Journal of Sustainability Science and Management
Volume 18 Number 10, October 2023: 176-186
eISSN: 2672-7226
© UMT Press

TOWARDS A SUSTAINABLE FUTURE IN ALUMINIUM PRODUCTION: ENVIRONMENTAL AND ECONOMIC BENEFITS OF REVOLUTIONARY INERT ANODE TECHNOLOGY

RAMIL I. HASANOV[1,2]*

[1]*Faculty of Economics and Management, Azerbaijan Technological University, AZ2011, Ganja, Azerbaijan.* [2]*Western Caspian University, 31, Istiglaliyyat Street, Baku, Azerbaijan.*

**Corresponding author: r.hasanov@uteca.edu.az*
Submitted final draft: 18 July 2023 *Accepted: 30 July 2023* http://doi.org/10.46754/jssm.2023.10.012

Abstract: The aluminium industry currently produces significant greenhouse gas emissions and relies on energy-intensive production technology, substantially burdening the environment. The primary goal of aluminium production is to achieve expertise in carbon-free technologies and alternative energy sources. Global business companies and scientific foundations are crucial in driving progress towards sustainability objectives. Reducing the average 16 tonnes of CO_2 emissions and 14,000 kWh of electricity required for every tonne of primary aluminium production presents a significant challenge. Traditional aluminium production can incur environmental costs of up to $1,000 per tonne. Addressing this issue is unfeasible without revolutionary scientific and technological innovations. The development of inert anode technology is considered one of the greatest innovations of the 21st century, potentially transforming the aluminium industry fundamentally. Due to the threat of global climate change, green strategies have become a top priority on the world's political and economic agendas, with many areas setting net zero CO_2 targets for 2050. This scientific study highlights the importance of integrating inert anode technology into the green platform of the aluminium industry as a crucial step towards achieving long-term sustainability.

Keywords: Green economics, sustainability, inert anode technology, aluminium production, innovation, technology.

Introduction

Excessive and increasing amounts of carbon dioxide in the atmosphere significantly threaten the world's ecosystem. Climate analysts attribute the primary cause of global warming to human activities since the Industrial Revolution. As a result, it has become inevitable to establish a necessary balance between the global economy and ecology, with the aluminium industry at the core of the problem. The industry's increasing demand requires building a sustainable ecosystem to minimise CO_2 emissions during aluminium production and bring them to zero. The urgent need for scientific research from a green economic perspective to develop sustainable models of the aluminium industry is evident. International research institutes, economic institutions, and companies committed to building sustainable future models struggle to find aluminium industry models compatible with green technology. Fundamental changes in energy supply and production technologies are necessary to create a green aluminium industry.

Two main strategic vectors have been identified to organise sustainable economic efficiency in the aluminium industry and prevent environmental problems: Transition to renewable energy sources and creation of production technologies according to ecological standards. Alternative energy projects have existed for over a century, and the world aims to transition to this system over time through specific programs set by the UN (United Nations, 2023) and EU (European Commission, 2023) strategies for 2030 and 2050. However, even if the industry's energy supply entirely relies on green alternatives, reducing greenhouse gases to zero is impossible without revolutionary innovations in production technologies. Inert anode technology is considered one of the most important revolutionary inventions for a sustainable future. This technology is a novel process still under development and the transition to inert anodes is one of the plant's future goals. Definitive information on the economic feasibility of this technology is not yet available. However, the environmental benefits of inert anodes are evident because of provide a carbon-free alternative to traditional anodes.

The inert anode technology employs non-consumable anodes to produce aluminium without releasing greenhouse gases. This technology has the potential to drastically alter the aluminium industry by making it more environmentally friendly and energy-efficient. Global companies such as Alcoa, Rio Tinto, Rusal, and Hydro are striving to develop this technology. Alcoa and Rio Tinto's Inert Anode Project, funded by \$20 million from the Canadian government, aims to eliminate 7 million tonnes of CO_2 emissions, equivalent to removing 1.8 million cars from circulation in Canada (Aluminium Today, 2021).

Hydro is developing a \$3.2 million pilot project and is interested in conducting scientific work on the process (Hydro, 2014). In 2021, Rusal tested inert anode technology for the first time, achieving stable production of aluminium on an industrial scale with a cell capacity of about 1 tonne of aluminium per day per cell at a current of 140 thousand amperes (Rusal, 2021). Startups working with giant aluminium-producing companies and developing projects are considered the main idea centres.

Alongside state-owned enterprises and aluminium corporations, worldwide electronic companies like Apple have shown interest in the inert anode project. As part of the global green movement, branded companies seek to partner with environmentally responsible aluminium producers to fulfil their aluminium requirements. The revolutionary inert anode technology is on the agenda as a project with great gravity regarding the aluminium industry and global green strategies. Conducting economic and environmental evaluations of this technology, whose pilot projects are underway, has become important for a sustainable future.

Research Question

The proposed study aims to evaluate the potential economic and environmental benefits of inert anode technology for sustainable aluminium production. The research question under investigation is, "What are the economic and environmental implications of implementing inert anode technology for sustainable aluminium production?" The study's primary objective is to test the hypothesis that inert anode technology presents significant advantages in terms of economic and environmental sustainability over traditional aluminium production methods. It is worth emphasising that the hypothesis is a provisional assertion that requires systematic research and rigorous data analysis to validate or refute. The study aims to provide comprehensive insights into the feasibility and potential impact of inert anode technology deployment in the aluminium industry by examining its potential benefits. Ultimately, the research seeks to contribute to the existing knowledge on sustainable production practices and enlighten industry stakeholders on the potential benefits of adopting inert anode technology.

Table 1: Main aluminium companies and startups dedicated to project development are actively pursuing the implementation of inert anode technology

Global Aluminium Companies	Startups for Inert Anode Technology
Alcoa	Elysis
Rio Tinto	Elysis
Rusal	En + Group

Literature Review

To comprehend the study from an epistemological standpoint, it is required first to grasp Inner Anode Technology. The scientific studies examined the inert anode project, an invention in science and technology that has a recent past. To analyse this revolutionary innovation in the aluminium industry, it is necessary to obtain scientific articles that have conducted studies on the technological production process, energy consumption, and emission volume of greenhouse gases. The main toxicity proof of this project is related to the core technological process, which does not use any carbon materials. Carbon materials can release harmful environmental pollutants like carbon monoxide and dioxide. By eliminating carbon materials from the process, the inert anode technology can significantly reduce the environmental impact of aluminium production.

In their scientific research, Feng *et al.* (2014) explain the aluminium electrolysis process and the shift from the traditional carbon anode method to the revolutionary inert anode project. They explore the potential use of chemical cermet as a partially inert anode for sustainable aluminium production. The authors examine the characteristics and effectiveness of the cermet anode and the impact of different operational variables on aluminium production.

Ratvik *et al.* (2022) thoroughly review the evolution and advancements in aluminium production techniques. The article highlights the challenges faced by the industry, including environmental concerns and increasing costs. The research emphasises the potential of inert anode technology as a promising solution for sustainable aluminium production, which has gained attention in recent years. The paper assesses the potential economic and environmental benefits of implementing inert anode technology in the aluminium industry. In the article, Xianxi (2021) presents a detailed examination of the advancement and current standing of inert anodes concerning aluminium electrolysis. The article elaborates on the performance of inert anodes in laboratory and industrial settings and their potential economic and environmental benefits. Galasiu and Galasiu (2014) aim to investigate and analyse the potential of utilising innovative technologies to minimise energy consumption during aluminium production. In the article, the authors provide a detailed explanation of the mechanisms involved in the process and emphasise the advantages of implementing inert anodes and cathodes to enhance energy efficiency, reduce energy consumption, and mitigate the environmental footprint associated with aluminium production. Brough and Jouhara (2020) thoroughly examine the current technologies utilised in the aluminium industry. The authors delve into multiple facets of aluminium production, including the energy consumed and the resulting CO_2 emissions.

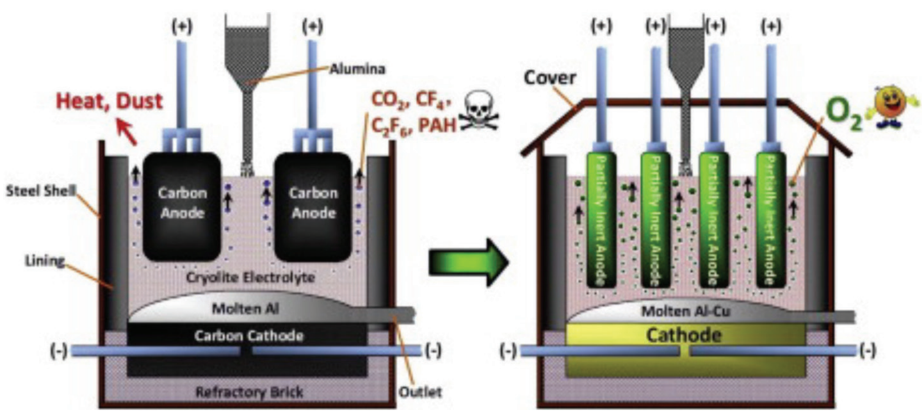

Figure 1: A visual representation of the transition from traditional carbon anode technology to inert anode
Source: Feng *et al.* (2014)

The research work progresses from theoretical analyses to practical applications. The article examines the economic and environmental sustainability of the aluminium industry from a technological perspective, utilising scientific data gathered directly from within the industrial complex.

Methodology

The fundamental methodology employed in this research entails a comparative analysis of the economic and environmental factors associated with conventional carbon anode technology and innovative inert anode technology. The main principle underlying this concept involves the evaluation of both economic usage and CO_2 emissions. To assess the environmental impact, it is crucial to establish the magnitude of carbon emissions associated with each technology. Subsequently, an overall evaluation of the environmental cost can be performed:

$$CO_2 = IAT - CAT$$
$$EC = CO_2 \times SCC \times P$$

where:

- CO_2 (Carbon Emissions Rate)
- CAT (Carbon Anode Technology)
- IAT (Inert Anode Technology)
- EC (Environmental Cost)
- SCC (Social Cost of Carbon)
- P (Annual production)

As the inert anode technology implementation is presently confined to pilot projects and lacks widespread practical application, precise economic assessments are unattainable. A simple econometric approach can be employed to assess the economic merits of utilising either carbon anode technology or inert anode technology by estimating the aggregate production cost for each method. The total production costs of both technologies can subsequently be compared to determine the more economically viable alternative. To ascertain the factors influencing the costs and energy savings of the two technologies, we must identify the variables that may be considered. These variables include:

- Energy consumption
- Capital cost
- Operating cost
- Lifetime of materials

To collect the required information about the variables related to both types of anode technology, gathering data from different sources such as industry reports, government statistics, and other pertinent sources is crucial.

Results

Environmental Analysis

Aluminium production involves a series of intricate processes that commence with the initial processing of raw materials. These processes produce substantial carbon dioxide emissions from energy consumption and chemical processing. To comprehend the procedure's core, it is essential first to grasp the fundamental concepts of the entire production technology. The process of primary aluminium production is founded on physico-chemical technology and equations. The electrolysis process is employed to obtain liquid aluminium from raw alumina (Al_2O_3) required for aluminium production, utilising carbon-containing substances. During aluminium production in the electrolysis cell, the carbon present combines with oxygen to produce CO_2. The conventional carbon anode technology employed in this process, which is known as the Hall-Heroult process, can be represented by the following chemical equation:

$$1/2\ Al_2O_3\ (\text{dissolved}) + 3/4\ C\ (s) = Al\ (l) + 3/4\ CO_2\ (g)$$ (Margolis & Eisenhauer, 1998)

The rate at which anodes are consumed during the aluminium production process varies between 0.4 to 0.5 kg of carbon per kg of aluminium, contingent upon the type of anode utilised and the electrolysis conditions. Consequently, the anodic gas produced due to this process is comprised of a mixture of 30% to 50% carbon monoxide and 50% to 70% carbon dioxide (Shkolnikov *et al.,* 2011).

Figure 2: Post-use carbon anode blocks
Source: Author

In the inert anode technology, carbon anode blocks are replaced by ceramic materials, and since carbon is not involved in the process, only oxygen is released into the environment:

Al_2O_3 (dissolved) = 2 Al (l) + 3/2 O_2 (g) (Van Leeuwen, 2000)

The current production of one tonne of aluminium is estimated to generate between 12 to 20 tonnes of CO_2 emissions. Most of these emissions do not directly arise from the aluminium production process but rather from the energy sources required to power the process. For instance, the use of coal-fired thermal power plants to produce one tonne of aluminium results in CO_2 emissions of up to 20 tonnes, while hydroelectric power plants can decrease these emissions by a factor of 10 to 2T. In light of the impact of aluminium production on climate change, there is a growing need to develop innovative technologies that significantly reduce carbon emissions associated with aluminium production. These technologies are crucial for the achievement of a sustainable future. The inert anode method, in particular, is a technological innovation of significant importance in reducing carbon emissions from aluminium production. Its adoption offers the potential for achieving 0% CO_2 emissions.

It is important to note that the amount of CO_2 emissions from aluminium production can vary depending on various factors, such as the type of technology utilised and the energy source. International Aluminium (2022) has reported that the direct process carbon dioxide emissions resulting from using carbon-based technologies to produce one tonne of primary aluminium amount to 2.3 tonnes. The use of inert anode technology in aluminium production represents a significant advancement in reducing the carbon footprint of the industry. Unlike carbon-based anodes, using inert anodes eliminates the need for carbon blocks, significantly reducing the carbon emissions associated with the production process. As a result, the direct aluminium production process utilising inert anode technology has the potential to become a green industry with zero carbon emissions:

$$IAT = 0T$$
$$CAT = 2.3T$$
$$CO_2 = IAT – CAT = -2.3T$$

The Social Cost of Carbon (SCC) provides a means for assessing the monetary costs of releasing an additional metric tonne of CO_2 into the environment. In this regard, the SCC considers multiple factors, including social, economic, and environmental impacts from climate change, such as health implications, property damage, and reduced productivity. Make high academically: In the United States, the official estimate for the SCC is \$51 per metric tonne, which signifies that economists and climate scientists anticipate the total harm resulting from an additional metric tonne of carbon emissions to amount to \$51 (Asdourian & Wessel, 2023). The Environmental Cost (EC) rate for the aluminium industry can be determined by applying the available statistical data to the Ganja Aluminium Complex*, which has an annual production capacity of 50,000 tonnes:

$$EC = CO_2 \text{ x } SCC \text{ x } P = \text{-2,3 t x \$51 x 50,000 t} = \text{-\$5,865,000}$$

According to the estimate, the application of inert anode technology in a manufacturing facility as observed is anticipated to yield an annual environmental benefit worth \$5,865,000.

An additional environmental benefit conferred by this technology is the production of oxygen during the process of manufacturing aluminium, as a one-cell equipped with an inert anode technology can generate a quantity of oxygen equivalent to that produced by an area of 70 hectares covered with trees (Enplusgroup, 2021). Considering that 84 aluminium cells operate in the Ganja Aluminium Complex (Azeraluminium, 2023), the extra green result of the complex is 5880 hectares.

*The only primary aluminium producer in the Caucasus region.

Energy Policy and Economic Analysis

The primary energy source for the aluminium industry is a critical factor, and hydroelectric plants are considered the most unique energy source for large aluminium plants. The shift towards using physical forces of nature, such as hydroelectric power, as the primary energy source for the aluminium industry is one of the major projects of the future. Several global aluminium companies are developing plans of action to implement this strategy. Several global companies aim to construct their power plants solely relying on renewable energy sources to minimise their indirect production emissions. Rio Tinto has solicited expressions of interest from external entities in central Queensland, seeking to procure 4,000 megawatts of wind and solar power by 2030 to supply Yarwun and the adjacent Boyne aluminium smelter (Greber & Ker, 2023).

One of the significant objectives of alternative strategies is to decrease the energy consumed during production procedures by employing advanced and innovative technologies. Norway's Hydro Aluminium Company is taking steps to decrease energy consumption in primary aluminium production by constructing riverside production facilities that utilise hydroelectric power and aims to produce large quantities of aluminium using this renewable energy source. Hydro has initiated the production of the initial batch of aluminium metal at its Karmøy technology pilot facility, signifying the commencement of industrial-scale validation of the HAL4e aluminium technology. Hydro has launched the HAL Ultra research and development project to achieve a specific direct current energy consumption of 10 kWh/kg for aluminium production while ensuring zero net carbon dioxide emissions. The plant comprises 48 cells that utilise the HAL4e technology, which has a specific energy consumption of 12.3 kWh/kg, along with 12 cells that employ the latest HAL4e Ultra technology, with a specific energy consumption ranging between 11.5-11.8 kWh/kg (Segatz *et al.,* 2016). Notably, these values are considerably lower than the global average energy consumption of 14 kWh/kg for aluminium production and Hydro's average of 13.8 kWh/kg.

The amount of energy necessary to manufacture 1 kg of aluminium with the help of inert anode technology can fluctuate based on various factors, such as the type of inert anode utilised, the particular production process, and the efficiency level of the equipment employed. Despite the variation in energy requirements, the inert anode technology is widely regarded as the most sustainable and unique approach among these energy strategies, with potential energy savings of up to 3-4% compared to the traditional carbon anode process (Gautam *et al.,* 2018). The potential economic benefits of energy conservation in the industrial sector are noteworthy. Specifically, for an enterprise engaged in the annual production of 50,000 tonnes of aluminium, such conservation efforts could lead to a profit of no less than $0.5 million in Azerbaijan (Tariff, 2021) and more than $2 million in the United States (Energybot, 2023) and Europe (Eurostat, 2022).

The employment of vertical electrode cells, as well as the use of a combination of inert anodes and wettable cathodes, are regarded as the measures with the greatest potential for reducing primary energy consumption, greenhouse gas emissions, and energy and CO_2 costs (Haraldson & Johansson, 2020). It should be emphasised that using inert anodes is an evolving technology, and further investigation is required to comprehensively grasp the prospective energy advantages and disadvantages of this technique in the production of aluminium.

In the conventional carbon anode technology, the production of one metric tonne of primary aluminium involves the utilisation of approximately 2 metric tonnes of alumina, 370 kilograms of coke, and 116 kilograms of tar, alongside a variable amount of synthetic cryolite, typically ranging from 15 to 30 kilograms (BGR, 2020). The carbon materials needed to produce one metric tonne of primary aluminium for the Ganja Aluminium Complex was approximately $800 in 2022 (Table 2). However, with the use of inert anode technology, anode costs can be mitigated by employing ceramic materials that are more cost-effective, environmentally friendly, and have significantly longer lifespans.

The implementation of inert anode technology in aluminium production processes has the potential to yield substantial cost savings. Specifically, the removal of carbon anodes as a consumable component eliminates associated costs such as capital investment, raw materials, and the expenses related to carbon anode manufacturing, baking, and anode rodding plant operations. These cost reductions may be particularly significant, with estimates suggesting a possible decrease of 25% to 30% in capital costs for a new potline that employs inert anode cell technology (Thonstad *et al.,* 2001). Integrating inert anode technology in aluminium production could have significant economic benefits beyond the environmental advantages of using more sustainable and durable ceramic materials instead of carbon.

The importance of adhering to green principles is growing in the global business environment, creating new market opportunities for companies prioritising sustainability. In pursuit of its objective to cut CO_2 emissions by 20% in its supplier network by 2030, BMW is taking a significant step forward by procuring solar-powered aluminium (BMW, 2021). The German car manufacturer has partnered with

Table 2: Overall sustainability benefits for an aluminium plant with an annual production capacity of 50,000 tonnes in Azerbaijan

Sustainability Benefits of Inert Anode Technology (The Comparative Case of the Ganja Aluminium Complex)
Environmental Benefits
Prevention of 120,000 tonnes of CO_2 emissions.
$5,865,000 environmental cost advantage.
Production of oxygen gas instead of carbon emissions.
Economic Benefits
Reduction of 25-30% in capital cost.
Reduction in costs of green supply chain management.
$500,000 reduction in energy costs.
Opening up new opportunities in the global business market.

Emirates Global Aluminium, which employs alternative energy sources and has signed a trade agreement to supply 43,000 metric tonnes (Sophia, 2021). A United Arab Emirates-based company has made history by being among the first global examples of generating economic profits solely through green technologies. This achievement is expected to influence other businesses, encouraging them to follow suit and adopt environmentally sustainable practices.

Discussion

Despite the numerous potential benefits associated with inert anode technology, several concerns must be addressed regarding its implementation. This is primarily because the inert anode process is still being developed as a new pilot project, and long-term economic evaluations cannot be conducted in practice now. Implementing inert anode cells in aluminium production poses several significant challenges, particularly concerning the technology's commercial viability. The feasibility of using inert anodes in large-scale production has not been fully demonstrated. Furthermore, various engineering obstacles must be overcome before inert anode cells become a viable and reliable technology. As such, it remains uncertain whether inert anodes will eventually be widely adopted in industrial aluminium production, and it is difficult to predict when, or even if, these challenges will be sufficiently resolved (Kvande & Drabløs, 2014). Given the complexity of these challenges, it is likely that several years will elapse before inert anode cells can be proven as a feasible and effective technology for commercial application.

An argument about inert anodes is their higher theoretical energy consumption compared to carbon anodes, which stems from their inability to use the chemical energy stored in carbon during the aluminium production process (Solheim, 2018). Another factor that contributes to the debate surrounding inert anode technology is the issue of material costs, which can vary depending on the approach taken. Ceramic, metal, and cermet anodes are non-consumable in inert anode technology to replace carbon blocks. Ceramic anodes are made of various materials, including magnesium, alumina, and zirconia. These materials have a low environmental footprint and are relatively inexpensive to produce. However, they have low electrical conductivity and durability. Metal anodes are made of titanium, iridium, and ruthenium and have high electrical conductivity and durability, but these materials are more expensive. Cermet anodes are composites of ceramic and metal materials with moderate electrical conductivity and durability. These materials are also moderately priced. Inert anode materials, such as cermet and oxide-based materials, are currently more costly than carbon anode blocks, primarily due to the higher expenses associated with raw materials and complex manufacturing processes.

Additionally, these materials are still in the early stages of development and are not yet widely used in large-scale aluminium production. Carbon anode blocks, by contrast, are made from inexpensive petroleum coke and pitch and have been utilised for many years in the production of aluminium. Despite recent increases in the cost of carbon, it remains relatively inexpensive compared to alternative materials. However, implementing inert anodes offers several potential advantages over carbon anodes, including greater energy efficiency, reduced greenhouse gas emissions, and longer anode lifespan. Consequently, ongoing research and development efforts aim to improve the performance and reduce the cost of inert anode materials, aiming to make them more cost-competitive with carbon anodes. According to Haraldson and Johansson (2018), inert anodes are still in the pilot plant stage and face significant challenges, including the high temperatures involved, the corrosive nature of the electrolyte, and the difficulty in finding conducting or semiconducting materials that are stable and do not dissolve in the electrolyte.

Finally, an interesting claim about environmental costs has attracted attention. Auffhammer (2022) reviews a recent paper that suggests the Social Cost of Carbon, which is the monetary value of the damages caused by emitting one tonne of carbon dioxide into the atmosphere, which is much higher than the current estimate used by the US government. The current estimate is $51 per tonne, but the new study argues that the SCC is $185 per tonne of CO_2, over three times higher.

Switching to inert anode technology worldwide is not feasible suddenly, as it requires a long-term process to fundamentally transform the traditional aluminium industry that involves producing millions of tonnes with significant investments. The discussions and debates around new technologies like inert anodes highlight the importance of innovation and the need for sustainable solutions for the future. As we face challenges like climate change and environmental degradation, new and innovative approaches must be explored to help us reduce our environmental impact and achieve a more sustainable future. While there may be debates and uncertainties around new technologies, it is important to continue investing in research and development to explore and test new solutions that can help us address these challenges.

Conclusion

The application of inert anode technology in the aluminium industry provides several benefits for sustainability. By substituting traditional carbon-based anodes with inert ones, greenhouse gas emissions can be significantly reduced, while economic efficiency can be increased. Adopting inert anode technology supports the global trend towards a more sustainable future. Investing in innovative solutions like inert anodes is crucial to fostering a cleaner and more sustainable future. Both aluminium companies and international organisations are pursuing this approach as they strive to establish themselves as environmentally responsible entities. The research has analysed the scientific basis of this innovation, which is considered revolutionary.

The article provides a brief overview of the technological process of primary aluminium production, innovative conversion approaches and comparative analyses from both global and local perspectives. The main objective of the scientific study is to conduct significant environmental and economic assessments of inert anode technology and comprehensively present sustainability indicators. One of the primary aims of this research is to bridge the gap between science and industry by demonstrating the eco-economic viability and potential prospects of inert anode technology in a practical industrial setting.

Acknowledgements

I would like to express my heartfelt gratitude to Universiti Malaysia Terengganu (UMT) and the Journal of Sustainability Science and Management (JSSUM) for their invaluable support and collaboration in the publication of my article titled “TOWARDS A SUSTAINABLE FUTURE IN ALUMINUM PRODUCTION: ENVIRONMENTAL AND ECONOMIC BENEFITS OF REVOLUTIONARY INERT ANODE TECHNOLOGY” in Volume 18 No 10 Issue.

The opportunity to share this research with the global scientific community is greatly appreciated. I extend my special thanks to JSSUM for their unwavering commitment to maintaining the highest standards of transparency, accuracy, and sincerity throughout the editorial and revision process. Their dedication to excellence has undoubtedly enriched the quality of this publication.

I am sincerely grateful for the platform provided by UMT and JSSUM, which has allowed me to contribute to the field of sustainability science and management. This experience has been instrumental in my academic journey. Once again, thank you for your support and collaboration.

References

Aluminium today. (2021). ELYSIS: Start of construction of commercial-scale inert anode cells. https://aluminiumtoday.com/

news/elysis-start-of-construction-of-commercial-scale-inert-anode-cells

Asdourian, E., & Wessel, D. (2023). What is the social cost of carbon? *Brookings*. https://www.brookings.edu/2023/03/14/what-is-the-social-cost-of-carbon/

Auffhammer, M. (2022). New U.S. study: Damage per tonne of CO_2 costs $185, not the official $51. *EnergyPost*. https://energypost.eu/new-u-s-study-damage-per-ton-of-co2-costs-185-not-the-official-51/

Azeraluminium. (2023). Istehsalat. Elektroliz zavodu. https://azeraluminium.com/az/f%c9%99aliyy%c9%99timiz/istehsalat/elektroliz-zavodu/

BGR. (2020). Aluminium. Sustainability Information. Bundesanstal für Geowissenschaften und Rohstoffe.

BMW. (2021). Harnessing the power of the desert sun: BMW Group sources aluminium produced using solar energy. BMW Group. Press club global, article. https://www.press.bmwgroup.com/global/article/detail/T0325353EN/harnessing-the-power-of-the-desert-sun:-bmw-group-sources-aluminium-produced-using-solar-energy?language=en

Brough, D., & Jouhara, H. (2020). The aluminium industry: A review on state-of-the-art technologies, environmental impacts and possibilities for waste heat recovery. *International Journal of Thermofluids*. https://doi.org/10.1016/j.ijft.2019.100007

Energybot. (2023). Electricity Rates By State (Updated Daily). *Energybot.* https://www.energybot.com/electricity-rates-by-state.html#:~:text=The%20Average%20Electricity%20Rate%20in,7.01cents%20per%20kilowatt%2Dhour.

Enplusgroup. (2021). Inert Anode Technology. https://enplusgroup.com/en/what-we-do/projects/Inert-anode/Europe Commission. (2023). A European Green Deal. Striving to be the first climate-neutral continent. https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en

Eurostat. (2022). Electricity and gas prices in the first half of 2022. *Eurostat.* https://ec.europa.eu/eurostat/web/products-eurostat-news/-/ddn-20221031-1

Feng, I., Xie, N., Shao, W., & Zhen, L. (2014). Exploring Cu2O/Cu cermet as a partially inert anode to produce aluminium sustainably. *Journal of Alloys and Compounds*. https://doi.org/10.1016/j.jallcom.2014.04.198

Galasiu, I., & Galasiu, R. (2014). Aluminium electrolysis with inert anodes and wettable cathodes and with low energy consumption. https://doi.org/10.1002/9781118448847.ch1d

Gautam, M., Pandey, B., & Agrawal, M. (2018). Carbon footprint of aluminium production: Emissions and mitigation. Environmental carbon footprints. *Industrial Case Studies,* 197-228. https://doi.org/10.1016/B978-0-12-812849-7.00008-8

Greber, J., & Ker, P. (2023). Rio Tinto wants special treatment for aluminium emissions. *Financial Review.* https://www.afr.com/policy/energy-and-climate/rio-tinto-wants-special-treatment-for-aluminium-emissions-20230315-p5cscz

Haraldson, J., & Johansson, M. (2018). Review of measures for improved energy efficiency in production-related processes in the aluminium industry – From electrolysis to recycling. *Renewable and Sustainable Energy Reviews, 93*, 525-548. https://doi.org/10.1016/j.rser.2018.05.043

Haraldson, J., & Johansson, M. (2020). Effects on primary energy use, greenhouse gas emissions and related costs from improving energy end-use efficiency in the electrolysis in primary aluminium production. *Energy Efficiency, 13*, 1299-1314. https://doi.org/10.1007/s12053-020-09893-1

Hydro. (2014). Hydro opens test pilot for new anode technology. https://www.hydro.com/

fr-CH/media/news/2014/hydro-opens-test-pilot-for-new-anode-technology/

International Aluminium. (2022). Greenhouse Gas Emissions Intensity - Primary Aluminium. https://international-aluminium.org/statistics/greenhouse-gas-emissions-intensity-primary-aluminium/

Kvande, H., & Drabløs, P. A. (2014). The aluminium smelting process and innovative alternative technologies. *Journal of Occupied Environmental Medicine, 56*(5 Suppl), S23-S32. doi: 10.1097/JOM.0000000000000062

Margolis, N., & Eisenhauer, J. (1998). Inert Anode Roadmap – A framework for technology development", The Aluminium Association, Inc. in conjunction with The U.S. Department of Energy. Energetics, Inc., Columbia, Maryland, USA, February 1998, 29 pp.

Ratvik, A. P., Mollaabbasi, R., & Alamdari, H. (2022). Aluminium production process: From Hall–Héroult to modern smelters. *ChemTexts, 8*, 10. https://doi.org/10.1007/s40828-022-00162-5

Rusal. (2021). RUSAL begins test shipments of the world's lowest carbon footprint aluminium. https://rusal.ru/en/press-center/press-releases/rusal-begins-test-shipments-of-the-world-slowest-carbon-footprint-aluminium/

Segatz, M., Hop, J., Reny, P., & Gikling, H. (2016). Hydro's cell technology path towards specific energy consumption below 12 kWh/kg. *Light Metals*. doi: 10.1007/978-3-319-48251-4_50

Shkolnikov, E. I., Zhuk, A. Z., & Vlaskin, M. S. (2011). Aluminium as an energy carrier: Feasibility analysis and current technologies overview. *Renewable and Sustainable Energy Reviews*, *15*(9), 4611-4623. https://doi.org/10.1016/j.rser.2011.07.091

Solheim, A. (2018). Inert anodes - the Blind Alley to environmental friendliness? *Light metals 2018* (pp.1253-1260). DOI:10.1007/978-3-319-72284-9_164

Sophia, M. (2021). BMW buys first aluminium made using solar energy from UAE's EGA. *The National News. Business.* https://www.thenationalnews.com/business/bmw-buys-first-aluminium-made-using-solar-energy-from-uae-s-ega-1.1158181

Tariff. (2021). Elektrik enerjisinin ölkədaxili tarifləri. Azərbaycan RespublikasıTarif (qiymət) Şurası. http://tariff.gov.az/?/az

Thonstad, J., Fellner, P., Haarberg, G., Hives, J., & Kvarde, H. (2001). *Aluminium electrolysis—Fundamentals of the Hall–Héroult Process* (3rd ed.). Düsseldorf, Germany: Aluminium-Verlag, Marketing and Kommunikation GmbH; 2001:1–359.

United Nations. (2023). Climate action. For a livable climate: Net-zero commitments must be backed by credible action. https://www.un.org/en/climatechange/net-zero-coalition

Van Leeuwen, T. M. (2000). An Aluminium Revolution. Equity Research Report, Credit Suisse First Boston Corporation, June 22, 2000, 110 pp.

Xianxi, W. (2021). Inert anodes for aluminium electrolysis. *The Minerals, Metals & Materials Series*. https://doi.org/10.1007/978-3-030-28913-3