

Integration of renewable energy and reversible solid oxide cells to decarbonize secondary aluminium production and urban systems

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ABSTRACT

This study explores an energy transition strategy that leverages reversible solid oxide cells (rSOC), power-to-gas (PtG) conversion, and CO₂ management to enhance the efficiency and sustainability of secondary aluminum production. A comparative analysis between conventional and integrated energy scenarios highlights the benefits of multi-technology integration. The results indicate that the integrated system increases total energy demand by 27% due to additional energy conversion steps, but eliminates natural gas consumption, reducing dependency on fossil fuels. Additionally, net CO₂ emissions are reduced more than fivefold, demonstrating the potential of carbon capture and utilization strategies. The seasonal storage of synthetic natural gas (SNG) and biogenic CO₂ further enhances system flexibility, allowing excess renewable electricity to be converted into storable fuels for winter use. Despite higher capital expenditures, the operational costs of the integrated system are 11% lower than the conventional approach due to improved energy efficiency and CO₂ taxation savings. These findings underscore the importance of process integration, energy storage, and renewable electricity utilization in achieving a low-carbon, resilient aluminum industry and urban heating networks.

Keywords: Secondary aluminum, renewable energy integration, power-to-gas, reversible solid oxide cells, CO₂ utilization, process optimization.

INTRODUCTION

Aluminium industry relies on fossil natural gas and emits 2% of global industrial emissions [1]. To reduce this dependency, an increased use of renewable energy and advanced conversion systems is aimed. Due to the intermittency of renewable energy, a set of technologies is needed to improve the energy integration and enhance the process resiliency in the heavy industry. Another untapped savings potential is waste heat [2], which can be recovered from stack gases or casting water. Aluminium is processed in semi-batch steps with metallurgical and technical constraints, adding complexity to waste heat valorization. To tackle this issues, advanced technologies including storage units, oxycombustion furnaces, carbon

abatement and power-to-gas systems, biomass thermochemical conversion systems, as well as electrified annealing furnaces [3, 4] can be integrated to handle seasonal renewable energy storage, targeting its utilization during periods of high electricity and natural gas prices. Meanwhile, high temperature reversible solid oxide cells can meet the energy balance of the overall system, while increasing exergy efficiency of the integrated facility. Power-to-gas-to-power systems can use renewable electricity and biogenic CO₂ to produce synthetic natural gas [5] to replace fossil fuels in the aluminium plant and supply the necessary power to other industrial and urban systems. In this way, a cyclic fuel production and utilization in an integrated aluminium remelting plant behaves as an industrial battery, which can use firstly high-grade waste heat for industrial applications, followed by air and

scrap metal preheating [2, 6], to finally cascade the low-grade waste heat to an urban system [7, 8]. In this work, a scenario of waste heat valorization and renewable energy integration is presented, in which the high-temperature waste heat from the aluminium processing plant is used to reduce the energy consumption in the power-to-gas and biomass energy conversion systems. Those systems facilitate the energy and CO₂ management and offset the problem of renewable energy resources intermittency. The performance of the decarbonization route is analyzed in the light of thermal, economic and environmental indicators and compared to a conventional setup based on fossil fuel furnaces and biomass boilers.

METHODOLOGY

Waste heat from the aluminium furnaces and the biomass energy conversion favors the integration of high temperature reversible solid oxide cells (rSOC). The post-combustion of the tail gas from the rSOC can partly supply the heat needed in the melter furnace, whereas the electricity generated in the cell can be used elsewhere, such as in electrical furnaces, rolling process, ancillary demands, and heat pumping systems of district heating network. Integration of renewable energy resources and technologies, such as gasification, has shown promising potential to attain net negative emissions when combined with electrification, power-to-gas systems, and carbon sequestration methods, adding flexibility to the energy and carbon management systems [9, 10,11].

In the aluminium plant, pure aluminium ingots are preheated from 25°C to 250°C. Next, the pure aluminium is mixed with scrap aluminium and sent to a melting furnace at 660°C. A holder furnace operates as a buffer for the subsequent direct chill casting process (DCC), where aluminium solidifies into ingots using groundwater. This hot water (50 °C) is rejected to the environment. In an improved scenario, the casting water is a heat sink integrated to a CO₂ network to supply heating requirements to a city. In the rolling plant, ingots are surface-polished and heated up to 550°C in pusher furnaces, before they go through a hot rolling process followed by an intercooling step and a subsequent cold rolling process powered by electricity. Some coils are sent to an annealing continuous line (ACL), wherein they are chemically and thermally treated.

In the gasification section, biomass moisture is reduced to 10% in a rotary dryer before is chipped consuming ~ 3% of biomass energy (LHV) [12]. In the gasifier (900°C), biomass is converted into syngas rich in CO, H₂, CO₂ and CH₄, among other components, using steam as the gasification agent (S/B ratio 0.75). Syngas is cooled to 400 °C and water-scrubbed to remove impurities and

compressed to 35 bar. Downstream water gas shift reactors increase hydrogen content. Syngas can be used for producing hydrogen or synthetic natural gas, whereas gasification waste heat is used for combined heat and power production instead of merely burning biomass. In addition, waste heat is used to produce the steam necessary to feed a solid oxide electrolysis cell (SOEC). As a result, an oxygen-rich stream is also produced. SOEC technology operates typically between 600 °C and 850 °C, which brings about higher thermodynamic efficiency and faster kinetics [13]. SOEC is operated at a thermoneutral voltage of 1.29 V and electricity consumption of 35 kWh/kgH₂. In the context of sustainable energy transition, SOECs are expected to play a role in harvesting and transforming renewable electricity into storable chemicals and fuels [14,15]. The reversible electrolysis cell also works as fuel cell (SOFC) consuming hydrogen and oxygen or air to produce electricity, which requires preheating reactants up to 850 °C [16]. The inefficiency of SOFC is exploited to harvest waste heat in a downstream post-combustion system using oxygen to drive high temperature aluminium melting furnaces. Meanwhile, the produced electricity can be used to drive other heating furnaces and appliances in the aluminium plant, as well as heat pumps of the district heating network. All in all, the integration of an rSOC enables energy storage and power generation [17], facilitated carbon separation, post-combustion carbon capture, and waste heat valorization. It occurs first at high-temperature for the melting of the aluminium, and later for the low-temperature CO₂ district heating network, composed of a closed loop of CO₂ that harvests waste heat from the industrial, biomass conversion and power-to-gas systems. CO₂ evaporates at 50 bar (~14°C) and can later release the condensation enthalpy in a heat pump that supplies space heating or domestic hot water to a nearby urban system. A superstructure used to provide the energy demands of the aluminium and the urban agglomeration also include heat pumps; gasification, methanation and gas treatment systems; CO₂ abatement units, electrification technologies, storage units and cogeneration cycles (Figure 1).

In view of multiple technological options and trade-offs between electricity, gas or biomass import, a systemic approach is developed to evaluate the most cost-efficient configuration to supply combined heat and power to the aluminium remelting process. OSMOSE platform [11] is used to solve a minimum energy requirements (MER) of the overall process. Subsequently, this framework handles the mixed integer linear programming problem (MILP) that works out the best energy technologies and their operating conditions. Aspen Plus® software is used to simulate different energy conversion systems. In this regard, the number of decarbonization options increases, calling for a systemic study to evaluate the most suitable processes and carbon neutral technologies to

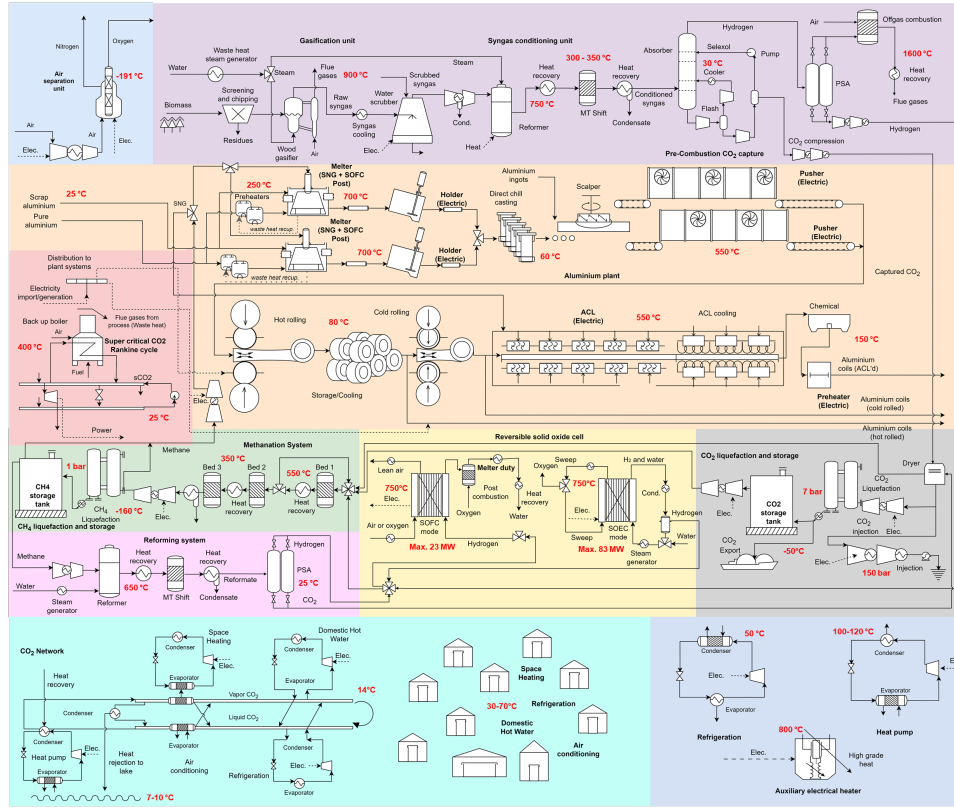


Figure 1: Integrated aluminium production plant and potential utility and decarbonization technologies.

supply the energy requirements to aluminium industry without significantly impacting the operational settings and process reliability. To this end, a mixed integer linear problem is conducted using OS MOSE platform [11] to maximize waste heat recovery and define the most economically, thermodynamic and environmentally favorable configurations to integrate the aluminium plant, the biomass conversion units and the grid into the urban system, considering the temporal variation of the prices and energy demands. The solver minimizes the total operating cost, Eq. (1), where $Cop1$ and $Cop2$ represent the fixed and variable operating costs of a unit (u) and $Cinv1$ and $Cinv2$ are the fixed and variable investment costs of a unit (u). Y_u is a binary variable related to the presence or absence of a unit (u), while M_u is its respective continuous load factor.

$$\min C_{tot} = \sum_{u \in U} [\sum_{t \in T} (Cop1_u \cdot Y_{u,t} + Cop2_u \cdot M_{u,t}) \cdot \Delta t + Cinv1_u \cdot Y_u + Cinv2_u \cdot M_u] \quad (1)$$

This objective function is subject to multiple constraints including unit existence and load conditions:

$$Y_{u,t} \cdot Fmin_u \leq M_{u,t} \leq Y_{u,t} \cdot Fmax_u ; \forall u \in U, \forall t \in T \quad (2)$$

$$M_{u,t} \leq M_u \quad (2)$$

$$Y_{u,t} \leq Y_u \quad (3)$$

Mass and energy balance constraints:

$$\sum m_{Input\ streams} = \sum m_{Output\ streams} ; \forall T \quad (5)$$

Power production or consumption constraints:

$$\sum_{w=1}^{N_w} M_w \cdot w_{w,utilities} + \sum_{Processes} W + W_{import} - W_{export} = 0, \forall T \quad (6)$$

Heat cascade constraints and balance at the temperature interval r :

$$\sum_{w=1}^{N_w} M_w \cdot q_{w,r} + \sum_{i=1}^N Q_{i,r} + R_{r+1} - R_r = 0 ; \forall r = 1 \dots N \quad (7)$$

And solution feasibility:

$$R_1 = 0, R_{N+1} = 0, \quad R_r \geq 0 ; W_{import} \geq 0, W_{export} \geq 0 \quad \forall r = 1 \dots N \quad (8)$$

where;

- N is the number of temperature intervals based on supply and target temperatures of streams [-]
- Q is the heat exchanged between process streams [kW],
- R is the heat cascaded from higher ($r+1$) to lower

(r) intervals of temperature [kW],

- N_w is the number of utility units available [-],
- $q_{w,r}$ is the specific heating or cooling flow supplied by a utility unit w within an interval r [kW],
- W is the power produced or consumed by the utilities and process units, or the grid [kW].

The mathematical formulation of the problem can be solved using any open-source mixed integer linear programming solver, compatible with AMPL® community edition. The costs of the commodities are assumed based on the current European market and are set as 3.50 Eur/m³ for water, 0.15 Eur/kWh winter - 0.05 Eur/kWh summer for electricity, 0.08 Eur/kWh winter - 0.06 Eur/kWh summer for biomass, 0.07 Eur/kWh for natural gas, and 100 Eur/t for the CO₂ tax.

RESULTS AND DISCUSSION

Table 1 compares the energy consumption of the conventional scenario (i.e. only natural gas-fired furnaces and biomass combustion-based district heating network) and the integrated solution proposed to decarbonize the aluminium plant and the city demands. The energy consumption in advanced integrated scenario is 27% higher than that of the conventional scenario since biomass needs to be converted internally in the battery limits of the integrated aluminium plant and urban system. However, the conventional scenario is strongly dependent on the consumption of fossil gas, which is subject to volatile market conditions and increasing surveillance due to associated direct and indirect atmospheric emissions. Also, it is worth noting an opportunity to increase the share of renewable input in aluminium industry and urban systems by importing nine times more electricity from the grid, which has lower associated indirect emissions than the fossil gas. In the rSOC, the power consumption during the electrolysis mode averages 57 MW, whereas the fuel cell power generation is 15 MW.

The rSOC together with the storage systems help managing the CO₂ and SNG streams. CO₂ produced and captured in the reformer, the auxiliary oxy-furnace, and syngas pre-treatment (see Table 3) can be later used to generate SNG that is stored in the summer season and consumed later on the winter season. By harnessing renewable electricity in summer, total biomass energy consumption can be reduced to 25% of the total amount consumed in less efficient biomass boilers for space heating and domestic hot water production. Yet, the most striking outcome is the complete replacement of fossil natural gas by renewable energy resources, such as biomass and electricity. Table 2 summarizes the CO₂ emissions balance including direct and indirect emissions for both

conventional and integrated scenarios. Net CO₂ emissions of the conventional scenario can be reduced more than five times if an integrated carbon management and sequestration system is employed. Captured and injected biogenic CO₂ allows offsetting indirect emissions associated to the supply chains of electricity and biomass

In the integrated scenario, total energy demand is around 30% higher, and total incremental cost is about 35% higher due to the additional investment (~22 MEur/y). Carbon tax associated to fossil direct and indirect CO₂ emissions in the conventional scenario adds a penalty of more than 4 MEur/y.

Table 1. Energy consumption remarks of decarbonization solutions for the aluminium remelting and the district heating network.

Parameter	Conventional solution	Integrated solution
Biomass consumption [GWh/y] ¹	218.04	51.95
Electricity import [GWh/y]	70.00	570.28
Natural gas import [GWh/y]	200.00	0.00
Total energy demand [GWh/y]	488.04	622.23
Electricity export [GWh/y]	0.00	0.00

1. In the conventional case, biomass is only consumed in a decentralized hot water boiler (eff. 70%) for district heating purposes

Table 2. Direct and indirect emissions CO₂ emissions for conventional and integrated aluminium plant and the district heating network.

Parameter	Conventional solution	Integrated solution
Direct CO ₂ emissions from natural gas consumption [kt/y]	40	0
Indirect CO ₂ emissions from electricity consumption [kt/y] ^{2,3}	1.60	13.30
Indirect CO ₂ emissions from biomass consumption [kt/y] ^{1,2}	2.00	0.467
Indirect CO ₂ emissions from natural gas consumption [kt/y] ²	9.90	0
CO ₂ injection (biogenic sequestered) [kt/y]	0	-5.19
Net CO ₂ emissions to environment [kt/y]	53.50	8.58

1. Biogenic CO₂ emissions are considered as circular emissions and they do not contribute to the net CO₂ emission to environment if eventually released. 2. Specific indirect emissions of biomass 0.0025 g_{CO2}/kJ_{biowood}; Specific indirect emissions of electricity 23.32 g_{CO2}/kWh_{elec}; Specific indirect emissions of natural gas 0.0138 g_{CO2}/kJ_{CH4}; 3. Maximum electrolyzer capacity 85 MW.

Figure 2 illustrates seasonal storage profiles for SNG and CO₂ gases. Loading of SNG tanks occurs during summer season when surplus electricity from renewable energy resources is available. It renders more attractive to harvest electricity and store it in the form of fuel to be

used later in the colder season. Biomass resource harvested during the summer season can be used to produce syngas or synthetic natural gas consumed in the SOFC. The CO₂ gas is used to refill the storage tanks that store CO₂ until is reacted in a methanation section to produce SNG in summer season. The benefit to store renewable energy in the form of gas is twofold: biomass consumption is drastically reduced and biogenic CO₂ produced is used to offset the CO₂ losses. Annualized investment and operational costs calculated for the conventional and integrated systems, are summarized in Table 3. Total cost of advanced technologies is 28% higher than for the conventional route, due to twenty times higher annualized investment. Yet, the annualized operational expenditure of the conventional solution is higher (11%) than for the integrated approach, due to cheaper biomass resources and use of electricity during the summer season to produce and store fuel using biogenic CO₂.

Table 3. Annualized investment and operational costs.

Cost [Eur/y]	Conventional solution	Integrated solution
Electricity consumption cost	6,074,580	31,861,130
Biomass consumption cost	15,537,550	4,155,900
Natural gas consumption cost	13,648,440	0
Fossil CO ₂ emissions taxation	5,313,070	518,640
Annualized operational cost	40,573,650	36,535,680
Annualized capital cost	1,456,350	21,869,870
Total annualized cost	42,030,000	58,405,550

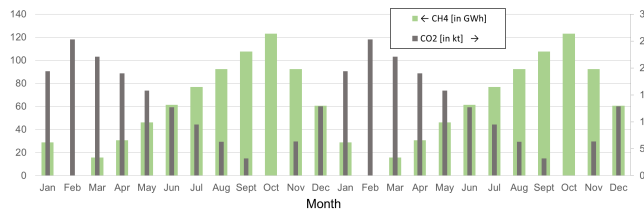


Figure 2: Seasonal gas storage

Figure 3 shows the integrated curves of the integrated aluminium plant, including the biomass energy conversion units, the power-to-gas system and the seasonal storage demands. These plots are useful to quantify the amount of waste heat available at different temperature levels, as well as to point out more rational energy uses and integration solutions, such as prioritizing the utilization of high-grade chemical and thermal energy in applications running at high temperatures, and only cascading waste heat down to lower temperatures after the high temperature energy demands have been met. In this way, the irreversibility of the overall energy system is minimized, and other energy technologies, such as heat pump systems, can be rather activated at the adequate temperature levels of heat supply. According to Figures 3a and b, the waste heat recovery from flue

gases, gasifier effluent, SOFC tail gas combustors, as well as auxiliary oxy-furnaces allows integrating the aluminium plant and the biomass conversion processes to the power-to-gas system. The solid oxide cell operates at elevated temperatures in order to increase the process efficiency and minimize the electrochemical losses, thus an internal waste heat recovery is fundamental to reduce the external energy imports. In summary, the high-grade chemical energy of the valuable biomass resource is used firstly at high temperatures in the most suitable applications, such as the aluminium melting process and the solid oxide cell, to be next cascaded down for being used at lower temperatures, such as in space heating and domestic hot water production. In this regard, the heat cascading efficiency principle allows reducing the biomass consumption, which otherwise would be burnt in a biomass boiler to merely produce hot water below 70 °C.

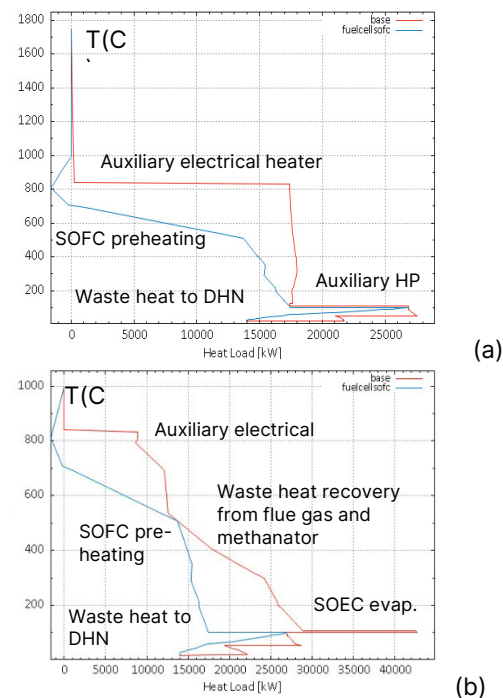


Figure 3: Integrated curves of the integrated aluminium plant (a) SOFC integrated curve in winter, (b) SOFC integrated curve in summer.

CONCLUSIONS

In this work, the advantages and challenges of the use of renewable energy resources and more advanced energy technologies for process integration and decarbonization of an aluminium remelting plant and a district heating network are presented. As a result, the energy consumption in more advanced integrated scenario is 30% higher than that of the conventional scenario based on natural gas. It can be explained by the fact that biomass needs to be converted internally in the

battery limits of the integrated scenario. The power-to-gas-to-power and the renewable energy storage systems also entail inherent inefficiencies while aiming to internalized fuel supply and emissions management. On the other hand, in the integrated aluminium decarbonization scenario, the direct fossil fuel consumption is completely avoided, despite the fact that indirect emissions linked to electricity mix are still significant, especially if electricity from the grid is partly composed of a non-renewable share at different scopes. In any case, the net CO₂ emissions of the conventional scenario using natural gas and biomass boilers achieve values higher than 50 kt/y, which is roughly 0.2 tCO₂/tAl. This value can be reduced by more than three times if an integrated carbon management and sequestration system is implemented. A district heating network can help to distribute the waste heat available through all the industrial process, but only after the high-grade chemical, electrical and thermal energy has been used at high temperature in the melting furnaces and solid oxide cells. The post-combustion of the tail gas from the SOFC cell can supply the heat needed in the melter furnace, whereas the electricity generated in the cell can be used elsewhere in the plant, such as in other electrical furnaces, rolling processes, ancillary power demands, and heat pumping systems of the district heating network.

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