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Assessment of Decarbonization Pathways for Key CO_2 Emitters in Austria's Aluminium Sector

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Abstract:

Aiming at a substantial CO_2 emission reduction of Austria's downstream aluminium industry, this paper, developed within the Zero-C-Alu project, presents an interim assessment of promising decarbonization pathways focusing specifically on the main CO_2 emission sources that are currently driven by fossil energy use in aluminium melting, thermal-oil-based heat supply, and associated thermal processes. The work is positioned at a comparatively high level of aggregation and serves as a structured preparation step for subsequent, model-based design and operation optimization and detailed techno-economic evaluation. The scope is therefore limited to major fossil-based energy conversion processes, encompassing both fuel switching and process electrification options, with particular attention to boundary conditions of the Austrian energy system and the practical constraints of retrofitting existing industrial sites.

Based on representative process configurations and typical operating conditions, the feasibility and expected impact of biogas substitution for conventional gaseous fuels, biomass gasification as a route to renewable process gases, plasma torches as high-temperature heat sources, induction-based electrification for targeted thermal duties, hydrogen utilization for combustion-driven heat supply, and biomass- and electricity-based heating concepts for industrial thermal-oil networks are discussed. The assessment emphasizes energy conversion characteristics and infrastructure implications, including the availability and quality requirements of renewable fuels, the integration of photovoltaic electricity generation, as well as the anticipated electricity demand and flexibility requirements associated with electrified heat provision.

The most important findings and technology pathways are investigated under Austrian context assumptions. Rather than concluding on a single preferred pathway, the paper provides a transparent mapping of technology choices and implementation challenges. The findings deliver a consolidated basis for the next project phase, in which a dedicated optimization environment and scenario-based modelling will be employed to quantify system-level impacts and to derive site-specific transition strategies for Austria's aluminium industry.

Keywords:

Decarbonization, Electrification, Renewable Gases, Techno Economic Analysis, Aluminium Industry

1. Introduction

In the context of climate change mitigation and the transition towards a low-carbon economy, the decarbonization of energy-intensive industrial sectors plays a central role. Among these, the aluminium industry is characterized by a high demand for thermal energy and electricity, with approx. 6.22 kt CO_2 emissions in 2024 originating from secondary aluminium production and associated downstream processes [1], [9], [10]. In Austria the downstream aluminium production is therefore highly relevant for achieving national and European climate targets [1]. The former contributor to the greenhouse gases from aluminium industry, SF_6 is phased out in Austria by 2024 [1]. The second most important energy carrier is natural gas, followed by electricity [11]. The paper comprises key findings from the Zero-C-Alu project coordinated by the Metaltechnology Austria Association (FMTI) and partly funded by the Austrian Research Promotion Agency (FFG).

While a substantial body of literature addresses the decarbonization of primary and secondary aluminium production, less attention has been paid to energy-intensive downstream aluminium processing such as melting, coating, drying, and thermal-oil-based heat supply under real industrial boundary conditions [11].

Many existing facilities rely on long-lived thermal assets, which constrains the applicability of greenfield solutions and necessitates stepwise transition strategies. Consequently, this paper focuses on major fossil-based energy conversion processes in Austria’s aluminium sector and evaluates feasible decarbonization pathways that can be integrated into existing industrial sites.

Electrification represents a key lever for industrial decarbonization, particularly in energy systems such as Austria’s, where renewable energy expansion is dominated by electricity generation from hydropower, wind, and photovoltaics. On the one hand direct electrification offers the advantage of avoiding conversion losses associated with secondary energy carriers. On the other hand, it also introduces challenges related to peak power demand, process related constraints, and limited large-scale storage options. For high-temperature applications, electrification must therefore be assessed alongside alternative pathways, including renewable hydrogen-based heat supply and other renewable energy carriers derived from biomass.

In addition to high-temperature melting processes, industrial thermal-oil systems used for drying and heat treatment represent a further relevant emission source. Their decarbonization requires an integrated assessment of biomass-based heat supply, electric heating solutions, storage concepts, and operational flexibility under dynamic load profiles.

Against this background, the present paper provides an interim, high-level assessment of promising decarbonization pathways for Austria’s aluminium industry. The analysis includes biomethane substitution, biomass gasification, hydrogen integration, induction and plasma-based electrification, photovoltaic integration, and alternative heating concepts for industrial thermal-oil networks. Rather than proposing a single optimal pathway, the paper delivers a structured comparison of technology options, infrastructure implications, and indicative performance parameters. The findings serve as a preparation step for subsequent design and operation optimization modelling within the Zero-C-Alu project, aiming to derive robust, site-specific transition strategies under dynamic boundary conditions.

2. Methodology

This study applies a combination of literature research, expert consultation, thermodynamic modelling, and economic evaluation. Relevant decarbonization pathways were identified based on published data and critically assessed under Austrian industrial boundary conditions. The literature findings were validated and refined through consultations with technology providers and industrial stakeholders. For selected technology options, simplified thermodynamic models were developed to estimate energy flows, efficiencies, and process interactions under representative operating conditions.

The remaining phase of the Zero-C-Alu project will focus on design and operation optimization modelling to systematically evaluate the identified technology options under dynamic boundary conditions. An optimization environment will be applied to investigate technology interactions, infrastructure constraints, and load-dependent operating strategies. Emphasis will be placed on identifying potential synergies between electrification, renewable fuels, storage solutions, and waste heat recovery. In addition, robust “no-regret” measures will be derived, representing options that remain beneficial across a wide range of future energy price and policy scenarios.

3. Pathway assessment

The following section presents the assessed technologies and gives an overview of advantages, disadvantages and major findings for each of the assessed pathways.

3.1. Industrial Use Case and Status quo

The current status quo for aluminium melting in Austria is predominantly based on natural gas-fired burner systems while on some sites liquefied natural gas (LNG) are in operation. The use cases addressed within this assessment originate from different industrial sites across Austria, reflecting the heterogeneity of the sector. Emphasis is placed on aluminium die-casting companies, which exhibit the highest specific energy demand due to the energy-intensive smelting processes. In addition, industrial sites performing downstream operations, such as coating and drying of aluminium components, were considered. These processes contribute significantly to the overall thermal energy demand and are therefore relevant for decarbonization strategies. Against this background, the following section presents and discusses the assessed technology pathways under real industrial boundary conditions.

3.2. Biomethane

Biomethane represents a technically straightforward substitute for natural gas, as it can be utilized within identical infrastructure, including existing gas grids and combustion systems. Raw biogas consists mainly of methane and carbon dioxide due to the underlying biological production processes. By separating CO_2 from the raw gas, biomethane with natural gas-equivalent quality is obtained. This upgrading can be performed locally. Alternatively, the biomethane certificate can be procured next to the gas which is delivered via the natural gas grid.

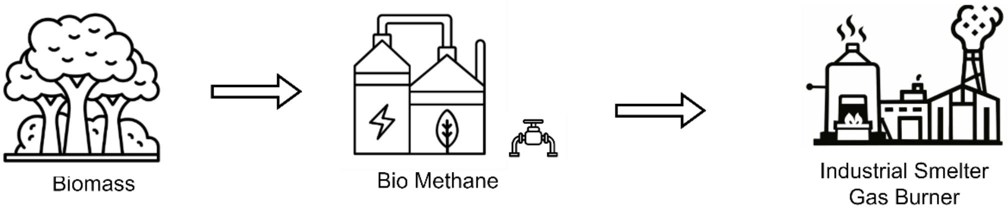

Figure 1: Schematic drawing of the CO2-neutral technology option smelting with bio methane.

From a regulatory perspective, biogas is commonly linked to tradable certificates. When the relevant sustainability criteria are fulfilled, these certificates may reduce the reported carbon footprint under the European Union Emissions Trading System (EU ETS I) or within greenhouse gas accounting according to the GHG Protocol. In practice, the environmental attribute is often traded separately from the physical gas molecule, which continues to be sourced via conventional wholesale markets. This decoupling enables stepwise decarbonization without major changes to the existing supply infrastructure.

Current market prices for biogas certificates typically range between 25 €/MWh and 60 €/MWh, depending on origin and certification scheme. Next to that, gas has to be procured at conventional gas markets. Preliminary assessments indicate that the import of biomethane from other EU Member States such as Germany and Poland may be a promising option in terms of availability and cost.

3.3. Biomass gasification

Biomass gasification was assessed as a molecular-based decarbonization pathway for supplying renewable syngas to industrial melting furnaces. The assessment concludes that steam gasification using a dual fluidized bed (DFB) reactor represents a technically suitable option for such applications compared to conventional air-based process routes. In contrast to applications where syngas is further processed for the synthesis of secondary energy carriers (e.g., methanol), its direct utilization in industrial burners requires only coarse gas cleaning. Additional fine gas purification steps, typically necessary for catalytic synthesis processes, are not required for combustion-based applications. As shown in Table 1, the volumetric heating value of the produced syngas can be compared to hydrogen, therefore retrofit measures are required. A higher volumetric flow rate must be accommodated, which implies the installation of additional gas nozzles or burners. While larger furnaces generally provide sufficient geometric flexibility for implementation, small melting furnaces may face spatial constraints. Moreover, existing burner systems may require adaptation due to differences in flame stability, gas composition and combustion characteristics.

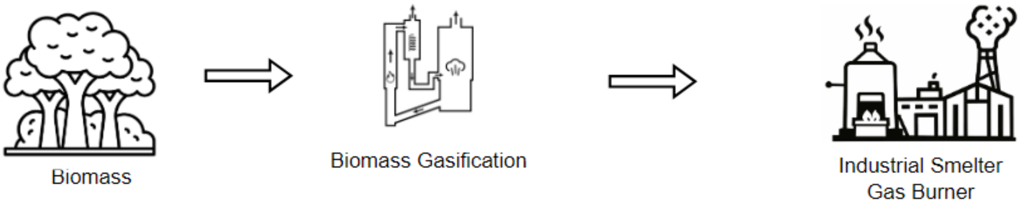

Figure 2: *Schematic drawing of the CO2-neutral technology option smelting with gasified biomass.*

Preliminary analyses indicate that wood chips and other residual biomass streams are available in distinct regions of Austria. Reported fuel costs in the range of approximately 20-60 €/MWh are considered competitive under current market conditions, based on own research and [7]. The overall energy efficiency of dual fluidized bed gasification is currently under investigation in parallel Austrian research projects and is expected to lie between 60 % and 80 %. Potential efficiency improvements due to industrial-scale upscaling have not yet been accounted for in the present assessment. The spatial footprint of a biomass gasification plant with a peak power output of 5 $MW_{Gas,LHV}$ is approx. between 1000 m² and 1500 m². The integration of such a plant must be investigated in the remaining project.

Table 1: *Exemplary values for steam gasification, own calculations and [6].*

	Unit	Steam Gasification	H_2	CH_4
CH_4	vol.-%	10.1	0	100
CO	vol.-%	21.8	0	0
CO_2	vol.-%	21.0	0	0
H_2	vol.-%	41.0	100	0
N_2	vol.-%	3.7	0	0
C_2H_6	vol.-%	1.2	0	0
C_3H_8	vol.-%	1.2	0	0
Lower Heating value	kWh/Nm^3	3.51	3.00	9.94
Adiabatic flame temperature	°C	2227.72	2452.06	2289.43

Published investment costs for biomass gasification plants are reported at approx. 2.1 $M€_{2026}/MW_{Syngas}$, while this value must be verified for dedicated industrial sites [4]. This value requires further validation within the remaining project duration and under site-specific boundary conditions. Overall, biomass gasification may represent a relevant decarbonization pathway in selected regions with adequate biomass availability, with energy supply costs potentially compatible with industrial requirements.

3.4. Induction furnaces

Induction furnaces enable the direct application of electricity for melting processes by transferring energy via electromagnetic fields generated through water-cooled copper solenoid coils [8]. The underlying physical principle is implemented in two main configurations: crucible furnaces, where the solenoid coil surrounds the melting vessel, and channel-type furnaces, where a dedicated induction channel below the main furnace body is encircled by the coils as shown in Figure 3.

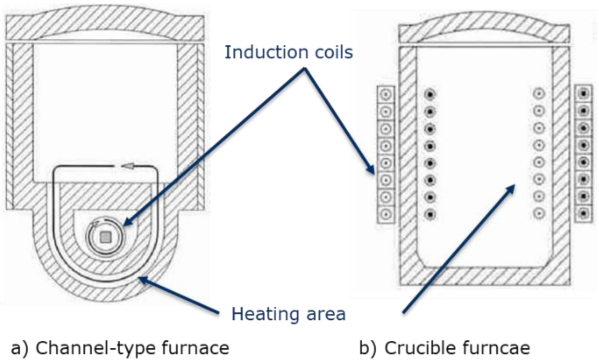

Figure 3: *Configurations of induction melting furnaces based on [8]*

Reported overall efficiencies range between 60 % and 80 %, referring to the conversion from electrical input to thermal energy in the melt. Channel-type furnaces typically show higher efficiencies due to their geometry [8]. Key advantages include the comparatively high efficiency and the electromagnetic stirring effect, which enhances bath homogeneity and supports the melting of circulating material. However, induction furnaces provide limited capability to oxidize oily or organic residues, as no combustion atmosphere is present.

Figure 4: *Schematic drawing of the CO2-neutral technology option smelting with an inductive smelter.*

From an operational perspective, induction technology allows for adaptations of established melting practices. For instance, high-power induction furnaces could be operated during periods of low electricity prices to melt base alloys, which are subsequently adjusted and held in larger, low power holding furnaces. Such a configuration may enhance flexibility and enable load shifting within the melting division. The assessment of investment costs for induction-based solutions and battery electric storages will constitute a substantial component of the remaining project work.

3.5. Plasma torches

Plasma torches represent an alternative electrification pathway for high-temperature heat supply in aluminium melting processes. Like induction systems, plasma technology enables the direct utilization of electrical energy. However, in contrast to electromagnetic heating, the electrical input is first converted into a high-enthalpy plasma jet. Typically, nitrogen or other process gases are ionized and subsequently introduced into the furnace, where heat is transferred predominantly via radiation owing to plasma gas temperatures of up to 3,000 – 5,000 °C and convection [3].

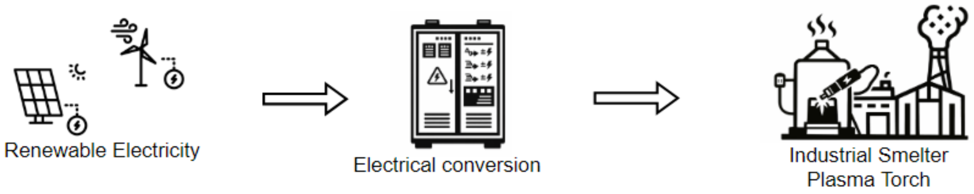

Figure 5: *Schematic drawing of the CO2-neutral technology option smelting with plasma torches.*

Compared to conventional natural gas-fired furnaces, the volumetric gas flow of plasma systems is substantially lower, typically by approximately one order of magnitude. Consequently, exhaust-related efficiency losses are reduced, potentially improving overall thermal performance. A key advantage of plasma torches lies in their retrofit capability, as existing furnace geometries can, in principle, be adapted to integrate plasma burners without complete redesign of the melting unit.

Nevertheless, the implementation entails significant implications for the electrical infrastructure, including the provision of high-capacity AC/DC power electronics and, where applicable, additional flexibility options such as battery storage. Furthermore, plasma operation requires a dedicated plasma gas. Nitrogen is frequently applied, offering the possibility of local production via air separation units during periods of low electricity prices, thereby introducing additional operational flexibility [3].

Investment expenditures remain site-specific and require detailed assessment. Given the current Technology Readiness Level (TRL 5–7), further industrial experience and demonstration activities are necessary to reduce technological uncertainty and to enable a robust techno-economic evaluation under real operating conditions [2], [3], [5].

3.6. Electrolyser and Hydrogen

The integration of hydrogen into existing aluminium melting processes requires the installation of dedicated electrolyser systems, additional storage capacities (either on the electrical or hydrogen side) and appropriate gas piping infrastructure. Depending on the specific furnace configuration, retrofitting of burners and, in certain cases, adaptations of the refractory lining are necessary. From a purely technical perspective, the assessment concludes that hydrogen-based combustion is feasible under industrial boundary conditions.

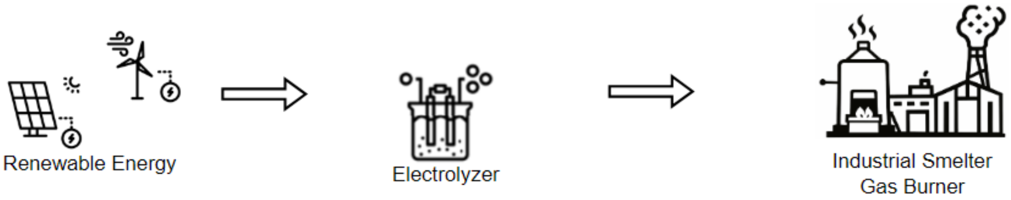

Figure 6: *Schematic drawing of the CO2-neutral technology option smelting with hydrogen from an electrolyzer.*

However, the economic implications are important. The additional energy conversion step from electricity to hydrogen in the electrolyser introduces considerable efficiency losses, while investment expenditures for generation, storage, and distribution infrastructure remain high. The research concludes in a first assessment, that hydrogen prices between 7 €/kg and 9 €/kg can be considered for the dedicated industrial sites. Consequently, waste heat recovery represents a robust and economically favourable measure that should be prioritized within the overall decarbonization strategy. This addresses the preheating of ingots or the utilization of recovered heat for auxiliary processes as more immediate and cost-effective mitigation measures.

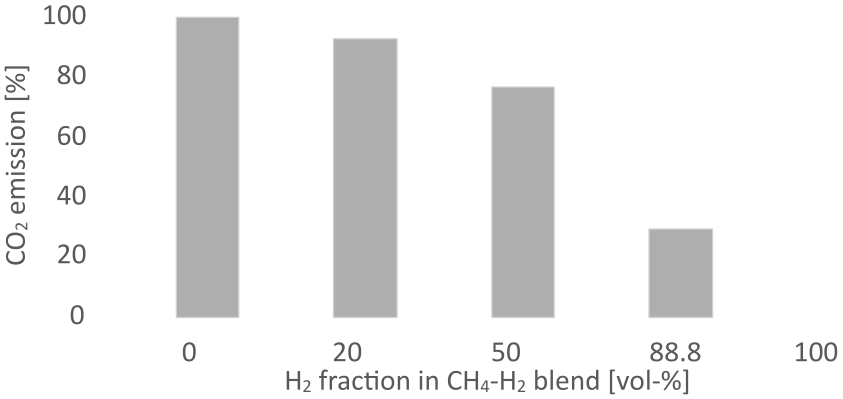

Figure 7: *CO2 reduction from CH_4-H_2 blends, own calculations*

Further, the project concludes that CO_2-reduction rates associated with hydrogen admixture exhibit a non-linear relationship with the volumetric share of hydrogen in natural gas, as shown in Figure 7. In many existing gas systems, blending up to 20 vol-% hydrogen is technically possible without major modifications to pipelines, valves, sealings, or burners. This moderate admixture allows continued operation of existing furnace equipment and production workflows. Nevertheless, a 20 vol-% hydrogen share results in a CO_2 emission reduction of only approximately 7 %, illustrating the limited decarbonization impact of partial substitution.

3.7. Photovoltaic

Photovoltaic (PV) systems are a key pillar for large-scale electrification of the energy system, as thermal processes are increasingly substituted by electrically driven technologies, overall electricity demand rises significantly. Literature shows that levelized costs of electricity (LCoE) is considerably low for PV-systems [7]. A physical direct line between the PV field and the industrial site is essential to ensure economic viability as network fees can be prevented. The industrial sites in the project can calculate with LCoE of onsite PV panels approximately between 70 €/MWh and 90 €/MWh which is in the range of literature values [7].

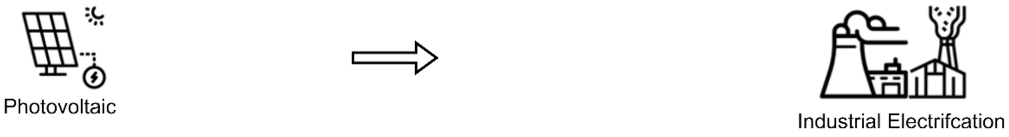

Figure 8: *Photovoltaic electrification of the industry.*

Within the project, contractual models were therefore assessed, with specific attention to the allocation of Guarantees of Origin (GoO). Seasonal generation patterns lead to substantial overproduction in summer months. Regulatory discussions confirmed that surplus electricity can be marketed while retaining the associated GoOs, which may later be used to claim green electricity during winter procurement.

However, the required PV capacities imply large land areas, often exceeding 10 hectares, coming with siting challenges. In this sense, Agri-PV can play an important role for public acceptance. In addition, the variability of PV generation necessitates flexibility options, making battery storage systems a crucial element for stable industrial integration and a focus of the next project phase.

3.8. Biomass heating for thermal-oil

Within the aluminium industry landscape, industrial heating networks can rely on thermal-oil heating systems. Therefore, the project assessed heating procedures for an industrial thermal-oil heat network, covering both biomass-based heat supply and electric thermal-oil heating concepts. A particular focus was placed on biomass heaters (e.g., wood-chip boilers), as they represent a mature technology with comparatively low and stable fuel costs [7].

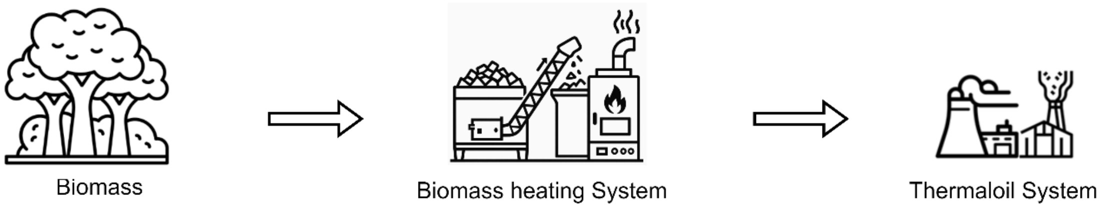

Figure 9: *Biomass heating for thermoil systems.*

Based on measured site data, the thermal-oil heat demand was found to be highly dynamic, exhibiting oscillatory load patterns that exceed typical ramping behaviour of conventional biomass systems. Consequently, the practical integration challenge is the mismatch between process dynamics and the intrinsically sluggish operational response of biomass combustion units.

To address these load ramps, multiple strategies were evaluated, including dedicated thermal-oil storage and operational concepts enabling temporary overheating. The option of using the thermal-oil loop itself as an effective short-term storage medium was discussed, combined with temperature control to maintain process supply temperatures. Further flexibility measures included concepts for auxiliary peak coverage (e.g., a supplementary gas burner) and advanced operational optimization approaches such as model-predictive control. In addition to weekday operation, weekend conditions were analyzed, as the heat demand drops substantially and may fall below the minimum stable load of conventional biomass boilers. For these low-demand periods, alternative operating modes such as storage charging prior to weekends and “glow-keeping” (embers preservation) strategies were considered. Overall, the work provides a structured basis for subsequent techno-economic evaluation and system-level optimization of biomass-based thermal-oil supply under realistic industrial boundary conditions.

3.9. Comparison of pathways

Table 2 provides a brief overview of the findings in the preceding paragraphs. The table focuses on the TRL, the retrofit complexity, the heat transfer mechanism and the required infrastructure.

Table 2: *Comparison of the findings in the preceding paragraphs*

	TRL	**Retrofit complexity**	**Heat transfer mechanism**	**Infrastructure**
Biomethane	9	low	Combustion, radiation and convection	/
Biomass gasification	6-8 (DFB)	medium	Combustion, radiation and convection	Gasifier and furnace retrofit
Induction Furnace	9	High	Electro-magnetic	Rectifier and Induction furnaces
Plasma Torches	5-7	Medium	Radiation and convection	Rectifier and Plasma torches
Electrolyser and Hydrogen	8-9	High	Combustion, radiation and convection	Electrolyzer, piping and burner retrofit
Photovoltaic	9	Low-medium	/	PV-Systems, potentially Batteries
Biomass heater for thermal-oil	9	medium	/	Biomass heating plant and storages

4. Conclusion

The present assessment provides a structured comparison of relevant decarbonization pathways for Austria's downstream aluminium industry under realistic industrial boundary conditions. The results highlight that multiple technically feasible options exist. However, their suitability strongly depends on site-specific infrastructure, process characteristics, and future energy price developments.

Across the assessed pathways, waste heat recovery and on-site renewable electricity generation emerge as robust no-regret measures that remain beneficial irrespective of the selected primary decarbonization pathway.

The next step within the Zero-C-Alu project is a comprehensive techno-economic assessment and scenario study based on a mixed-integer linear programming (MILP) approach. This will enable a systematic evaluation of technology combinations, infrastructure constraints, and operational strategies under dynamic boundary conditions. Emphasis will be placed on quantifying system-level impacts, identifying robust “no-regret” measures, and deriving site-specific transition pathways consistent with long-term decarbonization targets.

Acknowledgments

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Nomenclature

POS	Proof of Sustainability
TRL	Technology Readiness Level
DFB	Dual Fluidized Bed
EU ETS I	European Union Emissions Trading System I
EUA	European Union Allowances
GHG	Greenhouse Gas
GoO	Guarantees of Origin
LCoH	Levelized Cost of Hydrogen
LNG	Liquefied Natural Gas
MILP	Mixed Integer Linear Programming
PV	Photovoltaic
SNG	Sustainable Natural Gas
SF_6	Sulfur hexafluoride
LHV	Lower Heating Value

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