“Carbon-Free Technology : Implications for Aluminum”

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Global Metal Industry Carbon Foot Print (2018)

Metals	World Production (MMT)	CO_{2eq} (MT/MT)	% Global GHG
Iron & Steel	1,809	1.0	4-5
Aluminum	64.4	12	1-2
Copper	20	5.5	<1
Zinc*	10	3	<<1
Magnesium*	1	>18	<<1
Titanium*	0.1	>20	<<1

Source : Das, Allanore * estimated

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Alternative Aluminum Production Routes

Processes	t CO_{2eq} /t Al	Change
Average Hall- Héroult (H-H)	12	Base
Best H-H	10	-15%
Wetted drained cathode	9	-25%
Wetted cathode and inert anode	**8**	**-33%**
Carbothermic electric furnace	8	-33%
Clay carbochlorination & chloride electrolysis	8	-33%

Source : Das, JOM

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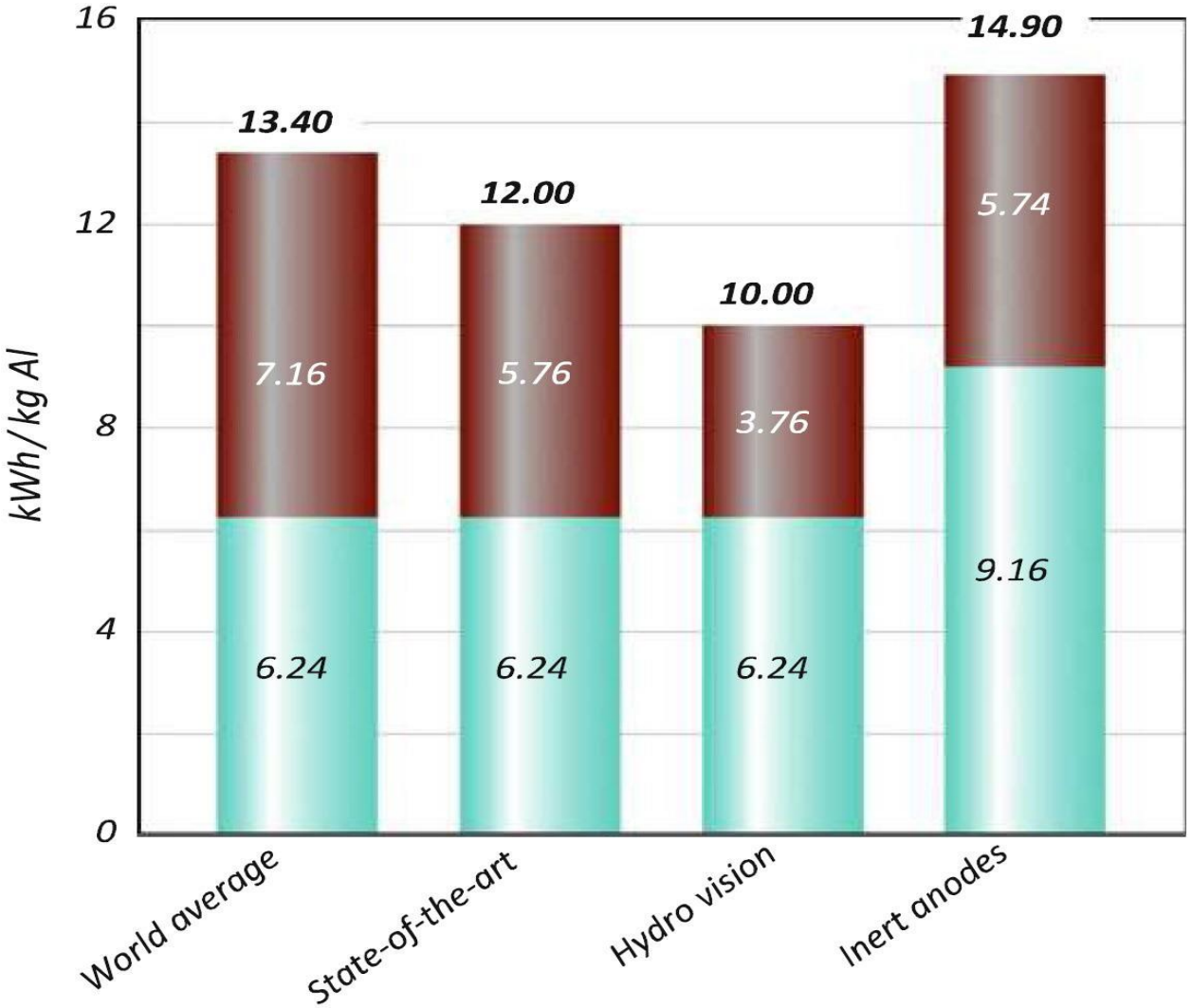
Hall- Héroult CO_{2eq} Emissions

	kg CO_{2eq} / tonne Al					
Emissions	Mining	Refining	Anode	Smelting	Casting	Total
Process			388	1,626		2,014
Electricity		58	63	5,801*	77	5,999
Fossil Fuel	16	789	135	133	155	1,228
Transport	32	61	8	4	136	241
Auxiliary		84	255			339
Per Fluoro-Carbons (PFC)				2,226		2,226
Total	48	992	849	9,790	368	12,047**

Source : Das, JOM *Average Grid ** 12 t CO2eq /t Al

Energy Consumption – Competing H-H Processes



Actual

Theoretical

Source : LMA (2019)

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Technology Terminology Description

Phrase	Implications	Focus
Oxygen Anode	Pure oxygen released	Aspirational Utopian
Zero- Carbon -Free	No C / energy required	Marketing/ Societal
Inert/Non-Consumable Dimensionally Stable	Zero anode dissolution	Technical
Low Carbon-footprint	**Lower GHG processes**	**Most appropriate**

Source : Das

Advantages of Low C-footprint Process

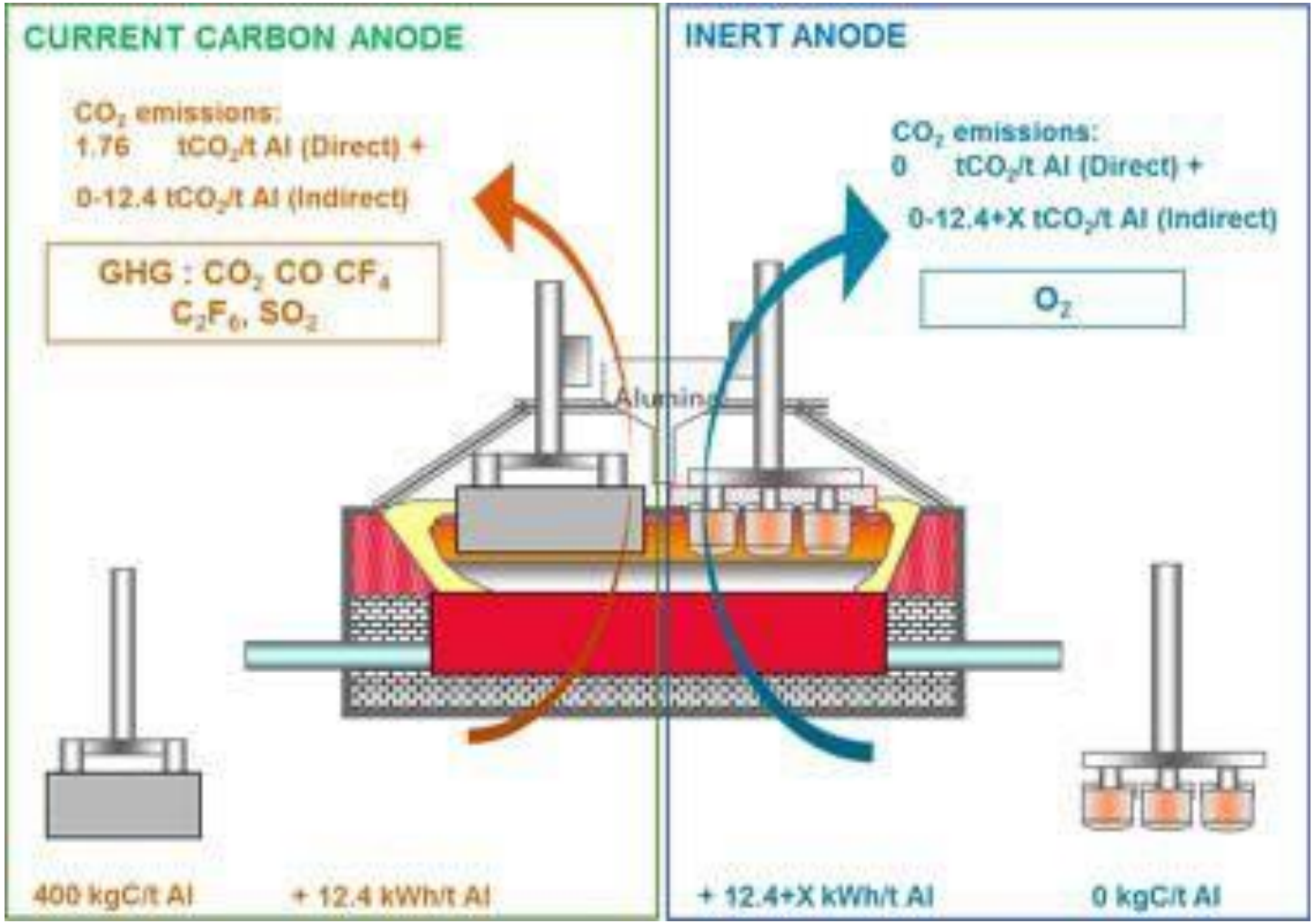
Reduced Carbon Footprint
- Carbon Dioxide
- PerFluoroCarbon (PFC)

Salable Product - Oxygen

Better Work Environment

Source : Image - LMA

Carbon Vs. Low C-footprint Process



Source : Image - AGRAL Process

Barriers, Challenges and Solutions

Barriers	Challenges	Solutions
High Temperature Fluoride Corrosion	“universal solvent”, dissolves alumina	“long lasting” Material Miracle
High Conductivity Lower “theoretical” kWh/kg	IR Losses 500 kA Heat Balance	Lower resistivity Innovative Design
Thermal Shock	C high thermal shock	Innovative Cell Designs
Physical Stability Retrofittable/Cost	Carbon - “cheap”, abundant	Innovative Design , Low Cost
Electrochemical Stability	Al Reactive	Dissolved elements more acceptable

Source : Modified by Das from Sadoway (JOM 2001)

Notable Efforts

Rusal, Rio Tinto and Alcoa are deploying inert anode technology in different ways in their Greenfield and brownfield smelters.

Elysis

- Elysis is a joint venture of the global mining giants Alcoa and Rio Tinto and is supported by the Canadian government
- It made its first commercial batch of low carbon aluminum using inert anode technology at the Alcoa Technical Center in Pittsburgh. Elysis is in the process of scaling up its supply chain and production.
- Elysis has supplied its pilot production volume to Apple, ABInBev, Audi and BMW.

En+ Group (Rusal)

- Rusal's Krasnoyarsk aluminium smelter has produced aluminium with inert anode technology which has specific emissions of 0.01t/tAl (Scope 1 and 2).
- ALLOW INERTA aluminium is produced in inert anode cells, using renewable hydropower.
- The smelter has already produced ALLOW INERTA aluminium at the pilot site and delivered to consumers.

Source : Das

Commercialization – Brownfield

POSITIVE	NEGATIVE	OUTLOOK
Sunk Capital	China > 50 % world capacity	**1-3 years** for Pot Rebuilds
Existing Infrastructure	"Old" technology fights	**4 -6 years** for Line Restarts
Swing Capacity "Life Line"	Alcoa /RTA/Hydro marketing low C Al	**7 -10 years** for Plant Conversions
Low C Products Markets	Elysis/RUSAL Licensing terms	**> 10 years** for wide spread use

Source : Das

Commercialization – Greenfield

POSITIVE	NEGATIVE	OUTLOOK
"Leap Frog" – New "Material Science" Age	Many develops. needed ⇧ "theoretical" kWh/kg	**1-3 years** R&D
Elysis -"Apple Magic" Alcoa/RTA "dream" team	IP , Financing $ New Capacity Location /	**4 - 6 years** Limited
"Green" Products	Will customer pay	**7-10 years** Likely
New Capacity Demand	New technology Chloride/Carbothermic	**> 10 years** More Likely

Source : Das