Aluminum flow representation in IAMS – a mini-material extension of a simple MESSAGEIX-FAIR model

Coursework in EP8900 – Nils Dittrich

1. Introduction

Aluminum production causes approximately 1.1 Gt of CO2 emissions annually(“Statistics International Aluminium Institute.,” n.d.), and is not only a widely used, but often irreplaceable material for technological development and even a potential bottleneck for the green transition (Billy and Müller 2023). Especially it ties to renewable energy technologies make it a prudent addition to the energy systems model of integrated assessment models. We therefore set out to develop a representation of the aluminum material flows in a simplified version of the MESSAGEIX-FAIR integrated assessment model.

2. Methods

We integrate aluminum material flows into the energy systems model by projecting the aluminum value chain into the same model form as the energy technologies. Figure 1 shows the a simple representation of the global aluminum system. In our energy systems model we represent process 1, 2, and 3 as technologies. We represent the input of fuel (A01) and output of emissions (A10) through input and emissions parameters; the flows of alumina, aluminum, and final aluminum products (A12, A23, A34) are expressed as the “aluminum” energy carrier at primary, secondary, and final level. The direct emissions in the smelting process, A20a, are represented explicitly. We expand the MFA model by including energy inputs of final electric energy for smelting and production processes. Losses and recycling are not considered. The demand for Al products, A34, is represented as an exogenous demand. The use phase or end of life of aluminum products and bauxite stock are not represented at all. Since the energy systems model is an optimization model working with costs, we assign variable operating costs for all three processes to achieve standard market prices for alumina and aluminum. The production process in general is currently representing the transformation of aluminum to products, but no default values for energy inputs, losses, or costs are available.

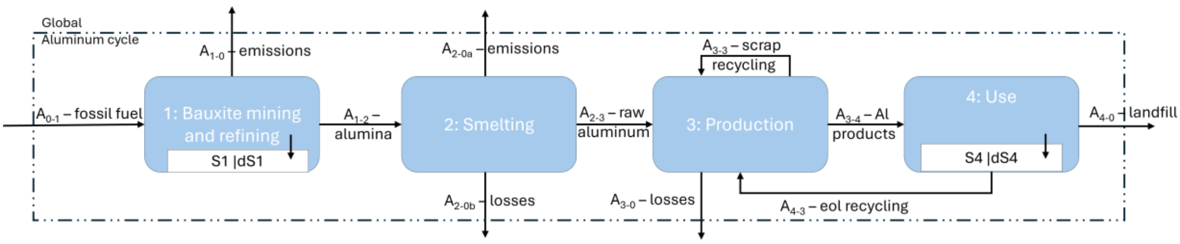


FIGURE 1: SIMPLIFIED GLOBAL ALUMINUM MATERIAL FLOW SYSTEM.

All three processes are initialized as technologies with default diffusion values. The inputs for energy come from the MESSAGE-MATERIALS AL data, while the input of alumina and output of CO2 in smelting are defined by the stoichiometry of the Hall Heroult process plus minimal losses, taken from Billy et al. 2022. We integrate inert anodes as an alternative smelting technology that lacks the CO2 emissions, but requires 20% more energy input, at the same operating costs as prebaked anode Hall Heroult smelting.

One last integration opportunity is to internalize the consumption of aluminum in the power sector. For this we need to couple the new capacity of the energy systems model with investment material costs. We introduce a new parameter that is specified over technologies and energy_level, specifying the investment requirements in aluminum products. Little reliable values were available for this, so we kept at assigning values from non-scientific reports for PV and wind energy, and a low estimate for all other types of power plants. We now can add this demand to the energy balance equation.

3. Results

The default results of the energy system and climate model without additional constraints showed an energy system dominated by coal power plants for electricity and solar for non-electric use. We therefore limited the production of coal and hydro production, and forced the model to include 3 PWh of PV electricity in 2050 to get a mix of technologies to start with – see Figure 2. We then add a 2°C relative global warming by 2100 goal in the FAIR component for most runs too.

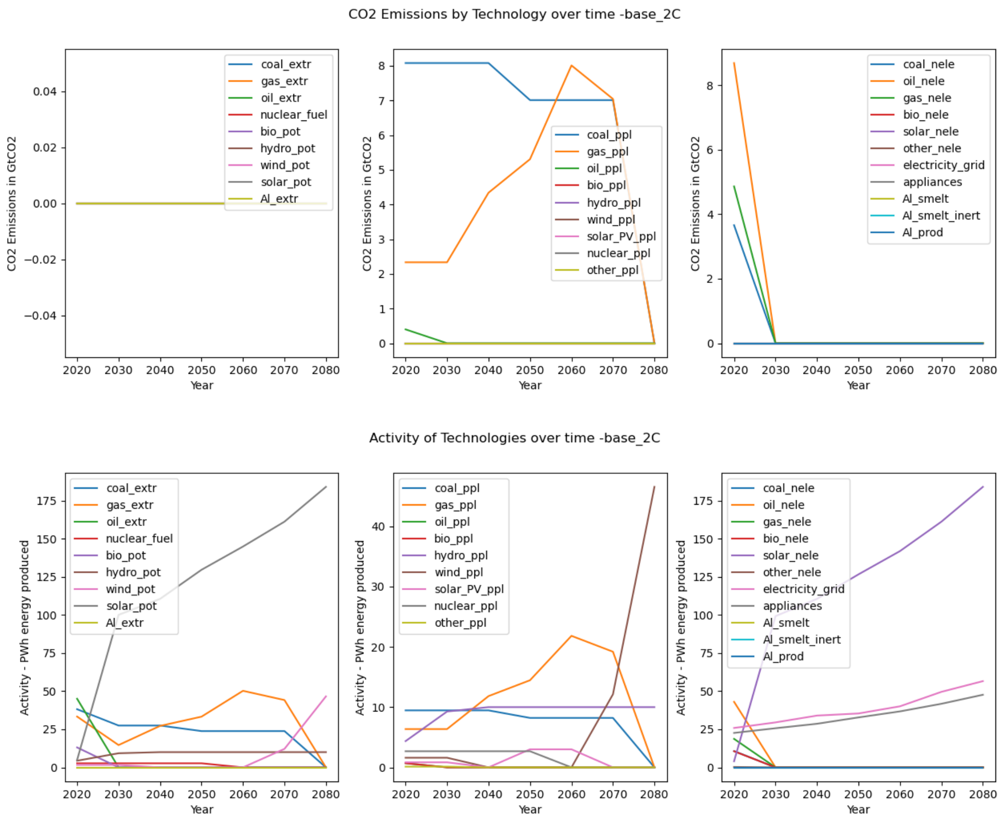


FIGURE 2: SOURCES OF EMISSIONS AND ACTIVITY IN THE BASE SCENARIO.

The integration of the aluminum flows, purely exogenously driven, does not yield large changes in the base characteristics, but we can investigate the sources of emissions and activity of all processes. In Figure 3 we see that the direct emissions are highest in the refining step, but the absolute majority of the emissions (Figure 4) occurs in the energy production, even in the 2°C setting. The production for all technologies follows the same curve, only the absolute values change by the input factor of alumina for smelting (slightly below 2).

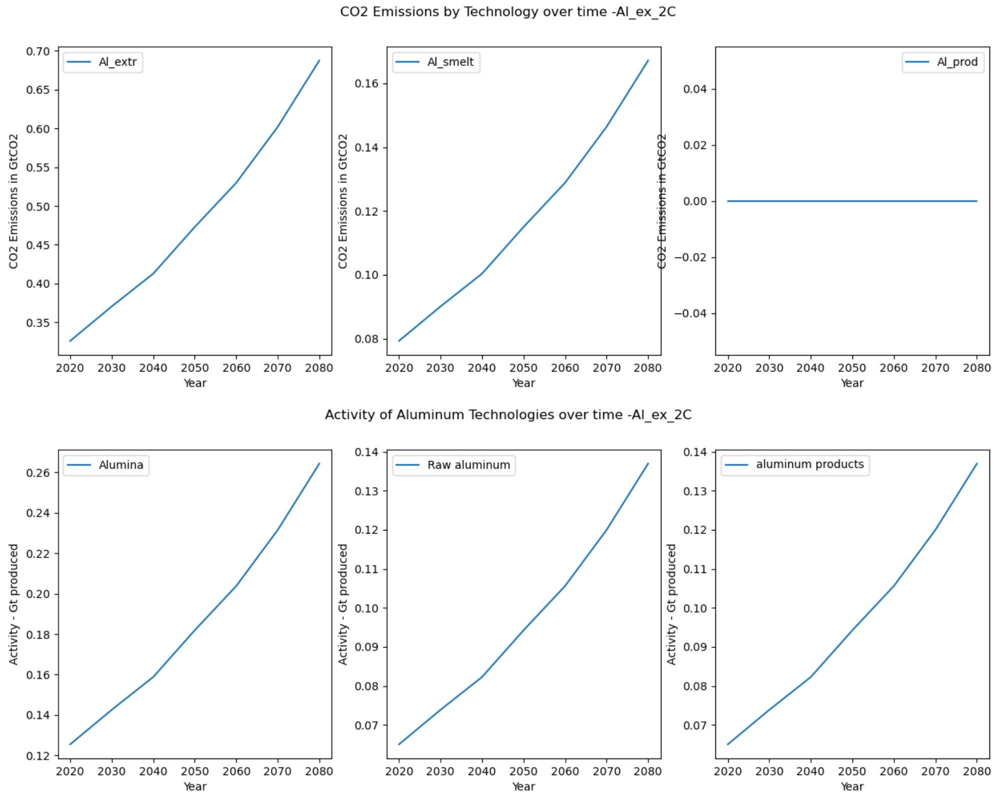


FIGURE 3: EMISSIONS AND ACTIVITY OF ALUMINUM TECHNOLOGIES.

When we disable the 2°C constraint, we can even see how much the emissions grow through the addition of aluminum, shown in Figure 4. We must consider unexpected edge behavior with fixed activities for the first step and a transition in the second, but when checking the aluminum-driven emissions from 2040 and onward, we are reasonably close to the estimates made by the International Aluminum Institute, which also gave the base demand of 65kt of aluminum in 2020.

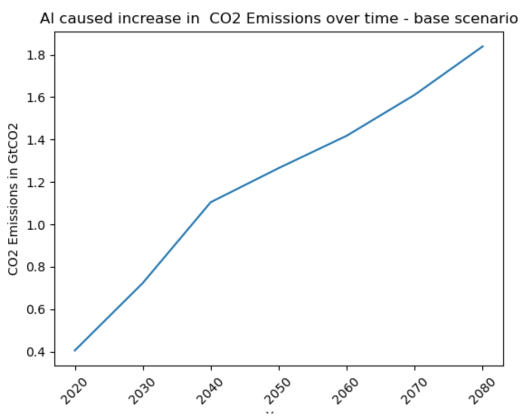


FIGURE 4: ALUMINUM INDUCED ADDITIONAL EMISSIONS IN A NON 2°C CONSTRAINED BASE CASE.

The endogenous demand of aluminum that we calculate is multiple orders of magnitude below the exogenous demand. Care needs to be taken to allow a slightly higher initial production to avoid infeasible models. The total emissions do not differ, but the model does in principle include its own material investment demand – a principle that could easily be extended to energy investments for renewable energy as well.

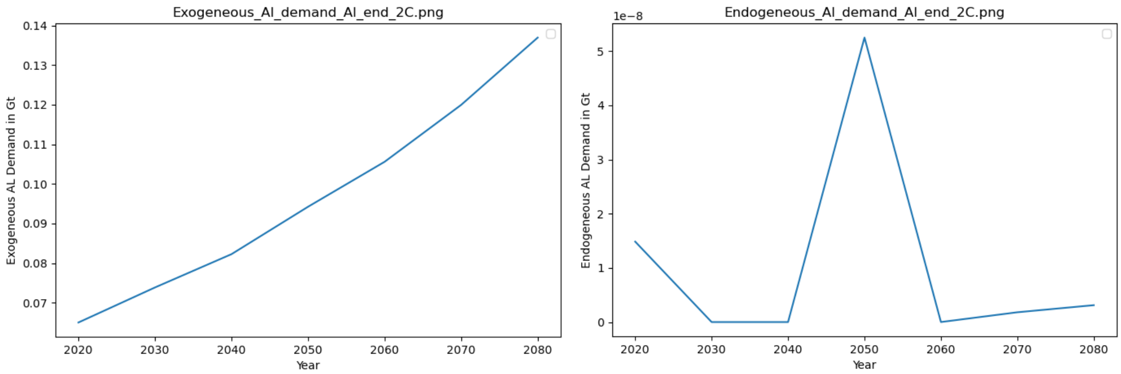


FIGURE 5: ALUMINUM DEMAND – EXOGENOUS AND ENDOGENOUS. NOTE THE SCALE OF THE Y-AXIS.

4. Discussion and conclusion

We have shown how aluminum flows can be integrated into the MESSAGEIX energy system model without structural changes by adding the material production processes as technologies. While this leads to a hybridization of the units, only very little complexity is added through this change, both by adding the materials and the endogenous demand. Data quality remains a critical factor for the robustness of the results. While this holds true always, it is particularly clear that the endogenous demand figures are indicative at best.

References

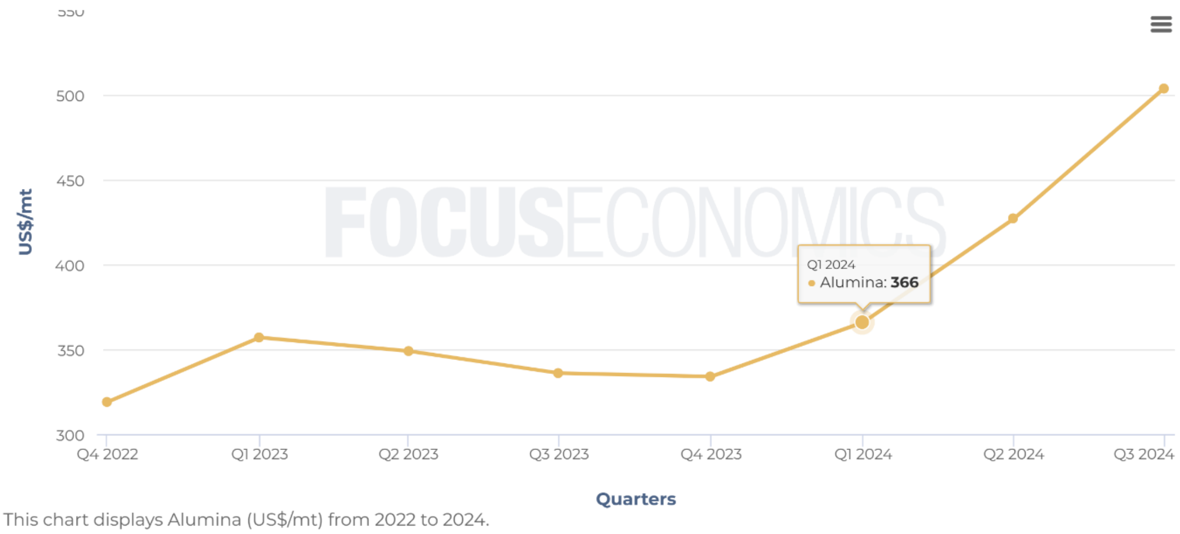
Billy, Romain G., Louis Monnier, Even Nybakke, Morten Isaksen, and Daniel B. Müller. 2022. “Systemic Approaches for Emission Reduction in Industrial Plants Based on Physical Accounting: Example for an Aluminum Smelter.” *Environmental Science & Technology* 56 (3): 1973–82. https://doi.org/10.1021/acs.est.1c05681.

Billy, Romain G., and Daniel B. Müller. 2023. “Aluminium Use in Passenger Cars Poses Systemic Challenges for Recycling and GHG Emissions.” *Resources, Conservation and Recycling* 190 (March):106827. https://doi.org/10.1016/j.resconrec.2022.106827.

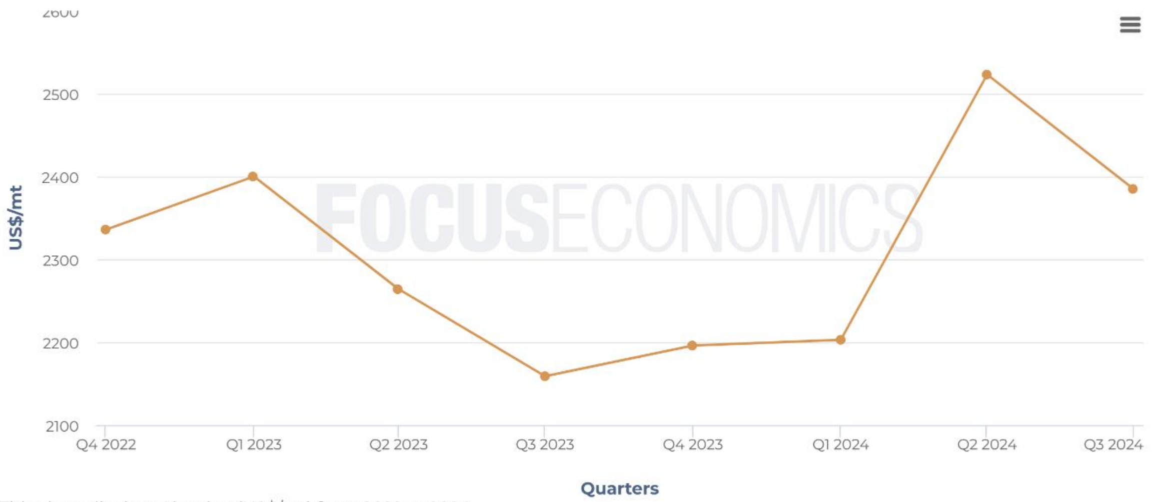
“Statistics IAIInternational Aluminium Institute.” n.d. International Aluminium Institute. https://international-aluminium.org/statistics-overview/.

Appendix A – Material prices

For the aluminum value chain, values from https://www.focus-economics.com/commodities/base-metals/alumina/ .



This chart displays Alumina (US$/mt) from 2022 to 2024.



This chart displays Alumina (US$/mt) from 2022 to 2024.

Appendix B – material intensity of energy technology

21kg/kw for solar is regularly mentioned, attributed to a private report by Wood Mackenzie.

https://www.shapesbyhydro.com/en/manufacturing/how-aluminium-is-supporting-historic-growth-in-solar-power/