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Stegra

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Executive Summary of the Thesis

Integrating Bio-Hydrogen Production for Optimal Hydrogen Supply in Stegra's Fossil-Free Iron and Steelmaking.

Laurea Magistrale in Chemical Engineering - Ingegneria Chimica

Author: Laura Pesaresi

Advisor: Prof. Flavio Manenti

Co-advisor: Klas Engvall (Division of Process Technology, KTH Royal Institute of Technology), Marita Nilsson (Hydrogen Technology and Innovation Lead, STEGRA), Joakim Lundgren (Division of Energy Science, Luleå University of Technology)

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1. Introduction

The iron and steel sector accounts for nearly 7.2 % of global CO_2 emissions, making it one of the most carbon-intensive industrial sectors worldwide [1]. Achieving the climate neutrality targets set by the European Union and international climate agreements requires a fundamental transformation of this sector [2]. In this context, hydrogen-based steelmaking is widely recognized as a promising pathway to eliminate fossil-based emissions [1].

Stegra, founded in 2020 and headquartered in Stockholm (Sweden), is fully committed to this transformation. The company's mission is to produce *green hydrogen, green iron, and green steel* by implementing a fully electrified and fossil-free process chain powered by renewable energy sources. Stegra's process concept replaces the traditional blast furnace route, in which coal and coke act as reducing agents releasing large amounts of CO_2, with a hydrogen-based direct reduction process coupled to an electric arc furnace. They aim to produce steel with up to 95% lower CO_2 footprint. A schematic comparison between the conventional process and Stegra's electrified route is reported in Figure 1.

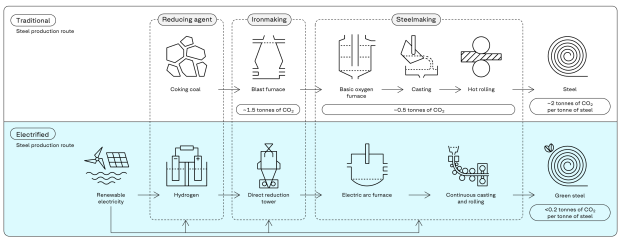

Figure 1: Comparison between conventional steelmaking (above) and Stegra's electrified, hydrogen-based process (below).

Stegra is currently developing large-scale industrial projects in Sweden, Portugal, Canada, and Brazil, with its main plant located in **Boden**, northern Sweden. The Boden facility is under construction and represents the pillar of Stegra's strategy, with operations expected to start in 2026. By 2030, the plant aims to reach a production capacity of up to 5 million tonnes of fossil-free steel per year. An aerial view of the Boden construction site as of March 2025 is shown in Figure 2.

Figure 2: Construction progress of Stegra's main plant in Boden, Sweden (March 2025).

This thesis is the result of an internship at **Stegra**, carried out in collaboration with the **KTH Royal Institute of Technology** and the **Luleå University of Technology**. The work specifically refers to Stegra's leading plant in Boden, and focuses on the integration of complementary bio-hydrogen production pathways to support the company's decarbonization goals.

2. Objectives of the Thesis

This thesis focuses on the production of renewable hydrogen, a key element of Stegra's decarbonized steelmaking strategy. In the Boden facility, hydrogen will be primarily produced by alkaline water electrolysis (AWE). The plant is designed with a total electrolyser capacity of 740 MW, corresponding to a nominal hydrogen production rate of approximately 148 000 $m^3\,h^{-1}$ at full load. This capacity will be achieved through 37 electrolyser units, each rated at 20 MW, distributed across two dedicated production buildings. The generated hydrogen will serve as the main reducing agent in the **Direct Reduction of Iron (DRI)** unit, where iron ore pellets are converted into direct reduced iron using a hydrogen-based reduction pathway.

The research question that motivated this work, raised by Marita Nilsson (Hydrogen Technology and Innovation Lead at Stegra and co-supervisor of this thesis), was whether part of the hydrogen demand could be produced via **biomass gasification**. Sweden has abundant woody biomass resources, and their valorization could provide several strategic advantages: diversification of hydrogen supply routes, cost mitigation, and the potential to achieve carbon-negative emissions through CO_2 capture and storage.

Accordingly, the thesis is structured around four main objectives:

1. assess mature and cost-effective gasification technologies for hydrogen generation and integration with electrolysis and steelmaking;
2. identify suitable biomass feedstocks based on regional availability;
3. perform a techno-economic evaluation of combined bio- and electrolytic hydrogen supply;
4. benchmark the performance and competitiveness of this integrated system against an electrolysis-only baseline.

The overarching goal is to determine whether complementary bio-hydrogen production can strengthen Stegra's hydrogen strategy, reducing costs and risks while maintaining the commitment to a fully fossil-free steel value chain.

3. Methodology

The methodology followed in this thesis was organized in three main steps: (i) process design, developed through literature review and technical discussions with industrial experts; (ii) process simulation, combining data from literature and industrial meetings with calculations in Excel and dedicated SATS and GASDS simulations; and (iii) techno-economic assessment, based on literature insights, industrial input, and cost modelling in Excel.

A crucial element of the work was a series of meetings with leading industrial players, arranged through the support of supervisors Marita Nilsson (Stegra) and Prof. Klas Engvall (KTH). These interactions allowed direct discussions with company representatives, providing insights into the rationale behind their process choices and access to technical data and economic assumptions not always available in the literature. In particular, exchanges with FerroSilva (Sweden), Torrgas (The Netherlands), and Topsoe proved especially valuable: the former two shared perspectives on biomass valorization for fossil-free sponge iron and syngas-based products, also providing inputs that supported the economic assessment, while a meeting with a Topsoe expert was particularly valuable in discussing the integration of a partial oxidation (POX) unit downstream of the gasifier to enhance hydrogen yield.

The knowledge gained from these meetings, combined with an extensive literature review and comparisons with existing plant data and previous studies, formed the basis for the process configuration and the assumptions adopted in this thesis. These inputs provided the starting point for the techno-economic simulations and cost calculations.

3.1. Process Design

The first step was to define the main units of the biomass-to-hydrogen process and their sequence. Literature data were combined with industrial feedback from the meetings to ensure realistic assumptions for efficiencies and operating conditions. Among the numerous studies reviewed, one key reference that served as a starting point for this stage was the work of Rajaee et al. [3].
The resulting process configuration is shown in the simplified block flow diagram in Figure 3. The main process units include biomass drying, a circulating fluidized bed gasifier (CFBG), a partial oxidation (POX) unit to enhance hydrogen yield, high-temperature gas cleaning, two water-gas shift (WGS) reactors in series (HT and LT) with sulfur removal, and a final pressure swing adsorption (PSA) unit for hydrogen purification. The process is integrated with carbon dioxide capture, oxygen supply from electrolysis, and hydrogen compression for delivery to the DRI plant.

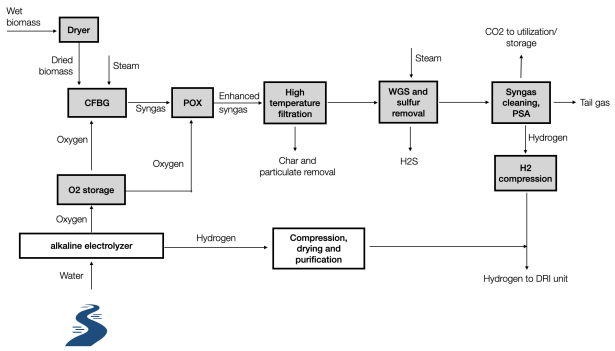

Figure 3: Simplified block flow diagram of the biomass-to-hydrogen process considered in this study.

The design was carried out to meet the hydrogen specifications required for the DRI process at Stegra's Boden facility. These requirements, summarized in Table 1, ensure the compatibility of the produced hydrogen stream with the reduction process.

Parameter	Requirement
Pressure	> 8 bar
H_2 content	$> 99.8\ \%_{dry}$
O_2 content	$< 0.2\ \%_{dry}$
H_2O content	$< 0.5\ \%$
Impurities content	$< 5\ ppm$

Table 1: Specifications of hydrogen flow for DRI production.

3.2. Simulation Approach

Each unit was modeled step by step, performing mass and energy balances to estimate inlet and outlet streams as well as hydrogen yields. The core calculations were carried out in Excel. Two tools developed at Politecnico di Milano were also employed: the **GASDS** package, used to simulate gasification kinetics and validate literature-based results, and the Sulfidric Acid Thermal Splitting (**SATS**) model, applied to recover hydrogen from H_2S-rich waste gases, thereby increasing the overall H_2 production while simultaneously generating valuable elemental sulfur.

3.3. Techno-Economic Analysis

Finally, a techno-economic analysis (TEA) was performed, considering four base scenarios defined by different combinations of steam supply strategy (fully purchased or partially generated on-site) and CO_2 handling options (vented to the atmosphere or captured and sold), all evaluated at the current market price of the selected biomass. The analysis included also a cost breakdown of both CAPEX and OPEX to identify the main cost drivers, along with two sensitivity studies: one assessing the impact of capital costs on achievable LCOH targets, and another evaluating how biomass price variations affect the overall competitiveness of the system.
All evaluations were conducted with an industrial perspective, aiming to identify the conditions under which the plant would be technically and economically feasible, thus providing Stegra with a practical decision-support tool for future investments.

4. Main Results

The results of the process design and techno-economic assessment are summarized in this section.

4.1. Hydrogen Production Performance

The biomass-to-hydrogen system designed in this work achieves the performance indicators reported in Table 2. At steady operation (8000 h/y), the plant processes around 437,000 t/y of woody biomass and generates about 17,500 t/y of hydrogen, corresponding to 87.4 MW of thermal output. The overall thermal efficiency reaches 58.3%, with a hydrogen yield of 40.5 kg H_2 per tonne of biomass. This production covers about 17% of the hydrogen required

by the DRI process in Stegra's Boden facility. In the CCUS scenarios, the plant is also able to capture around 318,400 t/y of CO_2, offering the potential for net-negative emissions in addition to renewable hydrogen supply.
The integration of the Sulfidric Acid Thermal Splitting (SATS) unit could further increase the hydrogen production, although in the simulated case the gain is below 1%. While this limited effect might not justify its implementation under current conditions, SATS represents an innovative approach to recovering hydrogen from toxic H_2S waste gases, turning a harmful by-product into additional hydrogen and valuable elemental sulfur.

Parameter	Value
Operating hours per year	8000 h/y
Biomass input	437,000 t/y
Hydrogen production rate	0.63 kg/s
Annual hydrogen production	17,500 t/y
Share of H_2 required for DRI	17%
Hydrogen LHV	140.4 MJ/kg
Hydrogen thermal output	87.4 MW
Biomass thermal input	150 MW
Thermal efficiency	58.3%
Hydrogen yield	40.5 kg $H_2/t_{biomass}$
Captured CO_2 (with CCUS)	318,400 t/y

Table 2: Key performance indicators of the biomass-to-hydrogen system.

The composition of the syngas leaving the gasifier was confirmed by GASDS simulations, which validated the gasification step and showed good consistency with literature data. These results are summarized in Table 3.

Species	%mol GASDS	%mol Calc.	%wt GASDS	%wt Calc.
CO	13.91	14.64	18.31	19.54
H_2O	38.45	40.38	32.55	34.64
CO_2	19.57	17.31	40.46	36.30
H_2	19.29	20.11	1.83	1.92

Table 3: Gas composition: comparison between GASDS simulation and calculated values (molar and mass fractions at the outlet).

4.2. Base Case Scenarios

The techno-economic results for different steam supply and CO_2 handling strategies are reported in Table 4, assuming for the woody biomass the current market price of 80.6 €/ton (based on the data provided by the Swedish Energy Agency [4] for woodchips in 2024). The lowest LCOH (3.6 €/kg H_2) is obtained with internal steam generation and CCUS with credit from CO_2 sales.

Scenario	ann. CAPEX [M€/y]	net OPEX [M€/y]	LCOH [€/kg$_{H_2}$]
1) No CCUS + Purchased Steam	29.4	53.9	4.7
2) No CCUS + Internal Steam	30.9	48.4	4.5
3) CCUS + Purchased Steam	30.3	37.9	3.8
4) CCUS + Internal Steam	31.8	32.4	3.6

Table 4: Base case results for different CO_2 handling and steam supply strategies (biomass price: 80.6 €/t).

Scenario logic and calculation approach
The four scenarios combine (i) the steam supply strategy and (ii) the CO_2 handling option.
For the steam supply, two cases were considered. In the first, steam is fully purchased from outside the system, adding an OPEX contribution of 30 €/t_{steam} according to literature values. In the second, steam is generated on-site: part of the demand is covered by process heat recovery, while the remaining share is produced by firing additional biomass. This increases both the OPEX (due to higher biomass consumption at the current market price) and the CAPEX of the steam generation section.
For CO_2 handling, two options were analyzed. If the gas is vented, no CCUS equipment is installed, leading to lower CAPEX, no capture-related utilities in OPEX and no penalties, as Sweden does not tax biogenic emissions. If instead CO_2 is captured and sold, additional costs arise from capture, compression, and transport (assumed at 50 €/t_{CO_2}), while revenues are credited using a selling price of 100 €/t_{CO_2} [5]. The resulting net credit of +50 €/t_{CO_2} reduces the hydrogen cost but requires higher utilities and auxiliary loads.
In all scenarios, the Levelized Cost of Hydrogen (LCOH) is calculated as:

$$\mathrm{LCOH} = \frac{\mathrm{CRF} \cdot \mathrm{CAPEX} + \mathrm{OPEX} - \mathrm{credits}}{\dot{m}_{\mathrm{H_2}} \cdot t_{\mathrm{op}}},$$

where CRF is the capital recovery factor (based

on an interest rate of 8% and a plant productive life of 25 years [3]). OPEX includes biomass feedstock, utilities, and fixed/variable costs, while credits account for CO_2 sales and other by-product revenues. The denominator refers to the annual hydrogen production, obtained from the operating hours and production rate reported in Table 2. For clarity, the values reported in Table 4 refer to *annualized CAPEX* (i.e., multiplied by the CRF) and to *net annual OPEX*, already accounting for revenues from CO_2 sales. This representation allows for a fast and direct comparison of the relative impact of different scenarios.

4.3. Sensitivity Analysis

From an industrial perspective, it is crucial to evaluate the costs required to achieve a target LCOH. For Stegra, the relevant range of interest was identified between 3 and 5 €/kg H_2. To better investigate the cost structure, the sensitivity analysis was divided into two complementary studies applied to each scenario. In the first, operating expenditures (OPEX) were fixed and the capital investment (CAPEX) was varied to determine the range of investment compatible with the target LCOH. In the second, CAPEX was fixed while OPEX was adjusted accordingly.
Since investment costs are inherently uncertain until equipment procurement, whereas OPEX estimates are generally more reliable, the first approach provides the most meaningful insights from an industrial standpoint. It indicates the level of capital expenditure that Stegra would need to sustain in order to reach the target range of 3–5 €/kg H_2. As an illustrative example, the results for Scenario 3 are reported in Table 5, where OPEX is fixed at 37.9 M€/y (base case scenario value) and the corresponding CAPEX range is derived.

LCOH [€/kg$_{H_2}$]	Annualized CAPEX [M€/y]
3.00	14.56
3.85	30.33
5.00	49.54

Table 5: Annualized CAPEX at different LCOH and fixing the OPEX (scenario 3).

A second sensitivity analysis was carried out on the biomass price. The current value, used in the base case scenario, is relatively high due to recent geopolitical factors. However, from an industrial perspective it is important to highlight how the LCOH would decrease if biomass costs returned to the levels of the past decades, in the range of 30–50 €/ton. This analysis provides a broader view of the competitiveness of biomass gasification under more favorable market conditions.

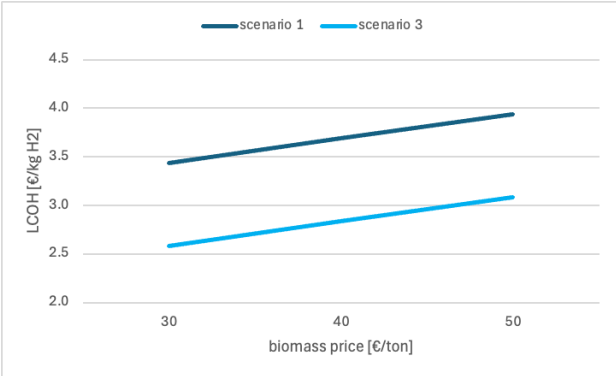

Figure 4: LCOH at different biomass price for scenario 1 and 3.

The results clearly highlight the strong influence of biomass price on competitiveness, as well as the importance of optimizing steam generation and carbon management strategies.
It should also be stressed that all the cost evaluations presented are valid under the assumption of a high utilization rate of the gasifier (8000 h/y). A reduction in operating time would increase the LCOH, since CAPEX and OPEX would be distributed over a smaller hydrogen output.

4.4. Economic Breakdown

Figure 5 shows the economic breakdown for Scenario 3 (representative scenario). The CAPEX is dominated by the biomass-to-syngas island, while the OPEX is largely driven by biomass feedstock costs. These insights provide Stegra with clear indications on which units and parameters are most critical to improve economic performance.

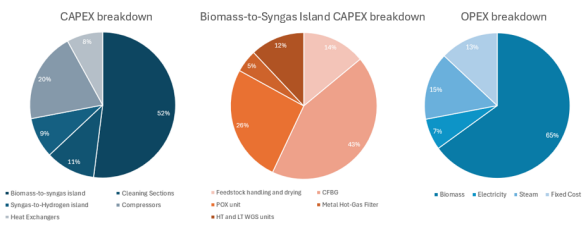

Figure 5: Economic breakdowns for Scenario 3: (a) CAPEX Breakdown, (b) Biomass-to-Syngas Island CAPEX Breakdown, (c) OPEX Breakdown

4.5. Strategic Relevance for Stegra

The results show that producing hydrogen from biomass gasification will not replace electrolysis at Stegra, but it can play an important complementary role. The main advantage is diversification: by not relying only on electricity, Stegra can reduce the risks linked to power prices and supply fluctuations. At the same time, Sweden has large amounts of forest residues that can be turned into a local energy resource instead of being wasted.

A second strong point is the possibility of achieving negative emissions. Biomass absorbs CO_2 from the atmosphere as it grows, and if the carbon released during gasification is subsequently captured and stored, the overall balance becomes net-negative. In this way, part of the CO_2 absorbed by biomass can be removed from the atmosphere, unlike in an electrolysis-only system.

Another key benefit is the integration with electrolysis. The oxygen produced by the electrolysers, which would otherwise be vented, can be directly used in the circulating fluidized bed gasifier (CFBG) and in the partial oxidation (POX) unit. Compared to using air, pure oxygen avoids the dilution of syngas with nitrogen, leading to a higher-quality gas stream and more efficient downstream conversion. By exploiting the oxygen already available from electrolysis, the process also eliminates the need for an expensive and energy-intensive air separation unit. In practice, this turns a by-product of electrolysis into a valuable resource that improves the overall economics of the system.

In short, even if the final hydrogen cost is slightly higher, biomass gasification gives Stegra strategic benefits in terms of security, sustainability, and long-term competitiveness.

5. Conclusions

The analysis carried out in this thesis demonstrates that biomass gasification can contribute up to 17% of the hydrogen required by Stegra's Boden facility. The most favorable configuration, based on internal steam generation and CO_2 capture with credit from its sale, achieves a Levelized Cost of Hydrogen (LCOH) of 3.6 €/kg H_2. The results are valid under the assumption of continuous operation close to 8000 h/y, and the competitiveness is strongly influenced by biomass price, which is currently high due to geopolitical conditions but has historically been lower.

Although the hydrogen cost (LCOH) is slightly higher than that of electrolysis at Stegra's plant, the system remains competitive thanks to several strategic advantages: diversification of hydrogen supply, valorization of local biomass, potential for negative emissions through CCUS, and the direct use of electrolytic oxygen, which avoids the need for an air separation unit.

In conclusion, biomass gasification should be considered not as a substitute but as a complementary route to electrolysis, strengthening the resilience, sustainability, and long-term competitiveness of Stegra's decarbonized steelmaking strategy. Future work should focus on verifying biomass availability and costs, optimizing operations, and experimentally validating the integrated process.

Beyond the technical outcomes, this work also represented a valuable opportunity to experience the challenges of process design and decision-making in an industrial context. The project required not only selecting technologies and assessing costs, but also presenting ideas, discussing assumptions, and addressing questions directly with an industrial partner. Interactions with Stegra and other companies provided first-hand insights into how industrial choices are made and markedly improved the ability to translate academic research into viable, industrial solutions.

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