

Energy Consumption Evaluation - Different Practices and Possible Approaches to Their Harmonization

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Abstract

Specific energy consumption (which is expressed in direct current, or DC) is a key economic indicator, since it directly reflects power expenses in monetary terms. In contrast, current efficiency (CE) and voltage are not directly expressed in monetary values but they directly affect power consumption: a decrease in voltage or an increase in current efficiency reduces power consumption. Therefore, all the world's leading aluminium producers take efforts to optimize said parameters to reduce the production cost. At industry conferences, energy efficiency is one of the main subjects; however, issues related to voltage and its precise measurement are cursorily discussed. In the literature and patents, it is taught that the mean, or average, voltage comprises the electrochemical reaction and losses in conductors but there are no clear methods for measuring the voltage, including information on where measuring wires are to be located. This leads to the following discrepancies: some publications consider only individual components, such as the voltage required for the reaction or partial losses in conducting elements. Many companies use compensation circuits (or loops) but they are silent on whether their voltage value considers the voltage drop in said circuits, or loops. Lack of standardization makes it difficult to compare results and develop universal approaches.

This paper researches the influence of the location of voltage measurement points in the cell on the voltage value that we have. This research may serve as a basis for developing standards and methods for measuring voltage, which will help obtain an objective picture when assessing energy efficiency in the aluminium industry.

Keywords: Aluminium electrolysis cell, Voltage drop, Energy consumption, Energy efficiency calculation, Comparison of energy efficiencies.

1. Introduction

The following three components form the voltage in an aluminium reduction cell. The first component is a decomposition voltage, i.e., the voltage required for the electrochemical reaction. The second component is an excess (or polarization) voltage; it occurs due to polarization at the electrode boundaries. The third component is an Ohmic voltage drop, which is caused by resistance in different parts of the cell. Since we have only limited influence on the first two components, the main attention should be paid to reducing the Ohmic voltage drop.

Although, global aluminium producers control the cell voltage, the question is how accurate such control is. There is often no information on whether they take into account the voltage drop in the cell busbar (as well as in the magnetic field compensation busbar, or loop). For example, if the

voltage drop in the busbar is only partially taken into account (excluding, for instance, a value of 100 mV from calculations), this will lead to an underestimation of energy consumption; in numerical terms, one may list a value of 12 800 kWh/t Al but the actual energy consumption will be close to 13 100 kWh/t Al. So, when taking into account the overall (total) voltage drop (including the busbars), the energy efficiency indicators may become comparable with the average numbers in the industry, and no expected benefits will be seen. Thus, ignoring the above in calculations may lead to incorrect energy consumption values (the values on which all global aluminium manufacturers focus).

This paper proposes to consider using a unified approach by taking into account the balance between voltage and energy consumption.

2. Methods for Measuring the Voltage

This paper considers various voltage measurement methods that are used in the course of aluminium electrolysis, or aluminium reduction. Figure 1 shows a voltage measuring circuit for both the total voltage of one potline and the voltage of a single potroom.

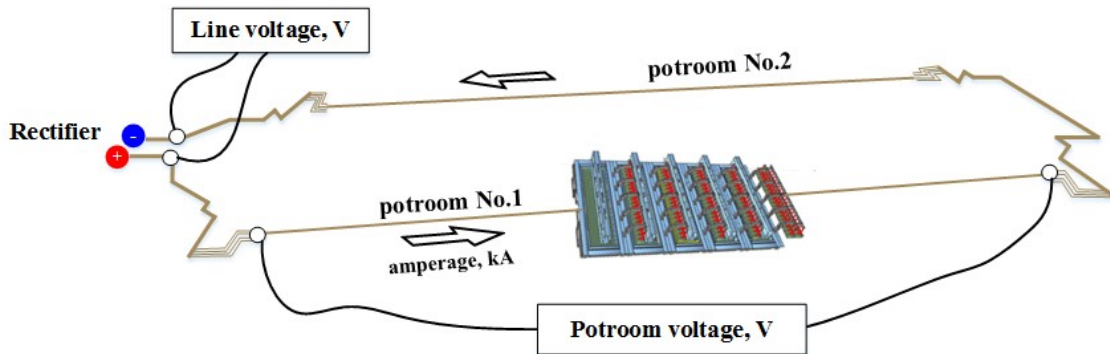


Figure 1. Voltage measuring circuit for both the total voltage of one potline and the voltage of a single potroom.

As can be seen from Figure 1, measuring the voltage at the (+) and (-) terminals of the rectifier allows determining the total voltage of a potline, which includes both the electrochemical component and all Ohmic losses when the current passes through all the parts of the busbar. If dividing this value by the number of cells, one can determine the average voltage per cell; this voltage value serves as a key indicator of the efficiency of the process at the moment of measurement and reflects the actual performance achieved.

In the case of using a compensation busbar (or loop) for a process with low resistance to MHD instability, it is necessary to take into account voltage losses in said loop [1-5].

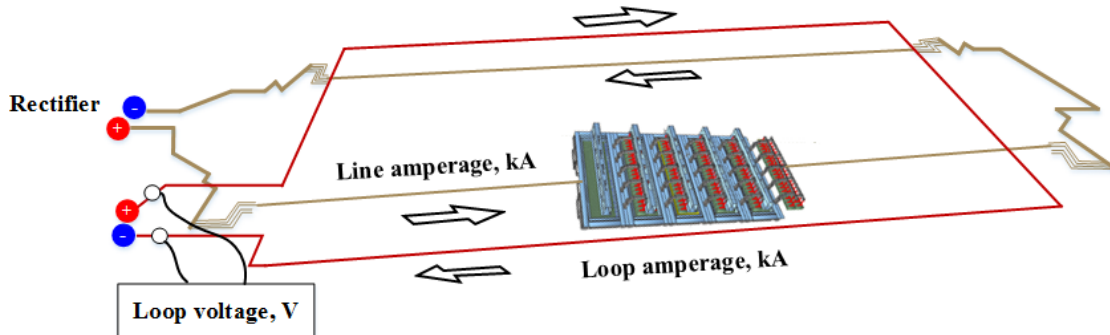


Figure 2. Voltage measuring circuit for the compensation loop.

Figure 2 shows a circuit for measuring the voltage in the compensation loop; the voltage is also measured at the (+) and (-) terminals of the rectifier. The value obtained will reflect the total voltage losses in the compensation busbar (loop). For a correct assessment of the energy consumption of an individual cell, this voltage drop should be divided by the number of cells, and then the energy consumption in the loop per cell should be calculated and added to the energy consumption of the cell, which is calculated from the measured cell voltage.

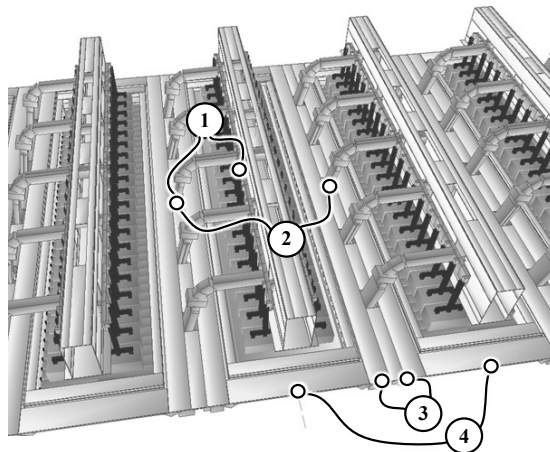


Figure 3. Cell voltage measurement.

There are various methods of measuring the voltage of individual cells, including variations in the location of measuring wires on the cathode and anode busbars. Figure 3 shows how the voltage of an individual cell can be measured. As can be seen from this figure, when the measuring devices (wires) are placed at point 1, the electrochemical component of the voltage is predominantly recorded, and this measurement includes only a small portion of the voltage drop in local sections of the cathode and anode busbars but excludes significant Ohmic losses in the main current conductors. To measure the total voltage of the cell, which includes both the electrochemical component and all the Ohmic losses in the buses and at interfaces, measurements should be taken at point 2, i.e., between a point on the busbar in one cell and an identical point in the adjacent downstream cell.

When measuring the voltage at point 3 (Figure 3), the voltage measured cannot be considered total. At point 3, only a small portion of the voltage drop in the busbar is recorded. It is important to note that the inaccuracy of such measurements may reach up to 50–150 mV. However, point 4 captures the full share of Ohmic losses in the busbars if the two measurement points are in an identical position on the cathode buses of the two cells being adjacent to each other.

3. Energy Consumption Levels Achieved

The authors of this paper have analysed a number of publications and materials [6–26]. The research considered the following key process parameters: voltage, energy consumption and current efficiency (CE). Figure 4 compares Specific Energy Consumption versus Voltage among the world's major producers. The figure confirms significant variations in said process parameters (the voltage varies in the range of 3.9 to 4.3 V, and the specific energy consumption varies within 12 000 to 13 500 kWh/t Al); such variations are due to differences in the process, cell design and climatic conditions. Of particular interest is the correlation between Voltage and Energy efficiency where modern process solutions demonstrate the potential for reduction in specific energy consumption down to 12 000 to 12 300 kWh/t Al, if and when optimizing all the voltage components.

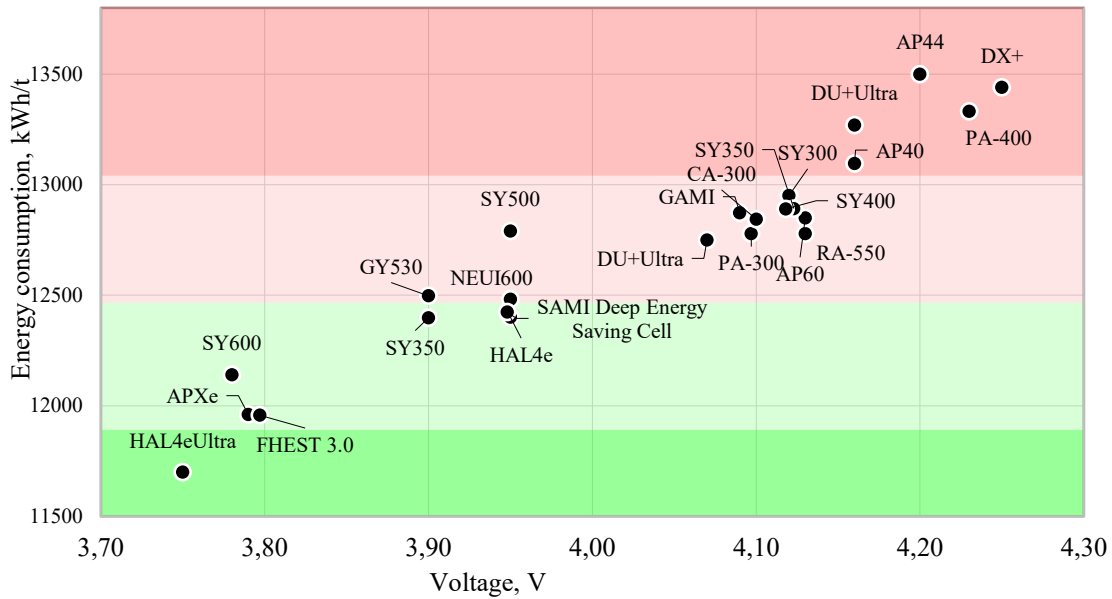


Figure 4. Energy consumption versus voltage.

The relationship between the key process parameters (specific energy consumption and current efficiency), which is presented in Figure 5, distinguishes three representative clusters, each of which demonstrates an inverse correlation between said parameters. This may be due to the following factors: different processes (or technologies) may use different control and optimization methods, there may be different approaches to calculating voltage, and there may be some supplementary variables (or conditions) that effect both parameters. If the current efficiency is more process-related, the voltage value mainly depends on the measurement method and its (the voltage) components.

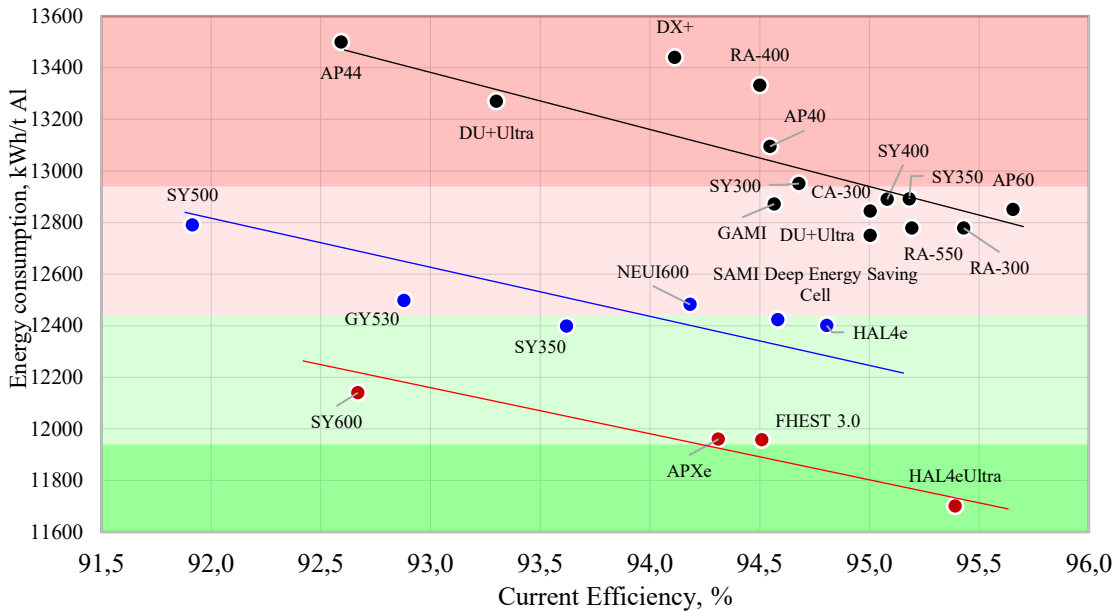


Figure 5. Energy consumption versus current efficiency.

The following discrepancies can often be found in the publications researched: 1) a discrepancy between the voltage declared and the calculated specific energy consumption, 2) low energy consumption at clearly overestimated voltage values, and 3) lack of information regarding how

the specific energy consumption at the voltage declared was calculated. In the examples listed below, these discrepancies are especially noticeable, which indicates the need for a more rigorous approach to the presentation and discussion of performance data in scientific publications.

Table 1 shows a comprehensive analysis of the performance of a smelter, where it was studied whether amperage creep was possible to increase metal production. After inventory corrections, the energy consumption in a test group was 13.58 kWh/kg Al, which is significantly better than the line performance. However, it is important to note how this energy consumption was calculated. Both the net and gross voltages are given in the table. If we take into account a total (gross) voltage of 4.6 V, energy consumption will increase to 14.49 kWh/kg Al, which is 0.910 kWh/kg Al higher than stated in the table. This is an example where companies may present their energy efficiency indicators in a better light (Actual values may be significantly higher and may not correspond to the industry’s benchmark values).

Table 1. Performance indicators of a smelter.

| KPI | Unit | Test group Test period 5 pots | Potline 1 Test period 160 pots |
|---|-------------|-------------------------------------|--------------------------------------|
| Amperage | kA | 215.4 | 196.9 |
| Metal production before inventory and solid metal corrections | kg/pot.day | 1 648 | 1 457 |
| CE before inventory and solid metal corrections | % | 95.03 | 91.86 |
| Metal inventory corrections | kg/ pot.day | -14 | - |
| Solid metal corrections | kg/ pot.day | 6.7 | 6.7 |
| Metal production after inventory and solid metal corrections | kg/ pot.day | 1 641 | 1 464 |
| CE after inventory and solid metal corrections | % | 94.61 | 92.30 |
| Base resistance set point (BRSP) / Voltage set point | μOhm / V | 11.98 / 4.23 | 13.10 / 4.23 |
| Net voltage | V | 4.31 | 4.35 |
| Gross voltage | V | 4.60 | 4.38 |
| Net specific energy: before inventory and solid metal corrections | kWh/kg Al | 13.53 | 14.11 |
| After inventory and solid metal corrections | kWh/kg Al | 13.58 | 14.04 |

Table 2 systematizes the performance indicators of a facility where a project was launched to increase metal production by increasing the amperage from 330 to 350 kA.

Table 2. Performance indicators.

| KPI | Unit | Initial design | Upgraded design |
|-----------------------------|-------------------|----------------|-----------------|
| Number of cells | | 280 | 280 |
| Anode current density | A/cm ² | 0.737 | 0.781 |
| Cell current | kA | 330 | 350 |
| Cell voltage | V | 4.050 | 3.947 |
| Current efficiency | % | 91.96 | 93.96 |
| DC power consumption | kWh/kg Al | 12.182 | 12.520 |
| Bath temperature | °C | 953 | 955 |
| Metal height | cm | 28.5 | 20.8 |
| Bath height | cm | 18.5 | 18.6 |
| Cell noise | mV | 23 | 18 |
| CVD (cathode voltage drop) | mV | 322 | 196 |
| Cryolite ratio | | 2.47 | 2.34 |
| Potline production capacity | t/y | 249 728 | 270 623 |

From the table above, it can be seen that the energy consumption at 330 kA was 12.182 kWh/kg Al. However, if we take into account the voltage given in the table (4.05 V), the energy consumption calculation will change, and the value will be equal to 13.124 kWh/kg Al, i.e., it is 0.942 kWh/kg Al higher than stated. If we do a so-called reverse calculation to determine how a value of 12.182 kWh/kg Al was obtained, we will get a voltage of 3.759 V. This value is 291 mV lower than the voltage stated in the table, which, most likely, corresponds to the voltage drop in the busbar, which is not included in the “cell voltage” measurements.

After increasing the amperage up to 350 kA, the voltage, as per the table, was 3.947 V. This figure most likely excludes losses in the busbar. If we take and add 291 mV to this value (to account for the losses excluded), the total voltage will be 4.238 V. The energy consumption (if calculated based on this value) will reach 13.44 kWh/kg Al, which exceeds the value stated in the table by 0.921 kWh/kg Al.

Thus, for an objective assessment of the energy efficiency of cells, it is necessary to take into account the total voltage drop in all current-conducting elements and standardize the location of measuring points.

4. Measurement of the Voltage of the RA-550 Reduction Cell

The RA-550 cell technology, which has a unique (on a worldwide basis) busbar design that uses anode risers on both sides of the cell, ensures significant energy savings: by 5 to 15 %, as compared to previous cell generations. High productivity (high metal production per cell) and excellent environmental parameters make the RA-550 cell technology a leading Al production technology in the industry [7–9].

However, for high-amperage cells with a complicated pinout scheme, there is a fundamental problem of measurement accuracy: the traditional arrangement of measuring wires. To control the process and assess the energy efficiency, it is necessary to use a two-level voltage measurement method: the APCS (automated process control system) voltage (Figure 6) determined between the “zero points” on the anode and cathode busbars, which is used to control the thermal balance, and the total voltage, which comprises both the APCS voltage and the voltage drop in the anode and cathode busbars.

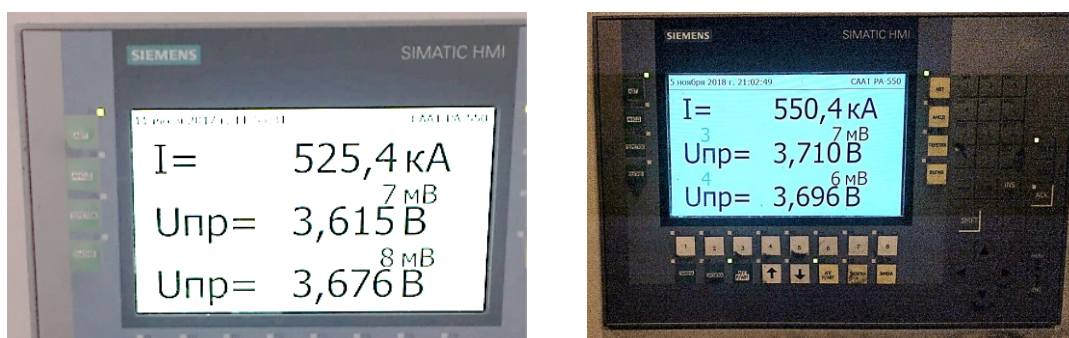


Figure 6. Voltage readings at 525 kA and 550 kA; RA-550 cell’s control panel.

Table 3. RA-550 cell - Voltage measurement points.

| No. of measurement | Measurement points | U, V |
|--------------------|---|------|
| 1 | Upstream side: Riser No. 2 of the cell being measured – Riser No. 2 of the following cell | 4.07 |
| 2 | Downstream side: at the centre of the anode busbar of the cell being measured – at the foot of Riser No. 5 of the cell being measured | 3.71 |

Based on the automated process control system (APCS) voltage (3.71 V), the specific energy consumption is 11 613 kWh/t Al (current efficiency = 95.2 %). However, if taking into account the total voltage comprising the voltage drop in the cathode and anode busbars (4.07 V), this value increases up to 12 740 kWh/t Al (the difference is 1 127 kWh/t Al). Taking into account the voltage drop in the line busbar, including transition buses ($\Delta U \sim 18$ mV), the overall (total) voltage of the cell will be 4.088 V, and the specific energy consumption will be 12 796 kWh/t Al for the RA-550 cell technology. This value reflects the real operating costs (OPEX), considering all losses in the infrastructure. These data emphasize the importance of accounting for all voltage components for an objective assessment of the actual energy consumption of the process.

5. Conclusions

The evaluation of the energy efficiency of cell technologies requires taking into account the total voltage drop, including the busbars (both anode and cathode), transition buses (buses between potrooms), as well as all deviations from the target voltage. This ensures the accuracy of calculations, helps avoid the underestimation of the energy consumption and shows the actual energy efficiency. If magnetic field compensation loops are used, the voltage drop in such loops should be distributed between the cells installed and included in a calculation of energy consumption.

For an unambiguous interpretation of data in publications, it is proposed to use the following wording:

- Cell internal voltage: Net cell voltage minus external (cell-to-cell busbar) voltage drop. This voltage is used for cell thermal balance calculations.
- Computer control voltage: Measured cell voltage between two points on the busbar of two adjacent cells, used for cell resistance control. This may include only a partial busbar voltage drop, depending on technology, e.g., between points 3 in Figure 3.
- Net cell voltage: Full cell-to-cell voltage, which is measured between two identical positions on two adjacent cells.
- Gross cell voltage: Full voltage, including all voltage drops in the cell current-carrying elements and line busbars, which is equal to “net voltage + voltage drop in busbar linkages”. This is equal to the potline voltage divided by the number of cells.
- Magnetic compensation loop voltage per cell. This is used for the calculation of energy consumption in the compensation loop, which has to be added to the energy consumption in the cell.

In this paper, we emphasized the importance of having a clear methodological approach to the presentation of voltage data; in particular, when publishing values of the specific energy consumption, it is necessary to indicate what voltage was included in calculations.

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