Final Report

BioEnergy Concept GmbH, Germany

by

the Institute for Applied Material Flow Management (IfaS),
Environmental Campus Birkenfeld,
Trier University of Applied Sciences, Germany

on

Comprehensive Assessment of Material Flows, Carbon Footprint, and Regional Added Value in Biomass-Based Hydrogen Production

IfaS

SUBJECT: Comprehensive Assessment of Material Flows, Product Carbon Footprint (PCF), and Regional Added Value (RAV) in Biomass-Based Hydrogen Production.

LOCATION: Lüneburg, Lower Saxony, Germany

CATEGORY: Advisory services, knowledge transfer on PCF and RVA

SYNOPSIS:

This report details the outcomes on PCF and RAV of an extensive assessment conducted on the Biomass-based Hydrogen Production technology developed by BioEnergy Concept GmbH, Germany. The primary objective is to assist BioEnergy Concept GmbH in achieving a climate-neutral product by offering guidance on establishing carbon accounting and management systems, along with outlining the product's carbon footprint. The RAV analysis evaluates the economic and social benefits generated by the biomass-based hydrogen production technology at a regional level. As a global pioneer in sustainable resource management and resource efficiency, the Institute for Applied Material Flow Management [IfaS] of the Trier University of Applied Sciences endeavors to provide with the international consultancy services to identify and evaluate opportunities with complex material flows. IfaS has been contracted to identify PCF and RAVA in the target company: Bioenergy Concept GmbH. This document presents the results of the comprehensive analysis of the product.

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List of Abbreviations

a	Annum
ATR	Autothermal Reforming
BAU	Business as usual
BTL	Biomass to liquid
bar(g)	Guage pressure
C	Carbon
CAGR	Compound Annual Growth Rate
CG	Coal Gasification
CH_4	Methane
CO_2	Carbon Dioxide
CO	Carbon Monoxide
°C	Degree Celsius
CHP	Combined Heat and Power
EF	Emission Factors
ESG	Environmental, Social, and Governance
FSC	Forest Stewardship Council
g	Grams
GHG	Greenhouse gas emissions
GWP	Global Warming Potential
h	hours
HAW	Hochschule für Angewandte Wissenschaften
H_2	Hydrogen
H_2O	Water/Steam
IfaS	Institute for Applied Material Flow Management
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standardization Organization
K	Kelvin
kg	kilogram
kJ	Kilo joules
MFA	Material flow analysis
mol	Mole
MW	Megawatt
MWh	Megawatt hour
MJ	Mega joule
m^3	Cubic meter
NCV	Net calorific value
NPV	Net present Value
O_2	Oxygen
PAS	Publicly Available Specification
PCF	Product Carbon Footprint
PCS	Protocol Corporate Standard
PEFC	Programme for the Endorsement of Forest Certification
PEM	Proton Exchange Membrane
PPA	Power Purchase Agreement
PSA	Pressure Swing Adsorption
RE	Renewable Energy
RFBO	Renewable Fuel of Biological Origin
SBTi	Science Based Target Initiative
SDG	Sustainable Development Goals
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser cell
SWOT	Strengths, Weaknesses, Opportunities, And Threats
t	Tonne / metric ton
US	United States
WBCSD	World Business Council for Sustainable Development
WGS	Water Gas Shift
WRI	World Resources Institute
WMO	World Meteorological Organization

km	Kilometer	$	US Dollars
KPI	Key performance indicators	%	Percentage
kWh	kilowatt hour		
LCA	Life Cycle Assessment		
l	litre		

About the document

This document is meant as a technical guidance to help Bioenergy Concept GmbH in analysing their material flows and PCF for production of Hydrogen (H_2) from Biomass in their system. It outlines IfaS’s own methodology to calculate cradle-to-tank PCF.

1 Executive summary

BioEnergy Concept GmbH's hydrogen production technology through biomass gasification represents a sustainable approach for clean energy solutions. BioEnergy Concept GmbH employs a modular 8 MW biomass gasification system, characterized by its efficient and continuous reactor for hydrogen gas generation of 0.2 t/h. The technology allows for the transformation of biomass, primarily consisting of 85 % Pinus Sylvestris (pine) and 15 % Pica Abies (spruce), into hydrogen. The process involves rigorous steps such as gasification, gas purification, compression, and transportation, ensuring a streamlined and sustainable production chain.

The mass flow analysis indicates minimal material loss within the system, achieving a H_2 conversion rate of 6 % from the supplied biomass in reactor. In terms of energy flow, the system demonstrates an overall efficiency of 55.9 %, achieving an energy input intensity of 59.59 kWh/kg H_2—outperforming similar biomass-based technologies.

A detailed analysis of PCF reveals this technology has a PCF of 4.16 – 4.96 kg $CO_{2eq.}$/kg H_2 for its design life, making it more favourable than traditional grey hydrogen and biomass-to-liquid methods. However, continuous improvements are needed to compete with blue and green hydrogen production. If the grid electricity becomes fully green, this technology, which relies heavily on Scope 2 emissions, will outperform current electrolyser technology with PCF of 0.33-0.4 kg $CO_{2eq.}$/kg H_2, especially when using PEFC or FSC-certified biomass. The technology's water intensity, standing at approximately 7.02 l/kg H_2.

Despite the identified opportunities for improvement, BioEnergy Concept GmbH is strategically positioned as a contributor to sustainable hydrogen production. The modular design, utilization of certified biomass, and a commitment to renewable energy (RE) sources showcase the company's alignment with global environmental goals. Future advancements could focus on further reducing carbon emissions, optimizing energy efficiency, and exploring innovative methods to enhance the overall environmental sustainability of the hydrogen production process.

The RAV assessment reveals significant economic benefits, with total RAV estimated at 487 M € over a 20-year operational period—representing 825% of the initial investment of 59 M €. The logistics sector emerges as the largest contributor, accounting for 307 M € (63%) through hydrogen-powered truck operations within a 150 km radius. The facility operator adds 38.5 M €, while biomass procurement, craft services, and energy suppliers contribute 31.5 M €, 29.5 M €, and 16.9 M €, respectively. Downstream infrastructure, such as refueling stations, generates an additional 31.2 M € (6.5%) in value creation. Financial benefits are widely distributed among key stakeholders, including municipalities, employees, credit institutions, and insurers, underscoring the project's broad regional economic impact.

In conclusion, the biomass-based hydrogen production facility presents a strong case for regional economic development and sustainable energy transition. While addressing energy intensity remains a priority, the project's substantial regional value creation, employment generation, and alignment with climate goals position it as a model for future renewable energy infrastructure investments.

2 Introduction

In recent years, the International Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO) have been sounding urgent alarms about the increasing likelihood of global warming surpassing the 1.5 °C threshold before 2030[1], because of which there is an imperative for the global economy to achieve net-zero and, eventually, negative greenhouse gas (GHG) emissions. This calls for a comprehensive exploration of decarbonization approaches across all economic sectors. Hence, exploration of sustainable and environmentally friendly alternatives is essential, given that over 80% of the world's energy demand is currently met by non-renewable sources[2].

The combustion of fossil fuels emits approximately 21.3 billion t Carbon Dioxide (CO_2) annually[3]. CO_2, a GHG, contributes to global warming by enhancing radiative forcing and elevating the Earth's surface temperature. Because of which fossil fuel supply networks and businesses are susceptible to geopolitical and economic instability, leading to interruptions in supply and fluctuations in prices. These uncertainties can escalate political tensions and conflicts, exacerbating environmental and socioeconomic risks. The Sustainable Development Goals (SDGs) aim to foster the development of clean and sustainable energy systems. Hydrogen, as an energy carrier, has the potential to significantly contribute to achieving the SDGs and accelerating the transition to clean, renewable energy sources, serving as a long-term substitute for fossil fuels. Green hydrogen can be used for various purposes, including electricity generation, transportation, and heating, making clean energy more accessible and affordable. Importantly, hydrogen used in fuel cells can generate power without emitting harmful pollutants.

In addressing supply chain challenges, the localized production and storage of hydrogen help reduce dependence on imports and mitigate supply chain risks. Over the next five years, global demand for hydrogen is expected to grow at a rate of 4-5 % annually, with the hydrogen generation market projected to reach 154 billion $ in 2022[4]. Therefore, the urgent need for environmental change has made hydrogen an appealing choice for long-term energy management.

In alignment with this vision, Bioenergy Concept GmbH's innovative concept demonstrates a dedication to producing sustainable green hydrogen from biomass.

2.1 About Bioenergy Concept GmbH

Bioenergy Concept GmbH, founded in 2007, has become an expert in all aspects of bioenergy projects, offering development, construction, maintenance, and supervision services for anaerobic digesters, pyrolysis systems, and photovoltaic plants. With global partners in the US, South America, India, and Ireland, they export German engineering, cutting-edge technology, and top-quality components for cost-effective, efficient, and long-lasting solutions.

Leveraging their expertise, Bioenergy concept GmbH is collaborating with potential partners on the construction of a cutting-edge process engineering plant in Lüneburg. This facility is dedicated to the conversion of woody biomass into syngas and thus refining it to hydrogen.

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[1] J. Full, S. Merseburg, R. Miehe, e A. Sauer, "A new perspective for climate change mitigation— introducing carbon-negative hydrogen production from biomass with carbon capture and storage (Hybeccs)", Sustainability (Switzerland), vol. 13, no 7, abr. 2021, doi: 10.3390/su13074026.

[2] Abdin, Z., Zafaranloo, A., Rafiee, A., Mérida, W., Lipiński, W., & Khalilpour, K. R. (2020). Hydrogen as an energy vector. Renewable and Sustainable Energy Reviews, 120, 109620. https://doi.org/10.1016/j.rser.2019.109620.

[3] Muradov, N. (2017). Low to near-zero CO2 production of hydrogen from fossil fuels: Status and Perspectives. International Journal of Hydrogen Energy, 42(20), 14058–14088. https://doi.org/10.1016/j.ijhydene.2017.04.101.

[4] Hydrogen management in refineries. Rabiei, Zahra. Petroleum & Coal. 2012, Vol. 54 Issue 4, p357-367.

2.2 Goal and scope of study

The primary goal of this study is to comprehensively assess the environmental performance of the proposed technology, with specific focus on GHG emissions. To achieve this goal, we will conduct a material flow analysis (MFA) to determine the status quo (based on the qualitative and quantitative evaluation of material and energy flows), encompasses the entire life cycle of hydrogen production process, from the initial biomass harvesting to the point of fuel delivery in refuelling station (cradle-to-tank).

2.2.1 Scope elements

PCF represents the cumulative GHG emissions produced throughout various stages in the life cycle of a product. As described, the PCF of the product follow the cradle-to-gate approach and represent a partial footprint. According to the predefined scheme of the GHG Protocol, this includes the steps of material procurement and pre-processing, production as well as transport and storage up to the "gate" as seen in Figure 1. The cradle-to-gate approach is partial Life cycle assessment (LCA) that evaluates the environmental impact of a product or service from raw material extraction upto the point when the product leaves the production facility. The product life cycle phases of use and disposal are excluded in order to guarantee comparability between different products of the same category, regardless of the storage methods of the retail trade and the use of the end customer.

NOTE: In general, cradle-to-gate assessments exclude downstream product transportation. However, at the client's request, this evaluation incorporates the transportation of the product in the downstream phase.

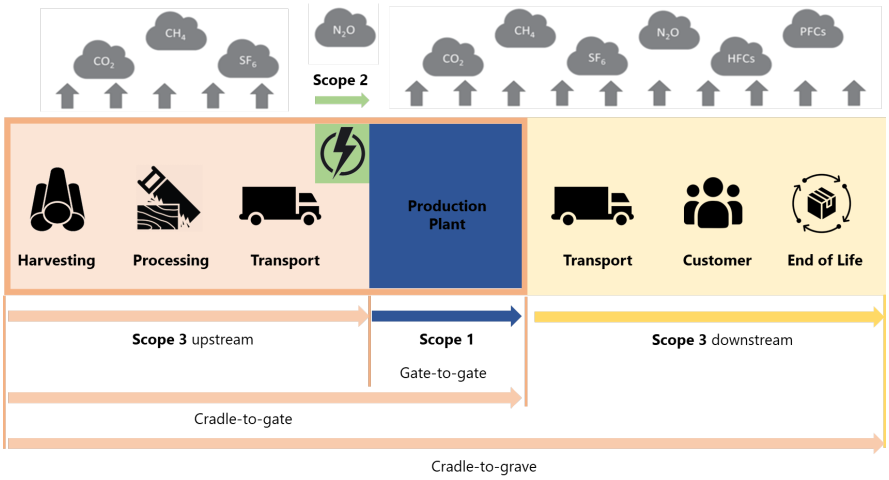

Figure 1: Life cycle phases of cradle-to-gate, gate-to-gate and cradle-to-grave.

In general, IfaS's analysis consider the complete production chain, including all the stages from sourcing of biomass to delivery of fuel. This includes biomass harvesting, collection, transportation, processing, hydrogen production and delivery at refuelling station. In this assessment the PCF is calculated with respect to Scope 1, 2 and 3 emissions.

The creation of the PCF adheres to the principles of the Greenhouse Gas Protocol Corporate Standard[5]:

- **Relevance:** Ensuring that the report and applied methodology meet the user's needs.
- **Completeness:** Ensuring documentation of all significant GHG emissions.
- **Consistency:** Ensuring methods that allow comparability of results over time.
- **Transparency:** Ensuring clear documentation of all relevant assumptions, methods, and sources.
- **Accuracy:** Ensuring the most precise representation of the product's emitted emissions.

As a methodological basis for the determination of the PCF, the Product Life Cycle Accounting and Reporting Standard of the Greenhouse Gas Protocol and the ISO 14067 standard of the Organization for International Standards which increases the recognition, plausibility, and accuracy of the accounting.

The PCF is calculated based on the production of 1 kg of H_2 produce regardless of its state (solid, liquid, gas), as its specific density is considered.

2.2.2 System boundaries

Determining the system boundary is essential for evaluating the PCF as it outlines the extent and constraints of the analysis, clarifying the stages of the product life cycle that are considered and excluded in the assessment. The diagram below illustrates the system boundary incorporated within the scope of this study.

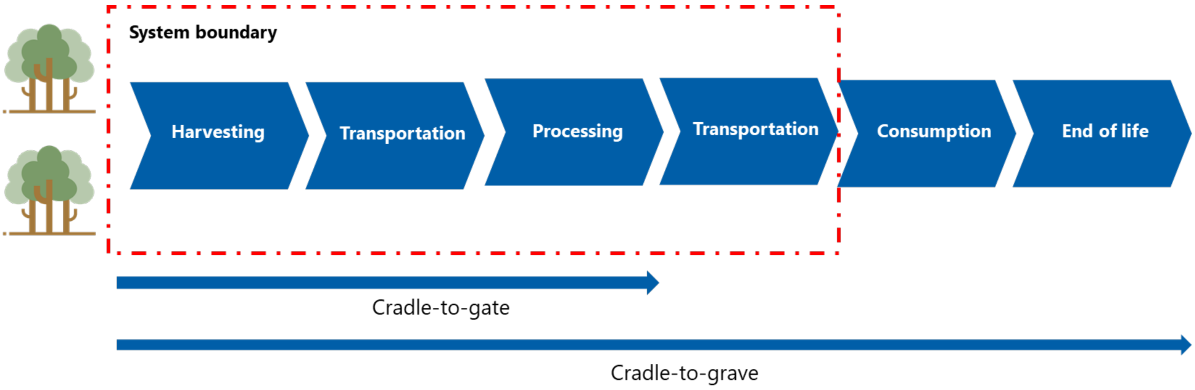

Figure 2: System boundary for the analysis.

In the cradle-to-tank PCF analysis, following activities shall be included or excluded as described in table below.

[5] Source: WBCSD and WRI. (2004). Greenhouse Gas Protocol: a Corporate Accounting and Reporting Standard.

Table 1: Scope of inclusion and exclusion.

Included	Excluded
Harvesting and transport of biomass.	Employee commuting or business trips.
Electrical energy consumption in processing facilities.	Non-product related activities in processing facility[6].
Utilities consumption in processing facilities.	Non-product related activities in upstream of processing facility.
Transportation of product and co-product from processing facility to refuelling station	Cultivation and land-use change for biomass[7].
	Maintenance of equipment and machinery.
	Any other activities not listed in included section.

2.2.3 Energy and mass balance

Main aspect of this study involves an in-depth analysis of energy and mass flow in the system. Energy and mass balance are crucial in a system because it provides a comprehensive view of the energy and mass flows, ensuring that the inputs and outputs are accounted for accurately. This MFA provides an overview on the current system design and consumption levels and serves as a basis to formulate the efficiency projects in future. These analyses guide the formulation of strategic projects aimed to optimise energy and mass flow and reduce waste, which will indirectly influence system efficiency. Ultimately, the goal is to create more sustainable and energy efficient system that enhances the competitive advantage of product. Detail discussion regarding the current system is included in section 5.1.

2.2.4 GHG emission accounting

In this assessment, GHG emissions for product are done, which includes emissions associated with respect to cradle-to-tank emissions. This helps to delineate direct (Scope 1), indirect (Scope 2) and other indirect emission sources along the value chains (Scope 3 upstream and downstream), improve transparency, and is seem as a starting point for corporate carbon accounting and its climate policies and business goals[8]. Following the carbon accounting, the definition of net-zero emission targets and the disclosure of respective commitments, e.g. using the Science Based Target Initiatives (SBTi) approaches, could be pursuit.

[6] Indirect procurement, often termed non-production-related procurement, involves obtaining goods and services that aren't directly involved in the company's product creation but serve to facilitate its operational needs. This category includes the acquisition of capital goods such as furniture, office equipment, and computers. Source: GHG Protocol Corporate Value Chain Standard.

[7] The effects of land-use change are also not taken into account quantitatively, as they cannot be reliably determined (especially with regard to soil carbon storage). In terms of quality, it should be noted that the supplied biomass and its value chain are certified by the Forest Stewardship Council (FSC) and Programme for the Endorsement of Forest Certification (PEFC). This means that the harvest of wood in is based on sustainable forest management: harvest and growth are in balance.

[8] GHG Gas Protocol (2015): Accounting and Reporting Standard. Retrieved from: https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

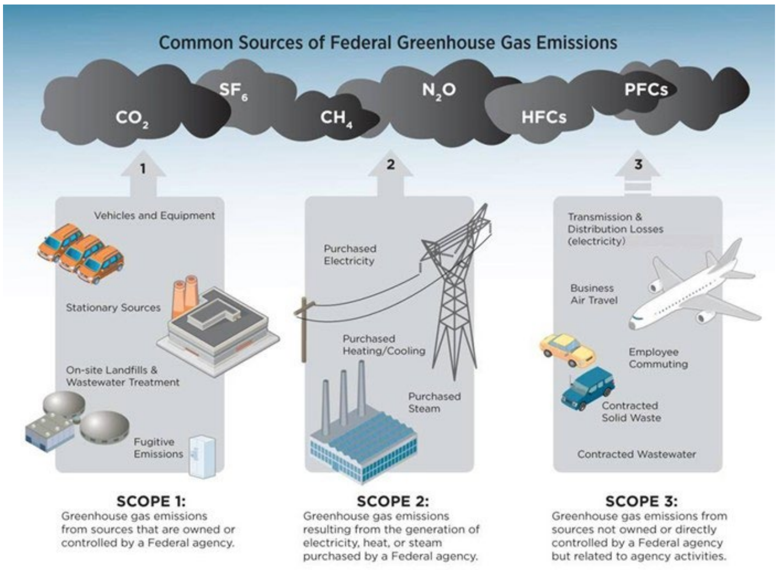

Figure 3: GHG Emissions Scopes[9].

As illustrated in Figure 3, the GHG baseline balance follows three "scopes" to report the $CO_{2eq.}$ emissions:

- **Scope 1 GHG emissions** are direct emissions from sources that are owned or controlled by the company. In this project, the scope 1 accounts for:
  - ➢ On-site usage of fuel (if applicable)[10];
- **Scope 2 GHG emissions** are indirect emissions from sources outside the system boundary that are not owned or controlled by the company. These emissions result for example from the generation of electricity, heat or steam purchased from a utility provider:
  - ➢ Electricity purchased from the local electricity supplier[11].
- **Scope 3 GHG emissions** are all other indirect emissions from sources not owned or directly controlled by the company but are rather related to the company's activities within its upstream (e.g. production material and its provision) and downstream (use and end-of-life phase of the product).
  - ➢ Emissions from biomass harvesting, utility usage and transporting to site.

[9] Source: United States Environmental Protection Agency (EPA)
[10] Heat or electricity generated from renewable sources such as PV, Wind, Biogas, Biomass etc. do not account for GHG emissions.
[11] Ibidem

3 Literature review

3.1 Current H_2 outlook

Presently, H_2 is commercially produced and serves various purposes, such as being a raw material in the chemical industry, utilized in refineries, incorporated into gas mixtures for steel production, and employed in heat and power generation. The worldwide production of pure H_2 is approximately 75 million t/a, with an additional 45 million t/a when part of gas mixtures[12]. H_2 production results in approximately 830 million t CO_2/a emissions, which accounts for about 3 % of the total global final energy demand, comparable to Germany's annual energy consumption[13]. With H_2 production rate of around 75 million t/a, this translates to roughly 12 kg $CO_{2eq.}$/kg H_2 produced.

Additionally, the majority of H_2 production relies heavily on fossil fuels as seen in Figure 4. Approximately 6 % of the world's natural gas consumption and 2 % of global coal consumption contribute to H_2 production. Merely 0.5 % of the global H_2 output comes from renewable sources, known as green H_2. In future it is predicted

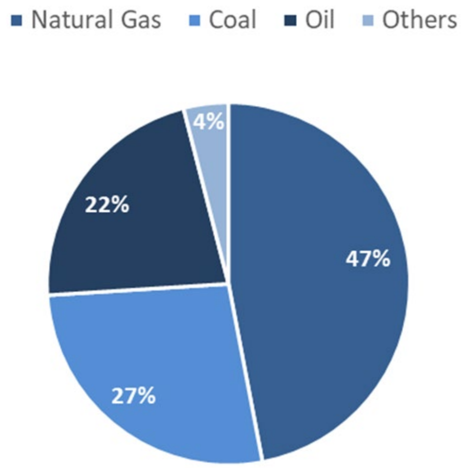

Figure 4: Share of H_2 production from different sources[6].

3.2 H_2 production technologies

Molecular H_2 can be derived from various sources, including fossil fuels, biomass, and water. The processes for H_2 production can be categorized into two main groups: those originating from fossil fuels and those utilizing renewable resources. Figure below illustrates diverse technologies available in the market for H_2 production.

[12] IRENA: Hydrogen. Retrieved from: https://www.irena.org/Energy-Transition/Technology/Hydrogen

[13] Suer, J.; Traverso, M.; Jäger, N. Carbon Footprint Assessment of Hydrogen and Steel. Energies 2022, 15, 9468. https://doi.org/10.3390/en15249468

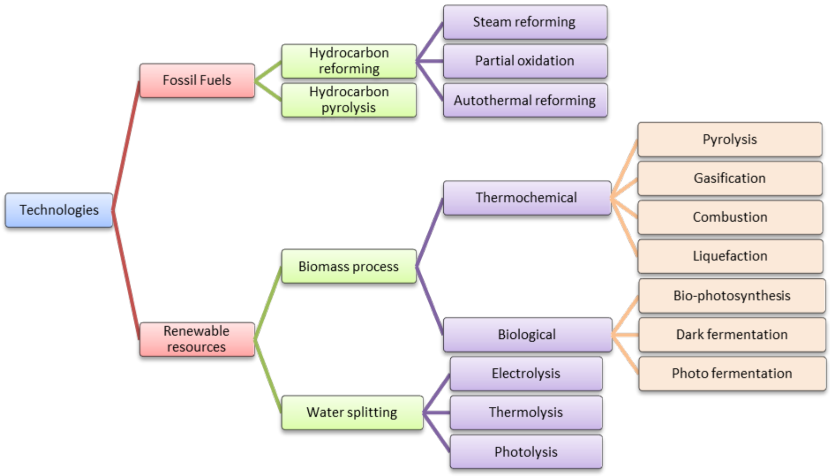

Figure 5: Different H_2 production technologies[14].

The following section covers some of the readily accessible technologies currently present in the market.

3.3 Current state of art

At present, global H_2 production mainly depends on fossil fuel inputs using two primary industrial-scale methods: reforming and pyrolysis. Historically, the H_2 fuel accessible in the market has predominantly been categorized as blue and grey, providing advantages like cost-effectiveness and the ability to be supplied in large quantities. A similar cost for H_2 can be achieved through the partial oxidation of hydrocarbon. However, it's crucial to note that GHG produced by thermochemical processes need to be captured and stored, leading to a potential increase in the H_2 price by 25–30 %.

Table 2 provides a summary of these technologies, their respective feedstocks, and the efficiencies they achieve. It's noteworthy that H_2 can be produced from a diverse range of feedstocks available almost everywhere, and several environmentally friendly processes are under development. The advancement of these technologies has the potential to reduce the world's reliance on fuels primarily sourced from unstable regions.

Table 2: Summary of available H_2 production technology in market[15].

Technology	Feedstock	Efficiency	Maturity
Steam reforming	Hydrocarbon	70-85 %	Commercial
Partial oxidation	Hydrocarbon	60-75 %	Commercial
Autothermal reforming	Hydrocarbon	60-75 %	Commercial
Coal gasification	Coal	35-55 %	Commercial
Electrolysis	Water and Electricity	65-80 %	Commercial

[14] Shiva Kumar, S., & Himabindu, V. (2019). Hydrogen production by PEM water electrolysis – a review. Materials Science for Energy Technologies, 2(3), 442–454. https://doi.org/10.1016/j.mset.2019.03.002.

[15] Kalamaras, C. M., & Efstathiou, A. M. (2013). Hydrogen Production Technologies: current state and future developments. Conference Papers in Energy, 2013, 1–9. https://doi.org/10.1155/2013/690627.

4 Plant overview

4.1 Infrastructure

The proposed facility will process approximately 3.6 t/h of biomass for process reaction and 0.5 t/h biomass for steam generation, resulting in the production of around 1,600 t/a H_2 (0.2 kg/h). The plant is designed to run for operating hours of 7500-8000 h/a. The infrastructure includes two hall buildings with approximately size of 30x60x12 m^3 along with an administrative building. Additionally, gas storage tanks for the produced H_2 of capacity 5 t and CO_2 of capacity 60-70 t will be installed on the site. Design life of processing facility is 20 years.

4.2 Biomass harvesting and transportation

Biomass harvesting is conducted in collaboration with a partner company, followed by the storage of biomass. The stored biomass is then transported using diesel-driven lorries, each boasting a 25 t capacity. These lorries operate 5 days a week within a 12 h delivery slot per day. Approximately 5 lorries are dispatched on each delivery day, covering a delivery distance of around 50 km from the harvesting site. The harvesters and loaders are also powered by diesel. Table below summaries the data for biomass harvesting and transport.

Table 3: Summary of data for biomass harvesting and transport.

Parameter	Unit	Value
Harvester		
Amount of biomass harvest	m^3/h	19
Diesel consumption for harvester and loader	lit/h	11.5
Biomass transport		
Capacity of trucks	t	25
Diesel consumption	lit/km	0.46
Operational day per week	d	5
Operational time per day	h/d	12
Operational lorries per day	Nos./d	5
Distance between sites	km	50

4.3 Raw materials

The biomass utilized in the reaction comprises 85 % Pinus Sylvestris (pine) and 15 % Pica Abies (spruce). The wood is sourced from certified forestry with PEFC and FSC certifications. The biomass when brought to site contains around 50 % residual moisture. To optimize its suitability for the reactor, a two-step processing approach is adopted: initial shredding to produce wood chips, followed by a moisture extraction step utilizing air dryers, ultimately achieving a final moisture content of 0 %. Currently, in ongoing discussions with the client, the biomass utilized for steam generation comprises residual components like barks, stems, and leaves, all of which exhibit a moisture content of 50 %. Notably, this biomass is introduced directly into the steam generation unit without any pre-treatment for moisture removal.

The fresh water supply to the unit is sourced from tap water, with a total intake of 1.4 t/h. This water allocation is divided, with 1.3 t/h designated for steam generation and 0.1 t/h directed to the water gas shift (WGS) unit. Table 4 below summarizes the raw material data taken into consideration for this assessment.

Table 4: Summary of raw material in processing facility.

Parameter	Unit	Value
Reactor biomass		
Certification	-	Certified forestry with PEFC and FSC certifications
Type	-	Woodchips (G80-G100)
Bulk density of biomass	kg/m^3	500[16]
Moisture content before drying	%	50
Moisture content after drying	%	0
Mass flowrate of biomass before drying	t/h	3.6
Mass flowrate of biomass after drying	t/h	1.6
Steam generation biomass		
Certification	-	Certified forestry with PEFC and FSC certifications
Type	-	Barks, stems, and leaves
Moisture content	%	50
Mass flowrate of biomass	t/h	0.5
Water		
Type	-	Tap water
Mass flowrate of water	t/h	1.4

[16] Density of wood-the ultimate guide. Retrieved from: https://matmatch.com/learn/property/density-of-wood.

4.4 Thermal and electrical power consumption

The facility's external electrical power consumption stands at approximately 2 MW_e, catering to essential components such as Pressure Swing Adsorption (PSA), the H_2 compressor, on-site Oxygen generation system, biomass drying, pumps, ventilation, and shredder. The total thermal power required during the reaction amounts to 8 MW_{th}. Additionally, there is a dedicated 2 MW_{th} allocated for steam production, met through an additional biomass supply. Table 5 presents the thermal and electrical power values for various equipment and processes.

Table 5: Thermal and electrical power input.

Parameter	Unit	Value
Electrical power requirement		
Shredder	MW_e	0.5
Air dryer	MW_e	0.15
Pre-compressor	MW_e	0.8
Post-compressor	MW_e	0.4
Oxygen generation unit	MW_e	0.2
Pumps, chiller and ventilation	MW_e	0.15
Thermal power requirement		
Reaction	MW_{th}	8
Steam generation	MW_{th}	2

Moreover, the processing facility incorporates a CO_2 liquefaction unit; however, the client has not provided information on its power consumption. This aspect will be addressed in the engineering stage. To facilitate this, technical parameters for CO_2 were sourced from IfaS and shared with various companies for the CO_2 liquefaction unit. From one of these companies, the electrical energy intensity was determined to be 0.22 MW_e/t CO_2. Table 6 outlines various technical parameters associated with the technology provided by the company.

Table 6: Technical parameters of CO_2 liquefaction.

Parameter	Unit	Value
CO_2 flow	t/h	2.4
CO_2 purity	vol.%	>99
Recovery	%	98.85%
Compressor	MW_e	0.25
CO_2 refrigeration unit	MW_e	0.35
Pumps, fans, air conditioning	MW_e	0.138
Nominal electricity consumption	MWh/t CO_2	0.22

4.5 Applied technology description

The technology offered by Bioenergy Concept GmbH is primarily based on the principle of biomass gasification. The biomass is primarily heated to reduce the moisture content with help of air dryer, then the processed biomass is subjected to a continuously operating biomass-steam reactor, where it is decomposed into its elemental gas components with the addition of superheated steam and oxygen as an additional oxidizing agent. Due to the process conditions within the reactor and the very high reaction temperatures, long-chain hydrocarbon compounds (tars) are cracked and broken down into their elemental constituents. The resulting gas mixture consists of H_2, Carbon monoxide (CO), CO_2, methane (CH_4) and traces of some other gases. The gas is further processed with help of WGS. In this WGS, the addition of further saturated steam converts CO into H_2 and CO_2. This process increases the hydrogen content of the gas mixture.

The gas leaving the reactor undergoes additional processing steps. It undergoes cooling, causing the extra water vapor to condense. Filtration is applied to eliminate particles (ash) present in the gas stream, and specialized adsorbers are used to remove any remaining traces of hydrocarbon compounds. PSA is employed for H_2 and amine washing for CO_2. The resulting hydrogen is compressed to the required pressure of 350 bar for storage and transportation using a compressor station and trucks to refuelling station. The residual tail gas is directed towards both the steam generator and reactor to enhance combustion. Subsequently, the separated CO_2, undergoes liquefaction before being dispatched to CO_2 storage. Transportation to customers is facilitated efficiently through the use of trucks. The residue from the reactor is the mineral ash derived from the biomass, which can serve as a fertilizer or, depending on the feedstock, may need to be disposed of. About 0.05 t/h of mineral ash generated, depending on the type of biomass utilized.

Table 7 summarise the reaction enthalpies in the applied technology.

Table 7: Reaction enthalpies of different processes.

Reaction	Enthalpy (kJ/mol)	Type of reaction
Partial oxidation ($2C + O_2 \rightarrow 2CO$)	-221	Exothermic
Steam reforming ($C + H_2O \rightarrow CO + H_2$)	131	Endothermic
Water gas shift ($CO + H_2O \rightarrow CO_2 + H_2$)	-42	Exothermic

5 Methodology

5.1 MFA

MFA is a systematic evaluation of the movement and quantities of materials, including energy, within a defined system in terms of space and time. It involves identifying and measuring all incoming and outgoing flows in a system to understand the exchange of resources between the system and its environment. The fundamental concept of mass balancing aligns with the first law of thermodynamics, asserting that matter (mass, energy) undergoes no creation or destruction during physical transformations. Accordingly, material inputs into a system should always be equivalent to material outputs plus any net accumulation within the system (material balance principle). Materials entering the system contribute to the buildup and maintenance of the system's material compartments or stocks, and conversely, all materials necessary for sustaining a system compartment or stock are integral parts of the system's pertinent material flows. The table below explain the basic material flow in Bioenergy Concept GmbH package.

Table 8: Mass balance of the processing facility.

Parameter	Unit	Value
Input Biomass supply		
Plant operating hours per annum	h/a	8,000
Capacity wood logs (50% Moisture)	t/h	3.2
Capacity wood chips (fully dried)	t/h	1.6
Oxygen generation system		
O_2 required for reaction	t/h	0.15
Air required to generate O_2	t/h	0.71
Air released to atmosphere	t/h	0.56
Partial oxidation		
Superheated steam from steam generator	t/h	1.3
Tail gas from H_2 separation	t/h	0.1
Syngas after reaction	t/h	3.1
Ash produce after reaction	t/h	0.05
WGS		
Water for temperature control	t/h	0.1
Syngas after WGS	t/h	3.2
Water exiting WGS process	t/h	0
Gas processing		
Syngas after gas processing	t/h	3.2
CO_2 separation		

Parameter	Unit	Value
Saturated steam from steam generator	t/h	4
Syngas after CO_2 separation	t/h	0.8
CO_2 generated after separation process	t/h	2.4
Condensate return	t/h	4
H_2 separation		
Tail gas to boiler	t/h	0.5
H_2 produce after separation	t/h	0.2
Boiler		
Biomass required for steam generation	t/h	0.5
Fresh water required to produce steam	t/h	1.3
Water		
Total freshwater requirement	t/h	1.4
Total mass balance		
Input	t/h	3.15
Output	t/h	3.15
Key performance indicator		
Percentage conversion of biomass to H_2 (50% Moisture)	%	6 %
Percentage conversion of biomass to H_2 (fully dried)	%	13 %
Required biomass per kg H_2 (50% Moisture)	kg/kg	16
Required biomass per kg H_2 (fully dried)	kg/kg	8
Fresh water required per kg H_2	lit/kg H_2	7.02
Product conversion		
Hydrogen	%	6 %
Carbon dioxide	%	74 %
Tail gas	%	18 %
Ash	%	2 %

Upon examining the table, it is evident that input mass flow matches with output mass flows, this signifies that there is no material loss in the system. When utilizing 4.1 t/h of total biomass, inclusive of both process biomass and the biomass required for steam production, approximately 0.2 t/h of H_2 is generated. This results in a conversion ratio of total biomass to H_2 of approximately 6 %. The water intensity for producing 1 kg of H_2 is approximately 7.02 l, this figure significantly surpasses that of existing electrolyser technologies in the market, which typically require 10 l.

Table 9 provides a comprehensive overview of the carbon balance within the processing facility. The input biomass contains 51 % carbon, with a total input biomass of 0.82 t/h. After CO_2 separation, the carbon content decreases to 27.27 %, resulting in 0.65 t/h of carbon in the separated CO_2. The tail gas and ash streams contain 19.51 % and 3 % carbon, contributing 0.12 t/h and 0.0013 t/h of carbon, respectively. Additionally, the table highlights 0.04 t/h of unaccountable carbon in the process, constituting 5 % of the total unaccounted carbon. This indicates that the carbon loss in the process is minimal and falls within acceptable limits.

Table 9: Carbon balance of the processing facility.

Parameter	Unit	Value
Input		
% C in biomass	%	51 %
C in input biomass	t/h	0.82
CO_2 separation		
% C in CO_2	%	27.27 %
C after CO_2 separation	t/h	0.65
Tail gas		
% C in tail gas	%	19.51 %
C in tail gas	t/h	0.12
Ash		
% C in ash	%	3 %[17]
C in ash	t/h	0.0013
Unaccountable C in process	t/h	0.04
Unaccountable C in process in %	%	5 %

The table lists the Net Calorific Values (NCV) of fuels and the combustion efficiency of biomass in a steam generation unit. This information helps evaluate the overall energy balance of the process.

[17] ECN Phyllis classification, Retrieved from: https://phyllis.nl/Browse/Standard/ECN-Phyllis.

Table 10: NCV of fuels.

Parameter	Unit	Value
Wood logs (50% M)	kWh/kg	3.9[18]
Wood chips (fully dried)	kWh/kg	4.95[19]
Bark, leaves (50% M)	kWh/kg	3.9[19]
Hydrogen	kWh/kg	33.33[20]
Tail gas	kWh/kg	4.75[21]
Diesel	MJ/lit	36[22]
Combustion Efficiency - Bark, leaves (50% M)	%	80 %[23]

The processing facility necessitates 1.3 t/h of superheated steam at 700 °C and 0.5 bar(g) for the reactor, as well as saturated steam of 4 t/h at 180 °C and 9 bar(g) for the CO_2 separation unit. Steam is generated in boilers using input energy from biomass, tail gas post-H_2 separation. The saturated steam utilized in CO_2 separation is then returned as hot condensate, reducing the heat demands for the economizer. The following Table 11 provides a concise summary of the overall energy consumption.

Table 11: Energy balance of the processing facility.

Parameter	Unit	Value
Electrical energy consumption		
Shredder		
Annual power consumption	MWh_e/a	1,040
Plant operations		
Annual power consumption	MWh_e/a	13,600
CO_2 liquefaction		
Annual power consumption	MWh_e/a	4,224
Total electrical energy	**MWh_e/a**	**18,864**
Thermal power consumption		

[18] Client Data. The client has supplied Net Calorific Value (NCV) data for a range of 3.6 to 4.2 kWh/kg. To account for this variation, the average of these values is being considered for analysis.

[19] Client Data. The client has supplied Net Calorific Value (NCV) data for a range of 4.8 to 5.1 kWh/kg. To account for this variation, the average of these values is being considered for analysis.

[20] H_2 data. Retrieved from: http://www.h2data.de/.

[21] Client data.

[22] Greenhouse gas reporting: conversion factors 2023. Retrieved from: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.

[23] Scottish forestry. Retrieved from: https://usewoodfuel.co.uk/guidance-for-biomass-users/planning-a-biomass-installation/understanding-efficiency/biomass-boiler-efficiency/.

Parameter	Unit	Value
Steam boilers		
Total input thermal energy	MWh_{th}/a	55,888
Total output thermal energy	MWh_{th}/a	48,837
System efficiency for boiler system	%	87%
Reactor		
Reaction enthalpy	MWh_{th}/a	64,000
Total thermal energy	**MWh_{th}/a**	**119,888**
Energy intensity (Thermal + Electrical)	**kWh/kg H_2**	**59.59**
System efficiency	**%**	**55.9%**

The current process exhibits lower system efficiency compared to steam reforming, partial oxidation, autothermal reforming, and electrolysis. Notably, it surpasses the efficiency of coal gasification and Biomass to liquid (BTL) technologies. In the context of the growing green hydrogen market, the current electrolyser requires solely electrical energy, with an energy intensity ranging between 49-55 kWh/kg H_2. In summary, optimizing the process and enhancing the overall resource efficiency could transform the proposed system highly effective and competitive in the market.

The processing facility incorporates a centralized heat collection system, efficiently harnessing waste heat from various sources including the boiler, WGS unit, water treatment process, pre-compressor, and compressor. The cumulative redundant heat generated amounts to approximately 3.6 MW. Notably, 1.6 MW of heat at 110 °C is directed towards an air dryer, while the remaining 2 MW at 30 °C is allocated for potential off-takers. The subsequent table shows the waste heat recovery from each source.

Table 12: Waste heat recovery from equipment.

Equipment	Value
Boiler	1.6 MW at 90-100 °C
WGS	0.3 MW at 90-100 °C
Pre-compressor	0.7 MW at 35 °C
Compressor	0.1 MW at 55 °C

The diagram presented below illustrates the MFA of the analysed system, depicting both the project's boundary limits, and each element considered within the system.

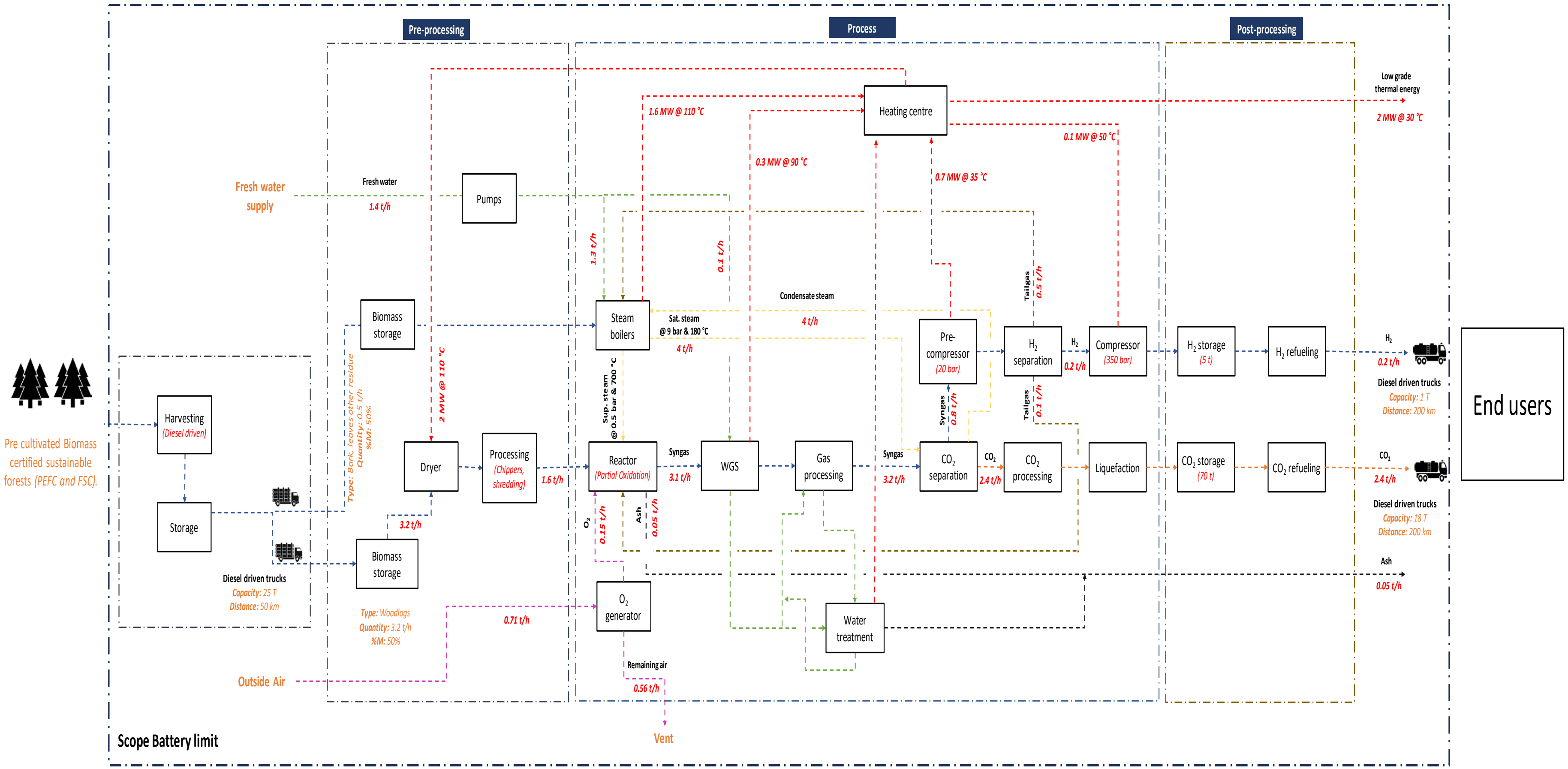

Figure 6: MFA and boundary limit of the system

5.2 Energy checks

5.2.1 Dryer

It is proposed to use air dryer in processing facility to dry the moisture in the biomass from 50 % to 0 % for reaction process. The air will be heated using waste heat provided by the heat collection system. The client has mentioned that 2 MW_{th} of energy will be needed to eliminate moisture from the biomass. To verify the accuracy of this reported value, an energy check was performed to determine the required amount of energy for moisture removal from biomass. The following are the results of the energy check.

Table 13: Energy check for air-dryer.

Parameter	Unit	Value
Specific heat capacity of water	kJ/kg °C	4.18
Latent heat of vaporization of water	kJ/kg	2,260
Specific heat capacity of air	kJ/kg K	1
Amount of moisture to be removed	t/h	1.6
Power requires to remove moisture	MW_{th}	1.15
Efficiency of heat exchangers	%	80 %
Actual power required	**MW_{th}**	**1.43**

Considering a heat exchanger efficiency of 80%, the thermal energy needed for moisture removal is calculated to be 1.43 MW_{th}. Hence, the assumed waste heat from the heating center aligns with the data provided by the client, indicating a satisfactory match.

5.2.2 H_2 compressor

In the processing facility, H_2 compressors are employed to compress H_2 from 15 bar(g) to 350 bar(g), followed by storage in a tank. The client has assumed a compressor power rating of 0.4 MW. To verify the proposed value, an energy check for the compressor was conducted, analyzing process data to determine the actual power required. The summarized results are presented in the table below.

Table 14: Energy check for H_2 compressor.

Parameter	Unit	Value
Suction pressure of compressor	barg	15
Suction temperature of compressor	K	293.15
Pressure at discharge of compressor	barg	350
Temperature at discharge of compressor	K	413
Isentropic efficiency of compressor	%	70%
Density of H_2	kg H_2/m^3	0.083
Efficiency of motor	%	95 %
Actual compressor power	**MW_e**	**0.35**
Rated compressor power	**MW_e**	**0.37**
Number of stages	**-**	**3**

Based on the assumption of an isentropic efficiency of 70 % and a motor efficiency of 95 %, the compressor's rated power was calculated to be 0.37 MW_e. Hence, the assumption regarding the compressor's rated power from the client is satisfactory. Additionally, the compressor will be 3-stage, and its energy intensity will be 1.84 kWh/kg H_2.

5.3 Product Carbon Footprint

IfaS conducted the PCF inline with GHG Protocol, which is widely recognized as the predominant international accounting tool for government and business leaders to comprehend, quantify, and manage greenhouse gas emissions.

Calculating the PCF involves a four-step process:

1. Goal and scope definition:

This involves defining the product under scrutiny, outlining the objectives of the evaluation, setting system boundaries, and identifying the target audience—whether internal or external stakeholders.

2. Data collection:

The second stage focuses on comprehensive data gathering, where a detailed list of all relevant inputs and outputs associated with the product's life cycle are investigated and compiled.

3. Impact assessment:

Utilizing specific emission factors, this stage involves aligning these factors with the activity data collected in the previous step to perform the actual PCF calculation. The impact assessment enables us to quantify the greenhouse gas emissions associated with the entire life cycle of the product.

4. Evaluation and interpretation:

In the final step, the results are evaluated and interpreted. This includes identifying opportunities for reducing negative environmental impacts throughout the product's life cycle.

When evaluating the PCF, the methodology prompts various questions for each stage from cradle-to-gate arises. These questions include:

- What raw materials are utilized, and what is their carbon content? How are they transported to the production site?
- How much electricity and energy are consumed, and what is their carbon content?
- What direct GHG emissions occur during the production process?
- What is the effective yield of the production process?
- How is the final product transported to the customer?

While some of these questions have straightforward answers, others may lead to complicated calculations or data reporting without significantly impacting the overall carbon footprint of the product. In certain cases, multiple answers may be possible, influencing the final result.

To calculate the GHG emissions inventory, we identified all relevant GHG emissions sources, collected activity data[24] from the relevant services and applied the emissions factors and thus calculate emissions from each source. These data were then aggregated to create the PCF of given technology's total carbon footprint.

In the current processing facility, two types of emissions are taken into account: direct and indirect emissions. Direct emissions (Scope 1) include CO_2 emissions released from fuel combustion within the process, such as the utilization of additional biomass for steam production and reaction. The biomass in question, certified by both FSC and PEFC, ensures that emissions related to its utilization are negligible. In other words, emissions from this biomass is effectively absorbed by the biomass in the forest, resulting in zero carbon emissions when it is either burned or released into the environment.

On the other hand, indirect emissions (Scope 2 and 3) pertain to emissions released from energy used in the process, office heating and lighting, and emissions associated with general office activities and employee commuting, upstream and downstream transportation.

The table presented below outlines a list of activities associated with the current processing facility. The data are categorized based on their relevance to Scope 1, 2, and 3 emissions.

Table 15: Activity data of the processing facility.

Scope	Activity
Scope 1	Use of additional biomass
Scope 2	Purchased electricity
	Purchased utilities
Scope 3	Harvesting of biomass
	Upstream activities
	Utility related emissions
	Downstream activities

[24] Activity data serve as a quantitative measure of activities that lead to GHG emissions.

The client has furnished aggregated data pertaining to scope 2 emissions. Scope 2 emission includes use of purchased electricity for the plant operation. To determine scope 3 emissions, various literature and reports that follow a similar process to the one implemented in the current processing facility.

The GHG emissions inventory was determined by applying emission factors (EF) to the pertinent activity data and consolidating the outcomes to compute the absolute carbon footprint. The table below outlines the assumed emission factors considered for this study.

Table 16: Assumptions on emission factors.

Parameter	Unit	Value
Electricity mix[25]	kg $CO_{2eq.}$/kWh	0.494
Biomass[26]	kg $CO_{2eq.}$/kWh	0
Diesel[27]	kg $CO_{2eq.}$/l	2.51
EF diesel truck[28]	g $CO_{2eq.}$/MJ	6
EF for diesel trucks (0% loaded)-Downstream[28]	kg $CO_{2eq.}$/km	0.54
EF for diesel trucks (100% loaded)- Downstream[28]	kg $CO_{2eq.}$/km	0.63
Water supply (Electrical)[28]	kg $CO_{2eq.}/m^3$	0.2
Heat[29]	kg $CO_{2eq.}$/kWh	0.352

5.3.1 Scope 1

The biomass, certified by FSC and PEFC, guarantees minimal emissions during its use. In simpler terms, emissions from this biomass is effectively absorbed by the biomass in the forest, resulting in zero carbon emissions when it is either burned or released into the environment. Hence, PCF with respect to scope 1 is zero.

5.3.2 Scope 2

The following calculations outline the determination of the PCF from Scope 2 emissions. The steps for the calculations are as follows:

1. Determine total electrical energy consumption (E_t):

Total electrical energy consumption (E_t) is calculated by multiplying the electrical power consumption (P_t) by the total number of operating hours of the plant (T_t).

[25] Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 - 2022 Retrieved from: https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2023_05_23_climate_change_202023_strommix_bf.pdf.

[26] Biomass is FSC and PEFC certified.

[27] Greenhouse gas reporting: conversion factors 2023. Retrieved from: https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.

[28] Client data

[29] Böing, F., & Regett, A. (2019). Hourly CO2 emission factors and marginal costs of energy carriers in future Multi-Energy Systems. Energies, 12(12), 2260. https://doi.org/10.3390/en12122260.

The formula is,

$$E_t\ (MWh/a) = P_t\ (MW)\ x\ T_t\ (h)$$

With a total operating time of 8000 h/a, the total electrical energy consumption (E_t) is determined to be 18,864 MWh/a.

2. Calculating total GHG emission:

The GHG emission per annum is determined by multiplying the total electrical energy consumption (E_t) by the emission factor in the electricity mix in Germany (EF).

The formula is,

$$Total\ GHG\ emission\ \left(T_{CO2\ eq.}/a\right) = E_t\ \left(\frac{MWh}{a}\right)\ x\ EF\ \left(\frac{kgCO2eq}{kWh}\right)$$

Based on this formula, the total GHG emission in a year with respect to electrical energy consumption is found to be 9,319 t $CO_{2eq.}$/a.

3. Evaluating PCF with respect to total electricity consumption:

The PCF is calculated by dividing the total GHG emission in a year by the total amount of H_2 production in a year.

The formula is,

$$PCF\ \left(kg_{\ CO2\ eq.}/kg_{\ h2}\right) = Total\ GHG\ emission\ \left(\frac{T_{\ CO2\ eq.}}{a}\right) / \ Total\ H2\left(\frac{T_{\ H2}}{a}\right)$$

Total H_2 produce is calculated with the formula,

$$Total\ H2\left(\frac{T_{\ H2}}{a}\right) = M_{h2}\ \left(\frac{kg}{hr}\right) x\ T_t\ (h)$$

Where,

M_{h2} is hydrogen produced per hour which is 0.2 t/h. Using the given hydrogen production rate, the PCF with respect to electrical energy is calculated to be 5.82 kg $CO_{2eq.}$/kg H_2.

Table 17 below summarizes the results.

Table 17: PCF with respect to scope 2 emissions.

Parameter	Unit	Value
Total GHG emission per annum	t $CO_{2eq.}$/a	9,319
PCF (Scope 2)	**kg $CO_{2eq.}$/kg H_2**	**5.82**

Energy consumption in buildings is not included in Scope 2 PCF at this stage, as the client will provide relevant data during the engineering stage of the project.

5.3.3 Scope 3

1. Harvester

Diesel-driven harvesters would be employed for wood log harvesting as discussed with client, with an average diesel consumption of 11.5 l/h, as indicated earlier. The same methodology outlined in section 5.3.2 was applied, and Table 18 provides a summary of the PCF specifically related to the harvesting process.

Table 18: Harvester’s PCF.

Parameter	Unit	Value
Total biomass required per annum	t/a	29,600
Total biomass required per annum in m^3	m^3/a	59,200
Annual fuel consumption for harvester and loader	lit./m^3	36,309
Annual GHG emission	t $CO_{2eq.}$/a	91
Total PCF (Harvesting)	**kg $CO_{2eq.}$/kg H_2**	**0.057**

2. Upstream transport

The transport lorries utilized for the transportation of wood logs are diesel-driven, each carrying 25 t of logs with a moisture content of 50 %. The transportation schedule involves operations on five days per week, with a 12-hour delivery slot each day. Approximately 5 lorries are dispatched per delivery day, covering a delivery distance of about 50 km from the harvesting site. The same methodology outlined in section 5.3.2 was applied, and Table 19 provides a summary of the PCF specifically related to the harvesting process.

Table 19: Upstream transportation PCF.

Parameter	Unit	Value
Total no. of trips per annum	nos./a	1,184
GHG emission per trip	kg $CO_{2eq.}$/trip	115
Total GHG emission per annum	t $CO_{2eq.}$/a	137
PCF transport (upstream)	**kg $CO_{2eq.}$/kg H_2**	**0.09**

3. Water use

Water use contributes significantly to GHG emissions through its production, treatment, and delivery processes. Typically, the energy consumption needed for water treatment and transportation to the facility falls under the scope emissions of the processing facility. In this assessment, we account for the energy consumption necessary to pump water from the reservoir to the processing facility. The same methodology outlined in section 5.3.2 was applied, and Table 20 provides a summary of the PCF specifically related to the harvesting process.

Table 20: Water use PCF.

Parameter	Unit	Value
Total water use per annum	m^3/a	11,222
Total GHG emission for water use per annum	t $CO_{2eq.}/a$	2
PCF (water use)	**kg $CO_{2eq.}$/kg H_2**	**0.001**

4. Downstream transport

Typically, cradle-to-gate analyses exclude downstream transportation, but in response to the client's request, this assessment incorporates it. Diesel-driven trucks are assumed for transporting H_2 at 350 bar, while CO_2 is transported in a liquefied state. The distance between the processing facility and customers is taken as 200 km. The same methodology outlined in section 5.2.2 was applied, and Table 21 provides a summary of the PCF specifically related to the harvesting process.

Table 21: Downstream transportation PCF.

Parameter	Unit	Value
Trucks (Downstream) - H_2 Transport		
Capacity of trucks [30]	t	1
Distance between production and customer site	km	200
Total no. of trips per annum	trips/a	1,600
GHG emission per trip	kg $CO_{2eq.}$/trip	30.2
Total GHG emission per annum	t $CO_{2eq.}/a$	48
PCF transport-H_2 downstream	**kg $CO_{2eq.}$/kg H_2**	**0.03**
Trucks (Downstream) - CO_2 Transport		
Capacity of trucks[31]	t	18
Distance between production and customer site	km	200
Total no. of trips per annum	trips/a	1,067
GHG emission per trip (0% loaded)	kg $CO_{2eq.}$/trip	108
GHG emission per trip (100% loaded)	kg $CO_{2eq.}$/trip	126
Total GHG emission per annum	t $CO_{2eq.}/a$	250
PCF transport-CO_2 downstream	**kg $CO_{2eq.}$/kg H_2**	**0.16**

[30] Hurskainen, M., & Ihonen, J. (2020). Techno-economic feasibility of road transport of hydrogen using liquid organic hydrogen carriers. International Journal of Hydrogen Energy, 45(56), 32098–32112. https://doi.org/10.1016/j.ijhydene.2020.08.186.

[31] The Engineer's Guide to CO_2 Transportation Options. Retrieved from: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4278858#:~:text=While%20pipelines%20are%20expected%20to,or%20are%20not%20technically%20or.

The table provided below offers a summary of the PCF concerning scope 3 emissions.

Table 22: PCF with respect to scope 3 emissions.

Parameter	Unit	Value
Total PCF (Harvesting)	kg $CO_{2eq.}$/kg H_2	0.057
PCF transport (Upstream)	kg $CO_{2eq.}$/kg H_2	0.09
PCF (Water use)	kg $CO_{2eq.}$/kg H_2	0.001
PCF transport-H_2 downstream	kg $CO_{2eq.}$/kg H_2	0.03
PCF transport-CO_2 downstream	kg $CO_{2eq.}$/kg H_2	0.16
Cumulative Scope 3 PCF	**kg $CO_{2eq.}$/kg H_2**	**0.33**

5.3.4 Cumulative PCF

The Figure 7 illustrates emissions across different scopes for the proposed processing facility, indicating that 83 % of emissions pertain to scope 2, specifically electricity purchase and usage in the facility's first operational year. Controlling this can be achieved by installing RE production facility and establishing a Power Purchase Agreement (PPA) with a solar or wind energy provider. The remaining 17 % of emissions, classified under scope 3, are generally uncontrollable but can be addressed by collaborating with suppliers to enhance energy efficiency, minimize waste, and implement sustainable practices.

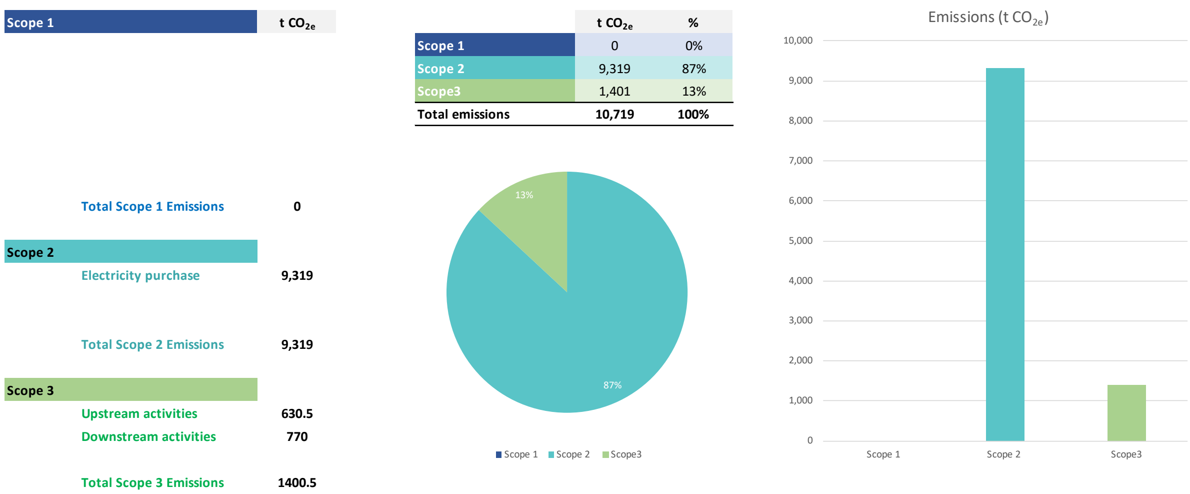

Figure 7: Associated GHG emissions (Scope 2+3).

The table below provides a summary of the first-year operational results of the PCF, specifically focusing on all scope emissions.

Table 23: Total PCF with respect to Scope 1,2 and 3 for 1st operational year.

Parameter	Unit	Value
Scope 1	kg $CO_{2eq.}$/kg H_2	0
Scope 2	kg $CO_{2eq.}$/kg H_2	5.82
Scope 3	kg $CO_{2eq.}$/kg H_2	0.33
Total PCF	**kg $CO_{2eq.}$/kg H_2**	**6.15**

Therefore, the overall PCF for H_2 production from biomass of the first-year operational is **6.15 kg $CO_{2eq.}$/kg H_2**.

Figure 8 illustrates a visual representation of how each activity contributes to the overall PCF.

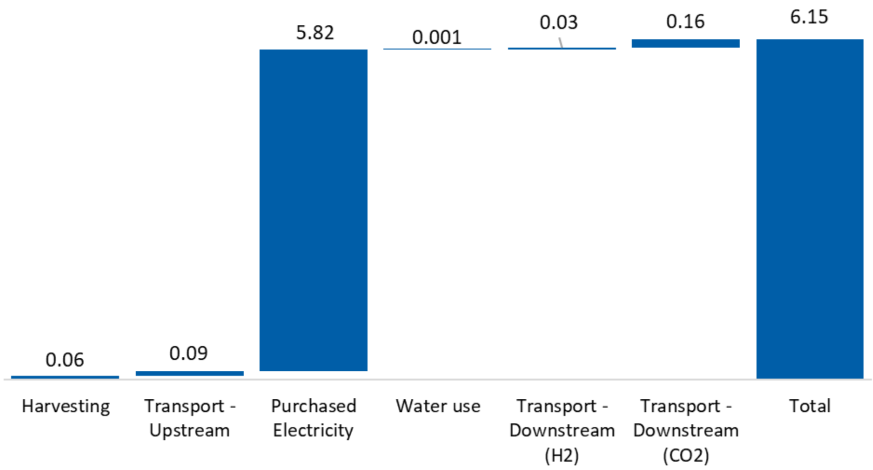

Figure 8: Graphical overview on activity-based contribution to PCF.

The PCF mentioned above is specific to the first year of operation and may not remain constant throughout the entire project's lifespan. In Germany, there is an expected decrease in emissions linked to Scope 2 due to a reduction in the EF, aligning with the country's target of achieving climate neutrality by 2045. Currently, there is no fixed rate of decline in the emission factor in Germany. Moreover, it is expected that the system's efficiency will decrease over time. As a result, a 0.5 % decline in efficiency for both scope 2 and 3 emissions is assumed. To determine the levelized PCF over the project's design life, two scenarios are considered and explained below.

1. Scenario 1

In this scenario, EF were estimated based on RE capacity in Germany. A consistent trend was observed, indicating an estimated annual increase in RE of 1.5 % from 2022 to 2030. This same iteration was utilized to project RE capacity in Germany throughout the design life, and EF were estimated accordingly.

2. Scenario 2

This scenario operates under the assumption of a 5 % decrease in EF compared to the preceding year.

The figure and table below provide a summary of the results for the two scenarios discussed earlier.

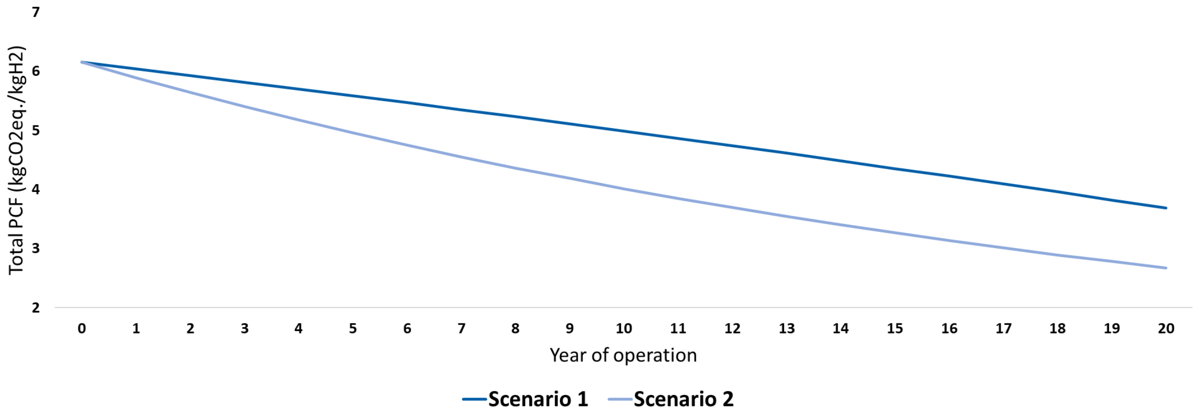

Figure 9: Variation of PCF for both scenarios.

Table 24: Levelized PCF for both scenarios.

Parameter	Unit	Value
Scenario 1		
Average Scope 2 PCF	kg $CO_{2eq.}$/kg H_2	4.62
Average Scope 3 PCF	kg $CO_{2eq.}$/kg H_2	0.35
Average PCF (Scenario 1)	**kg $CO_{2eq.}$/kg H_2**	**4.96**
Scenario 2		
Average Scope 2 PCF	kg $CO_{2eq.}$/kg H_2	3.81
Average Scope 3 PCF	kg $CO_{2eq.}$/kg H_2	0.35
Average PCF (Scenario 2)	**kg $CO_{2eq.}$/kg H_2**	**4.16**

Hence, it is estimated that, the average PCF for 20 years of operation of this plant with regards to its scope 1, 2 and 3 emissions range between 4.16 and 4.96 kg $CO_{2eq.}$/kg H_2.

5.3.5 Benchmarking with similar operations

The comparison between the current technology and alternative technologies like Combined Heat and Power (CHP) and BTL reveals insights into their performance using the same input material, mass flowrate and NCV. CHP stands out with the highest total energy output of 96,970 MWh/a, followed by Current Technology and BTL. Notably, CHP demonstrates a substantial GHG abatement potential, achieving the highest total reduction in CO_2 equivalent emissions at 42,330 t $CO_{2eq.}$/a. However, it is worth noting that the current technology, particularly concerning BTL, performs admirably and holds promise as a viable solution for future hydrogen production, especially for greener transport solutions.

Table 25: Benchmarking with similar operation.

General		CHP	BTL	Current Technology
Parameter	Unit			
Input				
Input biomass	t/a	29,600	29,600	29,600
NCV biomass	kWh/kg	3.9	3.9	3.9
Input thermal energy potential	MWh/a	115,440	115,440	115,440
Efficiency of system	%	84 %[32] (34% E + 50% T)	46 %[33]	56 %
Output				
Heat	MWh/a	39,250	0	16,000
Electrical	MWh/a	57,720	0	0
Total	**MWh/a**	**96,970**	**53,102**	**64,568**
Energy lost	MWh/a	18,470	62,338	50,872
GHG abatement potential				
Heat	$tCO_{2eq.}$/a	13,816	0	5,632
Electrical	$tCO_{2eq.}$/a	28,514	0	0
Fuel	$tCO_{2eq.}$/a	0	14,338	17,433
Total (Usage)	**$tCO_{2eq.}$/a**	**42,330**	**14,338**	**23,065**
Net saved in GHG	**$tCO_{2eq.}$/a**	**35,555**	**6,595**	**13,054**

[32] Combined heat and power. Retrieved from: https://archive.ipcc.ch/publications_and_data/ar4/wg3/en/ch4s4-3-5.html.

[33] Power and biomass-to-liquid: higher carbon conversion and lower production costs for second generation biofuels. Retrieved from: https://elib.dlr.de/104935/2/DGMK_2016_abstract_DLR_Vortrag.pdf.

5.3.6 Benchmarking with similar technology

The table below details the global warming potential (GWP) for various H_2 production technologies. Grey H_2, derived from reforming processes like Steam Methane Reforming (SMR), Autothermal Reforming (ATR) and Coal Gasification (CG), exhibits GWPs of 11.1 kg $CO_{2eq.}$/kg H_2, 11.9 kg $CO_{2eq.}$/kg H_2, 13.3 kg $CO_{2eq.}$/kg H_2 and 24.2 kg $CO_{2eq.}$/kg H_2. Grey H_2 from Proton Exchange Membrane (PEM) shows a GWP of 29.5 kg $CO_{2eq.}$/kg H_2, while grey H_2 from Solid Oxide Electrolyser cell (SOEC) records 10 kg $CO_{2eq.}$/kg H_2. Blue H_2 from SMR and ATR presents GWP of 2.55 kg $CO_{2eq.}$/kg H_2 and 4.67 kg $CO_{2eq.}$/kg H_2. Low-carbon electricity mixes, featuring a high proportion of renewable or nuclear energy, result in a relatively low carbon footprint, while coal-, oil-, and natural gas-based electricity leads to a higher footprint. Green H_2 from PEM demonstrates GWPs of 2.21 kg $CO_{2eq.}$/kg H_2 and 2.4 kg $CO_{2eq.}$/kg H_2, whereas green H_2 from SOEC shows a GWP of 5.1 $CO_{2eq.}$/kg H_2. The footprint is mainly influenced by the renewable electricity technology and the efficiency of the electrolysis process. The GWP of current technology is more than green hydrogen, but significantly outperforms technologies utilizing fossil fuels for hydrogen production. The initial stored energy in the biomass is 11.8 MW, and the energy content at the H_2 outlet is 6.66 MW, resulting in a system efficiency of 56 %. The process demonstrates more efficient energy conversion when compared to BTL technology. Given that current technology heavily relies on Scope 2 emissions, meaning it uses grid electricity, it's reasonable to say that if the grid electricity becomes fully green, this technology will outperform existing electrolyzer technology in terms of PCF. This is particularly true when biomass used in the process is certified by PEFC or FSC.

Table 26: GWP of different H_2 production technologies[34].

Technology	Efficiency [%]	Energy consumption [kWh/kg H_2]	GWP [kg $CO_{2eq.}$/kg H_2]	System boundary	Year of data
Grey H_2 from reforming process					
SMR	70-85 %	39-47	11.1	LCA analysis according to GaBi database.	2021
ATR	60-75 %	43-55	13.3	Includes natural gas production and transport	2025
CG	35-55 %	60-90	24.2	LCA of H_2 production	2018
Grey H_2 from electrolysis					
PEM	65-80 %	49-55	29.5	LCA of H_2 production	2018
SOEC	80 %	49-55	10	Grid mix Germany 2025	2025
Blue H_2 from reforming					
ATR	60-75 %	43-55 *	2.55	Carbon footprint analysis; grid mix Netherlands 2015	2015

[34] Suer, J., Traverso, M., & Jäger, N. (2022). Carbon footprint assessment of hydrogen and steel. Energies, 15(24), 9468. https://doi.org/10.3390/en15249468.

Technology	Efficiency [%]	Energy consumption [kWh/kg H_2]	GWP [kg $CO_{2eq.}$/kg H_2]	System boundary	Year of data
ATR	60-75 %	43-55 *	4.67	Includes natural gas production and transport	2025
Green H_2 from electrolysis					
PEM	65-80 %	49-55	1.57	LCA of H_2 production	2018
PEM	65-80 %	49-55	2.4	LCA of H_2 production	2012
Biomass to hydrogen					
BTL	40-45 %	74-83	N.A.	N.A.	N.A.
Current technology (current energy mix)	**56 %**	**59.59**	**4.16-4.96**	**Cradle-to-gate**	**2023**
Current technology (fully RE grid)	**56 %**	**59.59**	**0.33-0.40**	**Cradle-to-gate**	**2023**

5.3.7 Overall system balance

Overall system balance is conducted to assess the total energy requirements from various activities, including harvesting, transport, plant operation, and utility usage, to achieve the desired H_2 output and waste heat. The results, depicted in the table below, reveal an overall system efficiency of 50 %, with H_2 at output contributing 38 % and waste heat potential 12 %. The technology achieves an annual GHG emission reduction of 23,065 t CO_2, resulting in a net decrease of 12,349 t CO_2 (subtracting emissions from scope 2 and 3), with a 50 % overall system efficiency. The hydrogen produced by this technology stands as an efficient and environmentally friendly fuel for transportation.

Table 27: Overall system balance of the technology.

Parameter	Unit	Value
Input		
Harvesting	MWh/a	363
Upstream transport	MWh/a	545
Plant operation	MWh/a	134,304
Downstream H_2 transport	MWh/a	2,240
Downstream CO_2 transport	MWh/a	1,494
Total input	**MWh/a**	**138,946**

Output		
H_2	MWh/a	53,328
Waste heat	MWh/a	16,000
Total output	**MWh/a**	**69,328**
Overall system efficiency	**%**	**50 %**

6 Regional Added Value (RAV)

6.1 General Overview

The term "regional value added" refers to the economically quantifiable key figure for mapping the regional (added) value associated with investments in a plant for the production of renewable fuels of biological origin (RFBOs). In line with the importance of value creation as a general goal of industrial activity, it is not just about generating higher values from the transformation of inputs into outputs. Rather, the regional reference of all financial flows triggered by the investments in the individual stages of the value chain is brought to the fore and evaluated. Regional value added can therefore be expressed as an economic indicator in euros (€). In addition, regional value added can be used as a basis for argumentation to develop and implement economic development strategies at local level. Even today, regional value creation offers a wide range of opportunities to mobilize and optimize untapped potential. Implementation at regional level not only delivers local successes but can also make a significant contribution to achieving climate protection and sustainability goals, as well as triggering innovation and employment.

The indicator "regional value creation" is defined as the sum of all additional values created in a region or a geographically defined area within a certain period. The term "value" can have different subjective meanings, i.e., it can be understood economically, ecologically, and socio-culturally. In this context, the focus is on the economic evaluation of investments in an RFBO production facility. Regional value creation is used here as an indicator to quantify economic effects, meaning it evaluates the generation of monetary values within the regional context. This refers to the monetary values (€) generated by various economic actors that remain in the region due to the implementation of the facility. The consistent consideration of regional value creation aspects at all stages of the value chain presents considerable potential for revenue and employment. Although the results are calculated based on business management methods and follow good scientific practice, they are a rough approximation of the actual possible conditions. This is because the calculations are based on an initial economic feasibility study, which contains many uncertainties and assumptions. Thus, the quantification of regional value creation can only provide a rough analysis that highlights the fundamental effects and relationships.

For the successful implementation of regional value creation, the involvement of as many local stakeholders as possible (e.g., public administration, energy suppliers, plant operators, landowners, craftsmen, local service providers, financial institutions, and citizen initiatives) is a necessary prerequisite. These different actors should cooperate to ensure that the implementation in the "plant operator/surrounding area" system is as efficient, economical, low-emission, and socially acceptable as possible. Regional value creation, therefore, serves as a suitable instrument to present the implementation of the plant as a feasible option for local economic promotion—both financially, technically, and administratively, as well as socially and politically acceptable.

6.2 System Boundaries of Regional Value Creation

The following section provides a quantification of regional value creation resulting from investments in an RFBO production facility. A dynamic calculation model developed by IfaS is used for this purpose. The municipality where the facility is located, along with its administrative boundaries, defines the system boundary. In the given case a regional boundary is considered as 150km radius from the facility.

The content system boundaries for quantifying regional value creation are defined such that the investments in the facility serve as the basis for creating regional added value. Regional value creation occurs, for example, through the employment of local workers, services obtained from regional craftsmen/service providers, the involvement of local banks in financing, profits realized for local operators/investors/owners, tax payments to the region, and lease payments to landowners. In general, regional value creation can only be captured by locally and regionally based actors. In this assessment regional added value for downstream refueling station as well as logistics is also considered with in the region.

The revenue from hydrogen production has already been accounted for in the provided cash flow data by Bioenergy Concept GmbH. This revenue stream includes both hydrogen and CO_2 income. All the associated costs, revenue, and investment were summarized over a 20-year operational period as shown in Table 28.

Table 28: Summary of business plan for 20 years operational.

Parameter	Unit (in T €)
Plant costs	-53,100 €
Montage/Installation	-5,900 €
Revenue	257,217 €
Consumption of biomass	-34,916 €
Electricity cost	-33,843 €
Personal costs	-9,655 €
Maintenance costs R&W	-36,304 €
Insurance	-6,113 €
EBITDA	**136,384 €**
Depreciation	-38,283 €
Interest	-13,648 €
EBT	**84,452 €**
Company Tax	-25,922 €
EAT/Net profit	**58,531 €**

The revenue generated from hydrogen production and sale has already been integrated into the RAV calculation at the production plant level. At the fueling station level, the role of the distributor is to purchase hydrogen at a lower price and sell it at a higher price to truck owners, generating a surplus. The pricing structure for hydrogen distribution through fueling stations involves multiple components. Hydrogen is sold by the production plant to the fueling station operator for approximately 10 €/kg H_2(net). The fueling station operator claims revenues from GHG quota trading, which can range between 4-8 €/kg H_2 (net), depending on market conditions. Hydrogen is then sold to truck owners for 8–12 €/kg H_2 (net) or 10–15 €/kg H_2 (including taxes), with the final price influenced by the quota revenues. The distributor incurs expenses of about 2.50 €/kg H_2 for hydrogen logistics and fueling station operations. Overall, fueling stations achieve net revenues of approximately 1–2 €/kg H_2 of hydrogen, which remains partly within the region, further enhancing RAV.

Hydrogen produced by the plant is entirely utilized in the logistics sector, fueling trucks within a 150 km radius. With a production capacity to support 200 trucks per day, and trucks consuming an average of 8 kg of hydrogen per 100 km, the entire supply is effectively absorbed by the logistics industry. This contributes to the avoidance of diesel consumption and results in significant toll savings due to hydrogen fuel use. For trucks traveling 100,000 km annually, toll exemptions in 2028 would lead to savings of approximately €150,000 per truck per year.

Based on this business plan summary, the investment, revenue, and costs were then categorized to highlight their contributions to regional value creation in Table 29.

Table 29: Investment, Revenue, and Cost Segregation.

Summary	Investment [T €]	Revenue [T €]	Cost [T €]
Plant costs	53,100	-	-
Montage/Installation	5,900	-	-
Revenue EAT	-	257,217	-
Consumption of biomass	-	-	34,916
Electricity cost	-	-	33,843
Personnel costs	-	-	9,655
Maintenance costs R&W	-	-	36,304
Insurance	-	-	6,113
Depreciation	-	-	38,283
Interest	-	-	13,648
Company Tax	-	-	25,922
Sum	**59,000 €**	**257,217 €**	**198,686 €**

To determine the RAV contribution, each cost and investment item was further assessed based on its regional share. Table 30 below illustrates the regional share percentages assigned to each category. For example, employees working in the plant and craftspeople involved in installation are assumed to be fully (100%) sourced from the region, providing direct economic benefits. Additionally, electricity is assumed to have a 50% regional supply component, with the other half sourced from the national grid. Similarly, tax contributions are assumed to split evenly, with 50% going to local municipalities and the remaining 50% allocated to the state or national government.

Table 30: Regional Value-Added Share Assumptions.

Profiteers	Regional share [%]
Manufacturer (mechanical engineering)	10%
Wholesaler	0%
Retailer	0%
Personal	70%
Craft	70%
Insurance	50%
Institute credit	70%
Electricity purchase	50%
Biomass procurement	90%
Operator	65%
Company Tax	50%
Distribution-refueling station	65%
Logistics	100%

6.3 Regional Value Creation Effects from the Implementation of the RFBO Production Facility

The following section illustrates the potential for regional value creation. Various assumptions are made to demonstrate under which conditions regional value creation can be achieved in the study area. Energy prices and inflation rates are identified as key drivers in this regard.

According to the current economic analysis as seen in Figure 10, the total estimated investment volume for the construction of the facility is approximately 59 M €. These investments cover the entire facility, excluding the purchase of land. All technical components are included in the scope of delivery. Project management, engineering, regulatory procedures, assembly, and commissioning are also considered. Along with these investments and during the facility's 20-year operational period, total costs amount to approximately 199 M €. Revenues of around 257 M € offset these total costs.

The regional value creation derived from these investments, costs, and revenues amounts to around 487 M € through the construction of the facility, which corresponds to 825% of the investment. Since approximately 20% of the investments can likely be financed through subsidies/grants, the relative share of regional value creation in the investment requirement increases significantly. The largest portion of the regional added value, approximately 307 M €, is attributed to logistics, as the hydrogen-powered trucks operate within the defined system boundary. The results are shown in the following figure. These results are based on the assumption that regional economic cycles continue to close, meaning, for example, that required services and resources can be supplied within the study area. This allows for a high degree of financial resources to be retained locally.

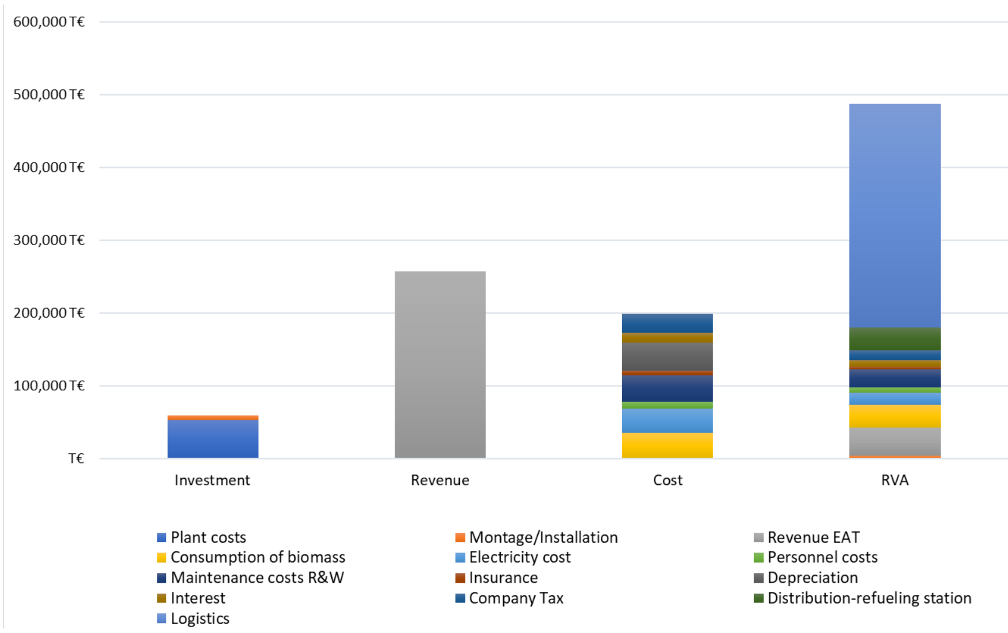

Figure 10: Potential Regional Value Creation from Facility Implementation.

6.4 Regional Value Creation by Economic Actors

When the individual actors are considered, regional value creation is distributed as follows:

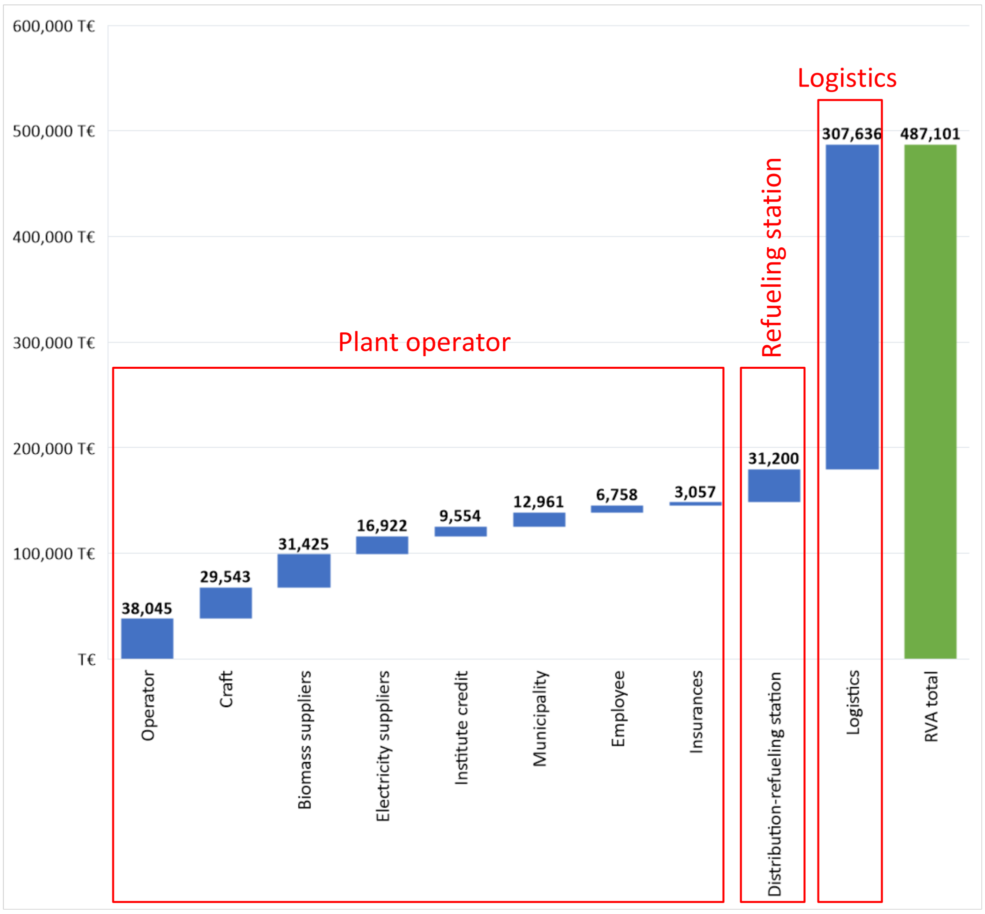

Figure 11: Distribution of Regional Value Creation by Economic Actors.

Approximately 38.5 M € of the RAV is attributed to the facility operator. Following this, craft businesses account for about 29.5 M €. The value creation in the craft sector is based on the installation, maintenance, and servicing of the facility. Biomass suppliers participate in RAV with around 31.5 M € through the sale of fuel to the facility, while energy suppliers generate a value creation share of approximately 16.9 M €. The value creation for energy suppliers is based, among other things, on revenues generated from the provision of various energy sources, such as electricity. Next, the credit institutions, involved in financing, participate with 9.5 M € in value creation. Based on the assumptions for RAV, the host municipality benefits from approximately 12.9 M € in commercial tax revenues. Employees, due to the staff required for facility operation, contribute around 6.7 M € to RAV. The insurance sector, through the facility's coverage, generates a value creation share of 3 M €. In total for plant operator total RAV accounts to 148 M € which is 250% more than the investment in the plant.

The RAV for the refueling station is approximately 31.2 M €, representing 6.5% of the total RAV. The highest RAV is observed in the logistics sector, amounting to 307 M €, which accounts for nearly 63% of the total RAV. This significant share is primarily due to the direct use of hydrogen in truck refueling, enabling the transport of goods within the system boundary. The resulting benefits include savings in diesel consumption and toll exemptions associated with hydrogen-powered trucks. Overall, the total RAV generated through the construction and operation of the facility amounts to approximately 487 M €, with substantial contributions from the plant, refueling station, and logistics sectors.

6.5 Scenarios

6.5.1 Scenario 1: Biomass Procurement and Operator at 50% Regional

In this scenario, it is assumed that 50% of biomass procurement and plant operations are regional. Under these conditions, the RAV decreases compared to the value discussed in the previous section. Specifically, the RAV is reduced to 95% of the original value, resulting in a drop of approximately 23 M €. The Figure 12 below provides a detailed breakdown of the RAV distribution for Scenario 1.

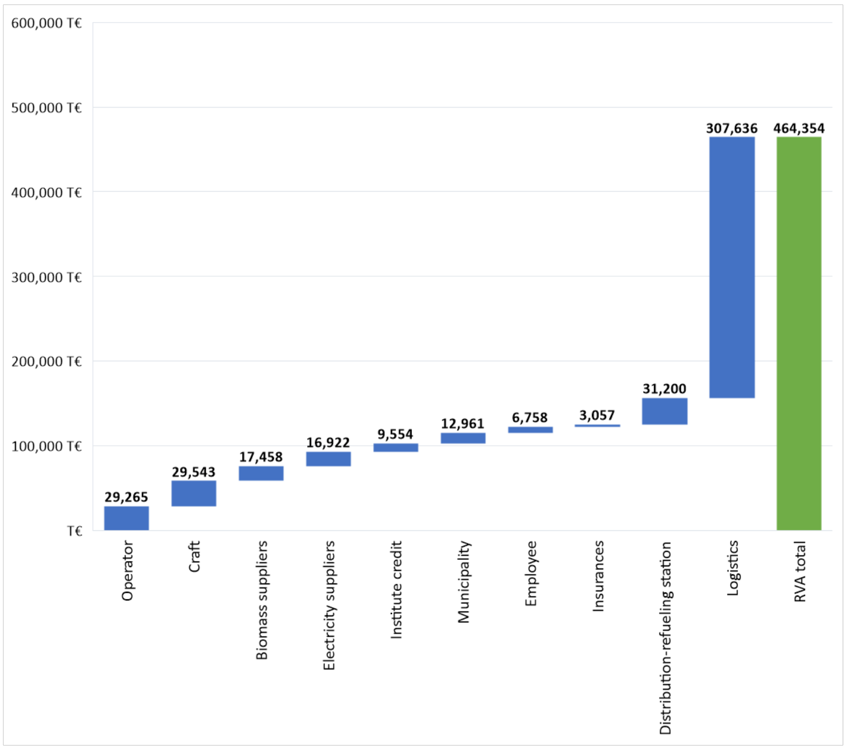

Figure 12: Distribution of Regional Value Creation by Economic Actors for Scenario 1.

6.5.2 Scenario 2: Electricity Purchase at 100% Regional and Craft at 50% Regional

In this scenario, it is assumed that 100% of electricity purchase and 50% of craft are regional. Under these conditions, the total RAV increases compared to the value discussed in the previous section. Specifically, the RAV is increased to 2.5% of the original value, resulting in a increase of approximately 12 M €. The Figure 13 below provides a detailed breakdown of the RAV distribution for Scenario 2.

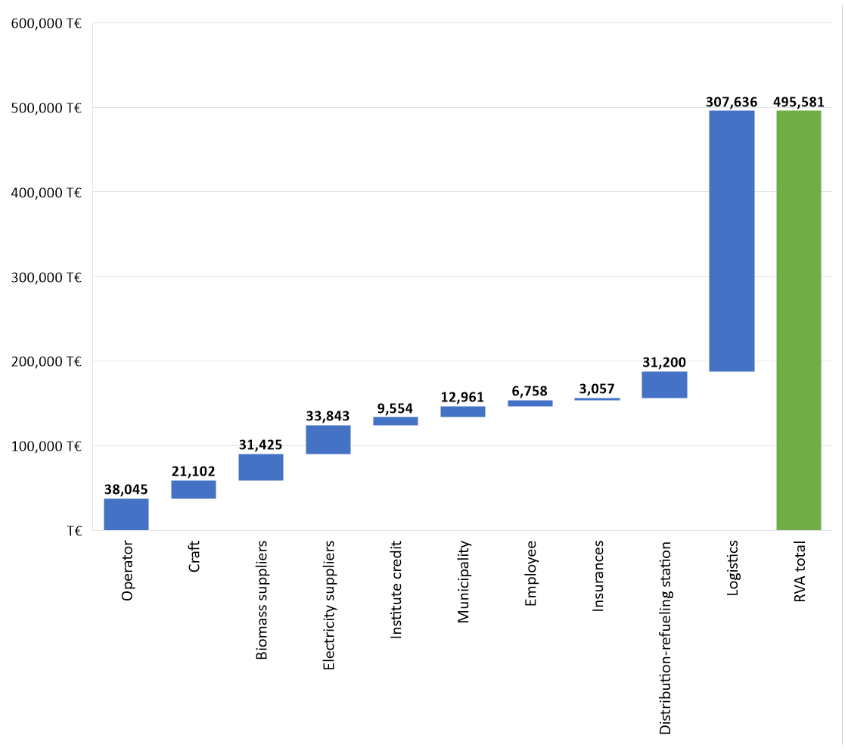

Figure 13: Distribution of Regional Value Creation by Economic Actors for Scenario 2.

6.5.3 Scenario 3: Logistics at 50% Regional

In this scenario, it is assumed that 50% of logistics is regional. Under these conditions, the RAV decreases compared to the value discussed in the previous section. Specifically, the RAV is decreased to 68% of the original value, resulting in a increase of approximately 154 M €. The Figure 14 below provides a detailed breakdown of the RAV distribution for Scenario 3.

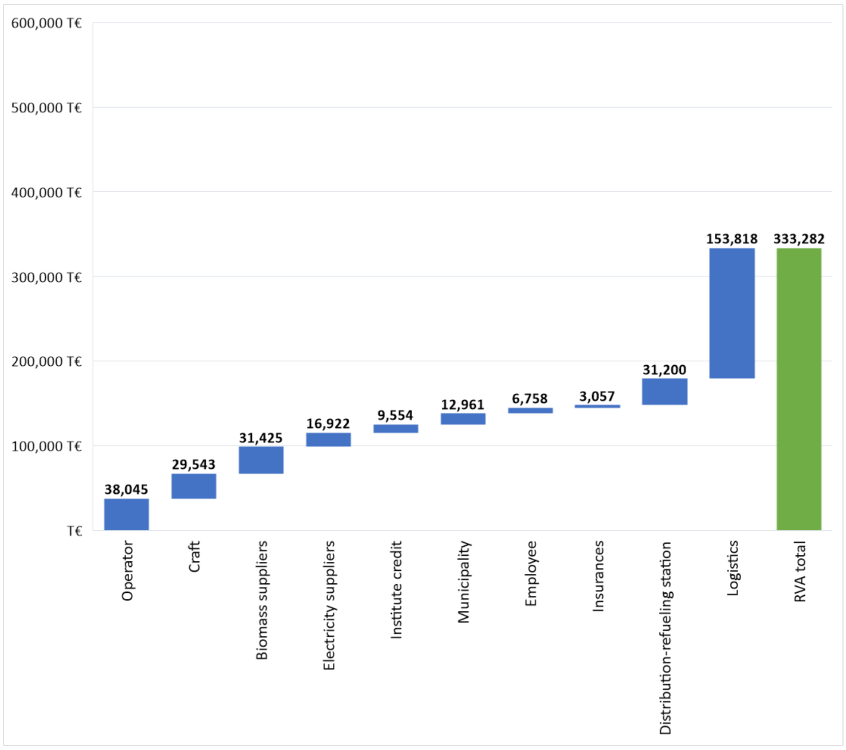

Figure 14: Distribution of Regional Value Creation by Economic Actors for Scenario 3.

7 Conclusion

The detailed analysis of the material flow and PCF for the hydrogen production technology derived from biomass provides valuable insights into its environmental implications. With an efficiency of around 6 % in converting total biomass to H_2, the technology shows potential to convert biomass into H_2 effectively. One notable aspect is the water intensity for producing 1 kg H_2, which is less with existing electrolyser technology standards at approximately 10 l. This suggests a competitive edge in water usage, making it a favourable aspect of the technology.

However, a significant concern arises when examining the total energy intensity, combining both electrical and thermal demands. The recorded value of 59.59 kWh/kg H_2 raises concern, especially when compared to the current market standard of approximately 49 kWh/kg H_2 for traditional electrolyser technology. This heightened energy intensity poses challenges in terms of sustainability and cost-effectiveness, calling for a critical evaluation of the technology's positioning in the hydrogen production market. However, this technology stands out as a better alternative than BTL technology, because of its higher energy efficiency and significant potential for reducing GHG emissions.

The levelized PCF stands at 4.16 – 4.96 kg $CO_{2eq.}$/kg H_2, taking into account all scope emissions for 20 years of operations. In comparison to conventional processes such as grey hydrogen production such as steam reforming of natural gas and coal gasification, this technology demonstrates a more environmentally friendly performance. However, it falls behind when evaluated against greener alternatives like blue hydrogen (steam reforming with carbon capture) and green hydrogen (electrolysis with renewable energy). If the grid electricity becomes fully green, this technology, which relies heavily on Scope 2 emissions, will outperform current electrolyzer technology, especially when using PEFC or FSC-certified biomass.

By understanding the environmental impact at the production stage, BioEnergy Concept GmbH can identify opportunities for improvement and implement strategies to minimize carbon emissions of this technology. Addressing these concerns will be pivotal for ensuring the technology's success and competitiveness within the dynamic and evolving field of hydrogen production. Additionally, a reduced PCF can contribute to cost savings by optimizing resource usage and improving overall operational efficiency. Ultimately, a lower PCF reflects BioEnergy Concept GmbH's dedication to sustainable practices, meeting regulatory standards, and responding to growing consumer demand for eco-friendly products.

Finally, based on the regional value-added assessment, the analysis demonstrates a substantial potential for regional value creation of 487 M € over a 20-year operational period, which corresponds to 825% of the initial investment of 59 M € in plant. This high multiplier effect highlights the substantial economic benefits of localized investments in renewable fuel production. The logistics sector accounts for the largest share of the RAV, contributing approximately 307 M € (63%), driven by hydrogen-powered truck operations. Additionally, the facility operator contributes 38.5 M €, while biomass procurement, craft services, and energy suppliers generate RAV contributions of 31.5 M €, 29.5 M €, and 16.9 M €, respectively. Further analysis indicates that downstream infrastructure, such as refueling stations, contributes 31.2 M € (6.5%) to the total RAV, showcasing the economic potential of hydrogen distribution. The value creation is further distributed across key economic actors, including credit institutions, insurance providers, employees, and local municipalities, demonstrating the broad economic benefits of the project. The successful implementation of the facility ensures maximum retention of financial resources within the region, enhancing economic resilience, promoting employment, and supporting sustainability goals. Overall, the project serves as a model for regional economic development through investments in renewable energy infrastructure.

7.1 SWOT Analysis

The following figure summarizes a quick analysis regarding the current situation of the technology in relation to its resiliency and sustainability.

STRENGHTS

- Utilization of carbon neutral biomass.
- Low water intensity.
- Local production of H_2.
- Better alternative than BTL.

WEAKNESES

- High energy intensity.
- 40% lost in stored biomass energy during conversion.

OPPORTUNITIES

- Increase energy efficiency of process system.
- Scope 3 emission reduction via strategic decision on sustainability.
- Anticipated growth in H_2 market.
- Heat integration.

RISKS

- Market dynamics.
- Competitive technology with respect to electrolysers.
- Supply chain risks.

Figure 15: SWOT analysis of the technology.

8 Future aspects of carbon accounting

Due to the increasing concerns of the climate crisis and the increasing pressure of various stakeholders towards decarbonisation and sustainable operations, more and more companies and organizations are quantifying the carbon footprint[35] of their products or the carbon footprint of their entire cooperation (corporate carbon footprint). Additionally, environment sensible organization may use the carbon accounting as means to improve market reputation, select best suppliers, increase the customers' portfolio and meet the (ESG reporting) demands of various stakeholders. Furthermore, internal carbon pricing combined with carbon product footprint allow a future-oriented scenario analysis on the competitiveness of different products with different designated carbon compensation prices (or negative prices if carbon capture opportunities occur). This future orientated strategic management approach is vital to include potential shadow costs if future carbon compensations in different export markets (e.g. European Union Carbon Boarder Adjustment Tax) are manifesting.

Most importantly, managing carbon emissions will increase the resilience of the business towards potential impacts of climate change and prepare for (inter-) national compliance facing the introduction of GHG reporting and/or carbon pricing duties.

An internal GHG emission accounting, management and reporting systems allows to identify specific GHG mitigation projects and prepare to achieve a continuous decarbonisation pathway as required by the Paris accord in 2015 in line with the 1,5° degree target.

There are several GHG reporting standards which can be used within an organization: ISO 14067, SBTi, GHG protocol and PAS2060.

8.1 ISO 14067- Greenhouse gases — Carbon footprint of products [36]

The ISO 14067 and 14060 family provides guidelines and requirements for quantifying, monitoring, reporting and validating or verifying GHG emissions and removals. It is to support sustainable development through a low-carbon economy. Benefits of the standards´ application are:

- Improve the environmental integrity of GHG quantification;
- improve the consistency, credibility, and transparency of GHG quantification, monitoring, reporting and verification;
- Support the development and implementation of GHG management strategies and plans and the implementation of mitigation actions through emission reductions or removal improvements;
- Facilitate the ability to track performance and progress in the reduction of GHG emissions and/or increase in GHG removals.

Applications of the ISO 14060 family include:

- Corporate decisions to identify GHG emission reduction opportunities and increase profitability by reducing energy consumption and increase efficiencies.
- Carbon risk management identification and management of risks and opportunities
- Voluntary actions, ex. participation in voluntary GHG registries, sustainability reporting initiatives;
- Participate in GHG markets, trading of GHG allowances or credits;

[35] Means of measuring, managing and communicating the total greenhouse gas (GHG) emissions related to goods and services is known as a Product Carbon Footprint (PCF). It is based on the life cycle of the product, from extraction of raw-materials, to end-of-life. It is measured in carbon dioxide equivalent (CO_2e). It is accepted to include the energy consumption to evaluate the performance of the entire value chain of the studied product.

[36] ISO 14067:2018(en), Greenhouse gases — Carbon footprint of products — Requirements and guidelines for quantification, iso.org

- Regulatory/government GHG programmes, such as credit for early action, agreements or national and local reporting initiatives.

8.2 SBTi (Science Based Targets Initiative) [37]

Science-based goals provide companies with a well-defined path to reducing GHG emissions, helping prevent the worst effects of climate change and increase the resilience of business growth. Goals are considered "science-based" when they are consistent with what the latest climate science deems necessary to achieve the goals of the Paris Agreement - limiting global warming to well below 2 ° C above pre-industrial levels and efforts to limit warming to 1.5 ° degrees. Companies in all the sectors are eligible to use the SBTi.

8.3 Greenhouse Gas Protocol Corporate Standard (GHG PCS) [38]

The GHG PCS, developed by World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD), supplies wide range of GHG accounting standards which are designed to provide a framework for governments, businesses and other entities to measure and standardized report their GHG emissions. The GHG PCS and the "Corporate Value Chain (Scope 3) standard" are designed as a guidance for companies and other organizations, preparing a corporate-level GHG emissions inventory including all upstream and downstream aspects.

8.4 PAS 2060 (Publicly Available Specification) [39]

The specification describes a steady set of requirements and measures for organisations, governments, communities and also for families and individuals to demonstrate carbon neutrality for a product, service, organisation, community, event or building.

Scope 1 and scope 2 emissions should be addressed completely while scope 3 emissions should be accounted to the measurements if that contribute more than 1% of the total footprint.

The organization or the entity must develop a carbon management plan which comprises a public commitment to carbon neutrality and outlines the following major aspects of the reduction strategy: a time scale, specific targets for reductions, the planned means of achieving reductions and how residual emissions will be offset.

[37] Science Based Targets Initiative (SBTi), https://www.mainstreamingclimate.org

[38] GHG Protocol, https://ghgprotocol.org/

[39] The British Standards Institution, www.bsigroup.com

Table 31: An overview of key aspects specified in carbon footprint protocols.

Specifications/Requirements		PAS 2050	PAS 2060	GHG Protocol	ISO 14067	SBTi
Goals		To provide a uniform specification for GHG emissions of goods and services		To provide detailed guidelines on accounting and reporting	To standardize the quantification process and the communication of GHG emissions	In line with GHG Protocol. Clearly-defined pathway for companies to reduce greenhouse gas (GHG) and to meet the goals of the Paris Agreement
Life cycle stage included		Cradle-to-grave		Cradle-to-grave	Cradle-to-grave Cradle-to-gate Gate-to-gate	Cradle-to-grave
		Cradle-to-gate		Cradle-to-gate	Partial life cycle	Cradle-to-gate
Cut-off criteria		Exclusion based on materiality (<1%); at least 95% of the complete product life cycle must be included; no scale-up requirement to account for 100%		No cut-off criteria exist, because 100% completeness is necessary	No specific criteria available	Targets must cover a minimum of 5 years and a maximum of 15 years from the date the target is submitted to the SBTi
Capital goods		Excluded		Excluded. but encouraged to be included when relevant	Excluded if the y does not significantly affect the overall conclusions	Depend on the preference
Biogenic carbon	Carbon storage	Stored carbon within 100 years shall be recorded and accounted for in the carbon footprint calculations		For cradle-to-gate system, credit is given to biogenic carbon storage	If carbon storage e is calculated, then it shall be separately reported but not included in the carbon footprint result	Must be included along with the company’s inventory. If Biogenic carbon is accounted for as neutral, must provide a justification
	Delayed emissions	A weighting factor is included and proposed		Shall not be included	Shall not be included	
Other Exclusions	Land-use change	Specific procedure and provides default soil emissions per country	Can be exclude or include. If excluded, an explanation should be given	Provides guidance for determining attributable impacts	Direct land-use change shall be separately documented; indirect land-use change should be considered	When relevant, companies are encouraged to account for direct land use change emissions and include them in their target boundary.
	Others	Other exclusions include the transport of workers to their workplace and consumers to purchase sites, human energy inputs to the process, and animals providing transport services				

9 Follow-up potential: Carbon Accounting and Reduction Initiative

The consultant suggests introducing an active carbon management into the overall strategic operations management. The steps could be:

- Complete the carbon accounting for all scopes and determine an automated data reporting and processing plan.
- Creating inhouse applied knowledge for future auditing and certification schemes, including carbon credits.
- Determining BAU-CAGR emission pathway based on weighted average carbon intensity for all products and constantly review (relevant) KPIs and benchmarking with peers.
- Determining own GHG reduction potential and defining pathways across all production steps and scopes until 2044, f.i.
    - Review energy efficiency (cp. present report) and maximised renewable options.
    - Selection of carbon accounting and disclosure option (mainly ISO14067 and SBTi).
- Establishment of a “BioEnergy Concept-DeCarp” branch or subsidiary for interior and exterior carbon management and consultancy.
- Timely acquisition of carbon removal certificates or development of in-setting options.
- Introduction of internal carbon pricing as strategic operations management tool

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