Dubai Aluminum Company Limited (DUBAL) built the largest single-site aluminum smelter at Taweelah in the Emirate of Abu Dhabi. Recently, in 2013 Mubadala Development Company of Abu Dhabi and the investment corporation of Dubai announced the merge of two state-owned entities, Dubai Aluminum (DUBAL) and Emirates Aluminum (EMAL) to become Emirates Global Aluminum (EGA), which is the largest industrial company in the UAE outside oil and gas that focuses on bauxite mining, alumina refining and primary aluminum smelting. The emergence of EGA has helped the UAE to become one of the world's largest aluminum producer, competing in global markets and serving an important role in building sustainable industry and economic development [17]. In 2018, EGA was the highest primary aluminum producer in MENA region, and recorded around 2.4 million metric tons of Aluminum as shown in Figure 4. EGA is also developing an alumina refinery in Abu Dhabi expected to meet 40% of EGA's alumina requirements and a bauxite mine in the Republic of Guinea in West Africa to produce 12 million tons per year. EGA continue to develop smelter's technology to stay at the forefront of innovation in the industry.

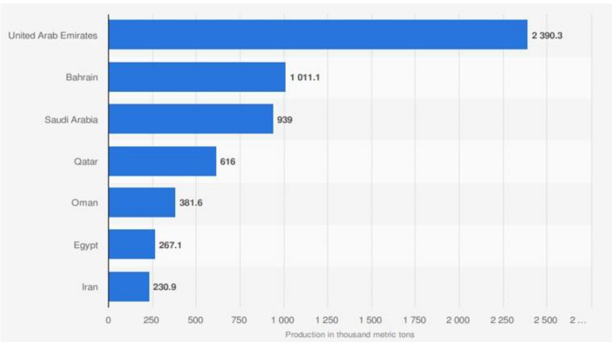


**Figure 4: Annual production volume of aluminum in the MENA Region in 2018 (in 1,000 metric tons) [18]**

The aluminum industry is constantly growing due to the increasing demand for its product, the availability of raw materials and the technology evolutions. The International Aluminum Institute predicted that by the year 2020, the global primary aluminum production will exceed 70 million tons per annum [19].

*C.Aluminum Industry in the UAE*

The Aluminum industry in the United Arab Emirates has been going through a transforming journey since the 1970s, where in 2018 the Emirates Global Aluminum was recognized as the world's largest premium aluminum producer accounting for 2.63 million tons of cast metal [20]. EGA has moved from being a regional company into a leading global integrated aluminum producer from mine to metal. It operates aluminum smelters at Al Taweelah in Abu Dhabi and at Jebel Ali in Dubai, Alumina refinery in Abu Dhabi, bauxite mine and associated export facilities in the Republic of Guinea. On the other hand, it sells its products to more than 350 customers in over 60 countries as well as its smelting industrial technology [21].

The aluminum production is an energy-intensive process that requires about 20% of the total energy generated in the country and is a major contributor to the emission of greenhouse gases such as $CO_2$, CFC and PFC [22]. The electricity used in EGA's operations is supplied from their own natural gas-fired power plants located at both Jebel Ali and Al Taweelah. As shown in Figure 5, the electricity consumption from fuel source increased between 2016 and 2017 due to the increase in aluminum production.

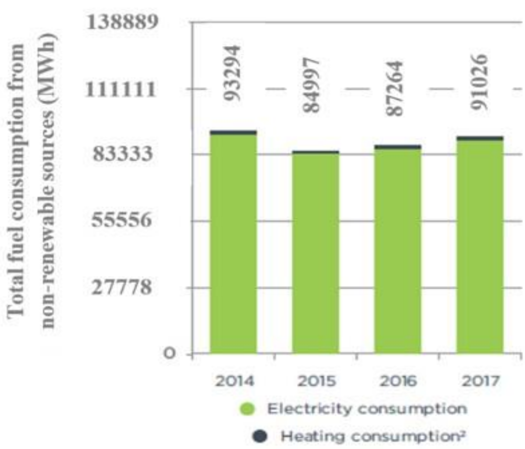


**Figure 5: Energy Consumption at EGA in UAE [23]**

*D.Industries Contribution to GHG Emissions*

The metal production including aluminum in 2016 contributed to the emissions of greenhouse gases by 73.3% of the total emissions of industrial sector as shown in Figure 6.

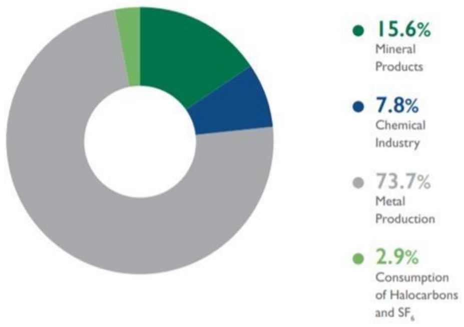


**Figure 6: Contributions of Industrial Processes towards total GHGs in Abu Dhabi in 2016 [24]**

Overall, the emissions in the UAE are regulated by the government who aspires meeting the environmental responsibilities and UAE's vision and Energy Strategy 2050 of reducing total greenhouse emissions. EGA have had emissions reduction strategies years ago where they developed advanced reduction cell technologies to maximize production and decrease the overall emissions. The total GHG emissions for EGA operations in the UAE decreased between 2017 and 2018 as shown in Figure 7 [25].

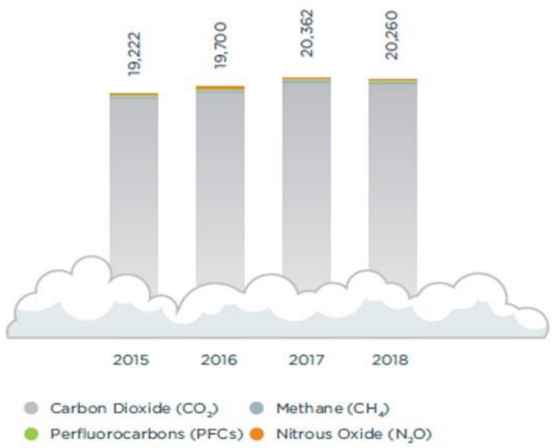


**Figure 7: GHGs emissions of EGA in the UAE (thousand tons of $CO_2$ e) [20]**

The intensity of greenhouse gases from smelting, casting and power production in EGA for 2018 was 7.93 t $CO_2$e/t Al which is an achievement as the actual target was estimated to be 7.97 t $CO_2$e/t Al [20]. The future targets of GHG emissions from EGA operations have been set in 2018 for years between 2019 and 2023 are shown in Figure 8.


**Figure 8: GHGs targets between 2019 and 2023 [20]**

EGA's R&D focuses on reducing costs and emissions by the development of smelter operating technology to be able to reduce the amount of energy required to produce each ton of aluminum.

*E.Aluminum Production Process*

The main raw materials needed for aluminum production include alumina, carbon, aluminum fluoride and cryolite. Through the process, 90% of the bauxite mined get consumed and the remaining get used in other products such as cement, ceramics and refractory products [15]. Aluminum was first produced in 1808 following three main steps shown in Figure 9, starting with mining of aluminum ore, most commonly bauxite, followed by the refining of bauxite into alumina, and ends with the electrolytic reduction of alumina into metallic aluminum. The aluminum production process requires huge amount of electricity and approximately two to three tones of bauxite to produce one tone of alumina.

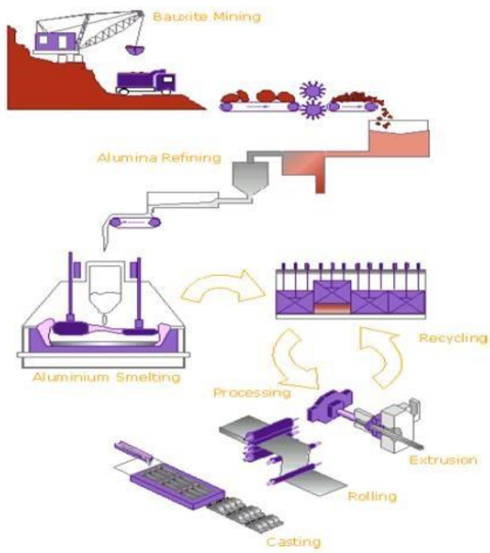

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**Figure 9: Flow Diagram of major steps of aluminum production and aluminum processing [25]**

The primary aluminum production is the process where alumina is smelted to new pure aluminum. On the other hand, the secondary production is where existing aluminum is recycled into reusable metal. Molten aluminum is extracted from alumina where the process of extracting alumina from ore includes mining the bauxite and then enriching it to produce what's called alumina ($Al_2O_3$) through Bayer process. The main steps of Bayer process include crushing the raw material, extracting the bauxite at high temperature and pressure, followed by clarification, precipitation, washing and finally calcination. The produced material is very similar to flour that goes through the reduction process or what's called the Hall-Héroult process shown in Figure 10.

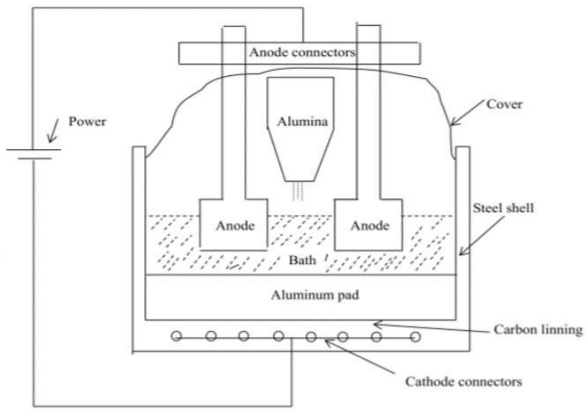


**Figure 10: Schematic of Hall-Héroult [26]**

Aluminum is produced according to the following chemical Reaction:

$$2Al_2O_3 + 3C \rightarrow 4Al + 3CO_2 \quad (1)$$

The alumina solution is electrolyzed in molten cryolite ($Na_3AlF_6$), where pure aluminum is produced. The reduction cell bottom serves as a cathode, and coal bars immersed in cryolite serve as anodes. Molten aluminum is deposited under a cryolite solution with 3-5% alumina. During this process, temperatures reach 950°C, considerably higher than the melting point of the metal itself, which is 660°C. During the reduction process, the coal anodes are consumed very quickly and should be replaced with new ones frequently.

*F.Heat Losses*

The electrochemical process of producing aluminum requires high range of electric current to be able to break the molecular bonds. The process consumes massive amount of energy around 14.2 MWh/t Al and releases huge amount of heat, around 50% of the energy input [15], [8]. Although, the materials used for the pots are carefully selected to ensure least amount of heat release, still minimizing the heat losses is a challenge. The distribution of heat loses through the walls of the aluminum reduction cell is shown in Figure 11.

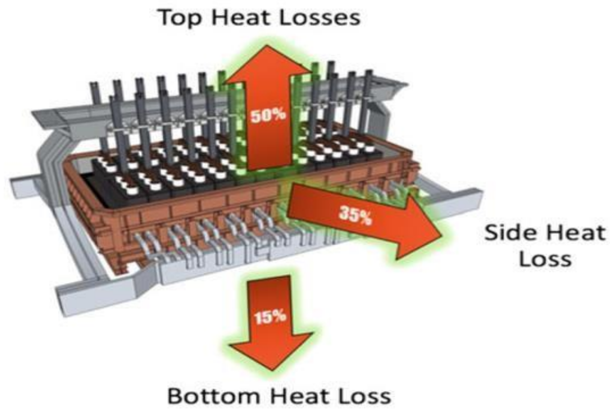


**Figure 11: Schematic of heat losses through the reduction process[15]**

With energy costs around 40% of the total production cost, it is clear that utilizing the waste heat has great economical potential to reduce both the overall cost of the process and total energy consumption of aluminum industry [27]. In addition, following this approach would reduce greenhouse gas emissions. The waste heat utilization includes direct use of extracted heat or through heat pumps and heat engines. Despite the abundance of waste heat in primary aluminum production plants, opportunities of thermal utilization are limited due to the low quality of the waste heat, large distances between heat sources and heat sinks and asynchronous availability of waste heat and heat demand. The waste heat from the pot lines comes from two distinct sources which are: the exhaust gas flow and the surface heat flux. The temperature of the exhaust gas differs depending on the outside air temperature, it varies approximately between 100 °C and 120 °C and it is mainly composed of $CO_2$ released from the Hall Héroult process [27]. The gas flow is collected through ducts from all the cells in the plant where it is transported to the Gas Treatment Center (GTC) before being released into the atmosphere. The sidewalls heat temperature range between 150 ℃ and 310 ℃ [28]. A sidewall heatexchanger can be used in order to capture only the excess heat which would keep the cell in safe mode, increase its efficiency by utilizing the waste heat, and create high potential of electricity generation. Several opportunities for heat recovery and heat-to-power cycles are possible, but feasibility analysis need to be taken to select the most appropriate suitable and efficient design.

### *G.Heat-to-power systems*

Energy intensive industrial processes, such as aluminum production, release large amounts of hot exhaust gases and waste heat. The rapid global economic growth, improvement of industrial technologies environmental destruction, and increased demand for clean energy are driving the development of waste heat-to-power system's market. The simple illustration of Waste heat-to-Power system is shown in Figure 12. This system is a process of capturing heat discarded from an active industrial process to generate power.

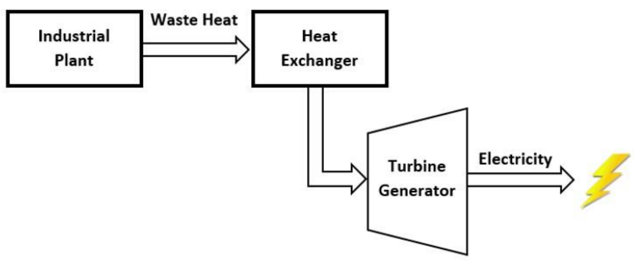


**Figure 12: Simple illustration of Heat-to-power system**

The conservation and utilization of waste heat is important not only economically, but also to reduce primary energy consumption as well as reduce carbon dioxide ($CO_2$) emissions.

### *H.Summary of Heat-to-power systems*

The development and application of waste heat-to-power conversion systems increase the overall efficiency of the plant by the utilization of waste heat to generate electricity and reduction in the environmental impact. The low adoption of this system in factories with potential waste heat resources is due to the high capital cost and the lack of adequate experience in design and operation of such cycles [29]. Table 1 below summarizes the main comparison factors of technologies that can recover the waste heat to generate electricity.

**Table 1: Summary of main comparison factors of Heat-to-power systems**

| Technology | Heat So Temperature | Efficiency | Capital Cost | Capacity | Reference |
|---|---|---|---|---|---|
| Organic Rankine Cycle | 80°C – 300°C | 10-20% | $1,5003,500/kW | Several MWs | [30], [31] |
| Kalina Cycle | 60°C - 200°C | 10-50% | $11001,500/kW | Several MWs | [32], [ [31], [34] |
| Encontech Engine | 200°C – 600ºC | 30-35% | $14302,900/kW* | Several MWs | [35], [36] |
| Thermoelectric generator | 230ºC – 650ºC | 2-5% | $20,00030,0000/kW | µW-kW | [31], [37] |

## III.PRODUCTION MODULATION CASE STUDY

Previous studies showed that energy input is responsible for more than 40% of the total aluminum production cost [38]. The continuous increase in energy cost and the integration of renewable energy requires smelters to change their operating strategy and introduce production variation through power modulation to allow optimal use of solar energy. However, the smelter is operating in a very critical conditions giving it limited power modulation window. The aluminum smelters are currently based on constant power input to achieve a bath temperature between 955 °C and 970 °C [39]. Several attempts of power modulation have been implemented for various purposes in the past years that will be discussed in the following sections.

### *A.Enpot Technology*

The aluminum industry is facing challenges to come up with a way that can modulate the production and reduce energy consumption. The shell heat exchanger (SHE) technology or EnPot was patented and developed by the Light Metals Research Centre (LMRC) of the University of Auckland to allow dynamic control of cell's power input [40]. It was developed to be used as a 'virtual battery' for the electricity network of Germany by modulating the production of Aluminum. This technology has been used to help the aluminum smelting industry be part of the solution to accommodate increased intermittency in our future renewable energy generation. The EnPot system provides dynamic control of the heat balance of aluminum smelting pots across the potline, so that energy consumption and aluminum production can be increased or decreased by as much as plus or minus 30% almost instantaneously [15]. The concept works by adding a shell heat exchanger (SHE) shown in Figure 13 to the cell to control the heat on the sides of the pot when there is major change in power input.

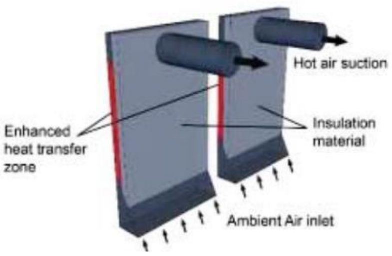


**Figure 13: Schematic of Shell Heat Exchanger Concept [40]**

Through the SHE, the heat transfer rate is regulated by altering the airflow through the heat exchanger units. When power input is increased, SHE allows heat loses through sidewalls to be increased to keep the cell at the desired temperature. On the other hand, when power input is decreased, SHE reduces the heat loses and preserve it to keep the cell operating safely. The concept of Shell Heat Exchanger (SHE) technology was implemented on 12 pots at
TRIMET's plant in Essen, Germany operated within 150 to 180kA and showed modulation as much as +20% to -13% for 48h using air as the working fluid for heat exchanger [40]. This new technology provides smelters with the means to free up power back to the grid, transforming the smelter from only an end user of power into a 'virtual battery' for the electricity network. The development of the new EnPot heat exchanger technology has a potential impact on the sustainability and economics of primary aluminum production.

*B.New Production Cycle with Power Modulation*

The EGA's DX+ Ultra aluminum cell has been used as a case study for integrating renewables, heat exchanger, and heat recovery system. Table 2 below shows the main parameters of the DX+ Ultra Technology.

**Table 2: DX+ Ultra Technology parameters [41]**

| Parameters | DX+ Ultra Technology (EGA Eagle pilot line) |
|---|---|
| Amperage | 454.8 kA |
| Voltage | 4.08 V |
| Specific energy consumption | 12.75 kWh/kg Al |
| Current efficiency | 95.1 per cent |
| Output | 3.48 t Al/pot/day |
| AE frequency | 0.009/pot/day |
| PFC emissions | 5 kg $CO_2$ eq/t Al |
| Carbon consumption | 0.402 kg C/kg Al |
| Aluminum purity | 99.93 per cent |

The thermodynamic model developed by [22] was able to determine an extended operating window of the industrial case of aluminum cell (DX+ Ultra) available in UAEto enable power modulation and facilitate the integration of renewable energy. Both energy supply and production of any aluminium cell can be controlled through altering the heat losses from the side walls by the addition of shell heat exchanger. The findings of [22] model includes cell voltage, aluminum production, specific energy consumption, and total heat loss. The key outputs are summarized in Figure 14 achieving two modulation schemes shown as region E and F. In region E, the aluminum production can be modulated between -16.9% and +5.2% from the nominal production rate which is 3481 kg of Al per day with power modulation between -14.5% and +8.6% from the nominal power equal to 1855.2 kW [22]. The cell in region E is bounded by an anodecathode distance (ACD) ranging between 3.4 cm and 5 cm and performed with nearly constant specific energy consumption around 13.2 kWh/kg Al [22]. The anodecathode distance shown in Figure 15 is the average distance between the anode bottom and the aluminum metal pad. In region F, further production modulation can be achieved with the lower limit of current density, where any further current production will reduce the efficiency of the process. Overall, using the thermal energy storage calculations done by [21], the power input to the cell can be reduced by 14.5% and can be increased by 8.6%.

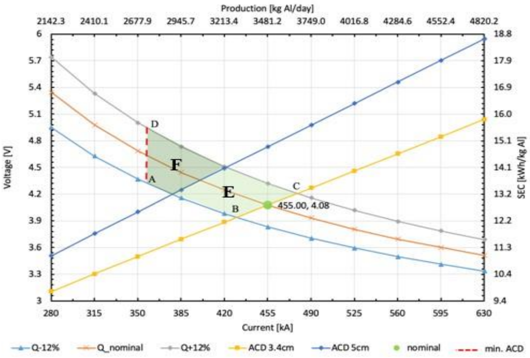


**Figure 14: Power Modulation Operating Window [22]**

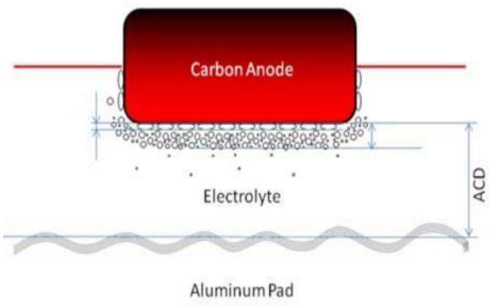


**Figure 15: Representation of Anode-Cathode Distance (ACD) [42]**

The power modulation window for the cell discussed earlier will be done between points B and C of the feasible area E. The specific energy consumption (SEC) is the ratio between the energy input and the specific aluminum production rate which is almost constant in the feasible range and equals to
13.2 kWh/kg Al. In the following section, the heat losses will be calculated according to this feasible range.

## IV.EVALUATION OF HEAT RECOVERY

### *A.Heat Recovery*

The incorporation of heat exchanger into the aluminum cell provides the ability to modulate production through adjusting the supplied power. The integration of renewable energy for example solar energy into the aluminum plant is facilitated by the incorporation of heat exchangers, as energy input would not be constantly supplied to the cell. The variation of power input requires the cell to adjust its thermal balance using sidewalls heat exchangers to keep the bath temperature between 955 °C and 970 °C [39]. During the process of thermal balance adjustment, excess heat needs to be extracted at high production level (above the nominal current level) and additional insulation need to be applied when power input is at lower level. Given the power modulation range that was determined and presented earlier, we can see in Figure 16 the power modulation used in our study and the corresponding heat losses generated from the EGA’s DX+ Ultra aluminum cell. The horizontal axis represents time of the day in terms of hours, the vertical axis on the right side represents the amount of heat lost in kilowatts, and the vertical axis on the left side represents the amount of power input in kilowatts. The horizontal straight paths shown in grey and orange presents the power input and heat losses respectively without power modulation or integration of renewables. The straight lines paths mean that both power supply and heat losses are constant all day. On the other hand, the paths in blue and yellow presents the heat losses and power input cycles respectively with power modulation. The power input increases during day hours and heat losses increases accordingly. During night hours, the power input decreases as solar energy is only available during the day which decreases the heat losses.

The temperature of the sidewalls heat loses of the cell ranges between 200 °C and 300 °C placing it in the lowmedium grade [22]. The power input increases during the day which creates high amount of heat losses, where part of it need to be extracted to keep the cell operating safely. Calculations of heat losses and power input is presented in the following section.

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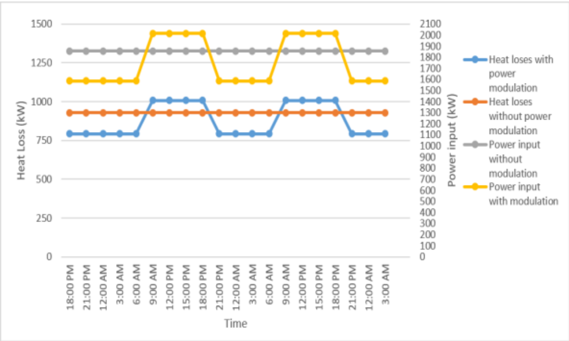


**Figure 16: Heat Losses and Power input paths**

*B.Heat Losses Calculations*

The energy that is not used in the smelting process needs to be removed from the cell and this is done through heat loss across all cell surfaces. The total heat losses from an Aluminium cell is almost 50% of the power input. As we discussed before, since the heat losses from the sidewalls account for 35% of the total heat losses, the corresponding sidewalls heat losses represent 17.5% of the total energy input as shown in **Error! Reference source not found.** below. Using DX+ Ultra data illustrated in Table 2, the heat losses will be calculated for cells with and without power modulation.

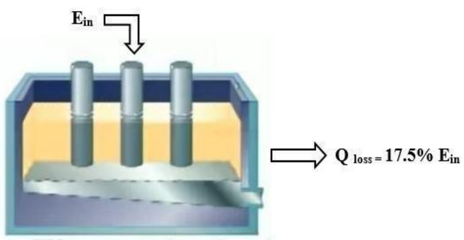


**Figure 17: Basic Representation of Sidewalls Heat Loss from Al Cell**

*1)Heat Losses without Power Modulation*

The power input and heat losses without modulation are constant and calculated as follows:

$$Ptotal\ heatloss = 924.68\ kW = 3328.848\ MJ/h$$

$$I = 454.8 \times 10^3 AV = 4.08\ V$$

$$P_{in} = IV = 454.8 \times 10^3 \times 4.08 = 1855.584\ kW$$

$$P_{sidewalls}{-}loss = 35\% \times P_{total}\ heatloss = 35\% \times 924.68$$

$$= 323.638\ kW = 1165.097\ MJ/h$$

$$\therefore Qsidewalls{-}loss = 323.6\ kWh$$

Using DX+ Ultra Cell data without any modulation, the sidewalls heat loss calculated is equal to 323.6 kWh.

*2)Heat Losses with Power Modulation*

The power input of the cell with modulation capability varies, where it increases to the maximum during the day and then it decreases to the minimum at night. The minimum and maximum values ofpower input and heat losses are calculated as follows:

- Minimum point:

$$P_{min} = P - (14.5\% \times P)$$

$$= 1855.584 - (14.5\% \times 1855.584)$$

$$= 1586.524\ kW$$

$$Pmintotal\ heatloss = 813.52\ kW = 2928.672\ MJ/h$$

$$Pminsidewalls{-}loss = 35\% \times Pmintotal\ heatloss$$

$$= 35\% \times 813.52 = 284.732\ kW$$

$$= 1025.035\ MJ/h$$

$$\therefore Q_{min}sidewalls{-}loss = 284.7\ kWh$$

- Maximum Point:

$$P_{max} = P + (8.4\% \times P)$$

$$= 1855.584 + (8.4\% \times 1855.584)$$

$$= 2011.453\ kW$$

$$Pmaxtotal\ heatloss = 1030.46\ kW = 3709.656\ MJ/h$$

$$Pmaxsidewalls{-}loss = 35\% \times Ptotal\ heatloss$$

$$= 35\% \times 1030.46 = 360.661\ kW$$

$$= 1298.380\ MJ/h$$

$$\therefore Q_{max}sidewalls{-}loss = 360.7\ kWh$$

Using the power modulation range found in [22], the range of sidewalls heat loss calculated is between 284.7-360.7 kWh.

## V.HEAT-TO-POWER SELECTED SYSTEM

*A.Encontech Engine*

Technologies capable of recovering waste heat from industrial processes have been investigated and discussed previously. Table 1 illustrated earlier, summarizes the most important features of each technology. The waste heat from aluminum smelting process is in the range between [200°C 300°C]. From Table 1 it is found that, the Kalina cycle currently operates in the market with temperatures between 60°C -200°C. Therefore, it is not suitable to be used as a heatto-power system for temperatures higher than 200°C. On the other hand, thermoelectric generators showed promising results in the fields of automobile and Medical application. Currently, TEGs are small in capacity and are not suitable for aluminum industry. Both ORC and Encontech Engine showed promising results in recovering waste heat at the required range of temperature. ORCs are operating in the market with low efficiency. On the other hand, the Encontech Engine is still new, but it is originally based on available concept and have higher efficiency range in comparison with ORC. In addition, studies claim that, the use of Encontech engines would overcome the benefits of ORCs and the results from the table supports it. Therefore, the Encontech Engine will be selected as the heat-to-power system due to its promising features. In the following chapter, technoeconomic analysis will be applied for this technology.

*B.Estimate of Power Generated*

The isobaric expansion engines are new concept, they work on the principles of hydraulic displacement, where the piston is displaced with the help of working fluids. The system can achieve efficiencies up to fifty percent depending on the temperature. The basic illustration of Encontech system is shown in Figure 18. It consists of heat source where waste heat is used, cold sink source, and an engine that produces hydraulic power which is converted to electricity using a generator.

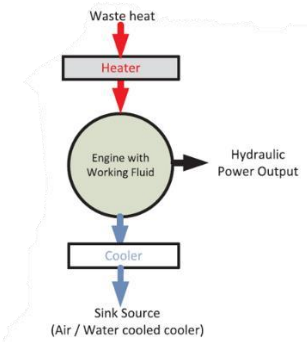


**Figure 18: Basic Representation of Ideal Encontech Engine [43]**

The heat flow calculated previously which is generated from the sidewalls of the aluminum cell will be used as a heat input source for the selected heat-to-power system. The Encontech engine is still new in the market and data about the technology is limited. Therefore, the power estimate will be calculated from the thermal efficiency of the cycle according to the following equation:

$$\eta_{th} = \frac{Output}{Input} = \frac{P_{out}}{Q_{in}} \rightarrow P_{out} = \eta_{th} \times Q_{in}$$

The efficiency of the Encontech engine ranges between 3035%. Since the minimum and maximum efficiencies of the engine are very close, the energy estimate will be calculated using 30% efficiency. The energy estimate will be calculated using the heat losses obtained from the cells with and without the integration of power modulation. The values of power estimate ($P_{out}$) for one aluminum cell are calculated using efficiency equation and summarized in Table 3 below using the following assumptions and the heat losses calculated earlier.

**Table 3: Power Recovered estimate values for heat losses with and without power modulation**

| | Without Power Modulation | With power modulation | |
|---|---|---|---|
| $Q_{in}$ | Q (kWh) | $Q_{min}$ (kWh) | $Q_{max}$ (kWh) |
| | 323.6 | 284.7 | 360.7 |
| $\eta_{th}$ | $P_{out}$ (kW) | | |
| 30 | 97.1 | 85.4 | 108.2 |

The power estimate generated from heat losses without power modulation is around 97.1 kWh for efficiency equals to 30%. On the other hand, the energy estimate from heat losses with power modulation ranges between 85.4-108.2 kWh for 30% efficiency.

## CONCLUSION

The energy efficiency of heat-to-power system according to [35] is highly dependent on many factors such as working fluid properties, ratio of the diameters of the displacer and piston, ratio of the temperatures of both the heater and cooler, and most importantly the efficiency of the heat regenerator.

The percentage of energy efficiency improvement is calculated using the ratio of power generated and the power input. The maximum energy efficiency improvement for cells is achieved using sidewalls heat losses from cells with power modulation. The data of the maximum point are summarized as follows:

- Required power input: $P$ = 1855.584 $kW$o Recovered Heat through sidewalls:

$$P_{max}Sidewalls-Loss = 360.7\ kW$$

- Converted heat into Power through Encontech engine:

$$P_{max} = 108.2\ kW$$

oPercentage of power input to power recovered:

$$Percentage\ (\%) = \frac{Recovered\ power}{power\ input} \times 100$$

$$= \frac{108.2}{1855.584} \times 100 = 5.8\%$$

The energy efficiency improvement for cells with power

modulation can reach up to 5.8%. Such great increase could services/environment-and-energy/water-andcontribute to global emissions reduction and reduce electric energy/energy-. [Accessed 13 10 2019]. demand in aluminum industry. [14] "chemsheets," 10 Jul 2012. [Online]. Available:

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## ACKNOWLEDGEMENT

This work is supported by Khalifa University of Science [15] M. and Technology under Award No. CIRA-2018-97.
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