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Decarbonizing The Production of Primary Aluminium Using Renewable Resource

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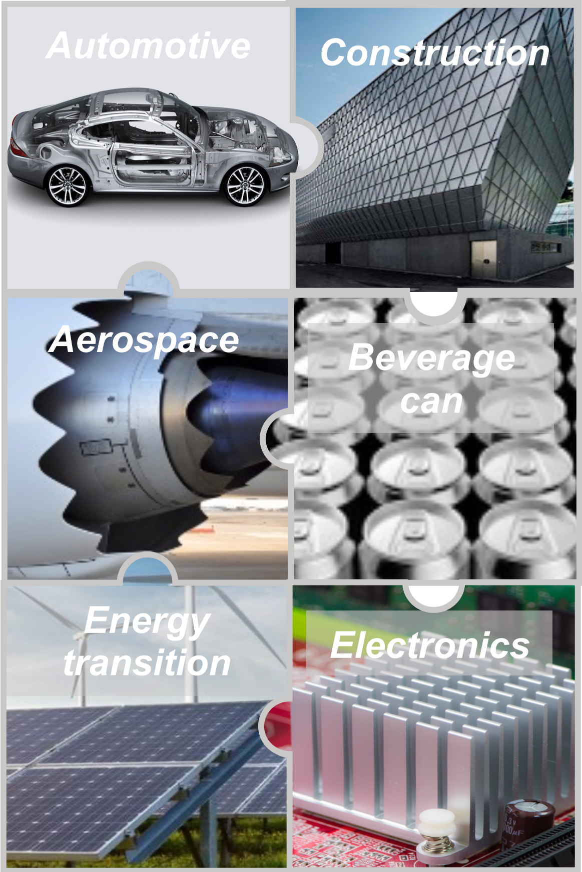
Importance & Applications

A mixture of $Al_2O_3.3H_2O$, Fe_2O_3 and SiO_2

Not pure form!!

Essential component for the global energy transition.

Applications



[1] Jonathan M. Cullen and Julian M. Allwood. “Mapping the Global Flow of Aluminum: From Liquid Aluminum to End-Use Goods”. en. In: Environmental Science & Technology 47.7 (Apr. 2013).

Primary Aluminium Production – State of the Art

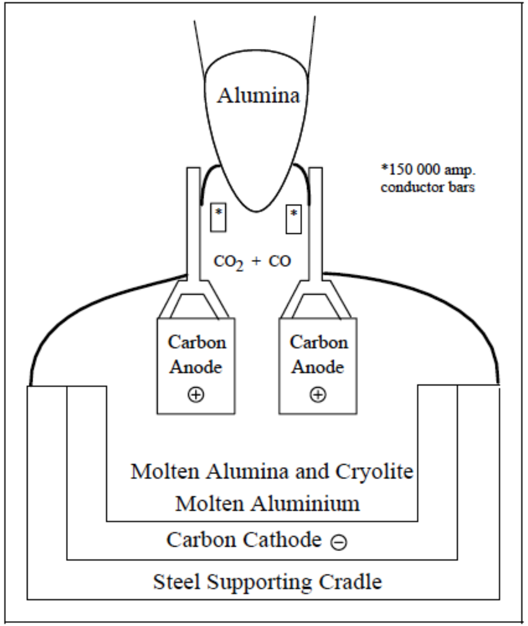
- Extracted from alumina: ***Hall-Heroult process***
- ***Electrolytic smelting: 13 – 15 kWh/kg Al***

Carbon anode:

$$2Al_2O_3\,(aq) + 3\,C(s) \rightarrow 4Al(l) + 3CO_2(g)$$

- *Indirect emissions*: ***Electricity*** ***13.6*** $\frac{t\,CO_2eq}{t\,Al}$

- *Direct emissions:* **Carbon anode** ***1.6*** $\frac{t\,CO_2eq}{t\,Al}$



Cross-sectional view of an aluminium reduction cell using carbon electrodes. [2]

[2] Welch, Barry, and Margaret Hyland. n.d. “The Production of Aluminium.” In, 2nd ed. Vol. 1. Chemical and Materials Department, School of Engineering, University of Auckland.

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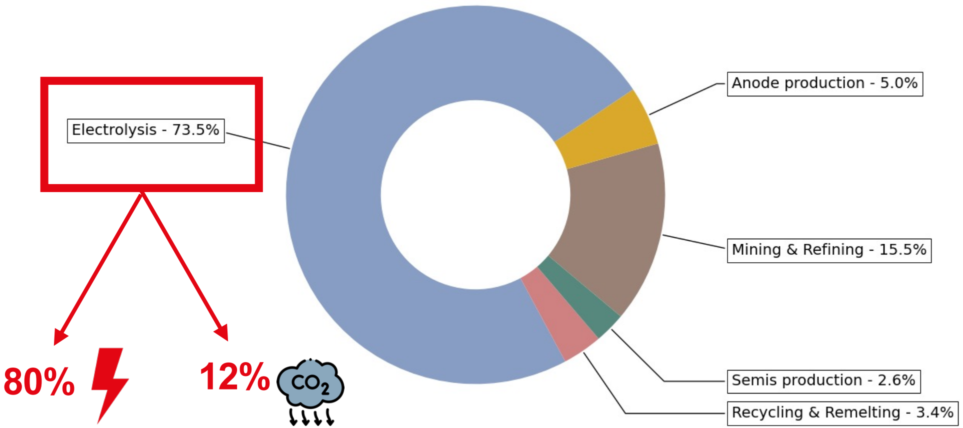
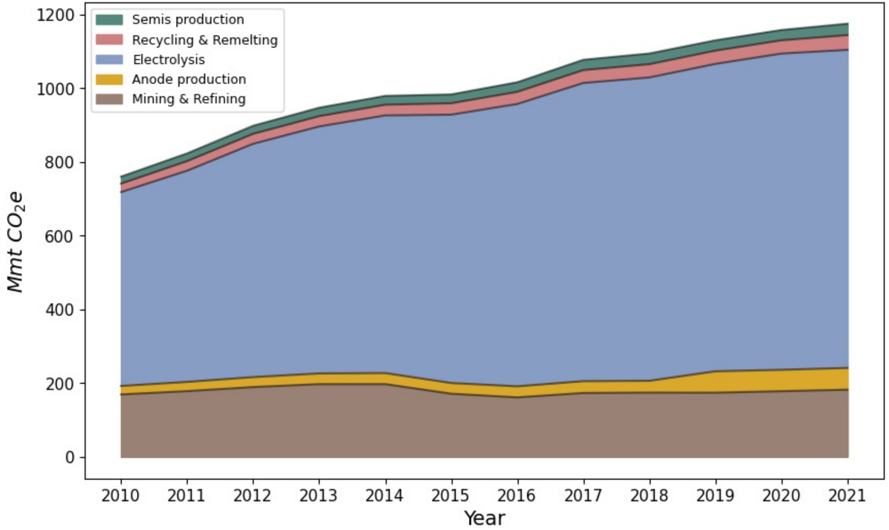
Energy Intensity & Carbon Footprint

- Aluminium **smelting**: 8% of global industrial electricity consumption [3]
- 2021 sector GHG emissions: 1.17 billion tCO_2eq [3]



Aluminium sector GHG emissions in 2021. Data reference IAI [3]



Historical growth trend and GHG emissions distribution of the aluminium sector between 2010 and 2021. Data reference IAI [3]

[3] IAI. Greenhouse Gas Emissions – Aluminium Sector. Jan. 2023.

Primary and Secondary (Recycled) Aluminium

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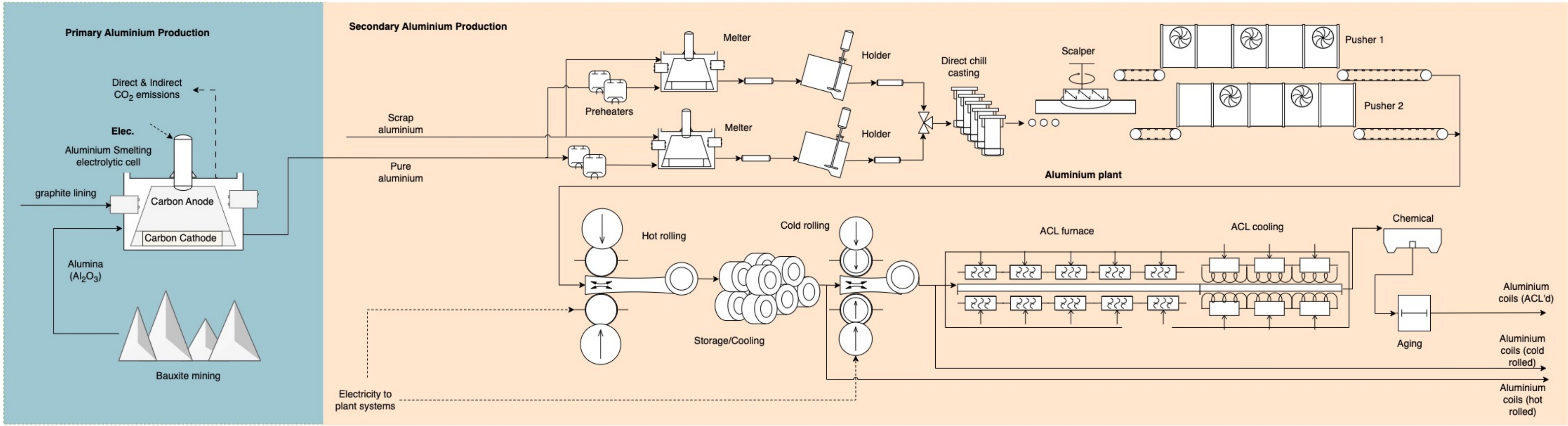
- Bauxite mining, refining, and alumina reduction using carbon anodes and large amounts of electricity.
- Primary and scrap aluminium remelting, annealing, and rolling.

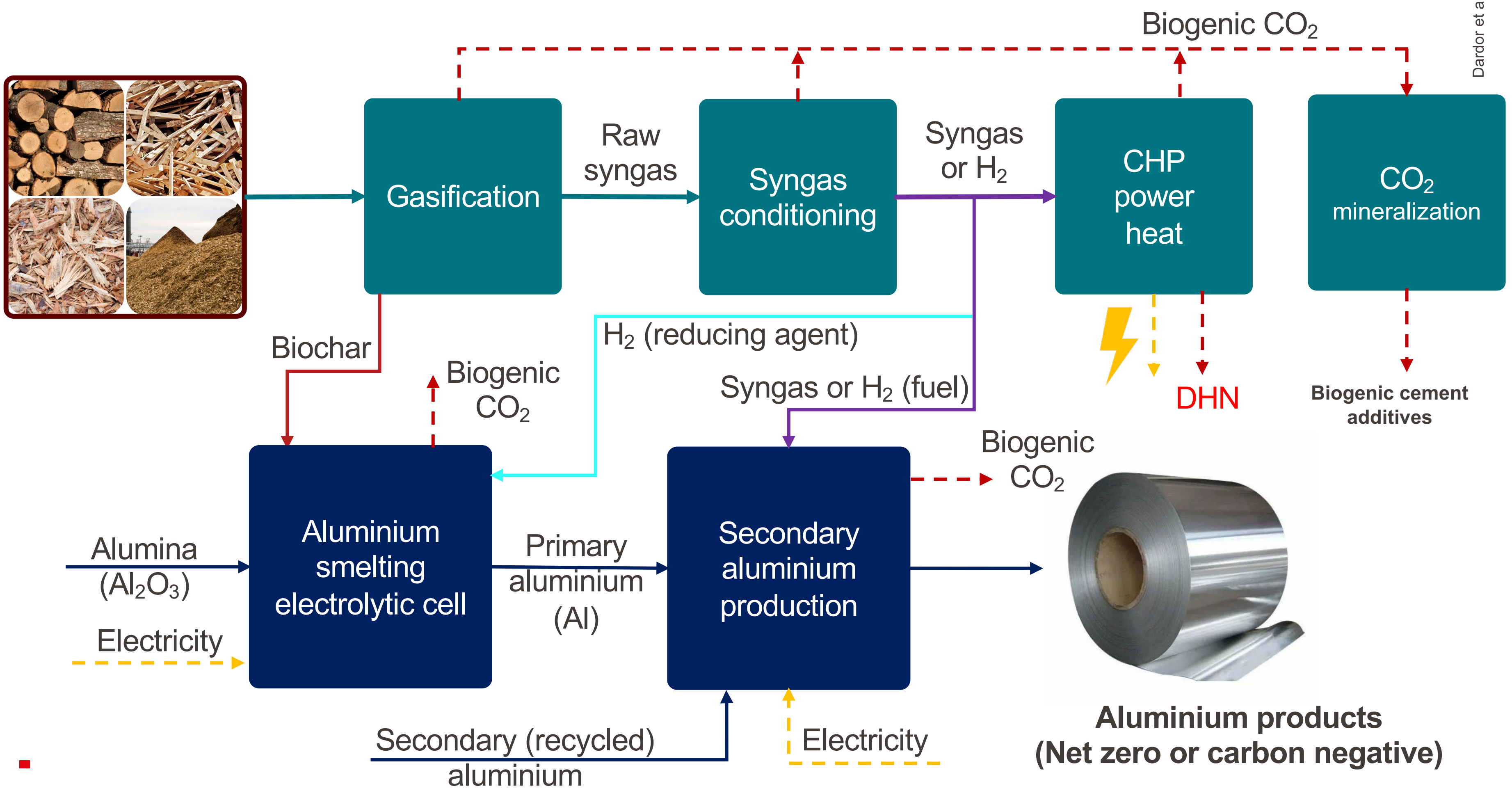
~50 kt primary Al/yr

Base case aluminium plant, ~200 – 250 kt/yr rolled Al sheets



Secondary aluminium production facility – case study: Novelis Sierre, Switzerland.

Alternative Aluminium Production



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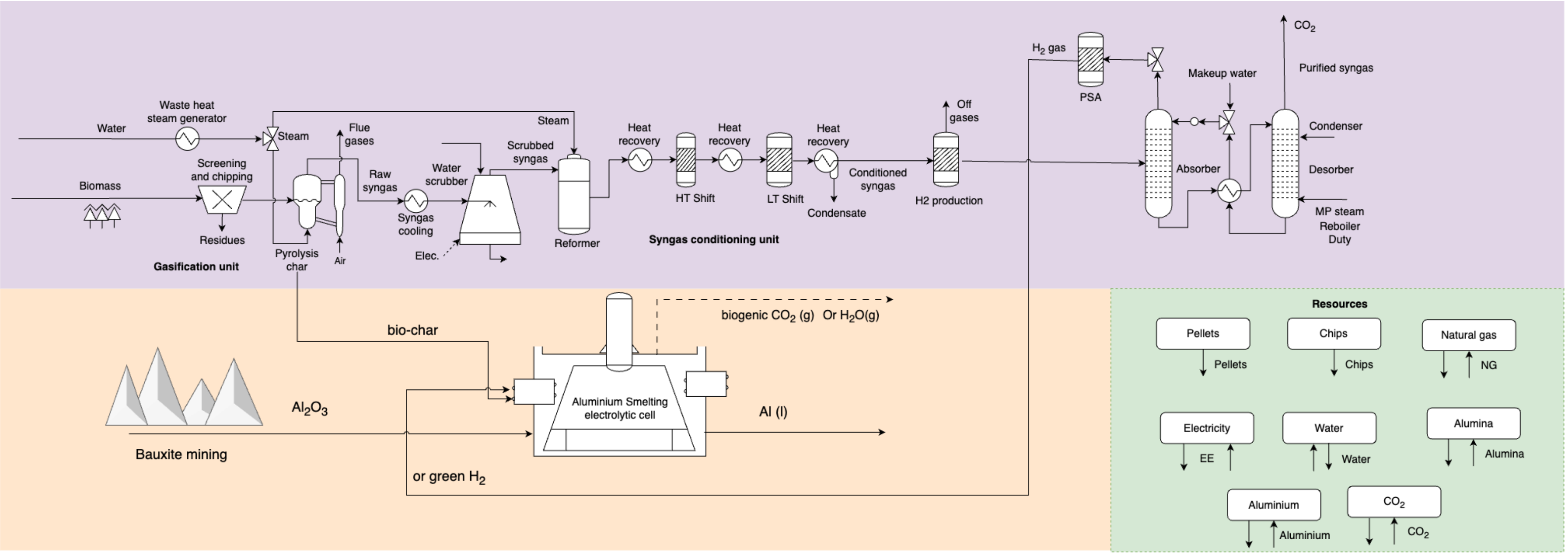
Alternative Aluminium Production

- Utilization of biomass to supply the reducing agent and energy needs of Al_2O_3 smelting: **Hydrogen or Biochar route**.



Methods

w = {utility units, resources}, y_w existence (binary) and f_w load factor variables

Optimization problem: minimum operating cost or maximum revenue:

$$\min_{f_\omega,\, y_\omega,\, R_r,\, W} \Bigg[f_{Biomass}(m\cdot c)_{Biomass} + f_{Alumina}(B\cdot c)_{Alumina} \pm f_{Elec}(W\cdot c)_{Elec} + f_{EnvEm}(m\cdot tax)_{EnvEm} + f_{Water}(m\cdot c)_{Water} \pm f_{CO_2\,\mathrm{Imp/Exp}}(m\cdot c)_{CO_2\,\mathrm{Imp/Exp}} + \frac{Z_{equip}\times Ann\_factor}{N_{hours\ per\ year}} - f_{\mathrm{Aluminium}}(B\cdot c)_{\mathrm{Aluminium}} \Bigg]$$

Subject to:

$$\sum_{\omega=1}^{N_\omega} f_\omega q_{\omega,r} + \sum_{i=1}^{N} Q_{i,r} + R_{r+1} - R_r = 0 \quad \forall r = 1..N$$

$$\sum_{\omega=1}^{N_\omega} f_\omega W_\omega + \sum_{\substack{chemical\\ units}} W_{net} + W_{imp} - W_{\exp} = 0$$

$$f_{\min,\omega} y_\omega \le f_\omega \le f_{\max,\omega} y_\omega \quad \forall \omega = 1..N_\omega$$

$$W_{imp} \ge 0,\ W_{\exp} \ge 0$$

$$R_1 = 0,\ R_{N+1} = 0,\ R_r \ge 0$$

c_{NG}= 0.45 EUR/kWh; cBiom = 0.014 EUR/kWh; c_{EE}=0.15 (Nov-Feb) or 0.001 (Mar-Oct) EUR/kWh; $c_{CO2import}$=0.0084 EUR/kg; $c_{CO2,tax}$=100 EUR/t

Methods

Process Modeling and Simulation:

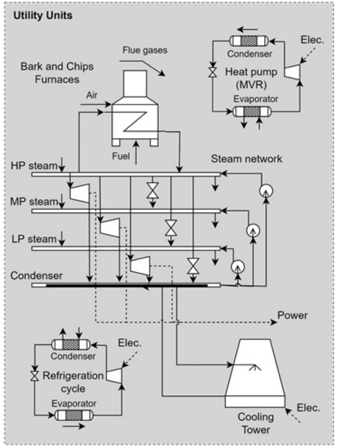
Sequential Modular Simulation

CoolProp

aspentech

Energy integration framework: OSMOSE Lua / Refprop

Equation Oriented Modeling and Simulation



$$\min_{R_r} R_{N_r+1}$$

Subject to

Heat balance of temperature intervals

Minimum Energy Requirement

$$\sum_{i=1}^{N} Q_{i,r} + R_{r+1} - R_r = 0 \qquad \forall r = 1 \,..\, N$$

Feasibility of the solution $\quad R_r \geq 0$

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Results and discussion

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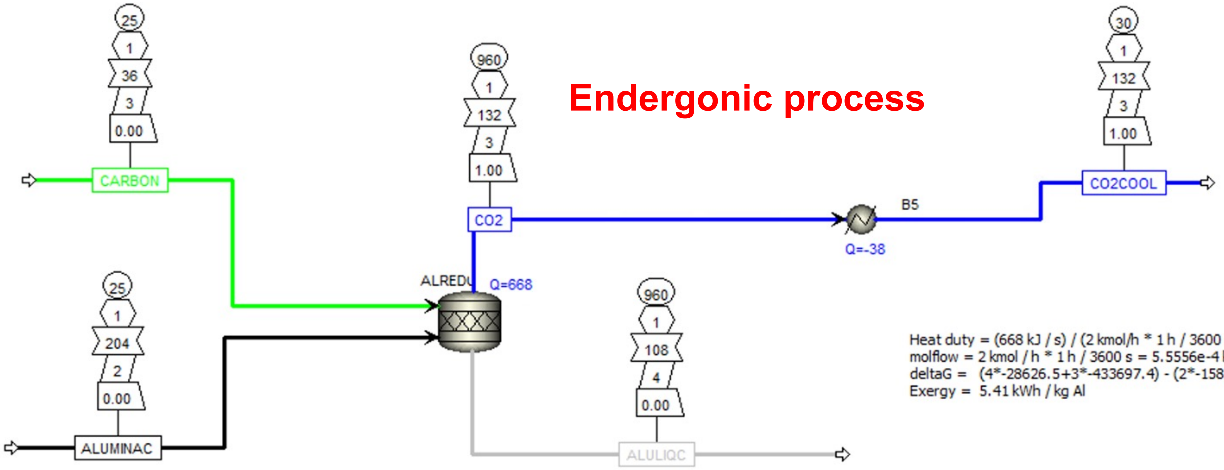
- **Alumina reduction using biomass-derived char**

The ideal electricity consumption is approx. 5.0 kWh/kgAl or half the amount reported for actual electricity consumption in smelters (~50% efficiency).

High temperature aluminium solidification heat can be recovered to produce hot water for district heating network (DHN) purposes.

Endergonic process



Heat duty = (668 kJ / s) / (2 kmol/h * 1 h / 3600 s) * 1 kmol /1000 mol = 1202.4 kJ / mol
molflow = 2 kmol / h * 1 h / 3600 s = 5.5556e-4 kmol of Al2O3/ s
deltaG = (4*-28626.5+3*-433697.4) - (2*-1582000 + 3*0) = 4.37e+5 kJ/kmol Al = 4.50 kWh/kg Al
Exergy = 5.41 kWh / kg Al

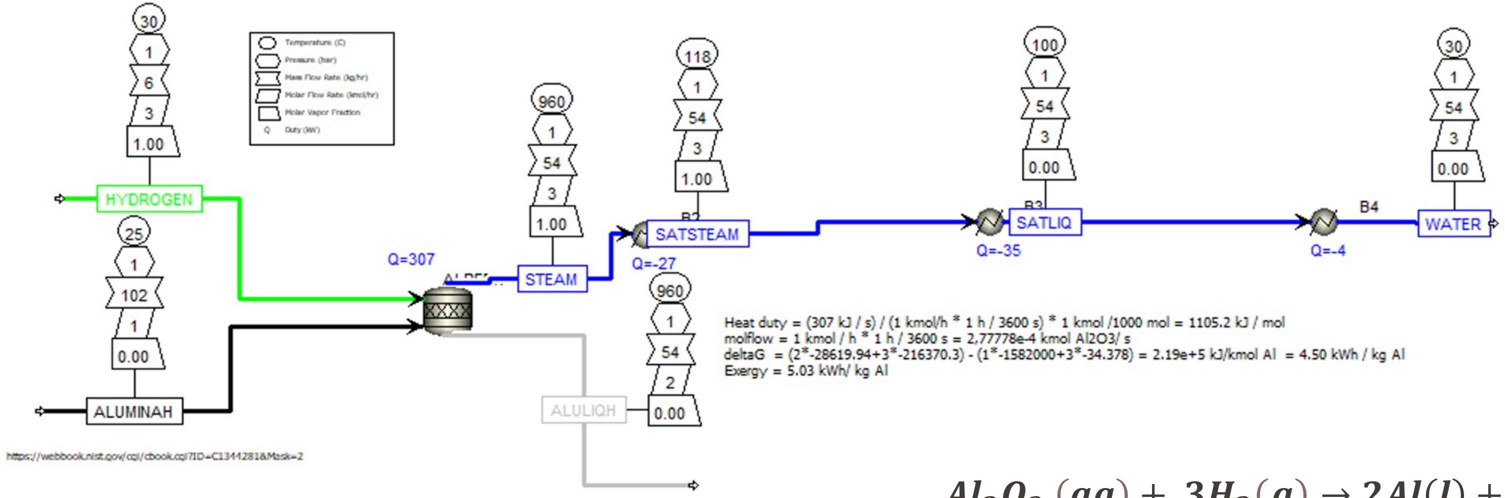
$$2Al_2O_3\ (aq) + 3\ C(s) \rightarrow 4Al(l) + 3CO_2(g)$$

Results and discussion

- **Alumina reduction using biomass-derived H_2**

With hydrogen as the reducing agent, steam replaces direct CO_2 emissions from the electrolytic process.
Waste heat recovery is also possible, besides the export of hydrogen to the grid.

Endergonic process



$$Al_2O_3\ (aq) + \ 3H_2(g) \rightarrow 2Al(l) + 3H_2O(g)$$

Results and discussion – BioChar Case

- Production:
  - ***250 kt rolled aluminium products / yr***
  - 55 kt primary Al/yr
  - **100** kt/y serpentine ($MgCO_3$) – Mineral additive for cement
- Consumption:
  - 450 MW biomass, no electricity import

Specimens of different biochar materials.
(Photo: UC Davis Biochar database)

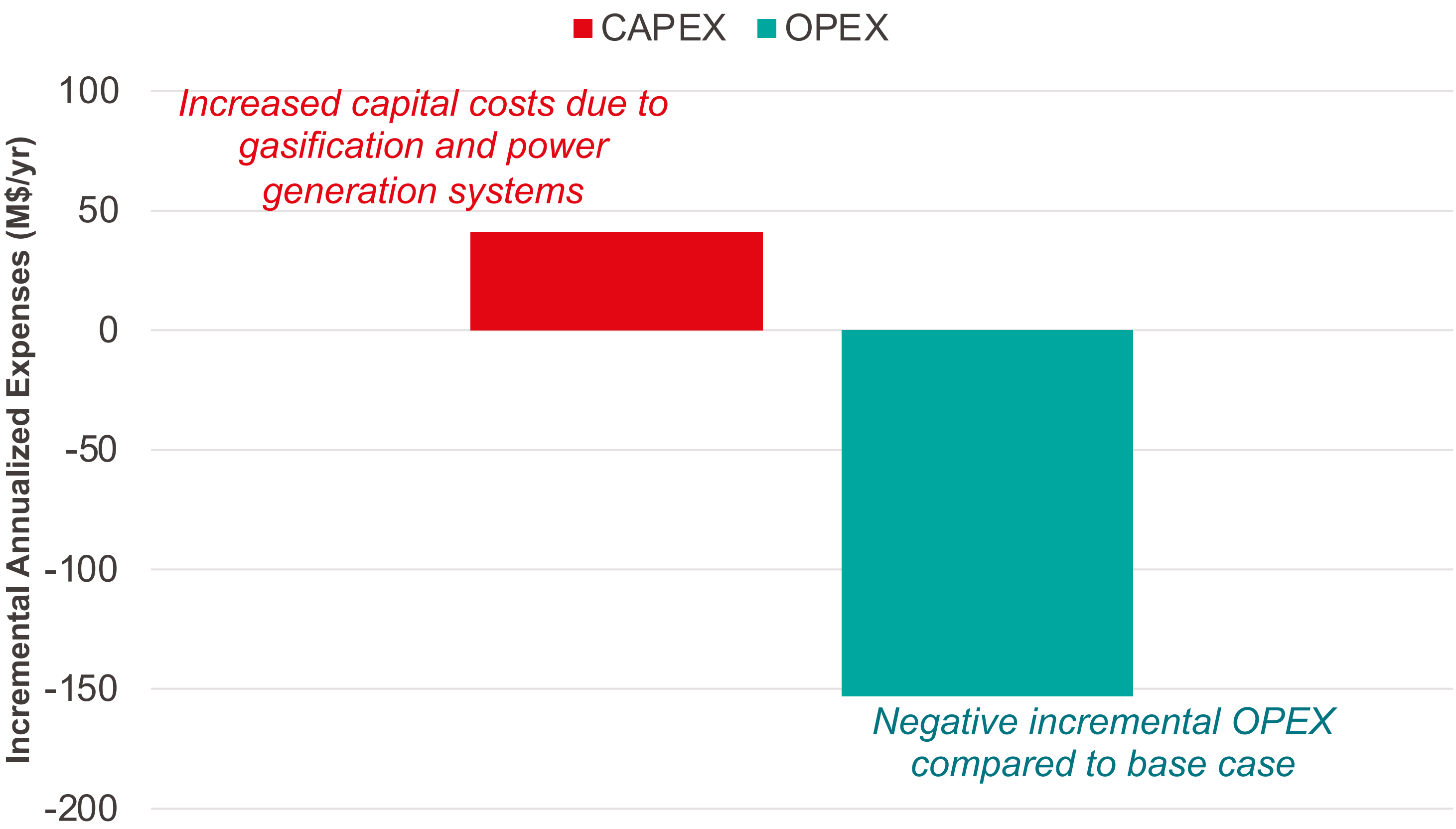
- Processing:

  102 kt Al_2O_3 and 23 kt biochar/yr

- Carbon negative aluminium products: ***– 350 kg_{CO2eq} per ton_{al}***

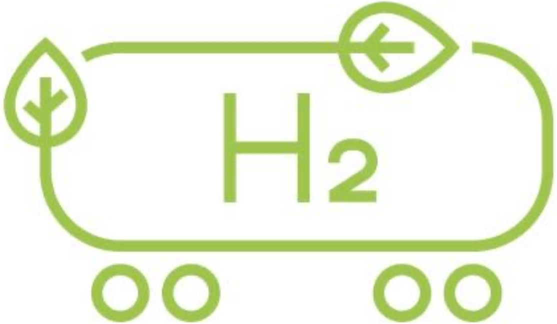
- Onsite production of electricity from excess syngas of gasification
  - Net export of renewable electricity to grid: ***~700 GWh/yr***

Results and discussion – BioChar Case



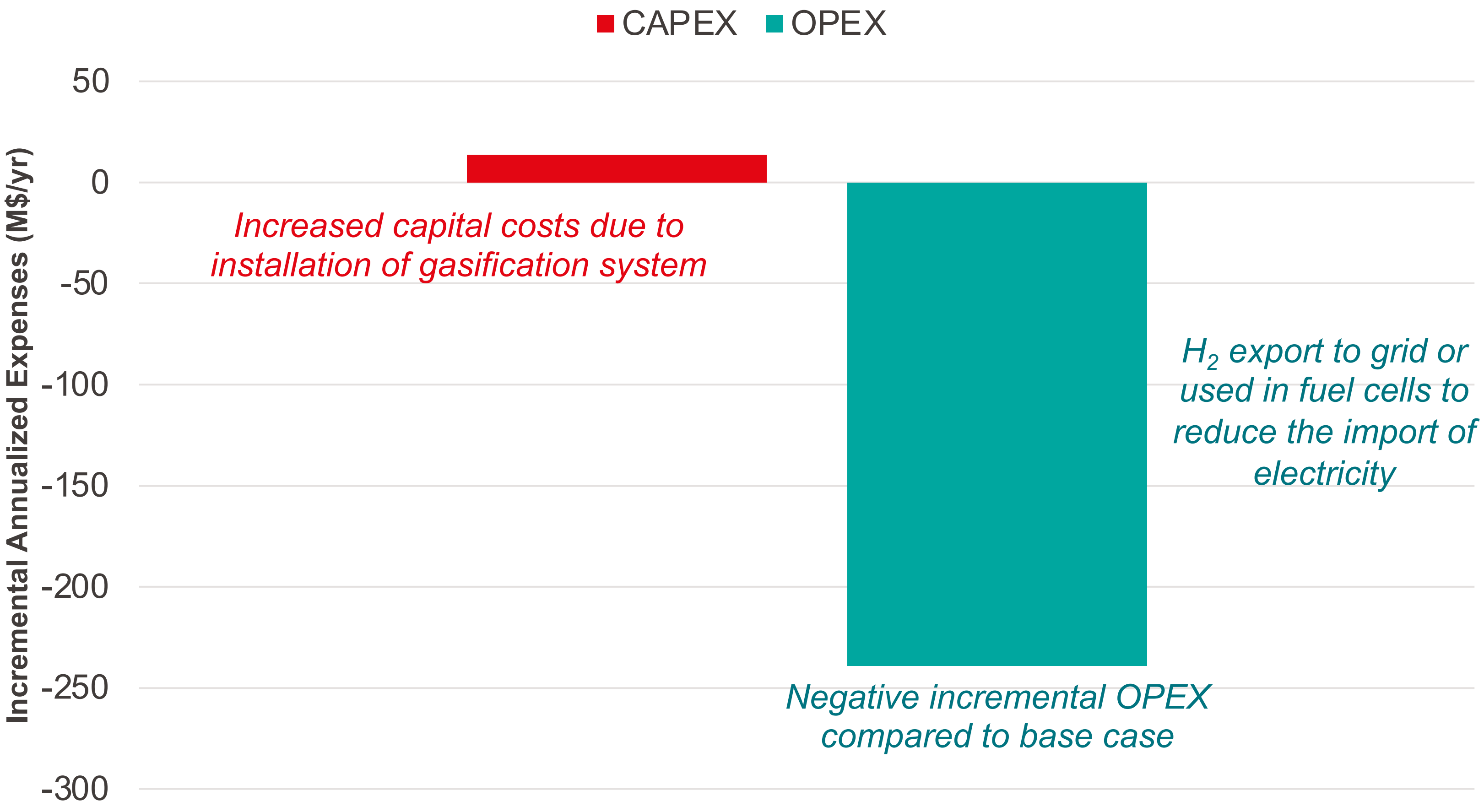
Results and discussion – BioH$_2$ Case

- Production:
  - ***250 kt rolled aluminium products / yr***
  - 55 kt prime Al/yr
  - **800** kt/y serpentine ($MgCO_3$) – Mineral additive for cement
- Consumption:
  - 300 MW biomass



- Processing:
  - 102 kt Al_2O_3 and 7.73 kt bioH_2/yr
- Carbon negative aluminium products → ***– 1500 kg$_{CO2eq}$/t$_{Al}$***
- Hydrogen export to grid integrating large scale gasification system
  - Export of renewable H_2 to grid → ***900 GWh/yr***
  - *Import of electricity from grid* ← ***1000 GWh/yr***

Results and discussion – BioH$_2$ Case



Conclusions

- Integrating biomass gasification with aluminium production yields:
  - ✓ Carbon negative aluminium products
  - ✓ Alternative to hydropower- and inert anode-based technology
  - ✓ Promising process path for decarbonizing aluminium
- Biochar is a good choice as it introduces only slight modifications to the existing alumina production process.
- Syngas, hydrogen, and char utilization are been tested among steel producers in DRI furnaces*
- Natural gas consumption in the aluminium industry could be phased out, thus, reducing its environmental impacts.
- Energy and mass **integration** and **waste heat recovery** will be crucial to make biomass resources sustainable in the long term: **Prioritize biomass utilization, cascade heat losses**.

* Experimental and pilot scale validations in progress

Acknowledgments

The authors would like to thank ***Swiss Federal Office of Energy*** for funding this research work in the frame of the Net Zero Lab, through the project grants:

(i) "*Sustainable natural gas (SNG) and aluminium production via biomass gasification and enhanced waste heat recovery in Novelis plant in Sierre City*"

(ii) "*Enhanced waste heat recovery approach for the reduction of fuel consumption in the aluminium industry*".

Thanks for your attention