D1.2 Report on the evaluation of H_2 technologies and on implementation of measurement technologies

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HYINHEAT

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Contents

Tables & Figures

List of abbreviations

Abbreviations	Explanation
AELs	Associated Emission Levels
AMI	ArcelorMittal Innovation
AMOB	ArcelorMittal Olaberria-Bergara
AMS	ArcelorMittal Sestao SL
BAT	Best Available Techniques
BEF	Befesa Aluminio SLU
BF/BOF	Blast furnace/basic oxygen route
BREF	Best Available Techniques Reference Document
CBAM	Carbon Border Adjustment Mechanism
CCU	Carbon capture and utilization
CDA	Carbon direct avoidance
CEL	Celsa Armeringsstål AS
CO2eq	Carbon dioxide equivalent
CTEC	Constellium Technology Center
DR	Direct reduction
DRI	Direct reduction of iron ore
EAA	European Aluminium
EAF	Electric arc furnace
EHB	European Hydrogen Bank
ESTEP	European Steel Technology Platform
ETS	European Union Emissions Trading System
EU	European Union
FMP	Ferrous Metals Processing Industry
FU	Functional Unit

HCL	Hydrochloric acid
HF	Hydrogen Fluoride
IAI	International Aluminium Institute
IED	Industrial Emissions Directive
LCA	Life Cycle Assessment
LNG	Liquefied natural gas
MFA	Material flow analysis
MYT	Mytilinaios Anonimi Etaireia
NEC	National Emission Reduction Commitments Directive
NECPs	National energy and climate plans
NFM	Non-Ferrous Metals Industries
NG	Natural Gas
NTNU	Norwegian University of Science and Technology
PCDD/F	Polychlorinated-p-Dioxins and related Furans
RED	Renewable energy directive
RFNBOs	Renewable fuels of non-biological origin
RWTH	Rheinisch-Westfaelische Technische Hochschule Aachen
SMR	Steam methane reforming
SPE	Speira Gmbh
SWE	Swerim AB
TRL	Technology Readiness Level
TME	Toyota Motor Europe NV
TVOC	Total Volatile Organic Compounds

Executive Summary

This deliverable sets a baseline for the evaluation of H_2 technologies (part A) and new measurement technologies and NOx emission limits (part B) that will be used in the subsequent work packages. Part A corresponds to task 1.2 and starts with a summary of the current policies and legislation regarding hydrogen within the EU energy landscape. Key definitions are explained and both, implemented measures and upcoming initiatives are highlighted. Then, the scope and goals for the inventory analysis of the Life Cycle Assessment are defined and the product systems of the studied demonstrator processes are explained. This is followed by the definition of the scope and concept for multi-layer plant-level material flow analysis, where individual case studies will be performed in more detail later in the project. Part A concludes with an assessment and overview of literature regarding material and energy demands and prices. Part B corresponds to task 1.3 and gives an overview of the parameters needed to develop and use measurement technology as well as defines NOx emission limits.

A. Scope, concepts, and evaluation framework (task 1.2)

A.1 Assessment of current and planned legislative context (EAA, ESTEP)

This chapter provides a summary of the current policies and legislation concerning hydrogen within the EU energy landscape as of July 2023. It includes key definitions related to hydrogen and highlights both implemented measures and upcoming initiatives. The role of the newly declared European Hydrogen Bank in supply and pricing of renewable hydrogen in Europe will be as well analysed.

A.1.1 Hydrogen in the general European energy policy framework

The current policy agenda in the European Union (EU) is primarily motivated by concerns over energy security and the need to align with energy and climate targets. The 'Fit For 55' (European Commission, 2021a) package, introduced in July 2021, aims to reduce greenhouse gas emissions by at least 55% compared to 1990 levels by 2030, ultimately achieving net zero greenhouse gas emissions by 2050.

The energy targets for 2030 were initially established in 2014 and revised in 2018 with the objective of increasing the share of renewable energies in energy consumption to 32%, improving energy efficiency by 32.5%, and interconnecting at least 15% of the EU's electricity systems. However, new proposed EU energy targets for 2030, agreed upon in March 2023, call for a more ambitious approach (European Council, 2023). These targets aim to raise the share of renewable energies in energy consumption to 42.5% initially, with the ultimate goal of reaching 45%. Additionally, there is a target to reduce primary and final energy consumption by 11.7% compared to the 2020 projections for 2030. In the industrial sector, this provisional agreement provides that industry would increase their use of renewable energy annually by 1.6%. They agreed that 42% of the hydrogen used in industry should come from renewable fuels of non-biological origin (RFNBOs) by 2030 and 60% by 2035.

The regulatory framework for energy in Europe encompasses various acts that cover different aspects, such as governance, electricity interconnectivity, electricity market design, risk-preparedness, energy efficiency, renewable energy, gas market design, taxation of energy products, trans-European energy infrastructures, cooperation among energy regulators, and adjustments following the United Kingdom's departure from the EU.

Under the existing energy framework, EU Member States are required to develop 10-year integrated national energy and climate plans (NECPs) for the period from 2021 to 2030. They must also submit progress reports every two years and establish coherent long-term strategies to achieve the agreed-upon energy targets and fulfil the goals of the Paris Agreement.

The 'Fit For 55' package included revisions to existing EU acts on climate and energy, incorporating provisions for decarbonized gas markets such as hydrogen. Furthermore, new regulatory proposals were made in the transport sector, addressing the deployment of alternative fuels infrastructure, aviation, and maritime initiatives.

However, the Russian invasion of Ukraine in 2022 disrupted the timeline for revising the energy framework. In response, the European Commission swiftly took action to enhance the security of the EU's energy supply. Measures were implemented, including a plan to reduce the EU's reliance on Russian fossil fuels, regulations for gas storage and purchases to mitigate high energy prices, and the establishment of an EU energy purchase platform to secure the supply of gas, liquefied natural gas (LNG), and hydrogen.

The European Parliament expressed its support for the review of the EU energy package and expedited the legislative process. Regulations were swiftly adopted to ensure minimum gas storage filling levels and to set a voluntary target for Member States to reduce their natural gas consumption. Emergency legislation was proposed and extended to address the energy crisis.

During the latter half of 2022, and particularly in preparation for winter, the Commission introduced urgent Council regulations, which effectively excluded the European Parliament from the legislative process. These regulations covered measures for reducing electricity demand, implementing temporary revenue caps on electricity producers, introducing a temporary solidarity contribution on excess profits from fossil fuel-based activities, accelerating the deployment of renewable energy, and establishing a suspension mechanism for natural gas transactions during periods of extremely high prices.

On 14 March 2023, the Commission proposed a reform of the electricity market design (European Commission, 2023f), returning to the standard co-legislative procedure. The proposal aims to revies the rules for electricity market design and aims to accelerate the adoption of renewables, phase out gas, stabilize consumer bills, protect against price spikes, and enhance the EU's clean and competitive industrial landscape.

A.1.2 Renewable Hydrogen as a solution for aluminium and steel industry decarbonisation

A.1.2.1 Current use for Hydrogen

Hydrogen nowadays has two main applications: **as an industrial feedstock and reductant**, and as an **energy vector** in the power system. Currently, over 90% of the hydrogen demand in the EU is related to industrial processes, where it serves as a feedstock and reductant (Florence School of Regulation, 2022).

As can be seen from Fig. 1, the demand for pure hydrogen, which has minimal contaminants or impurities, is largely driven by oil refining and ammonia production, particularly for fertilizer purposes. In 2019, the global demand for pure hydrogen reached approximately 75 million metric tonnes (Mt). Additionally, there is an annual demand of 45 Mt for hydrogen that is part of gas mixtures used as fuel or feedstock, which is not in its pure form. Methanol and steel production are the primary applications for this non-pure hydrogen. Currently the hydrogen in use as pure hydrogen is fossil hydrogen with most of it produced from natural gas (i.e., grey hydrogen) and coal (i.e., black or brown hydrogen). The dependence on natural gas and coal means that hydrogen production today generates significant carbon dioxide (CO_2) emissions. According to the International Energy Agency (2019) 10 tonnes of carbon dioxide are generated per tonne of hydrogen (t_{CO2}/t_{H2}) from natural gas, 12 t_{CO2}/t_{H2} from oil products, and 19 t_{CO2}/t_{H2} from coal. This results in total CO_2 formation of about 830 $MtCO_2$/yr, corresponding to the combined CO_2 emissions of Indonesia and the United Kingdom. Most of this CO_2 is emitted to the atmosphere, although in ammonia/urea plants the concentrated CO_2 streams from steam methane reforming (SMR) (around 130 Mt CO_2 each year) are captured and used in the production of urea fertiliser.

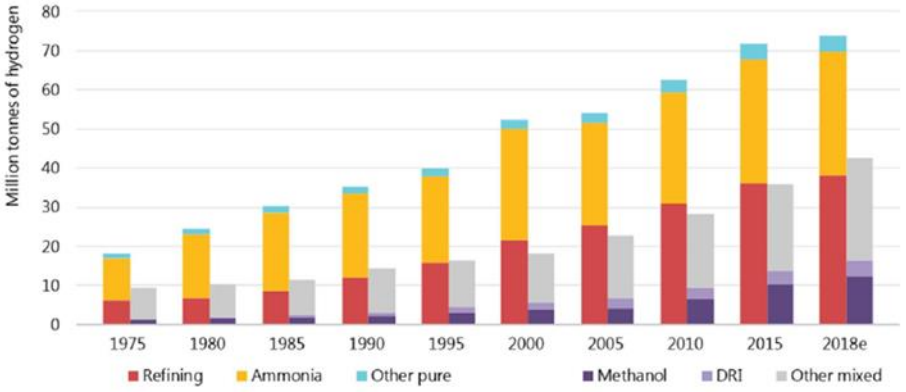


Figure A.1.1: Global annual demand for hydrogen since 1975. DRI: direct reduced steel production. Refining, ammonia and "other pure" represent demand for specific applications that require hydrogen with only small levels of additives or contaminants tolerated. Methanol, DRI and "other mixed" represent demand for applications that use hydrogen as part of a mixture of gases, such as synthesis gas, for fuel or feedstock. From Griffiths et al. (2021)

In a future characterized by decarbonization, the demand for hydrogen in the crude oil sector is expected to significantly decline as the demand for crude oil itself diminishes. This sector currently constitutes the largest consumer of hydrogen. As a result, the remaining demand for hydrogen, predominantly derived from fossil sources, will need to be replaced with more sustainably produced hydrogen, such as renewable hydrogen.

A.1.2.2 Renewable Hydrogen

The Commission's hydrogen strategy defines renewable hydrogen (European Parliament, 2023c) as hydrogen produced through the electrolysis of water powered by electricity from renewable sources or through the reforming of biogas or biochemical conversion of biomass. In EU legislation, renewable hydrogen and hydrogen-derived fuels produced without the use of biomass are referred to as renewable fuels of non-biological origin (RFNBO). The hydrogen strategy defines low-carbon hydrogen the one that is derived from non-renewable sources and produces at least 70% less greenhouse gas emissions than fossil natural gas across its full lifecycle (equivalent to 3.384 kg CO_2 per kg of H_2).

This definition of renewable hydrogen was detailed in February 2023 by the European Commission with the adoption of two Delegated Acts (reported in chapter A.1.3) (European Commission, 2023a) required under the Renewable Energy Directive. These Acts are part of a broader regulatory framework for hydrogen and include targets for renewable hydrogen in the industry and transport sectors.

In addition to defining the conditions for renewable hydrogen production, the second Delegated Act provides a methodology for calculating the life-cycle greenhouse gas emissions of renewable liquid and gaseous fuels of non-biological origin (RFNBOs), including renewable hydrogen. This methodology considers emissions across the entire lifecycle of the fuels, encompassing upstream emissions, emissions associated with electricity consumption, processing, and transportation. It ensures a comprehensive assessment of the carbon footprint of renewable hydrogen and its derivatives, even in cases where it is co-produced in facilities that also produce fossil-based fuels.

The carbon footprint calculation allows for a rigorous evaluation of the environmental impact of renewable hydrogen, facilitating informed decision-making and promoting the use of low-carbon alternatives.

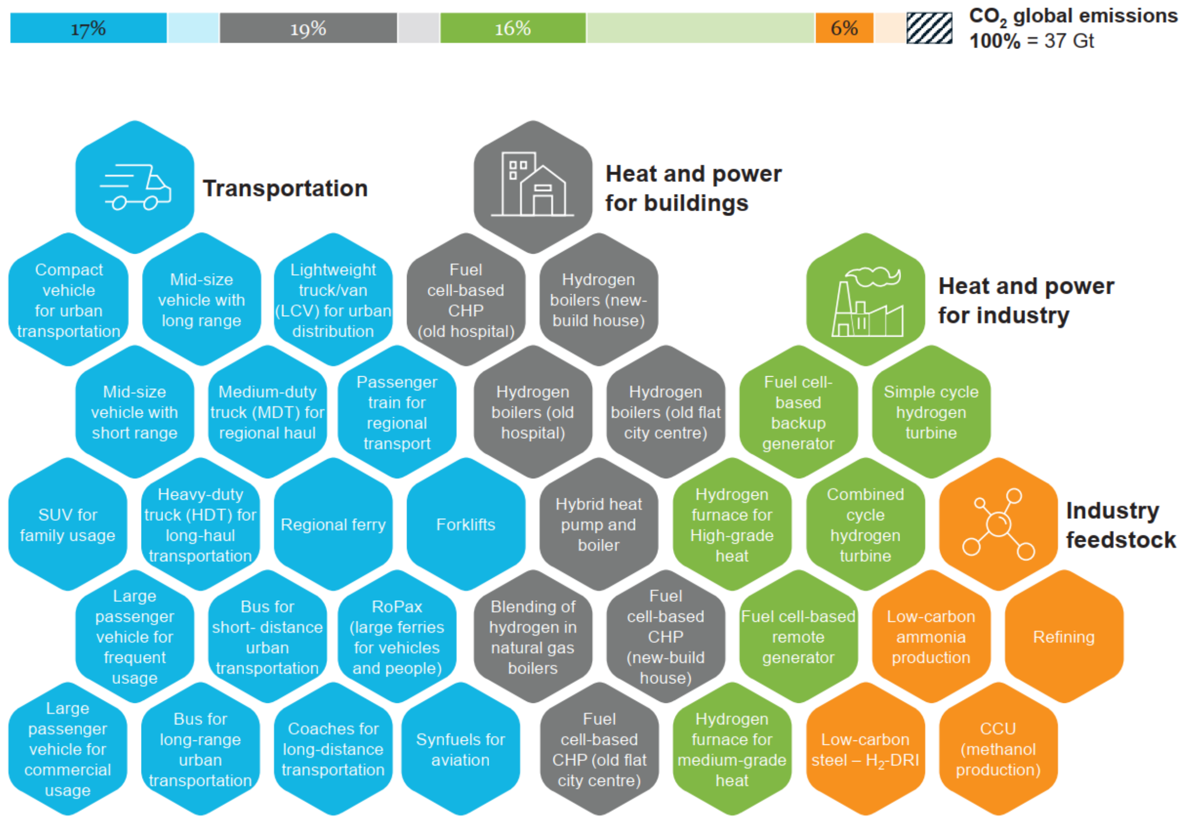
Furthermore, the Acts establish a certification system relying on voluntary schemes to ensure that producers, whether in the EU or in third countries, can demonstrate compliance with the EU framework and trade renewable hydrogen within the Single Market. This enables the tracking and verification of emissions reductions achieved through the use of renewable hydrogen and supports the EU's commitment to reducing greenhouse gas emissions in line with its climate targets.

Among the different certification schemes, the most relevant is the EU CertifHy, an initiative undertaken by a consortium led by HINICIO, composed of the Association of Issuing Bodies (AIB), GREXEL, Ludwig Bölkow System Technik (LBST), CEA, and TÜV SÜD and financed by the Clean Hydrogen Partnership. The CertifHy project aimed to prepare the implementation of "Guarantees of Origin" (GO's) for green and low carbon hydrogen. On March 2023, CertifHy confirmed that it has submitted its renewable fuels of non-biological origin (RFNBO) European Union Voluntary Scheme documents for approval by the European Commission, paving the way for wider hydrogen market trade (Hydrogen Central, 2023).

Besides Renewable Hydrogen (or Green Hydrogen), hydrogen is classified in different colours according to the way it is produced and the resulting GHG emissions. More information on the colour of the hydrogen and its associated production route, can be found here (Hydrogen Europe, 2023a)

A.1.2.3 Hydrogen uses in the future

Looking ahead, the Hydrogen Council, a global initiative comprising leading companies from various sectors across the hydrogen value chain, has identified four main categories as the future applications for hydrogen: transportation, heat and power for buildings, heat and power for industry, and industry feedstock (Hydrogen Council, 2020). These categories encompass a total of 35 highlighted applications, which are visually represented in Figure A.1.2.



In addition, hydrogen can also be used in, e.g.

Mobility: Container ships, tankers, tractors, container ships, motorbikes, tractors, off-road applications, fuel cell airplanes.

Other: Auxiliary power units, large scale CHP for industry, mining equipment, metals processing (non-DRI steel), etc..

Figure A.1.2: Hydrogen Application, from Hydrogen Council (2020)

A.1.2.4 Potential of renewable hydrogen in steel applications

The iron and steel sector are part of the hard to decarbonise sectors together with cement, aviation, refineries, and the petrochemical sectors. Currently, 60% of steel produced in Europe originates from the integrated blast furnace/basic oxygen furnace route (BF/BOF), which emits around 1.9 t_{CO2}/t_{steel}. Other routes, for instance, the natural-gas-based direct reduction of iron ore (NG-DRI) and scrap-electric arc furnace (EAF) generate lower emissions, with 1.4 tCO_2/t_{teel} and 0.4 tCO_2/t_{steel}, respectively ((EUROFER), 2023).

The European steel industry defined six areas of interventions comprising different technological pathways to decarbonise the steel production processes (ESTEP, 2021). Hydrogen and/or electricity will be considered to replace fossil carbon in steelmaking. The use of hydrogen in the blast furnace, direct reduction plant, and the electric arc furnace will significantly increase. If fossil carbon is used, the process gases containing CO_2 will be captured and further processed in order to meet the requirements for utilisation (CCU) and/or storage. CCU processes generally require hydrogen, for instance to generate chemical building blocks or fuels (RFNBO). In addition, higher levels of circularity will be explored by focusing for instance on the recycling of steel, the usage or recycling of residues, and resource efficiency. The availability of zero-carbon electricity and hydrogen is a prerequisite.

RePower EU mentions a decarbonisation pathway for low carbon primary steelmaking based on renewable electricity and green hydrogen. However, the anticipated speed of implementation depends on additional capacity for renewable electricity and green hydrogen, the growth of which is currently not in line with the future needs of the steelmaking industry.

The production of clean steel will require the high availability of **zero-carbon electricity and carbon-free hydrogen** produced from this electricity in both Carbon Direct Avoidance and Smart Carbon Usage pathways. Despite steel production became considerably more energy-efficient in recent decades, the transformation to clean steel will require a significantly higher amount of (green) electricity.

Carbon Direct Avoidance (CDA)

CDA includes technologies that **avoid carbon emissions during steelmaking**. CDA comprises steel production processes based on **hydrogen and green electricity**. For instance, carbonaceous sources can be switched to green hydrogen-based sources. The figure below illustrates an example of how the substitution of the Blast Furnace – Basic Oxygen Furnace (BF-BOF) route by the Direct Reduction (DR) - Electric Arc Furnace (EAF) route for crude steel production contributes to CDA. Hydrogen can be produced via water electrolysis powered by green electricity. The resulting green hydrogen is then used to reduce iron ore in a Direct Reduction (DR) shaft or other breakthrough technologies and the green electricity is used also for the EAF. The implementation of this technology enables the steel producers to reduce their CO_2 emissions by 80 to 95% compared to 1990 levels.

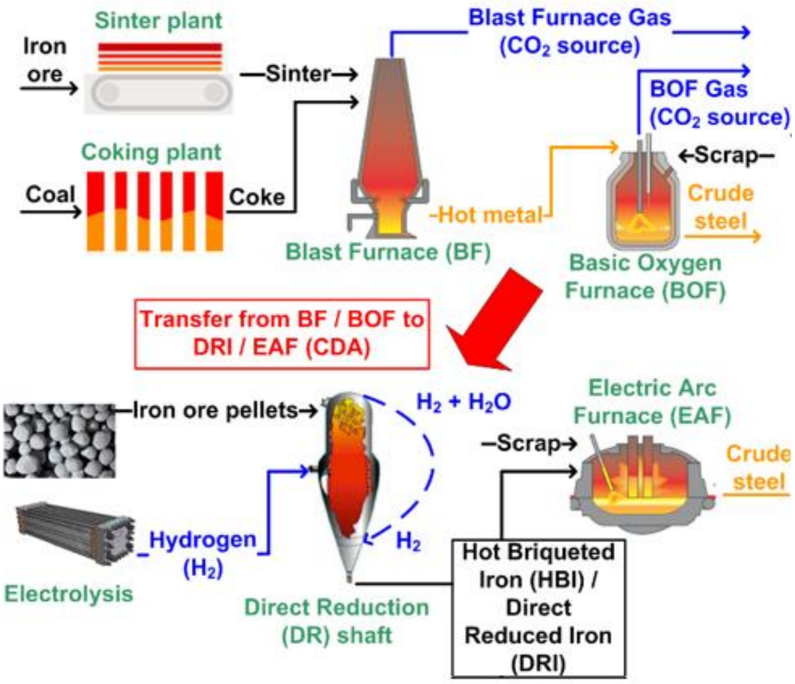


Figure A.1.3: LowCarbonFuture project (2019)

The use of CO_2-free fuels or CO_2-free electricity could lead to CO_2 emissions as low as 60 kg CO_2 per tonne of liquid steel in the **scrap-based EAF** as well as for purely green hydrogen/electricity iron-ore based CDA. The level of 60 kg $CO_2/t_{\text{liquid steel}}$ is an operational minimum as long as the EAF uses graphite electrode and some carbon dioxide is coming from the additions and the alloying material consumption (ESTEP, 2021).

Other gas injection options have the potential for very low CO_2 emissions but need intermediate steps before being ready for full industrial deployment (e.g., injection of high percentages of hydrogen in BF and EAF). Integration of gas injection with CO_2 capture and storage technologies will also contribute to the transition towards CO_2 neutral steelmaking.

- Injection will focus on hydrogen or at least hydrogen-rich gases or biogas to directly avoid the usage of fossil carbon as reducing agent in Blast Furnace, Direct Reduction or Fluidized Bed or as heat source in EAF operation.
- Main focus is on injection in EAF and DRI plants but the injection of hydrogen in BFs can also be rated as the first step towards hydrogen-based DRI.

The HYBRIT technology

SAB, LKAB and Vattenfall are making a joint effort to change the Swedish iron and steel industry fundamentally. Under the name HYBRIT (Hydrogen Breakthrough Ironmaking Technology), they are working together to develop fossil-free steel.

The HYBRIT technology (Hybrit fossil-free steel, 2023) has the potential to reduce Sweden's total carbon dioxide emissions by at least ten percent. This is equivalent to one third of the emissions from the industry and may, in the future, help to reduce emissions from iron and steel production globally.

HYBRIT is conducting trials on the direct reduction of iron ore pellets using hydrogen in the pilot plant in Luleå, Sweden. The plant has a direct reduction shaft, where the reduction takes place, and a number of electrolysers for the production of hydrogen using fossil-free electricity.

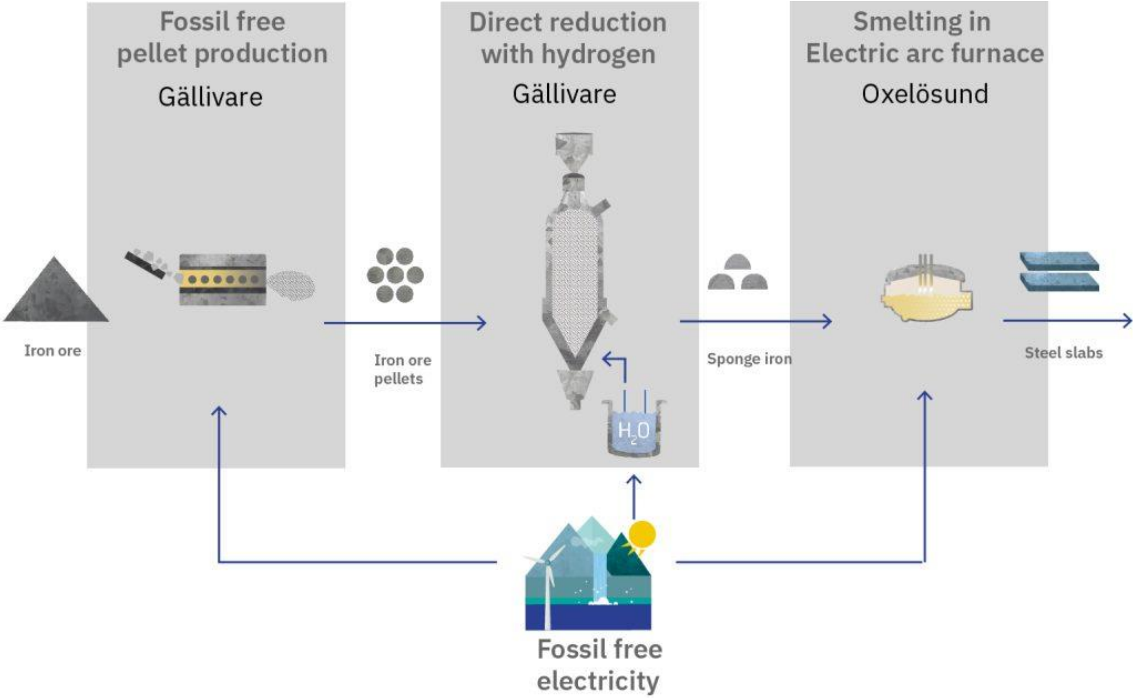


Figure A.1.4: Fossil-free steel production in the HYBRIT Demonstration project (Hybrit fossil-free steel, 2023)

Sixty per cent (94 Mt) of the total steel produced in Europe originates from the BF/BOF route and is more suitable for the hydrogen direct reduction route (H-DRI). Estimates suggest that 94 Mt of 'green steel' would require approximately 37-60 GW of electrolyser capacity, producing approximately 6.6 Mt of hydrogen per year. As a reference, the EU Hydrogen Strategy aims to have 40 GW of electrolyser capacity installed within the EU by 2030. It is estimated that these electrolysers would consume approximately 296 TWh of green electricity per year (European Parliament *et al.*, 2021).

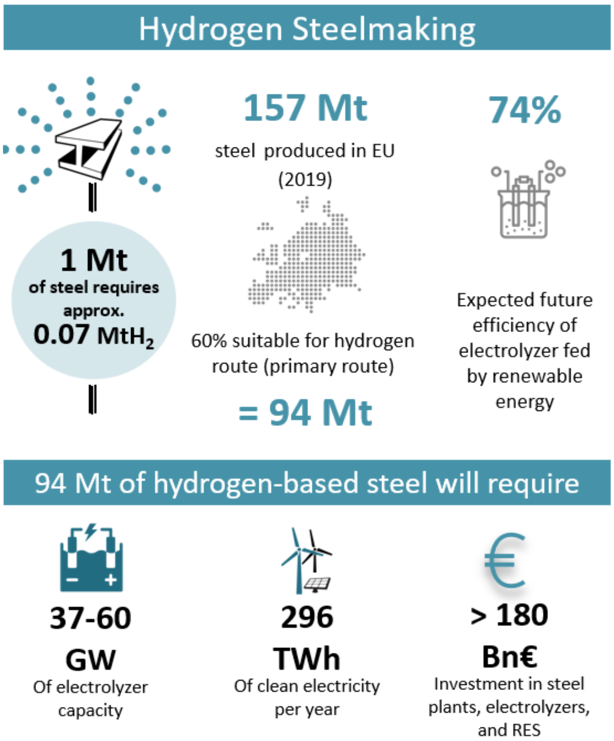


Figure A.1.5: High-level hydrogen-based steelmaking infographic (European Parliament, 2021)

A.1.2.5 Potential of renewable hydrogen in aluminium applications

When looking at the aluminium production, the aluminium primary production is already electrified, and Europe's carbon footprint is one of the lowest in the world. It requires a highly electro-intensive process, with 14-15 MWh electricity use per tonne of primary aluminium produced. This process requires a stable and uninterrupted supply of electricity, although this supply can be cut off for short periods of time in order to offer valuable load shedding services (demand response) to the Transmission System Operator (TSO). For recycling aluminium, the energy needs are significantly smaller, saving 95% of the energy used in primary production and allowing to achieve an equivalent reduction in CO_2 emissions. More specifically, for aluminium rolled sheet, for example, about only one-third of the energy used is originating from electric power. The other two thirds of the energy demand stem from the use of gas for different steps (e.g., refining, re-melting, temperature treatment) during the recycling process. Here, switching from gas to renewable electricity cannot be easily achieved given the significant investment costs and high temperatures needed. Furthermore, the global amount of recycled aluminium available to cover the present and future demand is limited to approximately 40% due to continuous market growth linked to long life spans of major use cycles (e.g., automotive / buildings) ranging between 20 and 50 years.

Hydrogen demonstrates significant potential for integration into the aluminium production process, particularly in areas where natural gas is currently used. Calcination involves high-temperature decompose the hydroxide and obtain alumina powder. By replacing natural gas with green hydrogen as a fuel source in this process, substantial reductions in carbon emissions can be achieved. Within the alumina production, calcination and, leaching process to a lesser extent, consume most of the thermal energy.

Moreover, hydrogen holds significant potential in the realm of aluminium recycling. Presently, the melting and remelting furnaces heavily rely on natural gas for generating heat. For the melting process, approximately 4 MJ of energy is required per tonne of aluminium produced (European Aluminium, 2018).

Considering that a tonne of hydrogen has an energy value of 120-142 MJ (low heating value) and taking into account statistics from European Aluminium indicating that 5 million tonnes of aluminium were produced from recycled sources in 2022, it can be estimated that approximately 30 kg of hydrogen will be necessary for each tonne of recycled aluminium produced, resulting in a total demand of around 0.2 Mt of hydrogen.

While the primary application of hydrogen in the aluminium value chain is expected to be in the calcination and remelting processes, there is additional potential for its use in other stages such as anode baking/cast house in the smelter and melting/pre-heating/annealing in the semi-fabrication phase. These secondary applications could account for an extra 0.3 million metric tonnes (Mt) of hydrogen . Considering energy requirements of 2.5 MJ for both these processes and respective European production levels of 4 Mt and 10 Mt, the total amount of hydrogen needed to completely replace natural gas in the entire aluminium value chain would be approximately 1 Mt annually.

Table A.1.1 presents the calculated data along with the potential CO_2 savings achievable through the use of green hydrogen as a substitute for natural gas.

However, there are still limitations to consider. Barriers to widespread hydrogen adoption in European aluminium production primarily revolve around costs, availability, and technical constraints. Existing gas infrastructure may have limitations in accommodating hydrogen due to legal requirements and technical considerations. Adapting infrastructure and combustion technologies would necessitate substantial investments, given the long lifespan of existing assets.

Furthermore, the growing demand for renewable hydrogen and electricity may result in competition between industries, posing a challenge for widespread hydrogen adoption in aluminium production.

Table A.1.1: Potential of hydrogen needed and CO_2eq Mt/year saved in different parts of the aluminium production where natural gas is currently used

Process	GJ used/ tonne	Yearly European Production (Mt)	Approximate hydrogen needed (annually)	CO_2eq Mt/year (from direct natural gas combustion)	
Alumina Production (from bauxite)	9	7	0.5	4	
Smelter (anode baking/cast house)	2.5	4	0.1	0.8	
Semi fabrication (melting/pre-heating/annealing)	2.5	10	0.2	2	
Recycling (melting)	4	5	0.2	1.5	
Total Demand for Entire Value Chain	1 Mt			Total CO_2eq Mt/year for Entire Value Chain	8.3

Despite these limitations and the limited real-world industrial applications, several companies have explored the use of hydrogen in aluminium production. Below are a few examples:

- In July 2023 Rio Tinto and Sumitomo Corporation collaborate on a hydrogen plant project in Gladstone, Australia, aiming to reduce carbon emissions from alumina production (Rio Tinto, 2021). The Yarwun Hydrogen Calcination Pilot Demonstration Program will utilize hydrogen in the calcination process, leading to a reduction of approximately 3,000 tonnes of CO_2 emissions annually during the trial phase. Full conversion to green hydrogen could result in emissions reductions of up to 500,000 tonnes per year. Construction is set to begin in 2024, with the plant expected to be operational by 2025.
- In March 2023, TRIMET Aluminium SE announced that they will use hydrogen-rich energy gas for process heat in its Gelsenkirchen plant's smelting furnaces (Trimet, 2023). This move is part of their basic conversion program towards climate-friendly and sustainable production, saving around 4,000 tonnes of CO_2 annually.

- In June 2023, Hydro produced the first batch of recycled aluminium using hydrogen fuelled production (Hydro, 2023). In collaboration with Fives, an industrial engineering group, Hydro conducted a test in its extrusion plant in Navarra, Spain, where hydrogen was used as an energy source in the aluminium production process. This test focused on the extrusion stage of the aluminium value chain.
- In June 2023, Novelis stated that they are actively exploring the use of hydrogen in its recycling operations to advance carbon-neutral production (Novelis, 2023). The company received a £4.6 million grant from the UK Government's Industrial Fuel Switching Competition for their Latchford plant. The funding supports hydrogen burning trials to reduce carbon emissions from aluminium recycling operations. The project, conducted in partnership with Progressive Energy, aims to replace natural gas with hydrogen, potentially achieving up to 90% CO_2eq emissions reduction compared to using an equivalent amount of natural gas.

A.1.3 Relevant legislation for production and use of renewable Hydrogen

The European Union (EU) has implemented a series of legislation pertinent to the production and use of renewable hydrogen.

The most relevant for the hydrogen production is the Review of the Renewable Energy Directive. The Renewable Energy Directive (RED II(EU) 2018/2001) (European Parliament and European Council, 2018), enacted in 2018, is a cornerstone in the European Union’s efforts to expand renewable energy use. It establishes a target of 32% renewable energy consumption within the EU by 2030, including a crucial role for Renewable Fuels of Non-Biological Origin (RFNBOs) such as renewable hydrogen, mainly in the transport sector. An RFNBO is defined as a "liquid or gaseous fuel which is used in the transport sector other than biofuels or biogas, the energy content of which is derived from renewable sources other than biomass". This generally includes hydrogen produced by electrolysis and other hydrogen-derived fuels. RED II also sets a greenhouse gas (GHG) emission savings requirement for RFNBOs. From 1st January 2021, RFNBOs need to deliver 70% GHG emissions savings compared to fossil fuels, equivalent to 3.38 kg CO_2 per kg of hydrogen in lifecycle emissions. If it meets this requirement, it counts towards the Member States' renewable energy targets. Furthermore, the average share of electricity from renewable sources in the country of RFNBO production, as measured two years before the year in question, determines the proportion of RFNBOs deemed renewable. In the context of RED II, the concept of "additionality" becomes pivotal. Additionality asserts that electricity is 100% renewable if there is a direct connection between the renewable electricity generator and the RFNBO producer, provided that no electricity from the grid is used for RFNBO production and the renewable electricity generator comes into operation at the same time or after the RFNBO producer.

The EU Commission's 2023 delegated acts provide further details on GHG savings and additionality, two years later than initially required by RED II. These delegated regulations set out rules for RFNBOs' production, stipulating that renewable electricity generation and hydrogen production must coincide temporally and be geographically correlated, meaning the renewable electricity generator must be located in the same bidding zone or an interconnected bidding zone with electricity prices equal or higher than where the hydrogen is produced. On the other hand, RED III, the proposed revision, broadens the scope of RFNBOs by eliminating the transport sector restriction used in RED II. It clarifies that RFNBOs would count as renewable energy, regardless of the end-use sector. If the proposed amendments are adopted, the delegated acts would apply to renewable hydrogen in all sectors. A trilogue agreement reached in March 2023 further underscores the importance of renewable hydrogen, setting targets for an increase in renewable energy use in industry and requiring that a certain percentage of hydrogen used in industry and transport be renewable by specific dates.

Thus, both RED II and RED III directives are instrumental in the EU's renewable hydrogen strategy. They foster the creation of a regulatory environment that will aid in the development and implementation of renewable hydrogen technologies and infrastructure, ultimately accelerating the transition to a low-carbon economy.

The European Union Emissions Trading System (ETS) is one of the key strategies used by the EU to combat climate change and reduce greenhouse gas emissions cost-effectively. It's the world's first major carbon market and is based on the 'cap and trade' principle. This principle sets a limit or 'cap' on the total amount of certain greenhouse gases that companies can emit. Companies covered by the ETS, such as power plants and industrial factories, receive or buy emission allowances, and they are allowed to trade these with one another. This structure gives companies the flexibility to cut their emissions in the most cost-effective way. Over time, the cap gets lower, reducing the number of allowances and driving companies to make bigger emission cuts. In the context of hydrogen, this becomes particularly relevant. Hydrogen is an energy carrier that, depending on its production method, can contribute to significant carbon emissions or can be virtually carbon-free. 'Grey' hydrogen, produced from natural gas without carbon capture, leads to high CO_2 emissions and thus requires a significant amount of ETS allowances. 'Blue' hydrogen, also produced from natural gas, but with carbon capture and storage, leads to fewer emissions. The least carbon-intensive is 'green' hydrogen, produced through electrolysis powered by renewable energy sources. However, the ETS impacts green hydrogen indirectly by influencing the cost of electricity, a significant factor in green hydrogen production. (European Parliament, 2023f)

The Carbon Border Adjustment Mechanism (CBAM) is another cornerstone of the EU's climate policy, proposed as part of the European Green Deal (European Parliament, 2023a). The European Parliament has proposed to introduce hydrogen in the CBAM from the start, gradually replacing the system of free allowances. The CBAM is intended to prevent 'carbon leakage' (Official Journal of the European Union, 2019), where companies move their operations to countries with less strict climate regulations, thereby undermining the EU's emissions reduction efforts. It would act as a carbon tax on imported goods, adjusting the price of imports based on their carbon content. In terms of hydrogen the CBAM framework could have a notable impact on its import and production (Marcu *et al.*, 2023). Imported hydrogen produced using carbon-intensive methods ('grey' and potentially 'blue' hydrogen) would likely become more expensive, making domestically produced 'green' hydrogen more competitive. This could stimulate local green hydrogen production and help the EU reach its goal of becoming a climate-neutral economy by 2050. However, there are potential complications. The CBAM might drive changes in hydrogen trade flows and influence how hydrogen is exported. For example, hydrogen producers might opt to export hydrogen in forms not covered by the CBAM, such as in the form of derivatives like ammonia, methanol, or synthetic gases. This could result in circumvention of CBAM charges, known as 'resource shuffling', potentially undermining the effectiveness of the mechanism. Additionally, hydrogen importers could face an increased administrative burden due to CBAM compliance procedures, potentially acting as a non-tariff trade barrier. Despite these challenges, the CBAM could play a vital role in achieving the EU's ambitious climate goals by encouraging the use of cleaner hydrogen production methods.

Other EU legislation can affect the hydrogen production and usage. These are:

- The upcoming ReFuelEU aviation legislation mandates a specific quota for sustainable aviation fuels, including RFNBOs which will be implemented from 2030. (European Parliament, 2023e)
- The proposed FuelEU maritime regulation along with an accompanying agreement encourages the use of RFNBOs in maritime transport. They propose to set a target for RFNBO usage from 2034, given that the RFNBO share in 2030 does not exceed 1%. (European Parliament, 2023h)
- The alternative fuels infrastructure regulation is designed with an objective to enhance the availability of hydrogen refueling infrastructure.
- A proposed revision of the Energy Taxation Directive could potentially advantage renewable hydrogen by increasing taxes on fossil fuels. (European Parliament, 2023g)
- The suggested gas and hydrogen regulation (European Parliament, 2023d) and directive (European Parliament, 2023b) are focused on easing network access and promoting the market presence of renewable and low-carbon gases. This includes low-carbon hydrogen, characterized as hydrogen originating from non-renewable sources with a greenhouse gas emission profile that is 70% lower than that of fossil fuels over their lifecycle. The exact calculation for these GHG savings from low-carbon fuels is expected to be specified in another dedicated act by the end of 2024 (European Commission, 2023e).

A.1.3.1 Hydrogen pricing and supply: the European Hydrogen Bank

The European Commission has proposed to produce 10 million tonnes of renewable hydrogen by 2030 and to import 10 million tonnes by 2030. To reach this goal, the European Hydrogen Bank has been established. The European Hydrogen Bank (EHB) has the aim to stimulate domestic production and importation of renewable hydrogen in the EU. The Bank is projected to be fully operational by the end of 2023 (European Commission, 2023b).

The primary goal of the EHB is to create a domestic hydrogen market within the European Union and facilitate the import of hydrogen by addressing the investment gap and accelerating investment. The financing system of the European Hydrogen Bank (EHB) encompasses various mechanisms to support the creation of a domestic hydrogen market within the EU and promote international hydrogen production. These mechanisms are designed to provide financial assistance and incentives to producers of renewable hydrogen. Here are the key aspects of the financing system:

- Domestic market creation: The EHB utilizes fixed premium auctions as a financing mechanism to support EU-based production of renewable hydrogen (the EC has not, as yet, elaborated on what will be considered as renewable hydrogen for the purposes of EHB investment, but it is expected that the term will be aligned with the definition laid out in the final versions of the Delegated Acts). Producers participating in these auctions will receive a fixed-price payment per kilogram of hydrogen produced for a maximum duration of ten years. The European Commission is currently in the process of designing the auction system for renewable hydrogen production within the EU.
- Innovation Fund: The EHB leverages the Innovation Fund to back the initial phases of the fixed premium auctions. The Innovation Fund provides financial support for innovative low-carbon technologies and projects, including those related to renewable hydrogen production. The first pilot auctions under the EHB are expected to be launched in autumn 2023, backed by 800 million Euro from the Innovation Fund.
- EU Auction Platform: To ensure coordination and prevent market fragmentation among EU Member States, the EHB establishes an EU auction platform. This platform offers "auctions-as-a-service" for Member States, using resources from both the Innovation Fund and national budgets. By utilizing this platform, renewable hydrogen projects can be funded without violating EU State aid rules. The auction platform allows for a single auction, where the Innovation Fund budget is used first, followed by Member States' budgets until they are exhausted.
- International hydrogen production: The EHB aims to facilitate the import of renewable hydrogen from third countries. To cover the cost gap between renewable hydrogen produced in these countries and its transportation to the EU, the EHB may establish an international financing mechanism. For fast-track financing of hydrogen imports, a green premium scheme (similar to fixed premium under the domestic pillar, through auctions) is under assessment, which will be capable of providing financial support to foreign hydrogen producers while ensuring long-term contracts of hydrogen supply at a fixed price for EU off-takers. For long term, the European Commission is analysing two solutions: The European Commission is proposing two options for enabling international purchases of hydrogen in the long term (Hydrogen Europe, 2023b).
- The first option involves the establishment of EU governance structures, such as the Team Europe initiative or the Aggregate EU proposal, which would allow EU joint purchases of hydrogen worldwide. This approach could solve the budget issue by relying on national contributions, potentially supplemented by EU top-ups. However, its implementation might take several years, potentially delaying mass imports of hydrogen to the EU, and could face challenges related to the necessary infrastructure for such deliveries. The second option involves building on the experience of existing mechanisms like the German H2Global model. This scheme would aggregate resources from interested partners, both public and private, to purchase hydrogen or derivatives from international markets and redistribute them to the targeted EU Member State(s) that provided the budget. While this solution has potential, it would also require time to create a new legal entity capable of acting as an EU market platform. Both options aims to facilitate international purchases of hydrogen, but they differ in their approaches and potential implementation timelines.

Regarding the actual prices of producing hydrogen, there are not many data available. According to an article from Independent Commodity Intelligence Service (Stones, 2023), their data reveals that renewable hydrogen prices in Europe could be as low as 1 €/kg, thanks to the support provided by the European Hydrogen Bank. According to ICIS assessment data from 4 April, renewable hydrogen produced in the Netherlands using a 10-year renewable power purchase agreement (PPA) starting in 2026 would cost 4.58 €/kg on a project breakeven basis. The assessment considers the recovery of the capital investment for the electrolyser over the duration of the PPA. Thus, by the end of the subsidized period, costs would be recovered. Considering that hydrogen producers could receive the full subsidy of €4/kg (cap of the subsidies), it means that only 0.58 €/kg of hydrogen would be required to achieve capital cost recovery. Therefore, producers would need to charge buyers less than 1 €/kg to ensure project breakeven.

The cost of production of renewable hydrogen is intrinsically tied to the renewable energy used to produce it. An article from Aurora Energy Research (2023b), from January 2023, analysed the cost to produce in Germany and to import renewable hydrogen. According to their study, renewable hydrogen production costs in Germany range from 3.90 to 5.00 €/kg H_2 by 2030, according to Aurora Energy Research. Co-locating electrolysers with solar and onshore wind generation offers the lowest costs. Importing renewable hydrogen from countries like Australia, Chile, Morocco, and the United Arab Emirates is economically attractive compared to domestic production costs in Germany. The cost of producing renewable hydrogen in Morocco is projected to be 3.2 €/kg H_2 by 2030, while in Chile and Australia, it is estimated to be 3.1 €/kg H_2. The United Arab Emirates (UAE) has a slightly higher cost of 3.6 €/kg H_2. When considering the additional transport and conditioning costs, importing hydrogen from Morocco to Germany via liquid hydrogen transport would cost 4.58 EUR/kg H_2. Using alternative methods such as liquid organic hydrogen carriers (LOHC) or transporting hydrogen as ammonia would result in costs of 4.68 EUR/kg H_2 and 4.72 €/kg H_2, respectively. Importing hydrogen from Australia and Chile would be competitive if transported as ammonia, costing 4.84 €/kg H_2 and 4.86 €/kg H_2, respectively. However, importing hydrogen from the UAE would not be cost-competitive, with the cheapest method (transporting as ammonia) estimated at 5.36 €/kg H_2. Another article from Aurora Energy Research (2023a) from March 2023, mentioned that by 2030, Ireland could produce green hydrogen at a minimal cost of 3.50 €/kg H_2, leveraging the country's abundant wind resources, which would make it the cheapest in Europe. However, the research also points out that without supportive policy interventions, the cost of green hydrogen, created through electrolysers powered by renewable energy, could be 82% higher than natural gas.

An article of the Financial Time of May 2023 (Palladino, 2023), estimates that while the European Hydrogen Bank and other initiatives provide support, additional capital investment is needed to meet the scale and demand for hydrogen. The author made a rough estimation of the costs of producing hydrogen and of the capital investment required. Here are the key calculations highlighted in the article:

- Renewable Electricity Cost: Generating 500 million tonnes of hydrogen annually would require nearly 25,000 TWh of renewable electricity, which is approximately 100 times the current electricity demand in the UK. The estimated investment for the required infrastructure, such as solar panels and wind turbines, is around $8 trillion.
- Electrolyser Cost: Electrolysers are used to split water into oxygen and hydrogen. The current cost of electrolysers is approximately $1,500 per kW, but it is expected to decrease to around $250 per kW by 2050. Taking a midpoint of $875 per kW, the estimated capital expenditure (capex) requirement for electrolysers would be around $7 trillion.
- Infrastructure Cost: The cost of transport and storage infrastructure for hydrogen depends on the specific technology. Repurposing gas pipelines and storage sites is the cheapest option, while supply chains involving ammonia are more expensive. The overall capex for infrastructure is estimated to be around $5 trillion.
- Total Capital Expenditure: Adding up the costs mentioned above, the total estimated capital investment required for producing and transporting 500 million tonnes of hydrogen annually would be approximately $20 trillion.

It's important to note that these calculations provide a rough estimate, and the actual costs may vary based on future technological advancements and market dynamics. Additionally, the article acknowledges that these figures do not consider operating costs and the return on capital for investors.

Therefore, while the European Commission has made significant investments in deploying green hydrogen in Europe, meeting the scale and demand for hydrogen may necessitate additional capital investment for infrastructure and technology. As the hydrogen sector evolves, these estimates will likely change due to advancements in technology and shifts in market conditions.

A.1.4 EU Initiatives and Partnerships

The European Union's hydrogen initiative includes several key elements, such as the Clean Hydrogen Partnership (Clean Hydrogen JU), the Clean Hydrogen Alliance, the Hydrogen Valleys, and the Hydrogen Energy Network. These initiatives are designed to promote investments, stimulate clean hydrogen production and use, and accelerate the decarbonization of industries in line with climate change objectives.

The Clean Hydrogen Partnership, also known as the Clean Hydrogen Joint Undertaking, is a unique public-private partnership in Europe that supports research and innovation in hydrogen technologies. Its main goal is to strengthen and integrate the EU's scientific capacity to accelerate the development of advanced clean hydrogen applications. The partnership is composed of three members: the European Union represented by the *European Commission*, the fuel cell and hydrogen industries represented by *Hydrogen Europe,* and the research community represented by *Hydrogen Europe Research*. (Clean Hydrogen Partnership, 2023)

Established in November 2021 as the successor of Fuel Cells and Hydrogen Joint Undertaking (FCH JU), the Clean Hydrogen JU operates under the Horizon Europe program. It is financially supported by the EU with 1 billion euro for the period 2021-2027, and private members of the partnership will contribute an equivalent amount of investment, raising the total budget to over 2 billion euro. The Clean Hydrogen JU aligns its research and innovation activities with the EU's Hydrogen Strategy and related policy developments to contribute to its implementation.

The partnership's primary focus is on renewable hydrogen production, as well as hydrogen transmission, distribution, and storage. Additionally, it concentrates on selected fuel cell technologies for transport, buildings, and industry applications.

Since 2014, the Clean Hydrogen Partnership's predecessor, FCH JU, has been developing the concept of "Hydrogen Valleys," which has evolved from the earlier concept of "hydrogen territories." The Clean Hydrogen Partnership is now investing in these Hydrogen Valleys and hydrogen production, aiming to solidify the EU's global leading position in electrolyser production. They also provide project development assistance and established a dedicated global platform for Hydrogen Valleys, facilitating the exchange of best practices and fostering collaboration. (European Commission, 2021b)

Hydrogen Valleys are regional ecosystems that integrate hydrogen production, transportation, and various end uses like mobility or industrial feedstock. They play a crucial role in advancing hydrogen technologies and promoting a sustainable hydrogen economy. The concept has gained significant momentum and has become a top priority for both industry stakeholders and the European Commission, with the goal of scaling up hydrogen deployments and establishing interconnected hydrogen ecosystems across Europe.

In a Hydrogen Valley, the focus is not only on demonstrating the efficient functioning of hydrogen technologies but also on their synergy with other elements such as renewable production, gas infrastructure, electricity grid, and batteries. The objective is to showcase the concept of "system efficiency and resilience," emphasizing the overall energy and economic efficiency of the integrated system rather than just the efficiency of individual applications. On the Hydrogen Valley Platform website all information on large-scale hydrogen flagship projects is reported. (The Hydrogen Valley Platform, 2023)

In July 2020 the European Union launched the European Clean Hydrogen Alliance with the aim to promote investment and encouraging the production and use of clean hydrogen. It is a part of the European Union's efforts to ensure industrial leadership and accelerate the decarbonization of industries in alignment with climate change objectives. (European Commission, 2023c)

Since its inception in July 2020, it has achieved notable milestones, such as publishing a report on barriers to large-scale hydrogen deployment, presenting a pipeline of investment projects, and organizing an Electrolyser Summit with a commitment to increase manufacturing capacities tenfold.

Moreover, twice a year, the Hydrogen Energy Network take place. The Hydrogen Energy Network is an informal group of representatives from the energy ministries in EU countries that aims to help national energy authorities build on the opportunities offered by hydrogen as an energy carrier. It acts as an informal platform to share information on good practices, experience and the latest developments in hydrogen, and to work jointly on specific issues. (European Commission, 2023d)

A.2 Definition of scope and goals for inventory analysis of Life Cycle Assessment case studies (RWTH-IOB, SWERIM)

The first step of a Life Cycle Assessment (LCA) consists of the definition of goal and scope. This phase has significant relevance to the intended application and subsequent phases. Also, these statements may be modified throughout the analysis, due to their iterative nature. In the following, the goal and scope definition for the steel cases and the aluminium cases are described. In relation to the steel cases, a ladle preheater in the facilities of Celsa (CEL) and a walking beam furnace at SSAB will be studied. On the other hand, in relation to the aluminium cases the following processes will be analysed: a reverberatory melting furnace in the facilities of C-TEC (CTEC), a rotary furnace at Befesa (BEF), a preheating station for liquid transfer at MYT with a holding furnace (MYT), a preheating furnace at Speira (SPE) and a artificial ageing furnace at Toyota (TME). In the project steel case demos will also be performed at Swerim (SWE) and Arcelormittal Sestao (AMS) and Arcelormittal Olaberria-Bergara (AMOB), however, no LCA will be performed on those cases. All actions described in this report and carried out during the LCA work in the project are in accordance with standards 14040 and 14044 which describes the procedure for producing an LCA. (International Organization for Standardization, 2006a, 2006b)

A.2.1 Goal definition

The goal of the LCA is to study how the environmental impact and emissions from different heating solutions within aluminium and steel industry will change when fossil fuel is replaced with hydrogen. Throughout this section, the main area of interest desired to accomplish in the LCA will be described. For that purpose, the intended application, the reasons to carry out the study and all the entities related to this study (audience, commissioners, and partners) are explained in the following.

A.2.1.1 Application and involved parties

The purpose of the Life Cycle Assessment (LCA) in this project is to assess the environmental impact of different approaches when implementing H_2 technologies. The retrofitting and greenfield study that will be assessed is based on the results of the demonstration of H_2 heating solutions in aluminium and steel production processes. The results from the LCA for the H_2 technologies will be compared with the actual environmental situation of the respective fossil fuel heating technology of the baseline scenarios.

The LCA investigations will study the environmental performance of Hydrogen in comparison with the current situation of natural gas or fossil oxyfuel in the energy-intensive industries of steel and aluminium. The LCA will give significant information for the industrial partners to identify the main sources of possible environmental impact, for example emissions of greenhouse gases, on their product portfolio. Therefore, it enables the possibility of reducing the CO_2 emissions of this industry sector, considering the objective of European long-term decarbonization goals and implementing a strategy for this purpose. The LCA will also provide significant data to align with forthcoming regulations related to emissions. Although the primary focus of the project is a technological evaluation, this LCA work will additionally provide an ecological and sustainable approach.

The resulting LCA report serves to inform the European Commission and the scientific and research community (universities, R&D companies, aluminium and steel industry and hydrogen producers). More into detail, special interest is focused on the participating industrial partners, their customers, stakeholders, and shareholders. In addition to this, other groups may be interested in the outcome, such as policymakers, NGOs (focused on the environmental impact of energy-intensive industries), legislation and certification experts or sustainability entities.

The project is funded by the European Union as part of the research and innovation program Horizon Europe with funding-ID 101091456.

In the study, partners from several different sectors are included. BEF, CTEC, MYT, SPE and the EAA belong to the aluminium sector, CEL, SSAB, AMS/AMOB, and the European association ESTEP belongs to the steel sector and TME represents the automotive industry. Danieli, GHI Hornos are furnace manufacturers, and SICK support the project with their know-how about measurement technology. Finally, the Institute of

Industrial Furnaces and Heat Engineering (IOB) from RWTH Aachen University and Swerim (SWE), which is a Swedish metals research institute, will be responsible for performing the LCAs for the aluminium and steel cases, respectively. TME will perform the LCA for their case.

A.2.2 Scope definition

In this section, the scope of the LCA is given. The scope describes the limits and conditions that will be met during the work. For that purpose, the functional unit, system, elements, boundaries, and limitations are explained. Then, more focus is laid on every case in section A.2.2.4. More in particular, this section explains the study context and the product system in detail. The final sections A.2.2.5, A.2.2.6 and A.2.2.7 focus more on the content of the LCA by presenting the methodology, impacts and data requirements.

A.2.2.1 Functional unit

The Functional Unit (FU) will be one ton of aluminium/steel output which is heated from a lower temperature T1 to a higher temperature T2. In the cases of ladle preheating, the functional unit will be the yearly number of ladles, including its refractories, which will be heated from a lower temperature T1 to a higher temperature T2. A more precise definition of the functional unit for all the different cases will be formulated when the LCA modelling begins and will be described in the final LCA report (D7.2).

A.2.2.2 System, elements, boundaries, and allocation procedure

The relevant system element and the system boundaries will as far as possible be similar for all the studied cases and the LCA will have a gate-to-gate approach.

The process for heating within the system boundary will be the specific furnace used in each case respectively. For the two cases where the preheating of ladles is studied, the process for heating is the preheating station used. In the preheating case for steel, there is no product to be heated, only the ladle itself is heated and given as output for further use. For the SSAB-case also the descaling unit is part of the heating process. Within the system boundary, primary data will be used for the heating process and the production of hydrogen. In the reference case, secondary data will be used for the production of fossil fuels (mainly NG).

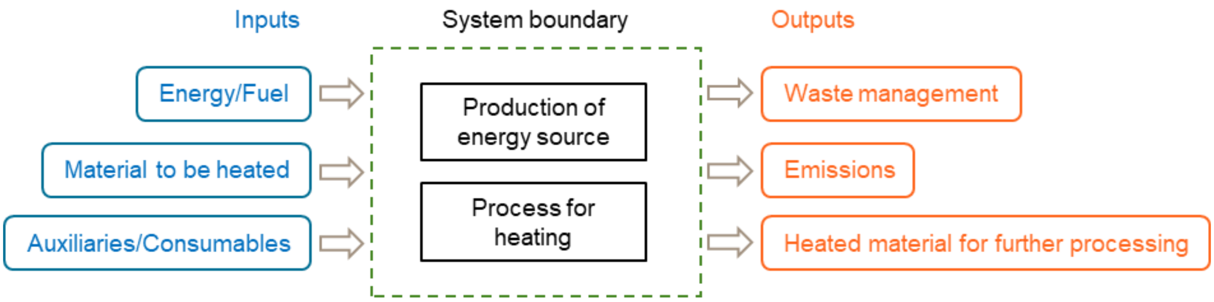


Figure A.2.1: Overview of the relevant system elements and the system boundary of the studied cases. For the steel case where heating of the ladle is studied there are no materials to be heated nor any heated material for further processing.

For the primary data, no allocation will be considered since there are no co-products in any of the cases and the few by-products that arise will be allocated according to every case. On one hand, considering the steel case, the only by-product considered is the scale, which is used in further processes. Therefore, for the CEL and SSAB cases the allocation will be addressed accordingly.

On the other hand, related to the aluminium case, the only by-product is the dross, except the case of Toyota, because it is a heat treatment process. This component will be used in other tasks of the project. However, similarly as commented in the aforementioned paragraph, every demo will individually allocate the dross. Therefore, every case will be addressed appropriately.

For secondary data, the ecoinvent database will be used. In the database, the allocation method APOS (allocation at the point of substitution) is used.

A.2.2.3 Usability and limitations

The results of the study can be used to increase the understanding of environmental sustainability aspects when integrating H_2 in different heating solutions within the aluminium and steel industry. It can also be used as a basis for decision-making in the industry's work to reduce the environmental impact of their processes.

Due to the gate-to-gate approach of the study, the focus in the LCA will be on the specific processes where H_2 is used. This means that raw material extraction and pre-processing of the material to be heated will not be included in the LCA. Similarly, the "End of Life", i.e., material handling when a product manufactured from the heated material has reached the end of its useful life, will not be included. Since the LCA system will start at the input of the studied furnaces and end at the output of the same furnaces, respectively, no transports, besides the transport and production of fuel, will be included in the LCA.

Further assumptions may arise during the modelling phase and have to be added later on accordingly. Due to the iterative nature of LCA, this procedure is common practice.

A.2.2.4 Study context and product systems

Throughout this section all the unit processes with their product and elementary flows will be explained. It is important to mention that the downstream and upstream processes from every demonstrator individually are not considered. Therefore, the analysis only covers the process which occurs in the furnace or ladle with the limitations and assumptions mentioned in section A.2.2.3. Also, all the information presented in the flowcharts show the current situation of the process. Moreover, all the flows were taken from the industrial partners and adapted to the LCA model. Therefore, the inputs and outputs from these flowcharts are modified in order to fit the LCA requirements. These modifications are defined as assumptions.

Industrial-size reverberatory melting furnace at CTEC

CTEC is the main research and technology centre of Constellium located in France. Constellium is a global leader in the development and manufacturing of aluminium products. They participate in the project with a reverberatory melting furnace of 12 tonnes of capacity. This furnace is equipped with two natural gas burners, which will be compatible with the replacement of hydrogen.

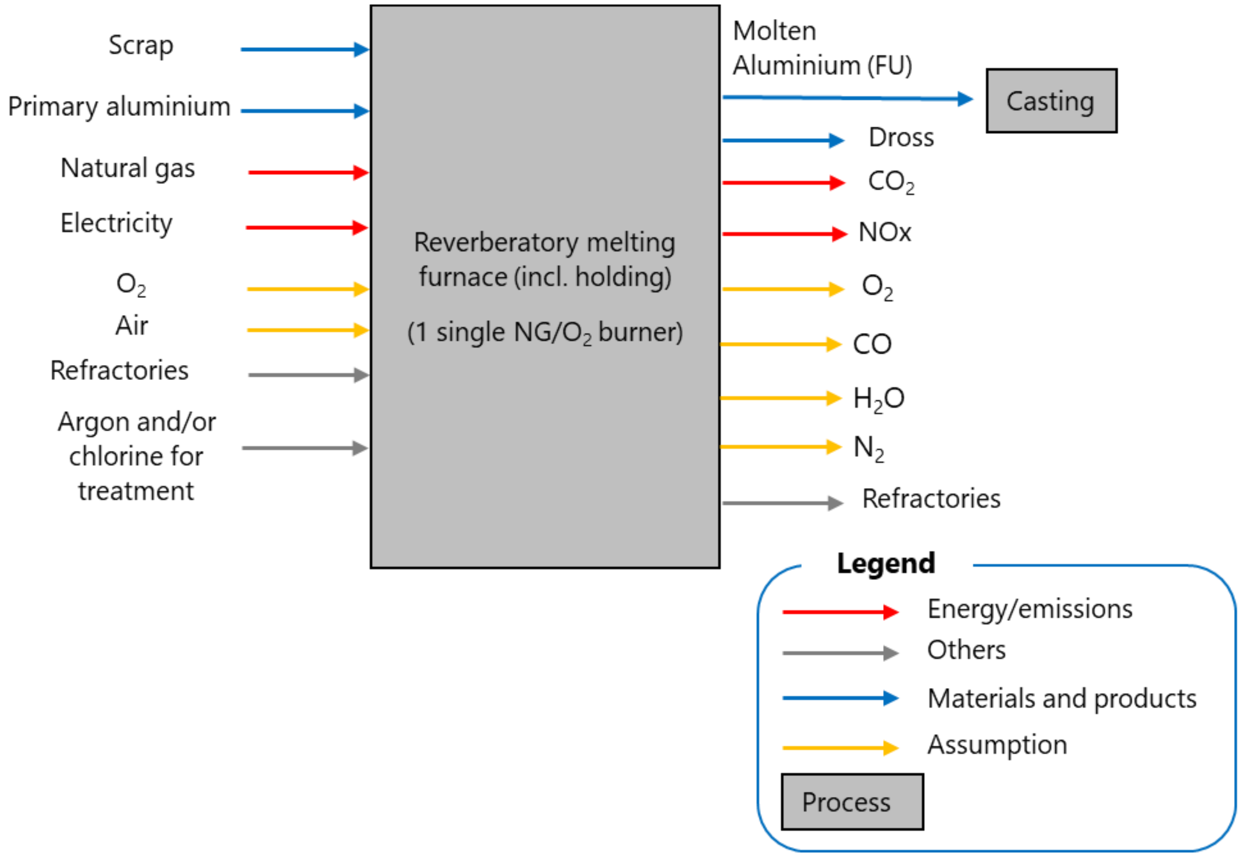


Figure A.2.2: Flowchart of the current status of the reverberatory melting at CTEC (simplified). The natural gas will be replaced by H_2 or H_2 mix (from 0 up to 100% of hydrogen).

The product system for the reverberatory melting furnace case at CTEC is a process step of aluminium scrap remelting for the secondary aluminium industry. In this case, Figure A.2.2 explains graphically the elementary flow of the aluminium scrap remelting process through a reverberatory melting furnace. The function of this product system is the production of liquid aluminium from scrap.

Rotary furnace at BEF

BEF is a leading international company that provides innovative sustainable solutions for the management and recycling of industrial residues. For this project, they will work in Spain with a rotary melting furnace of 1 tonne of capacity. This furnace is mainly used in the secondary aluminium industry for refining and remelting purposes. Along this part of the project, the remelting furnace will be replaced by a new tilting rotary furnace. In this furnace a burner with a mix of natural gas/hydrogen (0 - 100%) and oxygen will be installed (TRL 5).

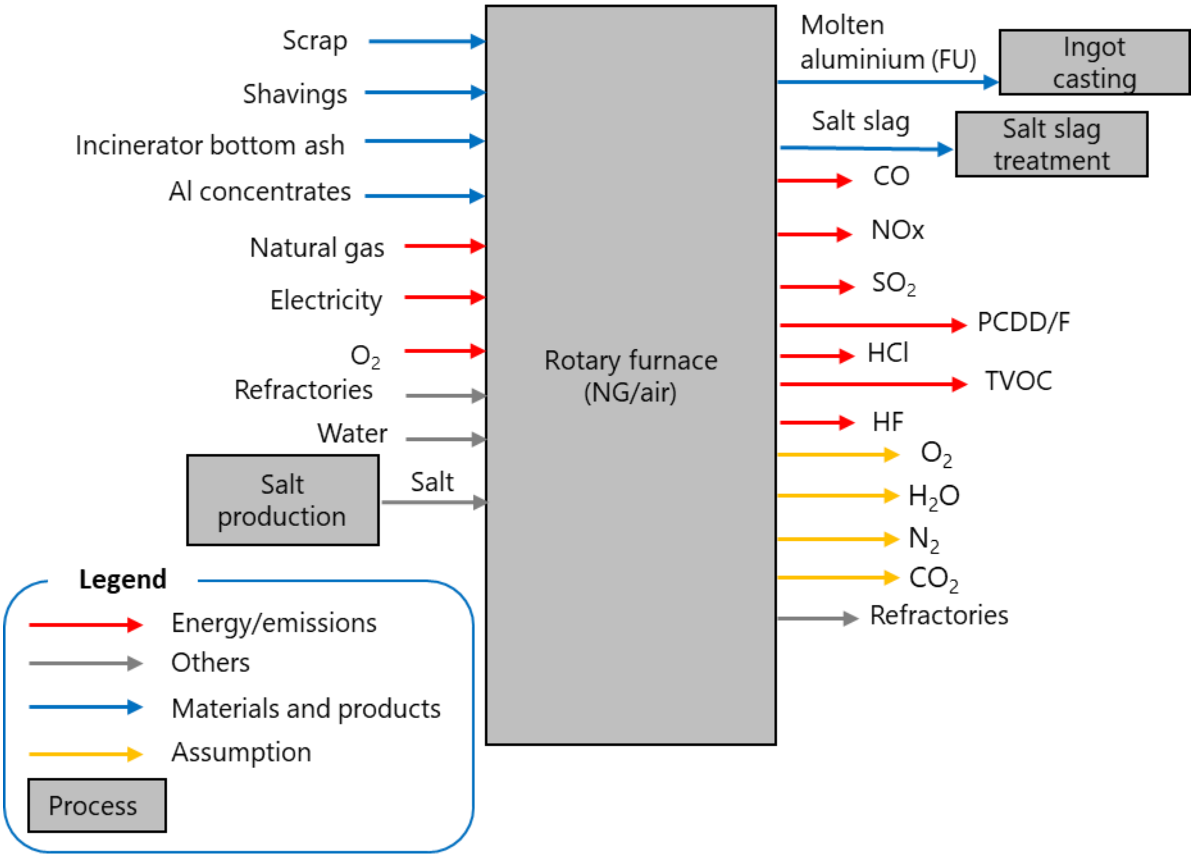


Figure A.2.3: Flowchart corresponding to the current status of the rotary furnace at BEF (simplified). In this case, a mix of NG/H_2 and O_2 burner in the new furnace will be installed.

The product system for the rotary furnace case at Befesa is a process step of aluminium scrap refining for the secondary aluminium industry. Thus, the function of this product system is the production of liquid high-purity aluminium from scrap. The Figure A.2.3 shows the aforementioned unit process including product flows.

Preheating station for liquid metal transfer at MYT

MYT is located in the plant Agios Nikolao in Greece. In this facility 195 kt of aluminium is produced per year. It will contribute to the project with a ladle preheating station for liquid metal transfer. More in detail, the 6t ladle that is installed there will be studied (TRL 5). This equipment is currently using natural gas and air burners for holding aluminium metal.

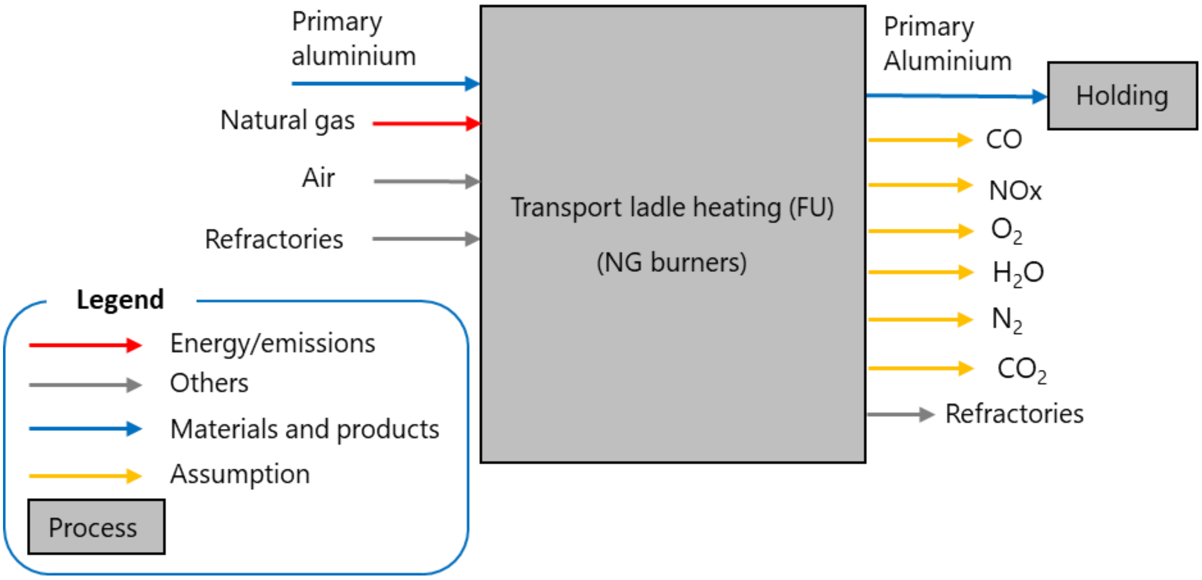


Figure A.2.4: Flowchart corresponding to the current status of the ladle preheater at MYT (simplified). it will be retrofitted to a H_2 mixed with O_2 demonstration.

In this case, two different processes are going to be considered: the preheating of the ladle and the holding process at a 35t furnace. The product system for the preheating station case at MYT is focused on the ladle preheating process. In particular, the function of this product system is the heating of the ladle for further transportation purposes of molten aluminium. This process is presented in Figure A.2.5.

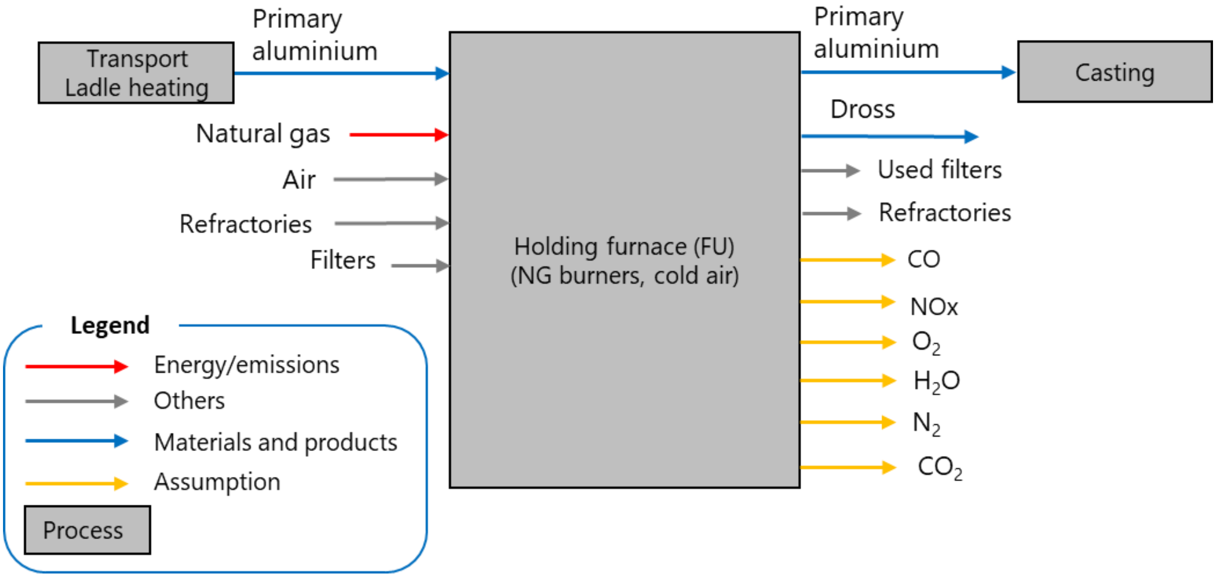


Figure A.2.5: Flowchart corresponding to the current status of the 35t holding furnace at MYT (simplified). In this case the retrofitting will be to a H_2/air heating.

In the same preheating station case at MYT, a study will also be done on the 35t holding furnace. The function of this product system is to maintain the temperature of the molten aluminium and the process is graphically described in Figure A.2.5.

Reheating furnace at SPE

SPE is a company with over a century of experience in Germany and Norway. In this case, the plant site is located in Germany. This manufacturer specializes in advanced rolled aluminium products and produces approximately one million tonnes per year. They will contribute to the project by providing a pusher-type furnace for ingots preheating. In particular, this furnace is made off 60 radiant tube burners (11 MW), 6 temperature zones and 10 burners per zone (TRL 4). In the project it will be retrofitted to an indirect fired reheating system with H_2 and air.

The product system of the aforementioned facility is a process of secondary aluminium reheating. The functional unit of this product system consists of preheating aluminium previous to hot rolling. This process is represented in the following flowchart.

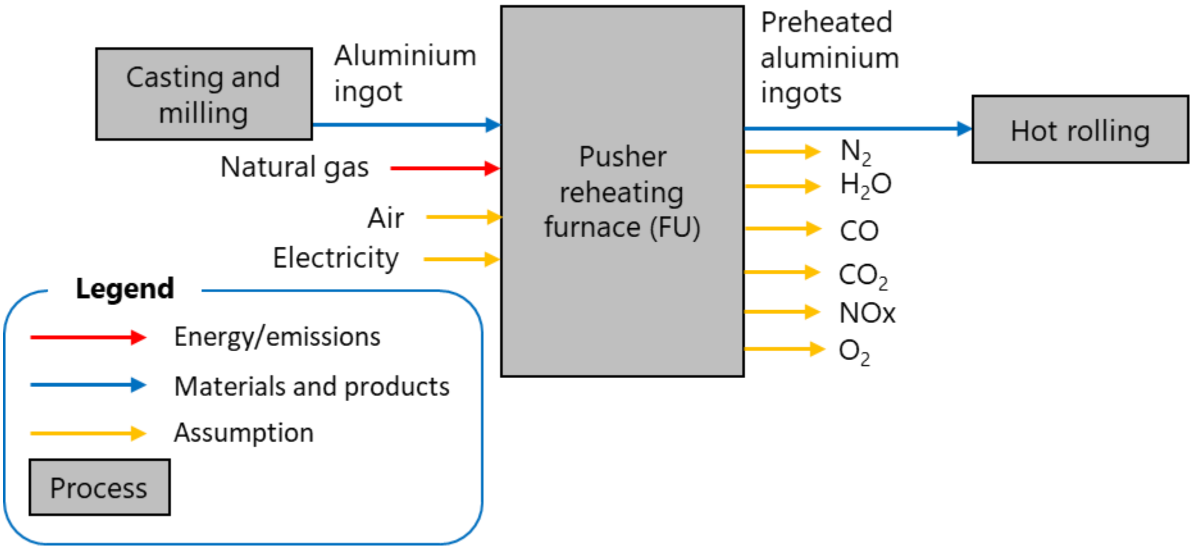


Figure A.2.6: Flowchart corresponding to the current status of the preheating furnace at SPE (simplified). In this case, the retrofitting will be to a H_2/air heating.

Artificial ageing furnace at TME

TME has several plants in Europe, one in which the Hydrogen implementation will occur. TME will contribute with their unit plant in Poland, where die-casting heads are heat treated. In particular, this heat treatment process is selected due to the relatively high furnace gas consumption/energy demand when compared to other operations. Therefore, they will participate with an artificial ageing furnace with one burner using natural gas and air (TRL 4). In this project they will make a demonstration of Hydrogen and air and H_2/O_2 in a production environment.

The product system for the annealing furnace case at TME is a process of aluminium heat treatment. Furthermore, the function of this product system is the improvement of the mechanical and chemical characteristics of the part. This process is graphically represented in Figure A.2.7.

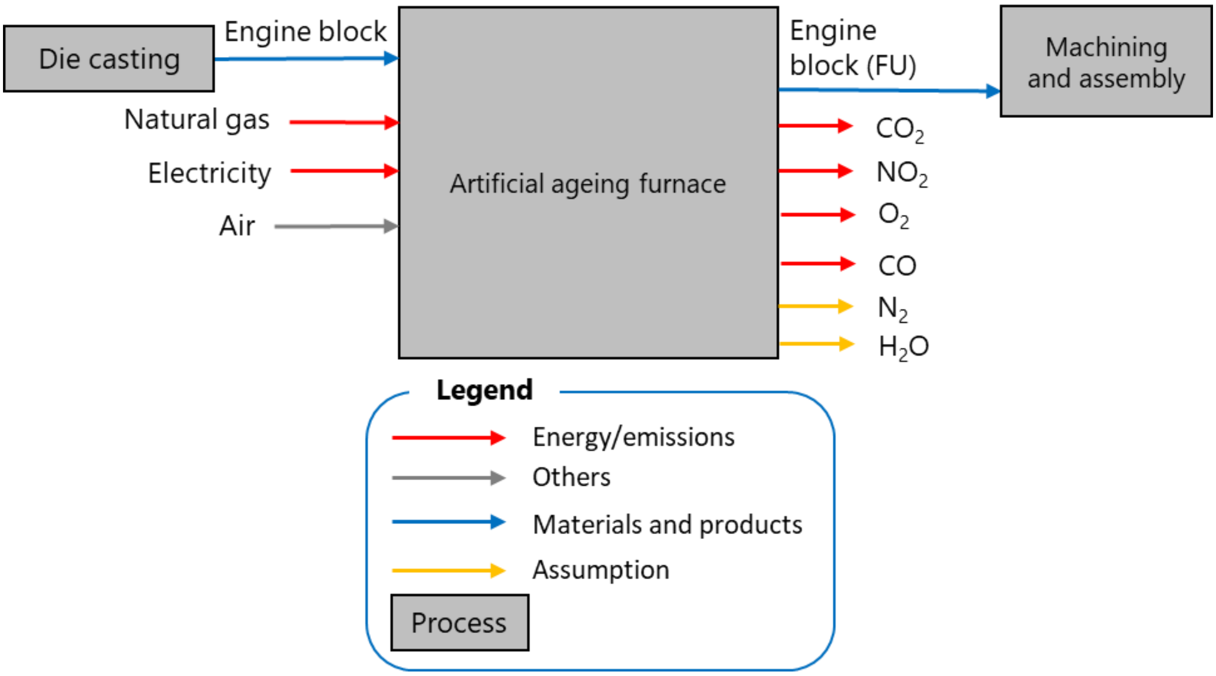


Figure A.2.7: Flowchart corresponding to the current status of the artificial ageing furnace at TME. In this case, there will be a demonstration of H_2 with O_2 and air.

Ladle preheater at CEL

CEL is a steel producer based in Mo i Rana (Norway), that produces around 600 kt/year of reinforced steel. In order to minimize thermal shock when pouring melted steel into the ladles used in production, as well as reducing temperature drop of the melt in the ladle and improving furnace life, the ladles are being preheated. In this project a burner using CO, combusted with air, as fuel, used today in the preheating station will be substituted by a H_2/O_2 combustion system. For the demonstration, trials with pure H_2 and NG/H_2 blends are planned. The evaluated H_2/O_2 system is at an industrial scale, however not production ready and only tested for a shorter time. In this project the aim is to reach TRL 7.

The product system at CEL is a process of ladle preheating, used in steel production. The ladle is to be used in a ladle furnace however the studied case is only the preheating of the ladle (Figure A.2.8), thus the function of this product system is to warm a ladle.

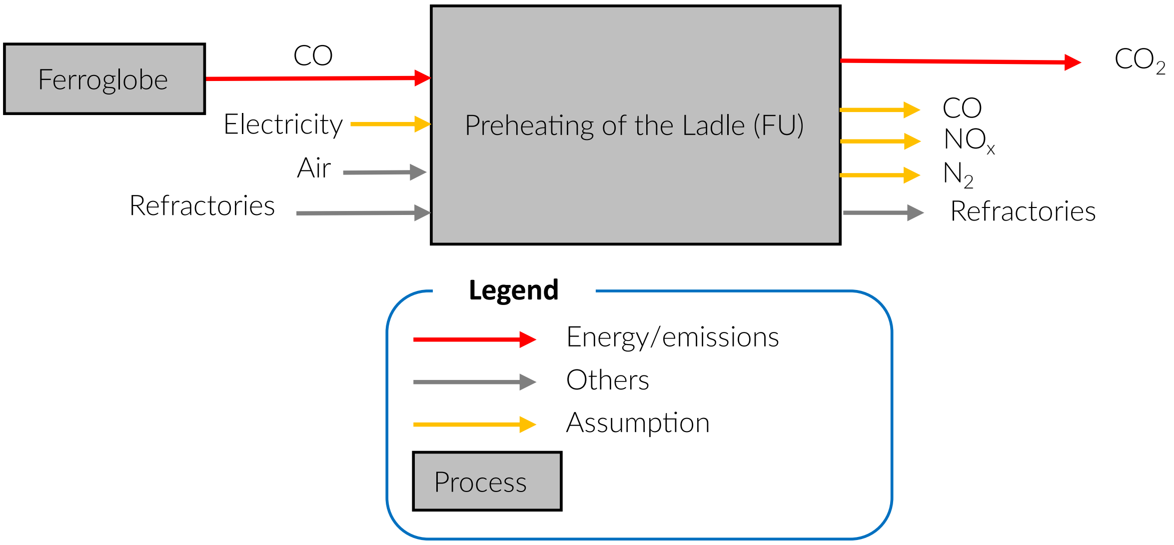


Figure A.2.8: Flowchart of the ladle preheating at CEL. The CO gas will be replaced with an H_2/O_2 combustion system where it is possible to also use NG instead of H_2 together with the O_2.

Greenfield study on the walking beam furnace at SSAB

SSAB is a global steel company producing advanced high-strength steels and quenched & tempered steels. They operate in over 50 countries and have a production capacity of about 8.8 million tonnes. In this project the walking beam furnace at their Oxelösund site in Sweden will be the subject of a greenfield study. The greenfield study will be a full-scale theoretical furnace (TRL 2) using hydrogen as fuel, and its environmental performance will be compared to a baseline study of SSAB's existing industrial-scale walking beam furnace running on fossil fuel.

For the walking beam furnace at SSAB the product system is a process of steel reheating, and the function of the product system is the heating of the steel slabs. A flowchart of the existing process is shown in Figure A.2.9. The greenfield study will start from the results of the retrofitted walking beam furnace demonstrator at Swerim and will be adapted according to the possibilities at the site of SSAB in Oxelösund (Sweden). In the greenfield study the possibilities to fire the walking beam furnace with oxygen-enriched H_2 instead of the traditional fossil fuel will be examined. For this to be possible a new design of the furnace will probably be needed including new dimensions, adjustments of the heating/soaking and conductive zones and a possible redesign of the off-gas system. The aim is a production capacity of over 100 t/h of slabs for hot rolling, with a special focus on energy demand, still keeping the required heating curves and a flexibility in the production. The specific flowchart for the greenfield study will be decided upon during the project.

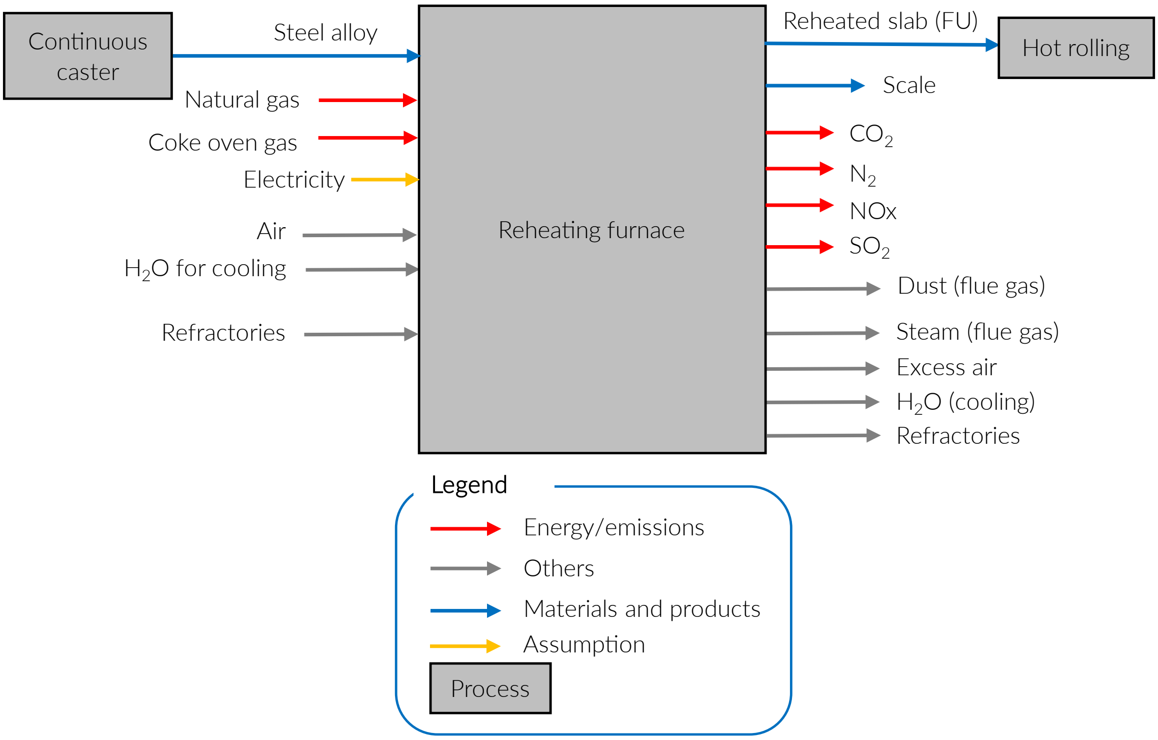


Figure A.2.9: Flowchart of the existing walking beam furnace at SSAB. In the project the burners using natural gas, coke oven gas and air will be replaced with O2-enriched H2 burners which will give corresponding changes in the output.

A.2.2.5 LCIA methodology

For the LCA modelling software, Umberto® LCA+ version 10 and SimaPro version 9 will be used for the aluminium and steel cases, respectively. For background data, the database ecoinvent® 3 will be used for all the cases. This database was chosen because it is mostly used by the scientific community in LCA applications. The impact assessment methodology will be ReCiPe 2016-Midpoint v1.13.

A.2.2.6 Types of impacts

In the following table, the types of environmental impacts categories considered in the LCA are shown. Other impact indicators may also be studied in more detail if they show a great impact when introducing H_2 as a fuel.

Table A.2.1: Impact categories applied in the LCA. Based on (European Aluminium, 2023c)

Impact category	Unit	Acronym
Global Warming Potential	kg CO_2 eq	GWP
Freshwater Eutrophication	kg P eq	FET
Ionizing radiation	kg U235 eq	IR
Marine Eutrophication	kg N eq	MET
Ozone Depletion	kg CFC-11-eq	ODE
Particulate Matter Formation	kg PM10-eq	PMF
Terrestrial Acidification*	kg SO_2-eq	TAP

*(instead of acidification, mol H+ eq)

A.2.2.7 Interpretation, data requirements and critical review

The standards ISO 14040 and ISO 14044 (International Organization for Standardization, 2006a, 2006b) suggest numerous possibilities to reach a proper assessment of the outcomes from the LCA. Completeness, consistency, and sensitivity tests will be performed to reach this objective. Furthermore, the initial identification of significant parameters to study will be done as well. Due to the iterative nature of the LCA work a first proposal/suggestion of significant parameters are done in task 1.1 corresponding to WP1, but they will get revised later. Nevertheless, the list of process parameters will be developed at the last phase of the LCA.

As stated by the ISO, the aforementioned standards require a critical review from an external partner expert in the topic. Nevertheless, in this case, it will be performed by other partners also responsible for this deliverable.

Regarding data requirements, the following criteria will be considered:

- Temporal: the project is framed from 2023 until 2026. Therefore, the primary data corresponds to the trials done on work packages 5 and 6 designated for 2025. More into detail, the aluminium cases, which belong to the WP5 will happen between month 19 and 36 of the project. For the steel cases, all the demonstrations will occur between month 16 and 36 of the project. Furthermore, secondary data will be taken from the database ecoinvent 3 as mentioned in previous sections. Also, another source of secondary data will be literature, which will be accordingly documented. The baseline data will be yearly averages from previous years, preferable within the last five years.
- Geographical: regarding the aluminium cases, their locations are the following: the industrial-size reverberatory furnace from CTEC is located in Voreppe (France), the rotary furnace from BEF is in Valladolid (Spain), the preheating station from MYT is situated in Biotia (Greece), the pusher reheating furnace from SPE is in Hamburg (Germany) and the artificial ageing furnace from TME is located in Walbrzych (Poland). Regarding the steel cases, their locations are the following: CEL´s ladle preheater is located in Mo i Rana (Norway) and data from the pilot walking beam furnace in

Luleå (Sweden) will be used in the green field study of the walking beam furnace at SSAB in Oxelösund (Sweden).

- Precision: this study uses data directly measured in the facilities. If this data cannot be measured or determined accurately, the researchers will estimate them based on trusted literature.
- Completeness: all the data gathered will be merged with datasets obtained from literature and various other pertinent sources. Additionally, validations of the data are conducted by performing mass and energy balance analyses.
- Consistency: the methodology is applied uniformly over all the different components by all the partners.
- Representativeness: all the data that will be used in the LCA-work will cover the temporal, geographical and technological criteria aforementioned. Therefore, the data is possible to be considered representative.
- Reproducibility: the presented information on modelling and the explanations regarding the data basis enables the results to be reproduced.
- Data sources: all the data will be taken from the same sources as the one corresponding to the temporal criteria. Therefore, industrial partners, scientific databases and expert estimates will be the sources of information.
- Uncertainties: possible uncertainties related to the used primary data are the ones corresponding to the measurements. Uncertainties about the estimations are valued at a maximum of 5-15% (Rypdal, Kristin, 2006).
- Data security: to ensure that the LCA report adheres to data security protocols and protects sensitive information, the implementation of measures that safeguard data confidentiality, integrity, and availability will be implemented. Moreover, a database management plan is addressed through the project to improve it.

A.3 Definition of scope and concept for Multi-layer plant level Material Flow Analysis case studies (NTNU-EPT)

In this section, the scope and concept for the plant-level material flow analysis case studies are defined. First, the scope and benefits of plant-level MFA is explained. This is followed by the general procedure of the MFAs and a concept for evaluating the industrial partners/plants in terms of their suitability for conducting a more in-depth MFA case study.

A.3.1 Scope definition

MFA models can be used to map and simulate relevant stocks and flows of total mass and individual chemical elements for products, by-products, waste, energy, and emissions for value chains such as steel or aluminium production. In addition, MFA can be used on a plant-level as well as on a regional, European, or global scale (WP7). Plant-level multilayer (ML) MFA models can be used to track flows and stocks of different chemical elements such as aluminium, iron, hydrogen, or carbon.

According to Billy et al. (2022), ML MFA can support the industry in:

- Quantifying GHG emissions of their facilities or plants based on mass balance consistent physical accounting;
- Identifying emission mitigation strategies to reach emission reduction targets – such as enhancing resource efficiency, substituting energy carriers, and improving specific processes; and
- Identifying new levers to improve the sustainability performance of an industrial site by addressing systemic effects.

For HyInHeat, the goal of the MFA models will be to analyse the impact of the fuel switch from fossil fuels to hydrogen and potential systemic effects to increase resource efficiency and reduce emissions within the industrial plants. Switching from natural gas or other fossil fuels to hydrogen combustion can lead to changes in the processes and flows of the production chain. The necessary infrastructure for hydrogen production and use as well as different energy demand, emissions and by-products compared to natural gas combustion need to be taken into account.

When hydrogen is produced within the system boundary of a plant, the energy and material demand need to be included in the MFA system. The amount and composition of by-products such as dross or scale can change due to the use of hydrogen and there are no direct carbon emissions when hydrogen combustion is used (in contrast to natural gas where CO_2 is emitted). However, NOx emissions need to be taken into account when using hydrogen as a fuel.

By using ML MFA models these changes can be modelled, analysed, and visualised to support the industry in the transformation process towards a carbon neutral production. Also, potentials for efficiency improvements can be discovered for both, general process optimization and hydrogen usage. This would not only be beneficial for HyInHeat but might also result in a tool for resource and emission monitoring and planning that can be used by the industrial partners.

Within HyInHeat the following industrial partners will update or retrofit their fossil combustion processes to hydrogen combustion or conduct brownfield and greenfield studies:

- ArcelorMittal Innovation (AMI)
- ArcelorMittal Sestao and ArcelorMittal Olaberria-Bergara
- Celsa
- Swerim
- SSAB
- Befesa
- Constellium Technology Center
- Mytilineos
- Speira
- Toyota Motor Europe

These cases are explained in more detail, including flow-charts of the industrial plants, and analysed in terms of their suitability for a plant-level MFA study later in this chapter.

The goal in WP2 will be to map the flows of materials, emissions, and energy within selected existing plants at various stages of the steel and aluminium supply chain. Hereby, up to 3 representative plants will be selected to perform more in-depth case studies.

However, to address the points mentioned above and to draw conclusions about systemic effects within the plants, it will be essential to include not only the demonstrator processes which will be retrofitted to hydrogen during the project, but also up- and downstream processes inside the plant. This will require close collaboration with the industrial partners.

A.3.2 Concept and procedure of plant-level multilayer material flow analysis

Material flow analysis (MFA) is described by Brunner and Rechberger (2004) as “a systematic assessment of the flows and stocks of materials within a system defined in space and time”. The system itself and all processes examined inside the system are balanced for total mass and selected chemical elements as well as energy. This makes the method attractive as a decision-support tool in resource, waste, and environmental management. In general MFA systems consists of processes, stocks, and flows and a system boundary.

Processes could describe the transport, transformation, or storage of materials. Stocks are material reservoirs or stored material, which can stay constant, increase (accumulation of material) or decrease (depletion of materials). Processes are linked by the flows.

Flows and stocks can either be measured or calculated via mass balance for each process (Eq. A.3.1) or transfer coefficients. Transfer coefficients describe the percentage of a total throughput or input that is transferred into a specific output good, for instance material efficiencies or chemical compositions.

$$\sum_i \dot{m}_i = \sum_o \dot{m}_o + \dot{m}_{storage} \qquad \text{Eq. A.3.1}$$

$\dot{m}$	Mass flow of in- or outputs
i	Inputs
o	Outputs

Temporal boundaries describe the time span over that a system is investigated and balanced. Commonly used are 1 h, 1 day or 1 year. Geographical boundaries can be a company, a region or in our case an industrial plant.

For the plant-level ML MFAs in WP2 the following steps will be followed:

1) System definition
2) Quantification for total mass and selected substances
3) Mathematical model formulation and calibration
4) Scenario development
5) Evaluation and interpretation

The system definition includes the determination of the temporal and geographical system boundaries of the steel and aluminium production routes and the relevant processes. The temporal boundaries or units depend on the available data, whereby flows per 1 year or per production of 1 ton of product are preferred. As described above, the physical/geographical system boundaries are preferred to include the demonstrating process as well as relevant up- and downstream processes. For instance, when the demonstrator process is a reheating furnace of steel slabs prior to hot rolling, it would be useful to include the steelmaking or scrap melting, the casting, and the rolling as well. In the case of not enough data the goal is to include as many relevant processes as possible. The system definition also includes the definition of all system parameters, so the determination of all relevant materials within the processes, all flows between processes and all flows entering or leaving the system boundary. Relevant materials are the aluminium and iron flows themselves, alloy elements, (by-) products or waste, auxiliaries, energy, and emissions.

To quantify all system variables, measured production data (e.g., production capacity, energy consumption or yield) will be used wherever possible. This will be provided by the industrial partners. Alternative data sources are material databases and literature.

For the modelling, all system variables and unknows are listed, necessary equations, such as balance and model approach equations, are defined. The modelling can take place in Excel as a first step and can be supplemented by models in python for more demanding calculations and visualizations. The models are built modularly and can thus be easily substituted and compared with the ones after switching to hydrogen combustion.

Production and recycling rates will be calculated within the material flow models. Different scenarios will be calculated so that material flows can be compared and evaluated with and without the new hydrogen technologies. The results are discussed and interpreted with the industrial partners. In case of inconsistencies, inaccuracies or major deviations, the models are adapted iteratively.

A.3.3 Choice of industrial plants for in-depth case studies

Although SSAB and CEL for the steel sector and SPE for the aluminium sector are planned to collaborate for the plant-level MFAs, it is still needed to evaluate which plant should be analysed in more detail. The goal is to gain valuable insight about the production chains with and around the demonstrating processes. Hence, it is intended to focus not only on the three cases mentioned above, but to also keep the options open to analyse other plants if this is beneficial. Simplified flow-charts of the production chains which is connected to the demonstration processes are shown in the figures below and are based on the questionnaires and further assumptions. The system boundaries are planned include as many processes in the industrial plants as possible. However, this can be adjusted based on the industrial partners and according to data availability.

In order to choose which demonstrators are suitable for a more in-depth case study, the criteria below are taken into account. To analyse these, ratings in a range from 0 (not suitable) to 3 (very good) are used (Table A.3.1). Together with an average rating, which is set to 0 when one criteria is rated with 0, this gives an overview of the potential industrial partners for the plant-level MFAs.

- Scale of demonstration
  - To be able to compare the reference case with fossil fuel heating directly with a production chain (partially) using hydrogen combustion, it would be beneficial if the demonstrator process will be actually retrofitted within HyInHeat. This would enable to base the modelling on measured data for material flows, energy demand, emissions. Thus, greenfield or retrofitting studies (without an actual retrofit) are less favoured for the plant-level MFAs.
- Data availability
  - Real process data should be available and industrial partners should be motivated to provide this information. For in-depth case studies, close collaboration with the industrial partners and plants is key. A first indication on the data availability and motivation to share the data can be gained from the questionnaires sent out during WP1.

- Additional workload
    - The additional workload for the industrial partners due to the in-depth case studies should be minimized. While it is planned for some demonstrator processes to collaborate more for the plant-level case-studies in Task 2.6 (CEL, SSAB and SPE), for some other processes it is only planned to adopt the MFAs and LCAs from WP2 based on the demonstration of H_2 heating solutions in WP5 and WP6 (MYT, BEF, CTEC, SPE, TME, CEL, SSAB). And for some (AMS, AMOB), no participation at all in MFA or LCA studies was planned. The capacities of the industrial partners to handle this (additional) workload and to provide the necessary data determines the level of detail which is feasible in the MFA case studies.
- Relevance
    - The production quantities, energy demand and emissions should be relevant in an European and/or global context. This means that the process or plant should operate on an industrial scale to be able to model a real industrial production chain. The energy demand of the demonstration process and/or the production chain should be at a relevant level to contribute to significant energy demand and emissions reductions.
- Systemic effects
    - The benefit of plant-level MFAs is also to gain insights about systemic effects within the plant. Examples are the improvement of the resource or process efficiencies by optimizing material flows and coordination between different processes. Also, synergy potentials between processes in terms of hydrogen production and/or use can be identified.
- Location of the plant
    - Plants should be accessible to visit them in an efficient way from Trondheim in Norway, where NTNU as the task leader of task 2.6 is located, whereby this criterion is not critical for the success of the plan-level MFA studies. Plant visits could also be combined with project meetings in the partner countries. The locations of the industrial partners are shown in Figure A.3.1.
- Sector
    - Case studies for both, the aluminium, and the steel sector, should be conducted in order to analyse both value chains.

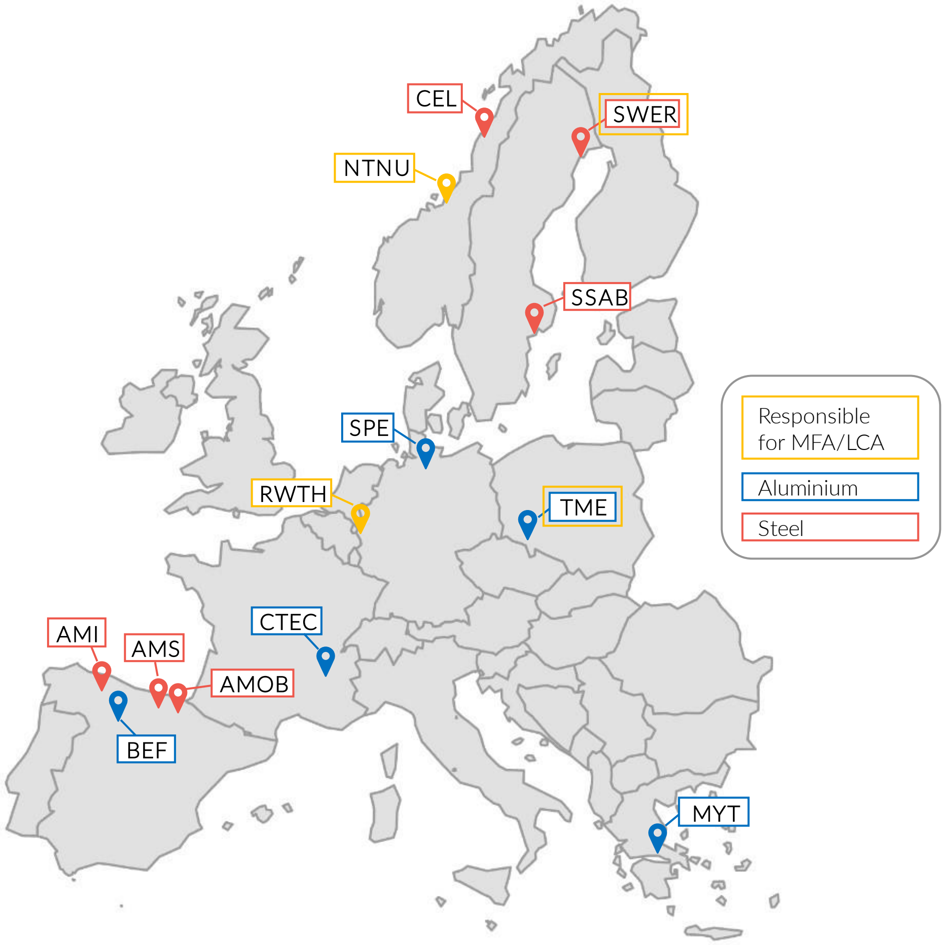


Figure A.3.1: Locations of industrial partners, demonstrators, and responsible partners for MFA and LCA case studies

All plants with only test or pilot scale processes are not suitable for the case studies since they are usually not connected to other industrial processes within the plant. Also, analysing systemic effects would not be possible. Thus, the processes of ArcelorMittal Innovation (AMI) and Befesa (BEF) can already be removed from the list of potential plants since they only have test or pilot processes.

SSAB's steel plant in Oxelösund

The steel reheating furnace of Swerim is only at a pilot scale, so relevance and systemic effects are low, but it is planned to be retrofitted to hydrogen combustion (H_2/air, H_2/oxygen enriched air (OEC), H_2/O_2) (Task 6.2), leading to a high scale of demonstration. The results from the retrofit will be used to draw conclusions about the greenfield study of the walking beam furnace of SSAB in Oxelösund. Even if the scale of demonstration and data availability is low due to only having a greenfield study, the results from the retrofit at SWER will be used to draw conclusions for SSAB's greenfield study. Thus, a collaboration with both partners would be meaningful for the plant-level MFA. The data available from SWER are detailed and their close cooperation to SSAB enables a close cooperation with both partners. Including the plant of SSAB would allow to cover the systemic effects when analysing their industrial scale rolling mill. SWER is only running tests on their pilot scale reheating furnace without having up- and downstream processes. The blast furnace steel making route at SSAB is planned to be replaced by an electric arc furnace route by 2027. A simplified flow chart showing the material, energy, and emission flows is shown in Figure A.3.2. The locations are Luleå and Öxlesund in Sweden for SWER and SSAB, so reachable from Trondheim. The additional workload is low, since SSAB is planned to contribute to the plant-level MFAs and SWER is already involved for the MFA and LCA case studies in WP6.

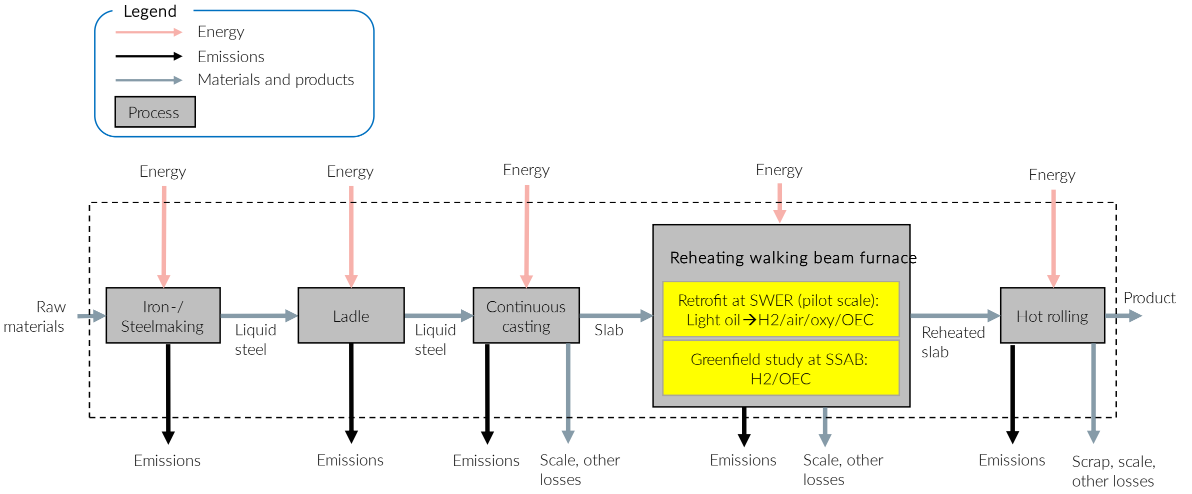


Figure A.3.2: Simplified flow chart of energy, emissions, and material flows at SSAB's steel plant. The system at SWER only consists of the reheating furnace.

Celsa's steel plant in Mo i Rana

A ladle preheating station for preheating steel transport ladles at Celsa's steel plant in Mo i Rana will be retrofitted from CO-gas from another neighbouring plant as the main energy carrier to hydrogen combustion (Figure A.3.3). So, the scale of demonstration is high within HyInHeat. Since the retrofit is only done at the preheating of the ladle, no liquid steel is involved. This would mean that the impact of using hydrogen on the production chain at the plant is limited, so the relevance and systemic effects are lower. However, when including the up- and downstream processes (e.g., EAF, continuous casting, rolling), the ladle preheating can be put in relation to the whole production chain and other potential systemic effects can be analysed as well. The data availability would still need to be improved for the plant-level MFAs. The location, Mo i Rana in Norway, is in close distance to NTNU.

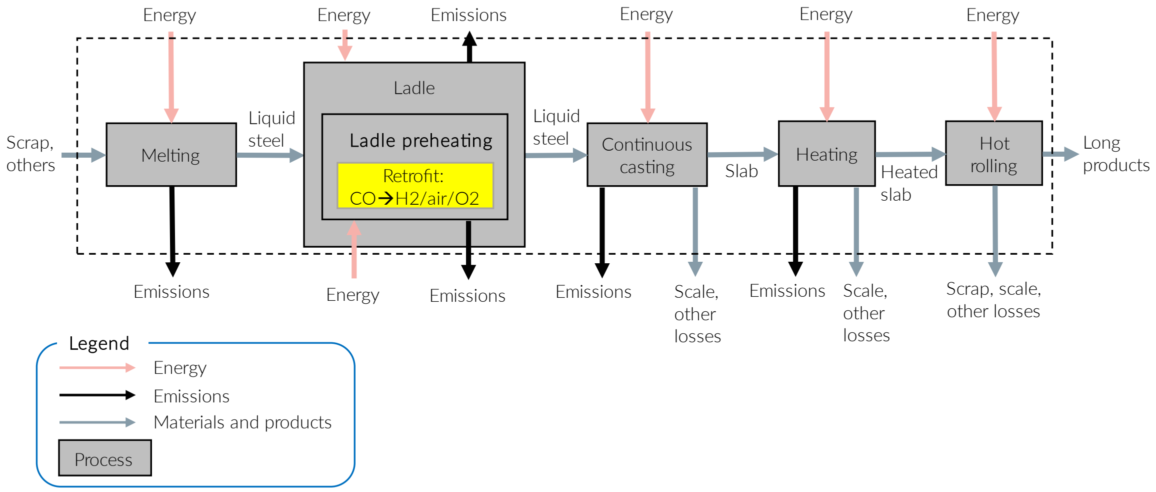


Figure A.3.3: Simplified flow chart of energy, emissions, and material flows at Celsa's steel plant

ArcelorMittal's steel rolling mills in Sestao and Olaberria

The steel reheating furnaces in the rolling mills of ArcelorMittal in Sestao (Figure A.3.4) and Olaberria (Figure A.3.5) will be retrofitted (in selected furnace zones) to H_2/O_2 and H_2/air combustion, so the scale of demonstration is high. Both processes are at industrial scale and an important part of the production chain of flat and long steel products, so relevance is high and also systemic effects can be analysed. However, it is not planned to include them in the MFAs or LCAs according to the proposal, leading to an increased workload for the plants if they would be included in the plant-level caste studies. However, a plant-level MFA including other up- and downstream processes (e.g., steelmaking, casting, rolling, finishing) and systemic effects would gain valuable insights for both, the project, and the plants. The data availability seems to be good according to the questionnaires and Tecnalia, as the leader of WP is closely cooperating with both. The locations in Northern Spain are suitable for combining plant-visits with the project meeting in November 2023 in San Sebastián.

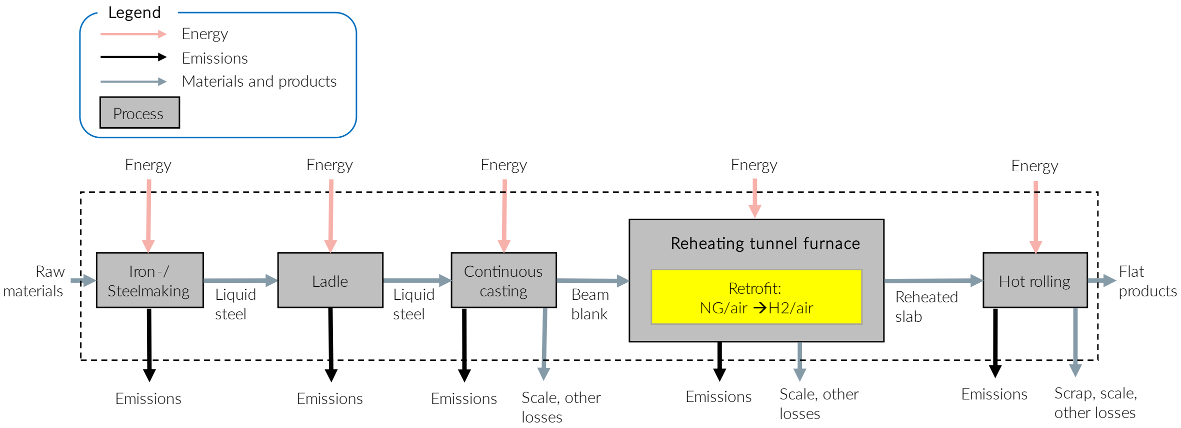


Figure A.3.4: Simplified flow chart of energy, emissions, and material flows at AMS's rolling mill

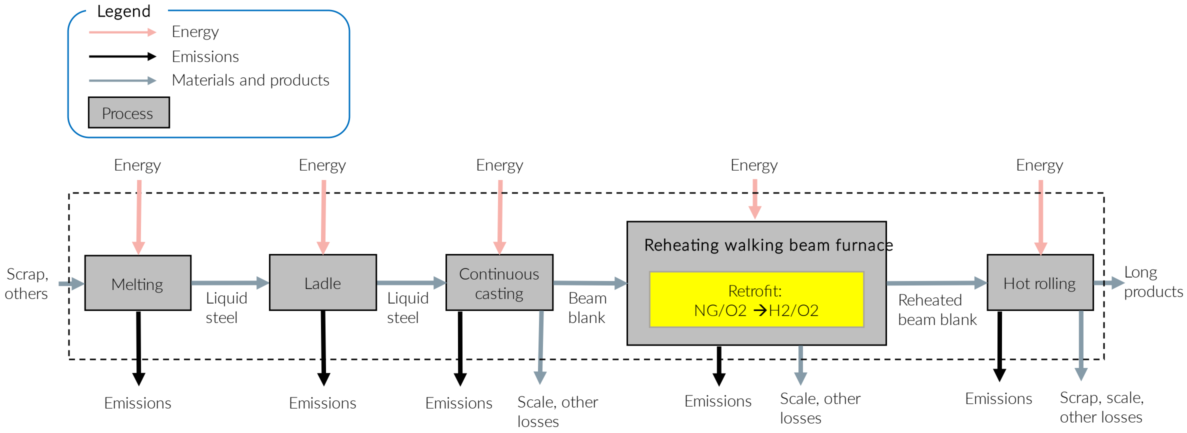


Figure A.3.5: Simplified flow chart of energy, emissions, and material flows at AMOB's rolling mill

CTEC's pilot aluminium casthouse in Voreppe

The industrial scale pilot casthouse of Constellium Technology Center (CTEC) in Voreppe, France, includes an aluminium reverberatory melting furnace that will be retrofitted to hydrogen combustion, so scale of demonstration is high. Although it is only a pilot plant, it includes an industrial size casting line with 2 melting furnaces (reverberatory and induction) and the casting itself. The aluminium cast products are used for both, production, and R&D purposes. The rating of the relevance and systemic effects is still okay, even if it is lower than for full industrial scale plants. Thus, a plant-level MFA would be feasible at CTECs plant covering a value chain including melting, holding, and casting. The data availability is good, and the additional workload would not be too high since updates of the MFAs are planned within WP5. However, it is considered as optional for our in-depth case study due to its pilot scale.

Mytilineos' aluminium smelter in Agios Nikolaos

At the aluminium smelter of MYT, a preheating station for transport ladles for transferring the liquid aluminium from the electrolysis to a holding furnace is retrofitted to hydrogen combustion (Task 5.1). Also, a design study of retrofitting the holding furnace is executed (Task 5.4). Thus, the scale of demonstration is not very good, but still sufficient to gain valuable insights. The data availability is good, and the additional workload would not be too high since updates of the MFAs are planned within WP5. When including both, the ladle preheating, and the holding furnace, and also the electrolysis and further downstream processes, large parts of the primary aluminium production chain can be covered, and systemic effects could be analysed. The location of the plant in Agios Nikolaos, Greece, is the furthest away from Norway when it comes to plant visits.

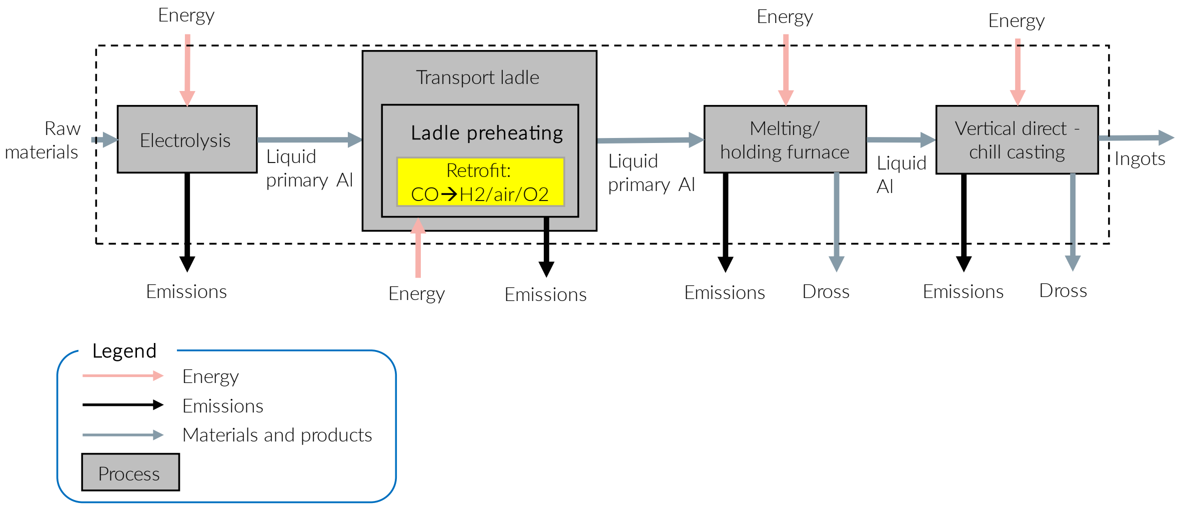


Figure A.3.6: Simplified flow chart of energy, emissions, and material flows at Mytilineos' primary aluminium plant

Speira's aluminium rolling mill in Hamburg

In the aluminium hot rolling mill of SPE in Hamburg, Germany, a retrofit study on a continuous indirect fired reheating pusher-type furnace is executed (task 5.4) to examine the use of hydrogen combustion (Figure A.3.7). At Speira's aluminium recycling plant in Grevenbroich, Germany, a lab scale melting furnace is equipped with hydrogen combustion (H_2/O_2) in task 2.1. However, only the reheating furnace in Hamburg is planned to be part of the retrofitting studies for MFA/LCA in WP5. Because there is only a retrofit study (meaning no actual retrofitting), data would be based on assumptions (lower scale of demonstration). Also, the data availability for the reference process and the connected up- and downstream processes need to be improved. However, the additional workload should be low since SPE is planned to participate in the plant-level MFAs. When including the entire hot-rolling production chain with melting, holding, casting, and heating, the relevance and potentials for systemic effects would be high. The plant location is also reachable in an efficient way.

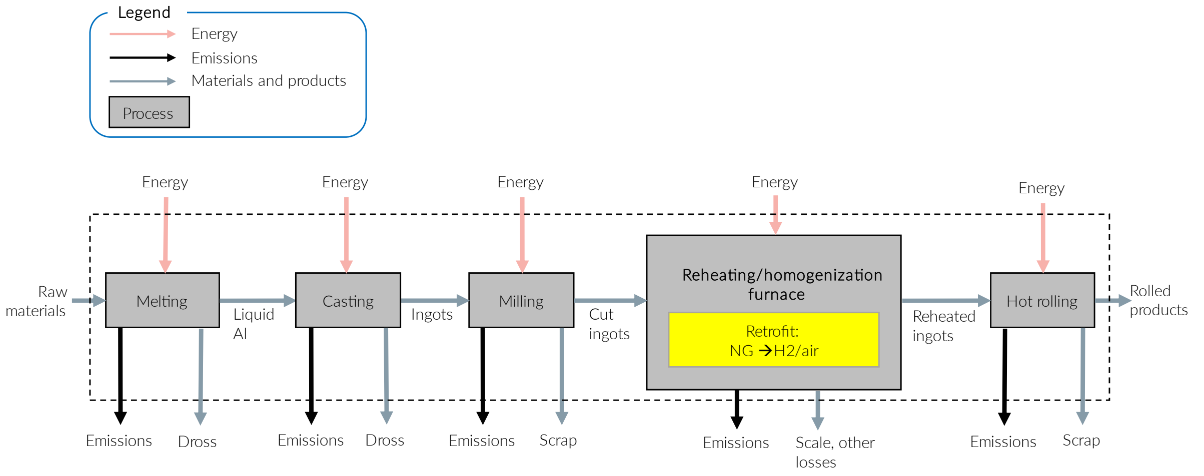


Figure A.3.7: Simplified flow chart of energy, emissions, and material flows at Speira's aluminium rolling mill.

Toyota Motor Europe's casting shop in Walbrzych

The heat treatment furnace at Toyota Motor Europe (TME) in Walbrzych, Poland, (Figure A.3.8) will be retrofitted within Task 5.5 to H_2/O_2 combustion, leading to a high scale of demonstration. The plant receives liquid aluminium from another company and includes processes such as holding and other heat treatment furnaces. Although the artificial aging furnace operates at relatively low temperature (230 °C) and throughput (1 t/h), leading to less relevance in terms of energy demand and production quantities, the hydrogen combustion can be scaled up to other heat treatment processes as well within the case study. Thus, the potential for systemic effects could be high and also the relevance can be increased by including all processes in the production chain. The plant location in Poland is not close and no project meetings are planned yet there, but it is still accessible.

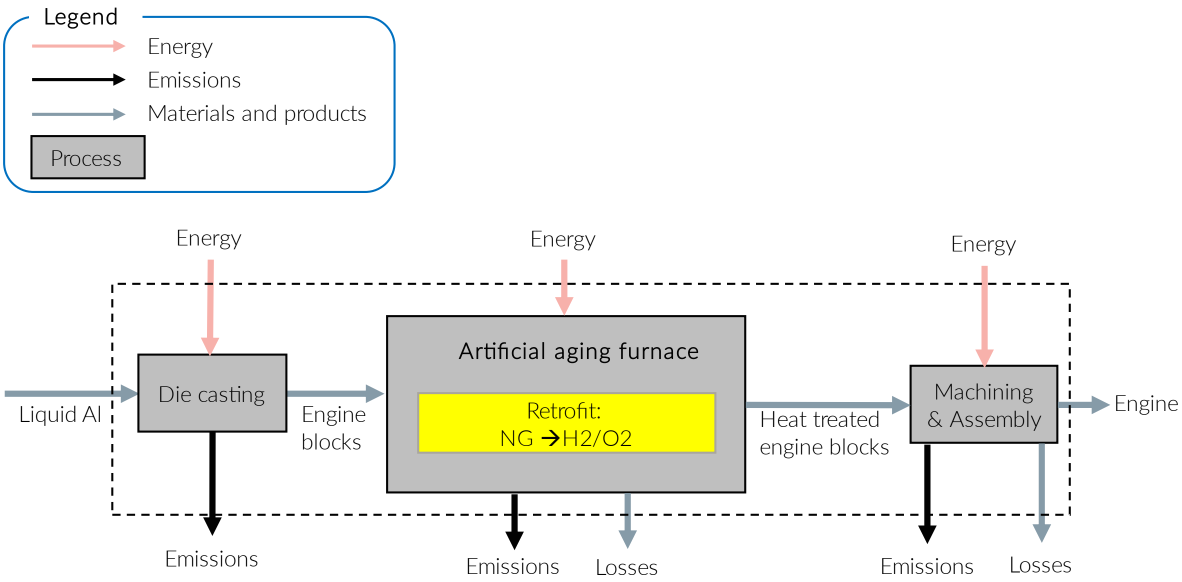


Figure A.3.8: Simplified flow chart of energy, emissions, and material flows at TME's manufacturing plant

Table A.3.1: Evaluation of potential industrial partners for in-depth plant-level MFA case studies

Partner (acronym)	Sector	Process	Criteria very good 3 2 1 0 not sufficient						
			Scale of demonstration	Data availability	Additional workload for industrial partners	Relevance	Systemic effects	Location	Average rating (0 if one is 0)
AMI	Steel	Burner test-rig	3	2	-	0	0	3	0
AMOB	Steel	Walking beam reheating furnace	3	3	1	3	3	3	2.7
AMS	Steel	Tunnel reheating furnace	3	3	1	3	3	3	2.7
CEL	Steel	Ladle preheating	3	2	3	2	2	3	2.5
SWER	Steel	Pilot walking beam reheating furnace	3	3	2	1	1	2	2.0
SSAB	Steel	Greenfield study on walking beam furnace	1	2	3	3	3	3	2.5
BEF	Aluminium	Pilot rotary melting furnace	3	3	-	0	0	3	0
CTEC	Aluminium	Pilot reverberatory melting furnace	3	2	2	1	1	2	1.8
MYT	Aluminium	Ladle preheating and holding furnace	2	2	2	2	3	1	2.0
SPE	Aluminium	Reheating furnace	1	1	3	3	3	3	2.3
TME	Aluminium	Heat treatment furnace	3	3	2	2	3	1	2.3

The evaluation shows that AMS and/or AMOB, CEL and SSAB would be the most suitable for more in-depth plant-level MFA studies for the steel sector. However, it would still need to be clarified which processes could be included and whether the partners have enough capacities available to collaborate since, for example, AMS/AMOB are not involved in any MFA or LCA studies within HyInHeat. At CEL, the data availability needs to be improved and especially other processes than the ladle preheating station should be included to ensure high relevance and the options to analyse systemic effects within the plant. Also, the steel plant of SSAB would be feasible to conduct a plant-level study for. However, there will be only a greenfield, so results of the retrofit of the pilot reheating furnace at SWER would need to be upscaled to an industrial scale reheating furnace at SSAB.

For the aluminium sector, SPE, MYT and TME are options to conduct the plant-level MFA. However, it is needed to clarify which processes could be included, especially since at SPE and MYT retrofitting studies are conducted without an actual retrofit. For SPE, the data availability of their reference case need to be improved. As the next steps, individual meetings and discussions with the industrial partners are planned.

A.4 Assessment of literature on historical and future material and energy demand and prices, including penetration of H_2 infrastructure (NTNU-EPT)

In this section, the literature on the historical and future material and energy demand of the aluminium and steel sectors, as well as prices are assessed. Data and explanations about the penetration of hydrogen infrastructure is presented in the first section of this report.

In general, statistics of the steel sector about production data are available in detail and with a high resolution on product categories and regions/countries. Statistics about the aluminium sector are less detailed and focus mainly on the primary production data and less on downstream products, such as semi-products. Specific energy demands can be found in literature while total energy demands are available at Eurostat on a European level for the “iron and steel” and “non-ferrous metals” sectors. European statistics on energy prices are available for natural gas and electricity at Eurostat. For an overview about current and planned hydrogen infrastructure, see the first section about the legislative context in this report.

A.4.1 Literature on material demands

Literature on material demand for steel and aluminium sectors can be find both in statistics and reports and scientific publications. Statistics and outlooks on material demands are published by association such as (British geological survey, 2023; European Steel Association, 2023b; International Aluminium Institute, 2023b; U. S. Geological Survey, 2023c; World Steel Association, 2023b). Scientific publications mostly focus on building up models for one or more sectors to model historic material demands and stocks and to develop future scenarios for the material cycles.

An overview of the literature on steel demand is shown in Table A.4.1 and Table A.4.2 together with a brieve summary on the content that is covered; the literature on the aluminium sector is shown in Table A.4.3 and Table A.4.4. Note, that these lists do not cover all literature available, but should give an overview.

A.4.1.1 Steel figures

World Steel Association (worldsteel) and European Steel Association (EUROFER) publish steel statistics in the “steel statistical yearbook” (World Steel Association, 2023b) and “European steel in figures” (European Steel Association, 2023b) each year. These reports cover figures on global and country level for iron ore, pig iron, crude steel, different steel products (flat and long steel products and more specific product types), steel consumption, scrap, imports, and exports. The global and European development of produced crude steel as well as flat and long steel products is shown in Figure A.4.1 to Figure A.4.4.

In 2022, ~1.9 Gt crude steel were produced globally (Figure A.4.1) of which ~72% were produced via the basic oxygen furnace (BOF) route and others, meaning mainly from iron ore, and ~28% via the electric arc furnace (EAF) route, meaning mainly from scrap (World Steel Association, 2023b). In the EU, the production of crude steel was declining since 2009, reaching ~136 Mt in 2022 (Figure A.4.2). The share of crude steel produced via the BOF route within the EU was ~57% in 2022 while ~43% were produced via the EAF route (European Steel Association, 2023b). The figures on the EU refer to EU27-2007 for the years 2005-2012, the EU28 for 2013-2019 and to EU27 for 2020 and later.

Steel products are produced via a hot rolling process and can be differentiated into long and flat products. Globally, ~1.6 Gt of hot rolled steel products were produced in 2022; ~821 Mt long products and ~782 Mt flat products (World Steel Association, 2023b). In the EU, ~125 Mt hot rolled products were produced in 2022; ~75 Mt flat products and ~50 Mt long products. EUROFER divides the flat products further into Quadro plate, hot rolled wide strip, and other flat products. Long products are divided into wire rod, rebars, merchant bars, heavy sections, and other long products. These figures can be found in EUROFER’s European Steel in Figures reports (European Steel Association, 2023b).

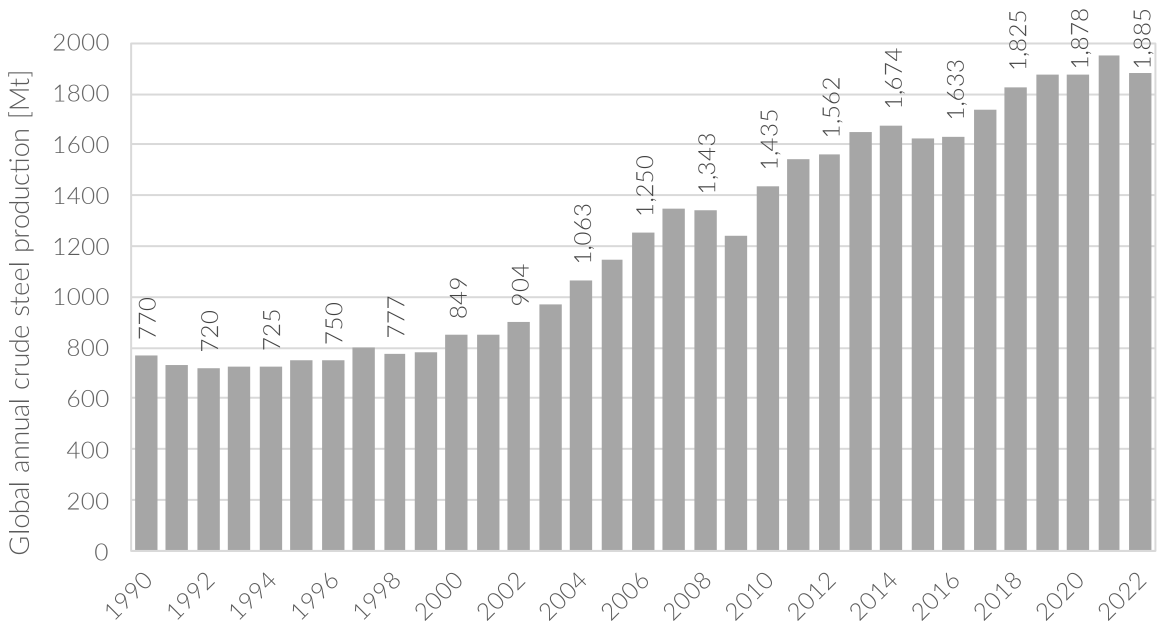


Figure A.4.1: Global crude steel production (World Steel Association, 2023b)

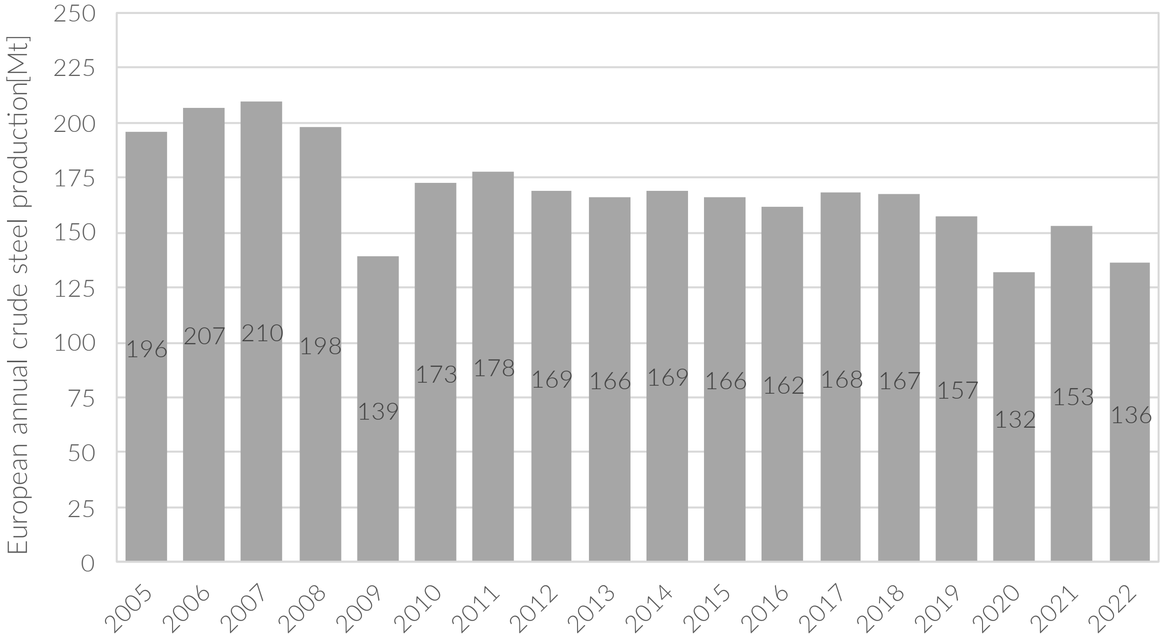


Figure A.4.2: European crude steel production (2005-2012: EU27, 2013-2019: EU28, 2020-later: EU27) (European Steel Association, 2023b)

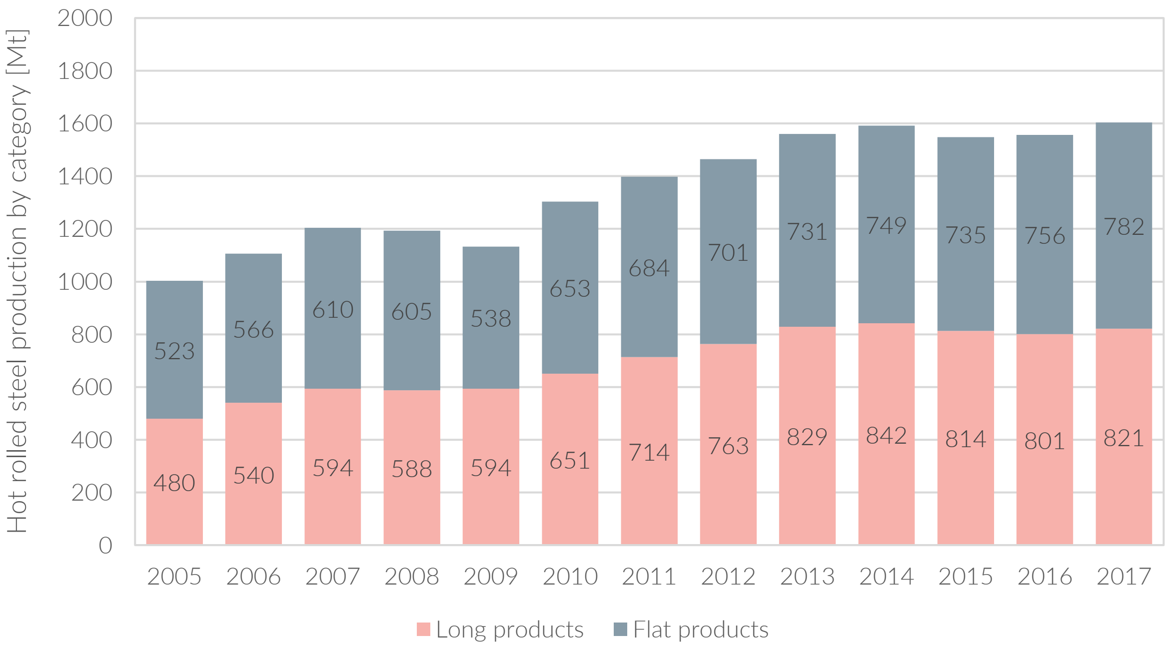


Figure A.4.3: Global production of hot rolled steel products by category (World Steel Association, 2023b)

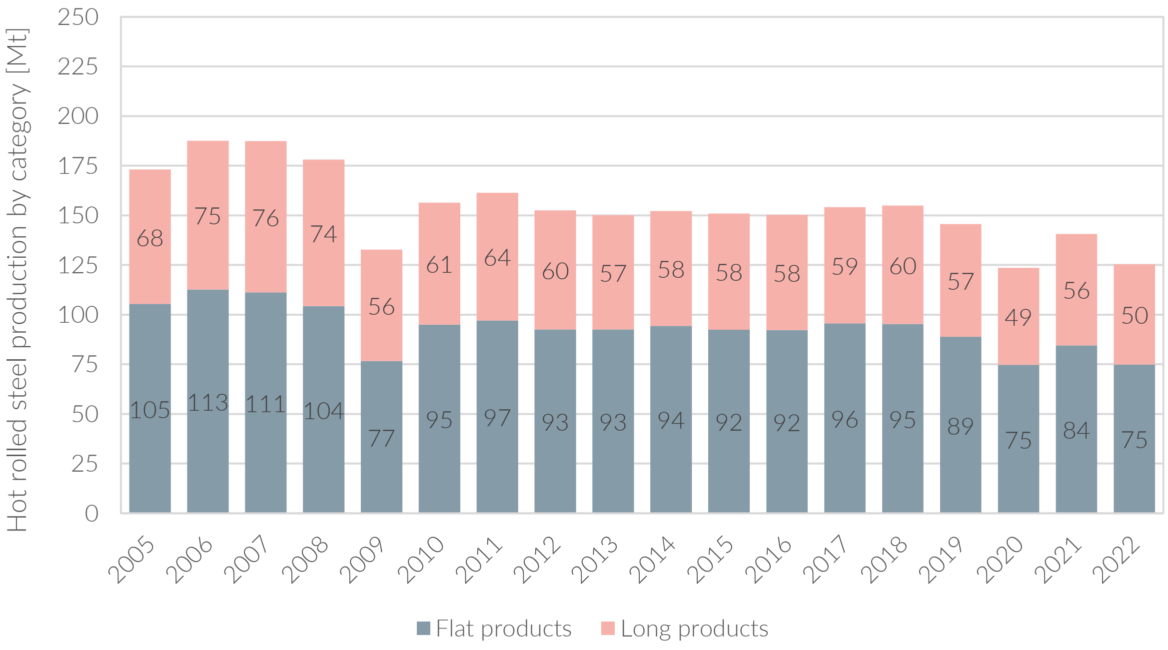


Figure A.4.4: European production of hot rolled steel products by category (2005-2012: EU27, 2013-2019: EU28, 2020-later: EU27) (European Steel Association, 2023b)

Short term outlooks on European steel demand are published every quarter by EUROFER for the current and the coming year (European Steel Association, 2023a). The apparent steel consumption is projected to decrease by 1% in 2023 compared to 2022 but to increase by 5.4% in 2024 compared to the previous year. In terms of global figures, worldsteel forecasts a 2.3% decrease for 2023 and a 1.7% growth in steel demand for 2024 compared to the previous years (World Steel Association, 2023a).

Long term outlooks are published in reports and scientific publications in the form of scenarios. For instance, the International Energy Agency (IEA) projects an increase in steel demand by 2050 by more than a third compared to 2019 (International Energy Agency, 2020).

A.4.1.2 Aluminium figures

Figures on primary aluminium production on a global, regional, and country level are published by (International Aluminium Institute, 2023b) (IAI) as well as (U. S. Geological Survey, 2023c) (USGS) or (British geological survey, 2023) (BGS). Global aluminium production more than tripled from ~20 Mt in 1990 to ~68 Mt in 2022 (Figure A.4.5). European figures for EU27 and EU27+EU27+EFTAk, respectively, decreased from ~4.3 Mt and ~2.1 Mt in 2017 to ~3.5 Mt and ~1.2 Mt in 2022 (Figure A.4.6) (European Aluminium, 2023b).

Figures on global aluminium semi-production and recycling are produced by the IAI in their Global Aluminium Cycle (International Aluminium Institute, 2021). Figures on the European production and shipments of flat rolled and extruded products (Figure A.4.7) are provided by (European Aluminium, 2023b). Production of flat rolled products and extrusions within EU27+UK+EFTA increased from 2017 to 2020 by ~11% and ~12%, respectively. The recycled aluminium within this region, including refiners' production and external scrap intake of remelters, reached ~5.1 kt in 2022 after declines in the years 2018 and 2020.

Short term outlooks for European aluminium demand and production are provided by (European Aluminium, 2023b) (see figures below). Primary aluminium production in EU27 and EU27+UK+EFTRA is forecasted to decline further in 2023 and to face a small increase in 2024 again, reaching ~3.2 kt and ~1.0 kt, respectively, by 2024. The production and shipment within EU27+UK+EFTA of flat products is forecasted to remain at 2022 level for 2023 and to increase in 2024. The figures for extrusion are expected to decrease in 2023 before increasing again in 2024.

Long term outlooks are published by the IAI in their Global Aluminium Cycle covering the years until 2050 in different scenarios (International Aluminium Institute, 2021). In a reference scenario they project primary aluminium production to increase by ~20% by 2050 compared to 2022, reaching ~81 Mt/year. However, this is expected to be increasingly covered by recycled aluminium, since the demand for final products is expected to more than triple from 2022 to 2050. The metal supply of primary and secondary aluminium together would increase from ~107 Mt to ~176 Mt by 2050 accordingly.

A report from the KU Leuven (Leuven and Eurometaux, 2022) analysis future demand and supply of several metals (among others aluminium) due to the clean energy transition and resulting demand increase for these metals. The authors report, that most of the future aluminium demand increase related to the energy transition results from EVs, followed by electric networks and solar power. They project that global demand for aluminium) is increasing from ~100 Mt in 2020 to up to 140 Mt by 2030 and up to 245 Mt. European (EU27+UK+EFTA) aluminium demand is projected to increase from ~14 Mt in 2020 to up to 20 Mt by 2050.

The EAA expects an increase of European (EU28+EFTA) demand for semi-finished aluminium products of 40% by 2050 compared to 2017, among other reasons due to the replacement of other materials such as steel, copper, plastics (European Aluminium, 2020). Again, the highest demand growth is expected in the transport sector where an aluminium demand increase of 55% is projected from 2017 to 2050. The amount of aluminium post-consumer scrap for recycling is projected to growth from 3.6 Mt in 2019 to 8.6 Mt by 2050, leading to a decline of primary aluminium demand.

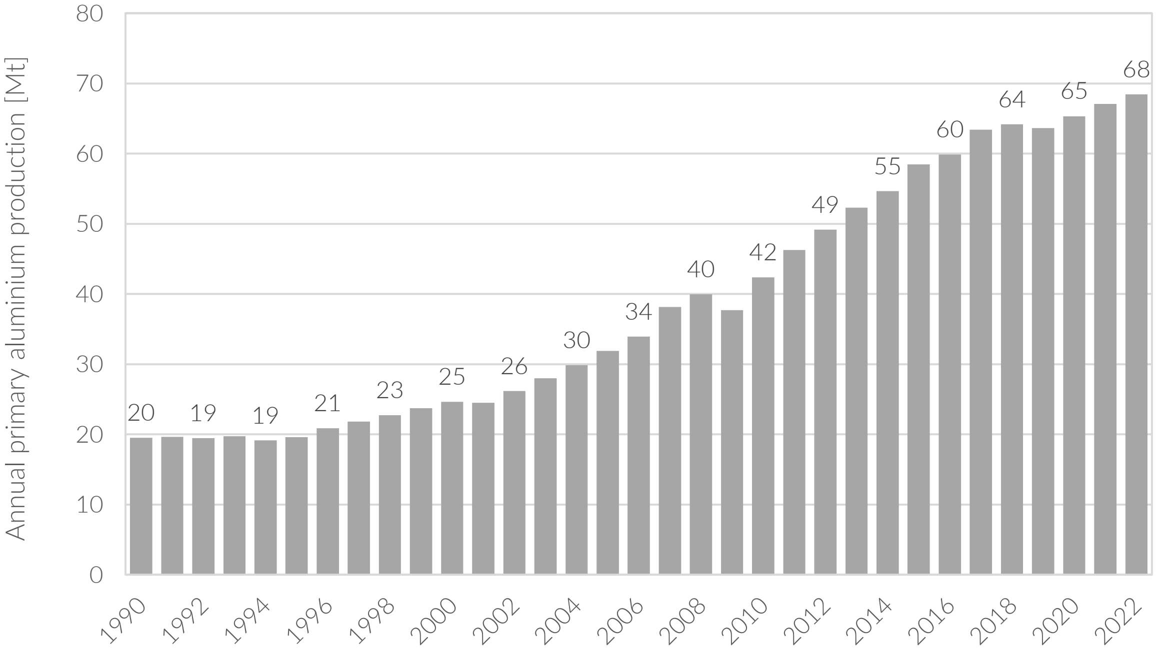


Figure A.4.5: Global primary aluminium production (International Aluminium Institute, 2023b): Global primary aluminium production (International Aluminium Institute, 2023b)

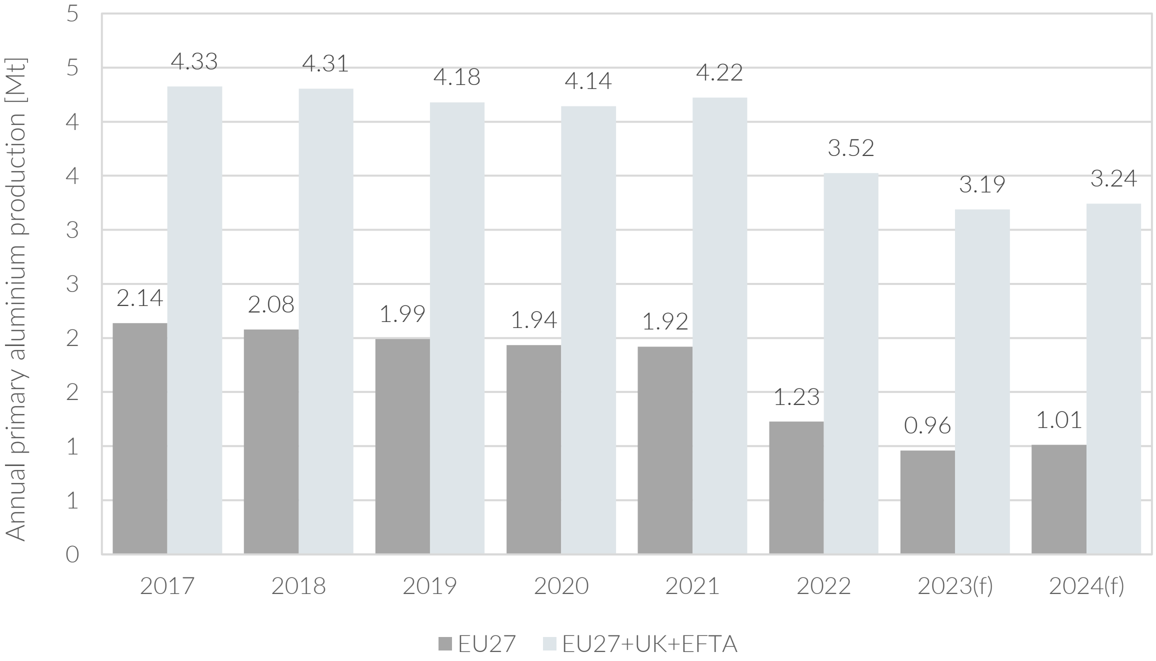


Figure A.4.6: European primary aluminium production (European Aluminium, 2023b): European primary aluminium production (European Aluminium, 2023b)

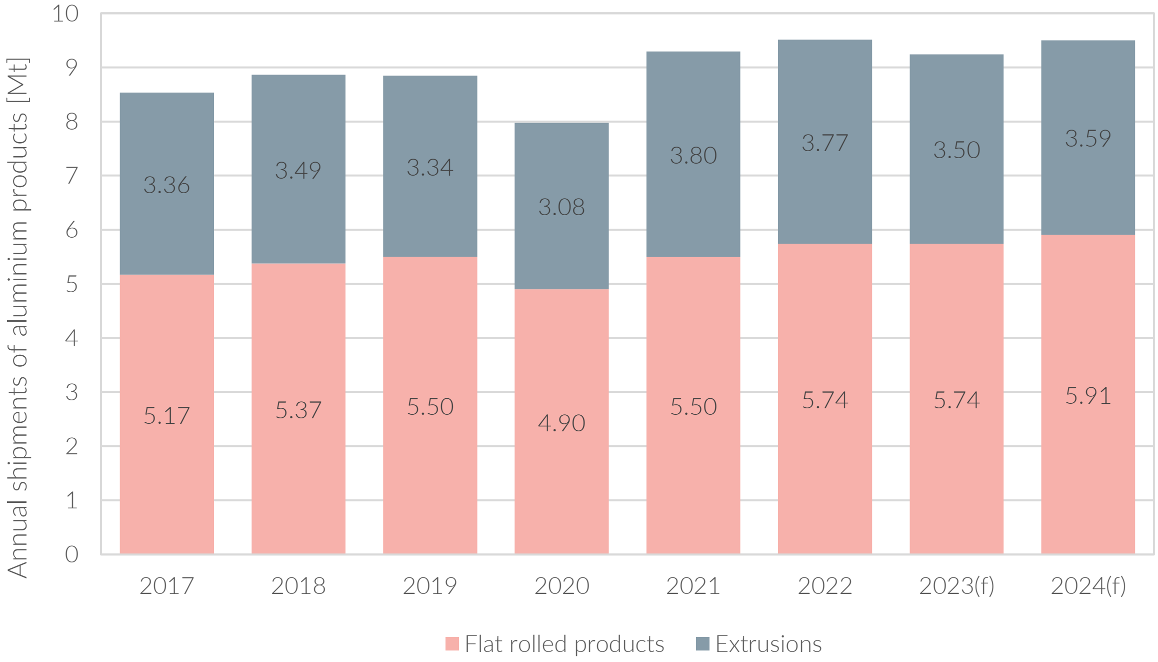


Figure A.4.7: European (EU27+UK+EFTA) production and shipments of aluminium products (European Aluminium, 2023b)

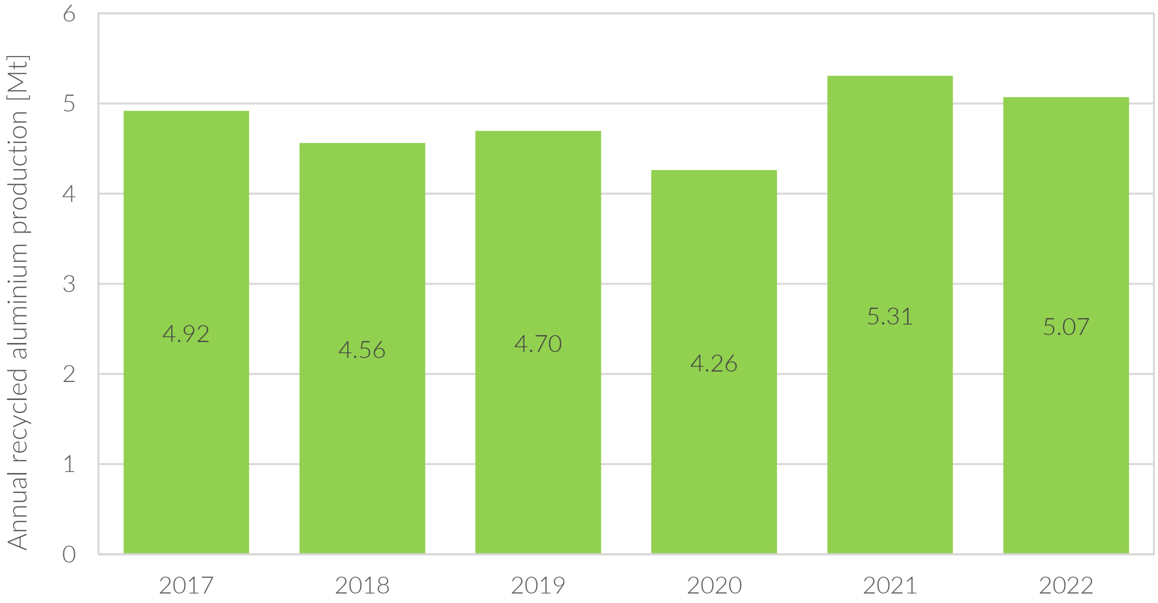


Figure A.4.8: European (EU27+UK+EFTA) recycled aluminium production (European Aluminium, 2023b)

Table A.4.1: Material demand of steel sector – Statistical data and reports

Data for	Timeframe		Regional scale	Source			
	Historic/future	Years		Author	Year of publication / frequency	Title	Content
Crude steel production	historic	1900-2022	Global	Worldsteel [1]	1990, 2000, 2010-2023	Steel statistical yearbooks	Several statistics about steel production, demand, trade, etc. Available for global and country level.
		1980-2022	Global, country level				
Crude steel production by process		1988-2022	Global, country level				
Steel production - Hot rolled products		1990-2019					
Steel production - Flat products		1990-2017					
Steel production - Long products		1990-2017					
Apparent consumption/steel use		1980-2022					
Scrap imports/exports		1980-2022					
Apparent steel use per capita		1980-2022					
Crude steel production		2005-2022	European	Eurofer [2]	2009-2022, annual	European steel in figures	Several statistics about steel production, demand, and trade data in Europe.
Crude steel production by process							
Steel production - Hot rolled products							product type resolution available as well
Steel production - Flat products							
Steel production - Long products							

Continuation of Table A.4.1: Material demand of steel sector – Statistical data and reports

Data for	Timeframe		Regional scale	Source			
	Historic/future	Years		Author	Year of publication / frequency	Title	Content
Market supply - Flat products	historic	2005-2022	European	Eurofer [2]	2009-2022, annual	European steel in figures	"market supply=apparent steel consumption (total steel delivered to steel market, including material being stocked). product type resolution available as well
Market supply - Long products							
Steel consumption per sector							
Imports/Exports - Flat products							
Imports/Exports - Long products							
Scrap imports/exports							
Production of iron ore, pig iron, crude steel	historic	1921-2021	Global, country level	British geological survey (BGS) [3]	1913-2023	World mineral statistics	Statistics about production data of iron ore, pig iron, crude steel since 1921
finished steel products	future	2023-2024	Global	Worldsteel [4]	2023, annual	Short Range Outlook April 2023	steel demand forecasts for finished steel products for world and different regions
finished steel products		2023-2024	European				
Steel consumption		2023-2024	European	Eurofer [5]	2023, every quarter	Economic and steel market outlook 2023-2024, second quarter	Real and apparent steel consumption in quantity and %-change
Steel-using sectors							Year-on-year %-change

Sources:
[1]: (World Steel Association, 2023b)
[2]: (European Steel Association, 2023b)
[3]: (British geological survey, 2023)
[4]: (World Steel Association, 2023a)
[5]: (European Steel Association, 2023a)

Table A.4.2: Material demand of steel sector – Scientific publications

Data for	Timeframe		Regional scale	Source			
	Historic/future	Years		Author	Year of publication / frequency	Title	Content
EU steel cycle 2002-2019	historic	2002-2019	European	Rostek [1]	2022	A dynamic material flow model for the European steel cycle	dynamic material flow model covering the entire European steel and iron cycle from 2002-2019. From iron mining to use and recycling
Generation and composition of EU steel scrap	historic	1946-2017	European	Dworak [2]	2021	Steel scrap generation in the EU-28 since 1946 – Sources and composition	Historic scrap generation are modelled for EU28, 1946-2017, MFA
EU flat steel production	historic	2013	European	Flint [3]	2020	Material Flow Analysis with Multiple Material Characteristics to Assess the Potential for Flat Steel Prompt Scrap Prevention and Diversion without Remelting	Material flow analysis of flat steel produced in Europe in 2013, by grade, thickness, and coating. Discussion of potential ways to prevent and divert scrap
EU scrap	historic	1945-2013	European	Panasiyk [4]	2016	Steel stock analysis in Europe from 1945 to 2013	Dynamic MFA, steel stocks in use and distribution through sectors, potential scrap flows
EU steel cycle	historic	2015	European	Passarini [5]	2018	Material flow analysis of aluminium, copper, and iron in the EU-28	MFA of the EU28 iron flows; from mining to recycling
Regional and EU steel cycle	historic	2000	Global, regional level	Wang [6]	2007	Forging the Anthropogenic Iron Cycle	Regional-level iron cycles for 2000 (Europe, and several others)

Continuation of Table A.4.2: Material demand of steel sector – Scientific publications

Data for	Timeframe		Regional scale	Source			
	Historic/future	Years		Author	Year of publication / frequency	Title	Content
EU steel cycle	historic	2008	Global	Cullen [7]	2012	Mapping the global flow of steel: from steelmaking to end-use goods.	Mapping the global steel supply chain and identifying biggest steel flows to reduce emissions
In-use stock and demand	historic/ future	1980-2050	Global, country level	Hatayama [8]	2010	Outlook of the World Steel Cycle Based on the Stock and Flow Dynamics	Dynamic MFA, for 42 countries; global in use stock modelled from 1980-2005 and scenario until 2050
Primary iron and steel production in line with 2°C scenario	future	2010-2100	global	Watari [9]	2020	Global targets for metal flows, stocks and use intensity in line with 2°C	Global targets for metal flows, stocks, and use intensity in line with a 2 °C climate goal. Covering six major metals (iron, aluminium, …)
Primary and secondary iron and steel production by SSPs	future	2010-2100	global	Yokoi [10]	2022	Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals	Connected to Watari et al.; projecting future GHG emissions from primary and secondary metal production of aluminium and iron (among others) for SSPs

Sources:
[1]: (Rostek *et al.*, 2022)
[2]: (Dworak and Fellner, 2021)
[3]: (Flint *et al.*, 2020)
[4]: (Panasiyk, Laratte and Remy, 2016)
[5]: (Manfredi *et al.*, 2018)
[6]: (Wang, Müller and Graedel, 2007)
[7]: (Cullen, Allwood and Bambach, 2012)
[8]: (Hatayama *et al.*, 2010)
[9]: (Watari *et al.*, 2020)
[10]: (Yokoi, Watari and Motoshita, 2022)

Table A.4.3: Material demand of aluminium sector – Statistical data and reports

Data for	Timeframe			Source			
	Historic/ future	Years	Regional scale	Author	Year of publication/ frequency	Title	Content
Alumina production	historic	1974-2022	global, regional level	International Aluminium Institute [1]	2023	Alumina production	Also on regional (e.g., Western & Central Europe, etc.)
	historic	1990-2022	global, country level	United States Geological Survey [2]	1996-2023	Bauxite and Alumina Statistics and Information	Statistics on supply and demand of bauxite and alumina
	historic	1970-2021	global, country level	British geological survey (BGS) [3]	1921-2021	World mineral statistics	Statistics on production and trade data of alumina and primary aluminium production
Primary aluminium production	historic	1973-2022	global, region level	International Aluminium Institute [4]	2023	Primary aluminium production	Statistics on primary Al production for different word regions
	historic/ future	1962-2050	global, region level	International Aluminium Institute [5]	2021	Global aluminium cycle 2021	Regional aluminium stocks and flows of all production stages including trade links
	historic	1990-2022	global, country level	United States Geological Survey [6]	1994-2023	Aluminium Statistics and Information	Statistics on supply and demand of aluminium
	historic	1913-2021	global, country level	British geological survey (BGS) [3]	1921-2021	World mineral statistics	Statistics on production and trade data of alumina and primary aluminium production
	historic/future	2017-2024	European	European Aluminium [7]	2023	European Aluminium Statistics	forecasts until 2024, EU27 and EU27+UK+EFTA
	historic	1980-2022	European	European Aluminium [8]	2023	European aluminium supply by source	EU27+UK for 2021 and onwards, EU28 and other EU versions before
Semi-production	historic/future	1962-2050	global, region level	International Aluminium Institute [5]	2021	Global aluminium cycle 2021	Regional aluminium stocks and flows of all production stages including trade links
	historic/future	2017-2024	European	European Aluminium [7]	2023	European Aluminium Statistics	Extrusions and flat rolled products, forecasts until 2024

Continuation of Table A.4.3: Material demand of aluminium sector – Statistical data and reports

	Timeframe			Source			
Data for	Historic/ future	Years	Regional scale	Author	Year of publication/ frequency	Title	Content
Recycling	historic/future	1962-2050	global, region level	International Aluminium Institute [5]	2021	Global aluminium cycle 2021	regional aluminium stocks and flows of all production stages including trade links
	historic	2017-2022	European	European Aluminium [7]	2023	European Aluminium Statistics	
	historic	1980-2022	European	European Aluminium [8]	2023	European aluminium supply by source	EU27+UK for 2021 and onwards, EU28 and other EU versions before
	historic/future	1962-2050	global, region level	International Aluminium Institute [5]	2021	Global aluminium cycle 2021	regional aluminium stocks and flows of all production stages including trade links
Demand semi-finished aluminium - per sector	historic/future	2017, 2030, 2050	European	European Aluminium [9]	2020	Action plan 2030 - A strategy for achieving aluminium's full potential for circular economy by 2030	Report assessing strategies to increase recycling of aluminium end-of-life products in Europe
Aluminium demand	future	2030, 2040, 2050	European, global	KU Leuven [10]	2022	Metals for Clean Energy: Pathways to solving Europe's raw material challenge	Aluminium demand (primary and secondary together) for energy transition depending on STEPS or SDS developments
Recycling							Secondary supply potential for 2030, 2040, 2050. Old and new scrap. With and without optimized recycling rates

Sources:
[1]: (International Aluminium Institute, 2023a)
[2]: (U. S. Geological Survey, 2023b)
[3]: (British geological survey, 2023)
[4]: (International Aluminium Institute, 2023b)
[5]: (International Aluminium Institute, 2021)
[6]: (U. S. Geological Survey, 2023a)
[7]: (European Aluminium, 2023b)
[8]: (European Aluminium, 2023a)
[9]: (European Aluminium, 2020)
[10]: (Leuven and Eurometaux, 2022)

Table A.4.4: Material demand of aluminium sector – Scientific publications

Data for	Timeframe		Regional scale	Source			
	Historic/ future	Years		Author	Year of publication/ frequency	Title	Content
Material demand for primary and secondary aluminium	future	2000-2100	global	Liu et al. [1]	2012	Stock dynamics and emission pathways of the global aluminium cycle	Material demand scenarios for primary ingots, internal remelting, and secondary ingots for "no action" pathways and after implementing collection rate and yield improvements
Global aluminium flows	historic	2007	global	Bertram et al. [2]	2009	Material Flow Analysis in the Aluminium Industry	Material flows in the global aluminium cycle
Global aluminium flows, future scrap flows	future	2030, 2035, 2040	global	Van den Eynde et al. [3]	2022	Forecasting global aluminium flows to demonstrate the need for improved sorting and recycling methods	Global aluminium cycle modelled on an alloy series resolution, estimating the composition of the recovered scrap flows
Global aluminium flows, trades	historic	2014	global, region level	Bertram et al. [4]	2017	A regionally-linked, dynamic material flow modelling tool for rolled, extruded, and cast aluminium products	Quantification of regional stocks and flows of rolled, extruded and casting alloys
Primary aluminium production in line with 2°C scenario	future	2010-2100	global	Watari et al. [5]	2020	Global targets for metal flows, stocks and use intensity in line with 2°C	Global targets for metal flows, stocks, and use intensity in line with a 2 °C climate goal. Covering six major metals (iron, aluminium, …)
Primary and secondary aluminium production by SSPs	future	2010-2100	global	Yokoi et al. [6]	2022	Future greenhouse gas emissions from metal production: gaps and opportunities towards climate goals	Connected to Watari et al.; projecting future GHG emissions from primary and secondary metal production of aluminium and iron (among others) for SSPs

Sources:
[1]: (Liu, Bangs and Müller, 2012)
[2]: (Bertram, Martchek and Rombach, 2009)
[3]: (van den Eynde *et al.*, 2022)
[4]: (Bertram *et al.*, 2017)
[5]: (Watari *et al.*, 2020)
[6]: (Yokoi, Watari and Motoshita, 2022)

A.4.2 Literature on material prices

Prices for aluminium and steel can vary depending on several factors, such as the global supply chain, raw material and energy costs, or geopolitical factors and trade policies. Data on material prices is rare and often confidential or only available for sale, such as data from the CME group (CME Group, 2023). Aluminium and steel are both traded on the stock exchange, such as London Metal Exchange (LME). For steel, LME provides for instance free data for the last six on prices of hot rolled coils in Europe (LME Steel HRC NW Europe), ranging between ~680 and ~930 US$ per ton (London Metal Exchange, 2023c, accessed in August 2023). Data on steel scrap (LME Steel Scrap CFR Turkey) is available for the last 2 years and ranges between ~340 and ~710 US$ per ton (London Metal Exchange, 2023d). For aluminium (LME Aluminium Official Prices), prices of the last 5 years can be accessed, ranging between 1400 and 4000 US$ per ton (London Metal Exchange, 2023a). Aluminium scrap (LME Aluminium UBC Scrap US) ranges between 1500 and 2000 US$ per ton for the last 4 months (London Metal Exchange, 2023b).

A.4.3 Literature on energy demand and prices

A.4.3.1 Energy demand

European statistics on energy demand for different sectors and energy prices can be found at Eurostat (2023b). The total final energy consumption of the EU27 states (Figure A.4.9) was between 10 and 12 PWh per year from 1990 until 2021. The industry sectors, excluding blast furnaces and coke ovens which are listed under the energy sector and not in the final energy consumption, make up around a fourth of this. Of the industry sector, the iron and steel sector accounts for ~10% (not accounting for the blast furnaces and coke ovens) and the non-ferrous metal sector for ~4%.

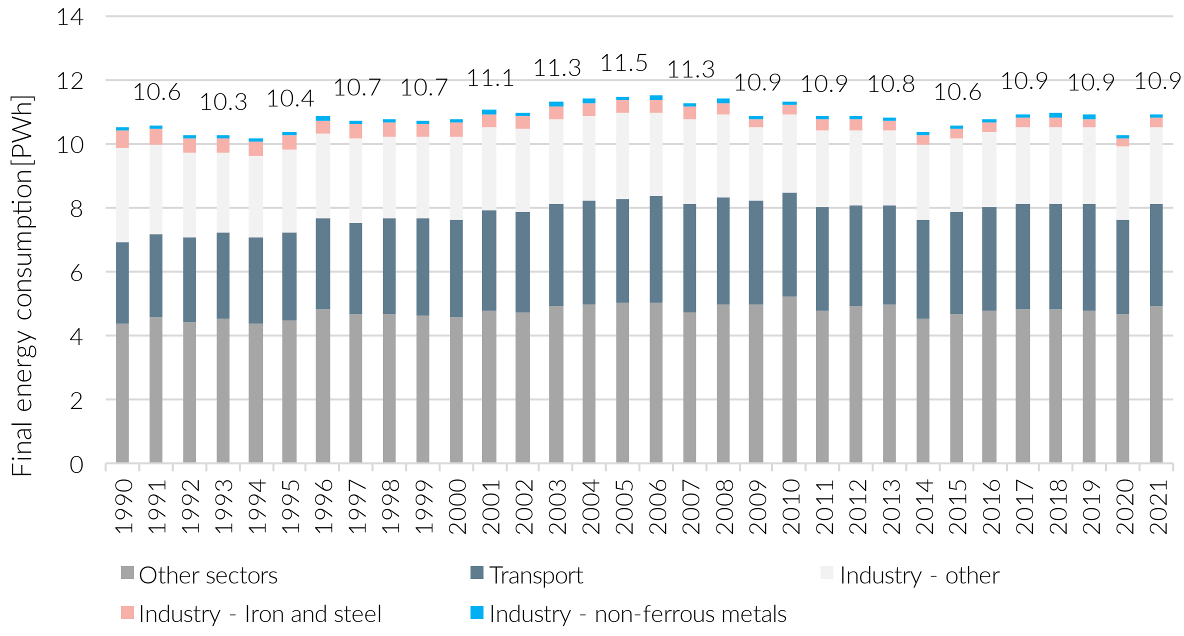


Figure A.4.9: Final energy consumption of EU27 (Eurostat, 2023b)

The final annual energy consumption of the European (EU27) iron and steel sector was between ~560 and ~270 TWh per year in the years 1990 until 2021, with a declining trend (Figure A.4.10). Blast furnaces and coke ovens are, as mentioned before, not included in the iron and steel sector energy demand but listed as transformation processes in the Eurostat database. In 2021, blast furnaces and coke ovens accounted for additional 360 and 340 GWh, respectively. Most of the energy consumed by the iron and steel sector in 2021, excluding blast furnaces and coke ovens, was due to the use of electricity (37%) and natural gas (31%).

Eurostat does not list the aluminium sector separately but only the non-ferrous metals sector in total (Figure A.4.11). The final energy consumption of the non-ferrous metal sector ranged between 130 and 100 TWh per year between 1990 and 2021 and is dominated by electricity (54% in 2021) and natural gas (39% in 2021).

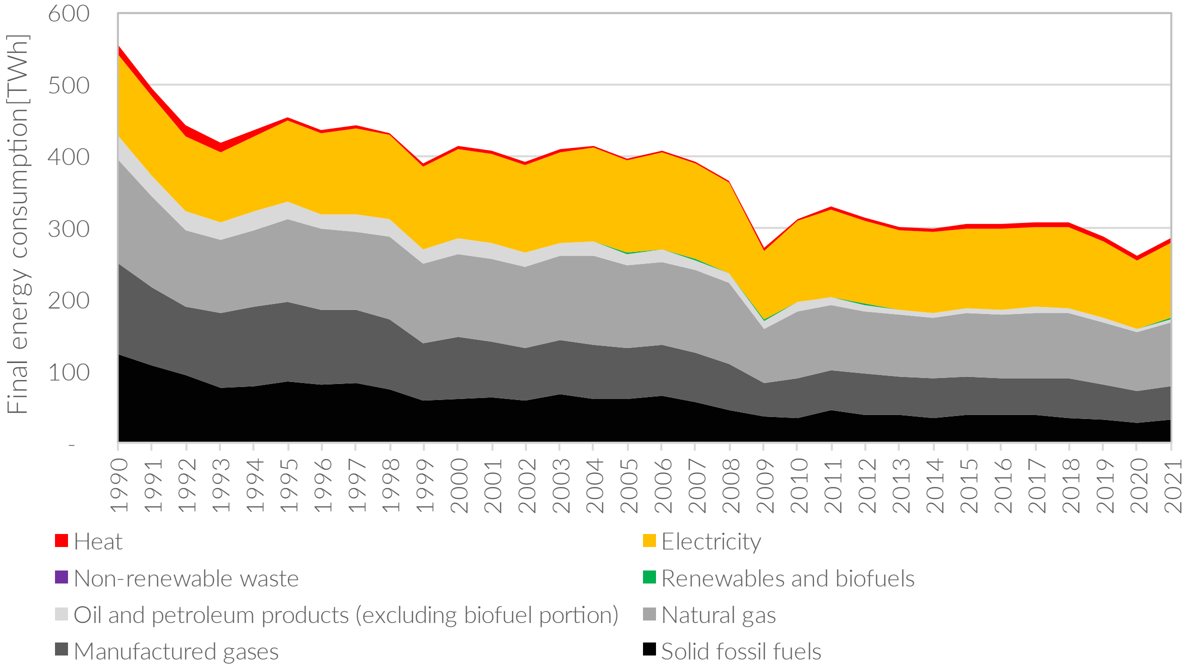


Figure A.4.10: Final energy consumption of the European (EU27) iron and steel sector, excluding blast furnaces and coke ovens (Eurostat, 2023b)

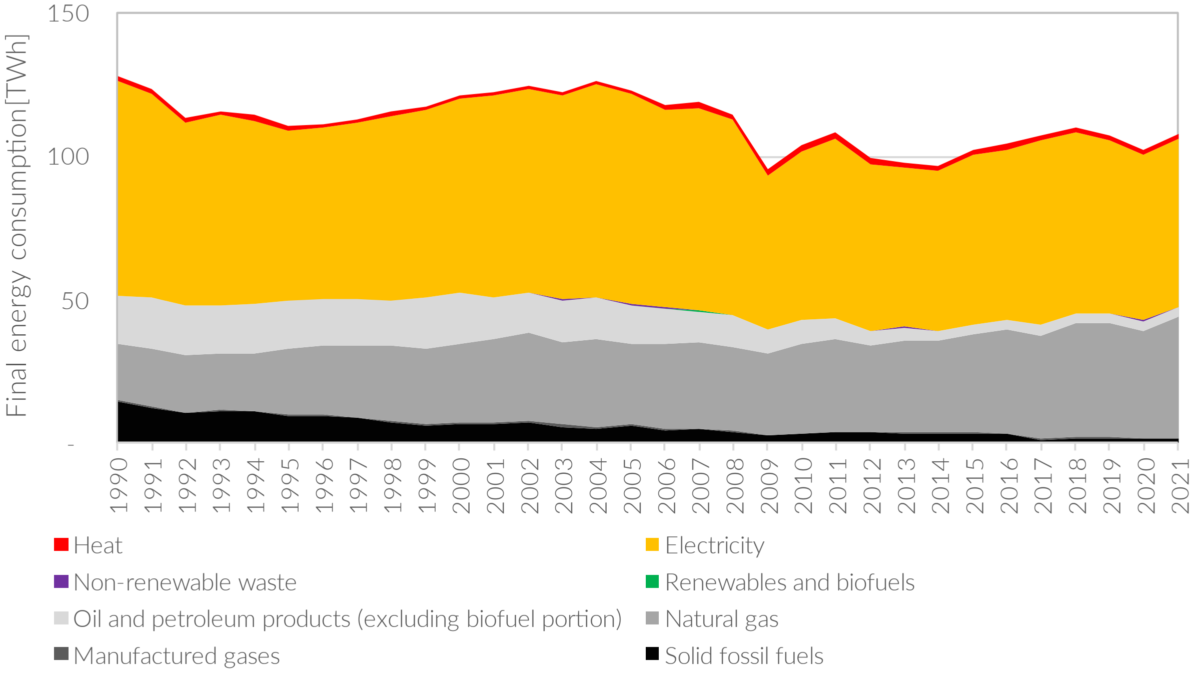


Figure A.4.11: Final energy consumption of the European (EU27) non-ferrous metals sector (Eurostat, 2023b)

The energy demand for primary aluminium production for both, smelting and refining, are also reported by the International Aluminium Institute for 8 different world regions and global data, for different energy sources and since 1980 and 1985, respectively (International Aluminium Institute, 2022).

Specific energy demands for individual processes of the steel and aluminium production and manufacturing can be found in literature but is not presented here in detail. The specific energy consumption of primary production, melting, holding, or heating furnaces as well as processing depends on a wide range of factors, such as heating technology, age of the plant, input material, capacity utilization, and way of operation.

An overview of specific energy and material consumption for the iron and steel making for both, the blast furnace route and the electric arc furnace route, including ladle preheating and casting, can be found, for instance, in the Best Available Techniques Reference Document (BREF) (Joint Research Centre *et al.*, 2013). Energy and material consumption of the downstream processes, such as reheating, heat treatment, rolling and finishing can be found, for instance, in (Joint Research Centre *et al.*, 2022).

Specific energy and material consumption for the aluminium sector, about bauxite mining, alumina refining and smelting, as well as melting, casting and processing can be found in (Joint Research Centre *et al.*, 2017) or the Environmental profile report from European Aluminium (2018), for instance.

A.4.3.2 Energy prices

Energy prices are published for electricity and natural gas by Eurostat (Eurostat, 2023c). The datasets include figures for different price components, such as network prices, taxes or other levies, and different consumer types. Relevant consumer types for the industries are non-household consumers. However, prices differ for different consumption bands. Eurostat defines medium-sizes consumers as consumers with an annual consumption between 500 and 2000 MWh per year for electricity and between 10000 and 100000 GJ per year for natural gas (Eurostat, 2023a, 2023d).

The electricity price for a medium size industry consumer in the EU27 (Figure A.4.12) was between ~0.1 €/kWh and ~0.15 €/kWh from 2007 until the end of 2019 and reached ~0.25 €/kWh in the second half of 2022. Taxis and levies increased over the years from less than 0.04 €/kWh to more than 0.07 €/kWh by 2021 and were reduced in 2022 to ~0.05 €/kWh. Electricity prices for larger consumers (Figure A.4.13) are in general much lower and were less than 0.1 €/kWh until 2021 for very large consumers with an electricity consumption of more than 150000 MWh/year.

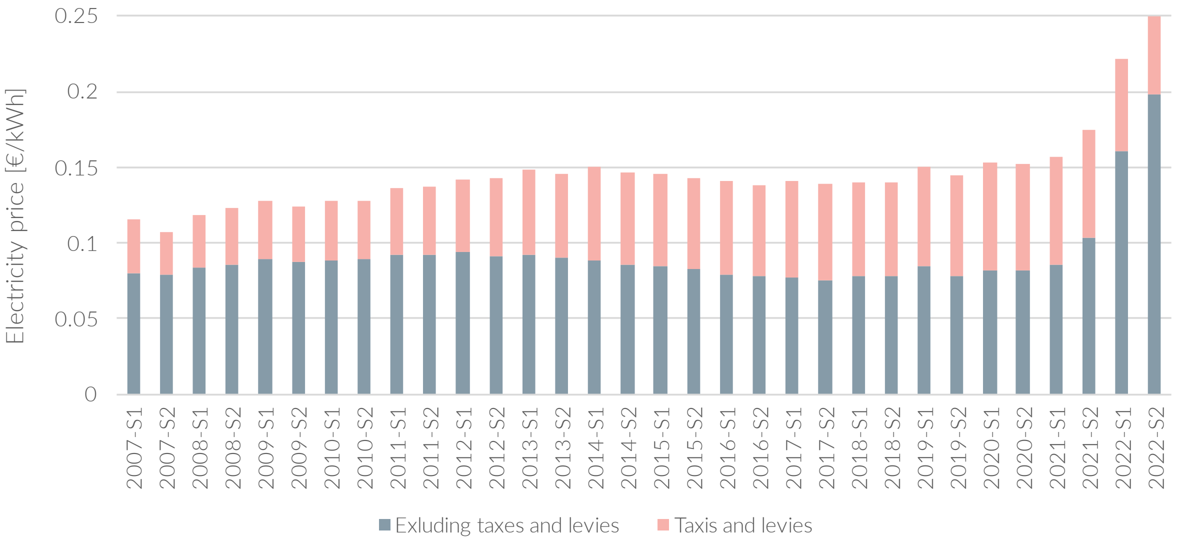


Figure A.4.12: Electricity prices (EU27) and taxes and levies for non-household consumers (medium standard consumption, 500 to 1999 MWh/year) (Eurostat, 2023c)

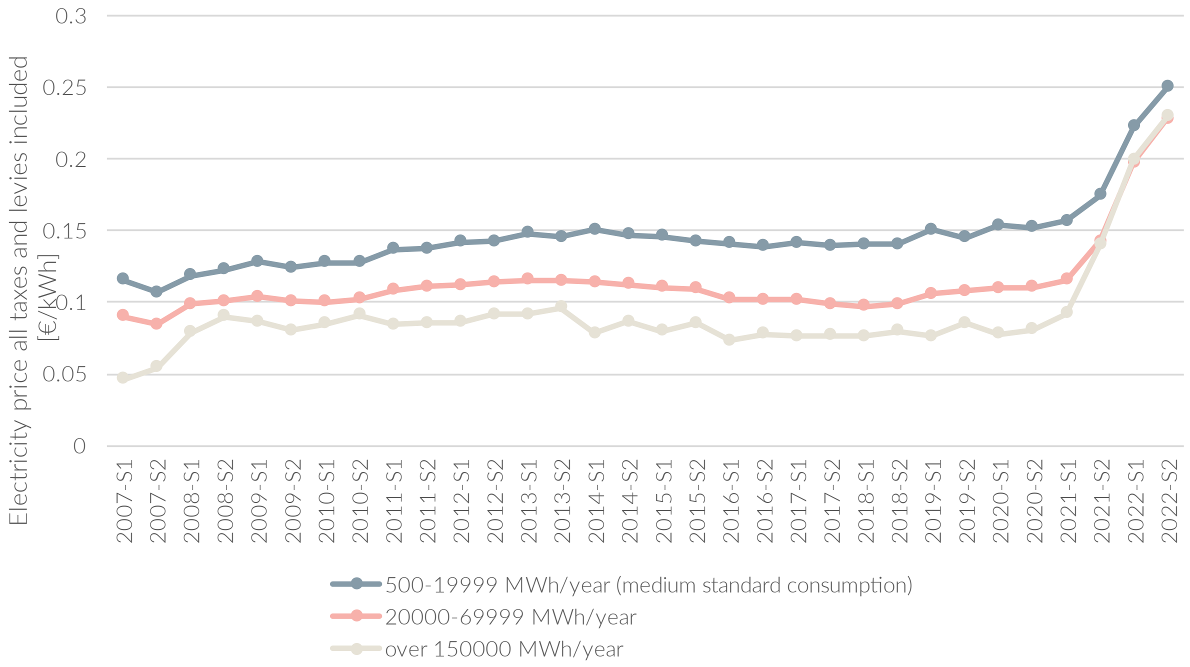


Figure A.4.13: Electricity prices (EU27) including taxes and levies for different consumption bands (Eurostat, 2023c)

The natural gas price for a medium size industry consumer in the EU27 (Figure A.4.14) was between ~0.03 and ~0.05 €/kWh from 2007 until the end of 2021 and increased significantly to more than 0.09 €/kWh in the second half of 2022. Taxis and levies have been relatively constant until the end of 2021, between ~0.008 and ~0.012 €/kWh and increased to ~0.017 €/kWh by 2022. As for the electricity prices, natural gas prices have been lower for larger consumers (Figure A.4.15) for the past years. However, natural gas prices for larger consumer reached the same or higher figures since the second half of 2021.

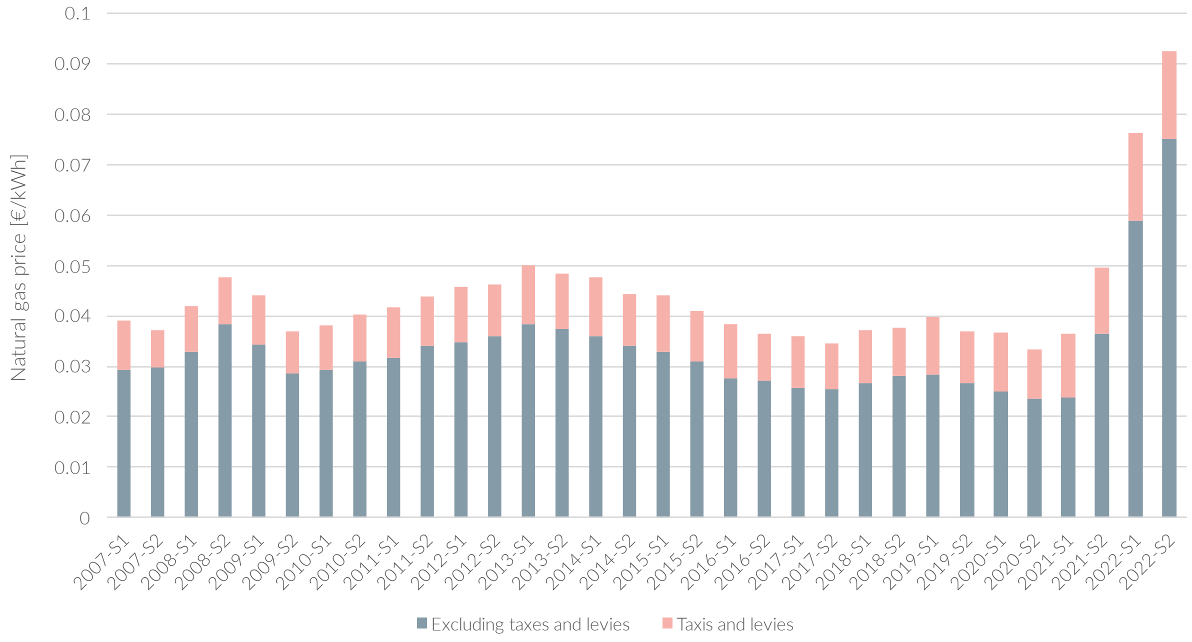


Figure A.4.14: Natural gas prices (EU27) for non-household consumers (medium standard consumption, 10000 to 100000 GJ/year) (Eurostat, 2023c)

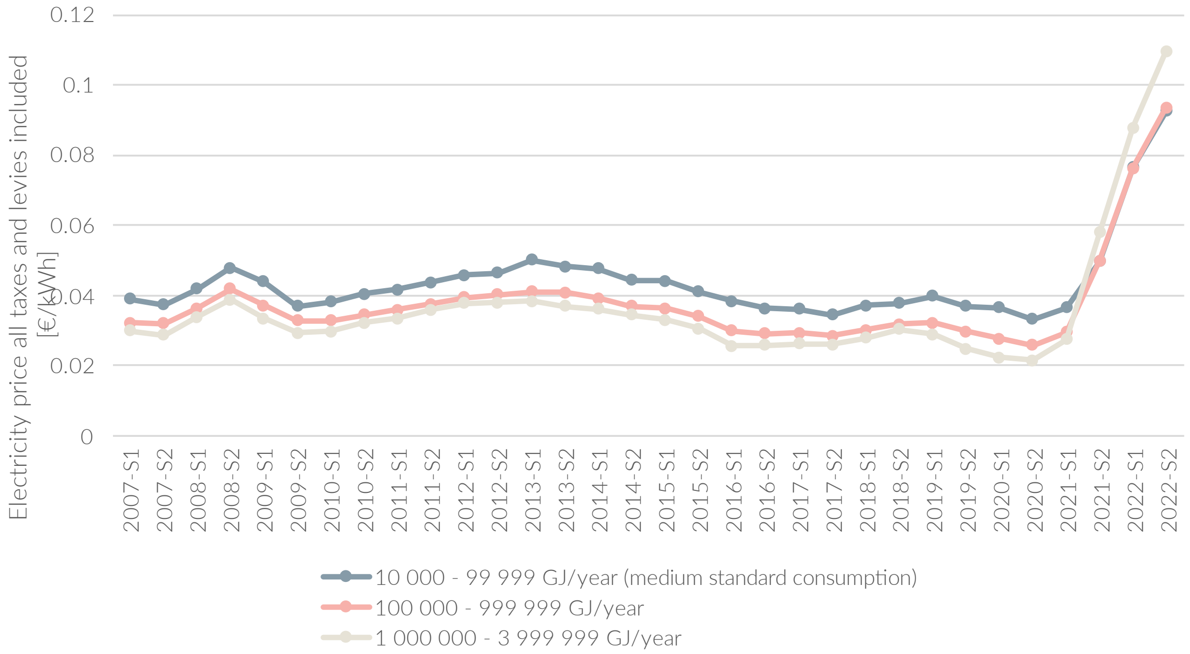


Figure A.4.15: Natural gas prices (EU27) including taxes and levies for different consumption bands (Eurostat, 2023c)

As part of the energy prices, carbon prices have to be considered as well. Carbon prices result from the EU Emissions Trading System (EU ETS) as described in A.1.3. Figures of historical carbon prices are published, for instance, by Sandbag (2023) (Figure A.4.16) and Ember (2023). The price increased especially after the start of the phase 4 in 2021 and more than doubled from less than 40 €/t CO_2 up to almost 100 €/t in 2022. In September 2023 carbon prices reached ~82 €/t. Carbon prices are expected to increase further in the future due to the decreasing emission cap (Reuters, 2023).

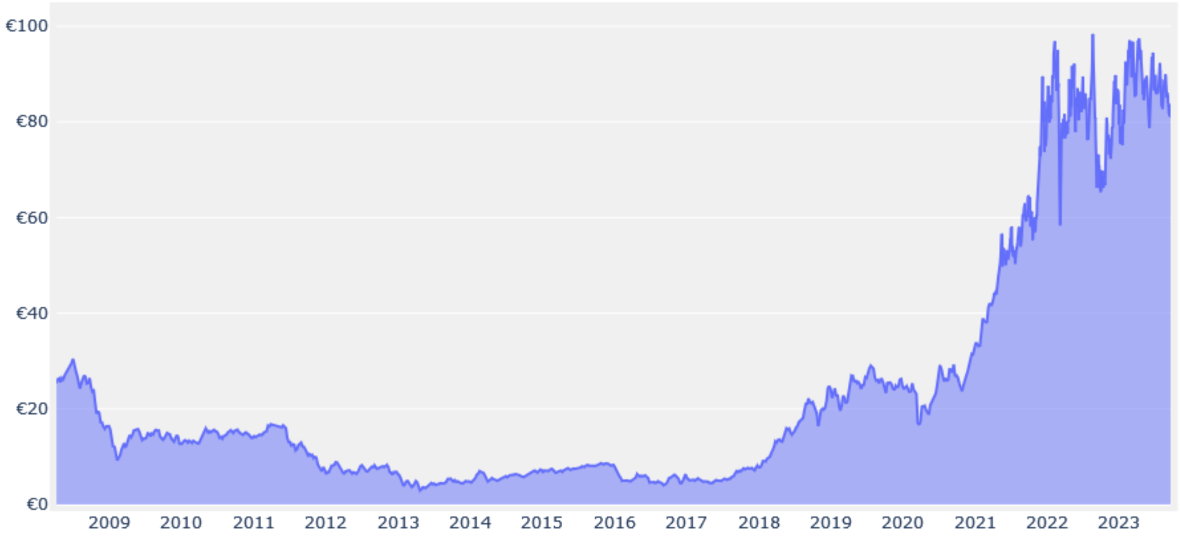


Figure A.4.16: Carbon Price Viewer for the EU Emission Trading System in €/t CO_2 (Sandbag, 2023)

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B. Baseline definition for new measurement technologies and NOx emission limits (task 1.3)

B.1 Overview and questionnaire

NOx emission limit analysis was performed by RWTH. The questionnaire was made by the T1.3 partners and sent to WP1 partners for feedback. Afterward, the questionnaire was sent to all eight demonstrator partners. The questionnaire included inquiries about:

1. Information of all the measurements that will be conducted by SICK and LUX at the demonstrator furnaces.
2. General questions about standard operation practices, such as existing measurement equipment, temperature/pressure data, and flow control.
3. Specific questions to SWER and CTEC about OES installations (see the section on OES).
4. Process gas matrix (gas species and their measurement range in the points of interest).
5. Process conditions (temperature, pressure, flows, etc.).

All the eight demonstrator partners provided some answers to the questionnaire, but some of the filled questionnaires missing information that either could not be sufficiently determined by the demonstrator, or they didn't know the answers at the time. The most important questionnaires regarding the demonstrator installations at SWER and CTEC clarified with CTEC in a separate meeting with the T1.3 partners and interviews were planned by SICK to clarify some of the information provided.

The questionnaire answers were analysed by SICK and OULU to facilitate the next actions for development of measurement devices in WP4 that will be used in WP5 and 6. The following chapters go through the NOx emission limits together with the installation requirements and plans of SICK's and LUX's equipment.

B.2 NOx emission limits and definitions (RWTH)

B.2.1 Definition of nitrogen oxides

In industrial applications, nitrogen oxides mainly include nitric oxide (NO) and nitrogen dioxide (NO_2). Most industrial combustion processes emit NO, which reacts further to form NO_2 at lower temperatures in the off-gas duct or in the atmosphere. The National Emission Reduction Commitments Directive (NEC) EU 2016/2284 (European Parliament and the council, 2016) identifies nitrogen oxides (NO_x) as a major air pollutant due to the toxicity of NO_2 and its derivatives (WHO, 2006).

Several pathways, listed below, can lead to the formation of NO in combustion processes (Glarborg *et al.*, 2018):

- Thermal NO (Zeldovich-NO) (Zeldovich, 1946).
- Prompt NO (Fenimore-NO) (Fenimore, 1971).
- Fuel NO (Glarborg *et al.*, 2018).
- NO formation from reactions of NNH radicals (Bozzelli and Dean, 1995).
- NO formation from reactions of N_2O (Bozzelli and Dean, 1995).

In thermoprocessing applications, the thermal and prompt formation pathways are the two main sources of NO, particularly in conventional combustion regimes and using gaseous fossil fuels (Pfeifer, 2015). In these cases, NO formation is based on the molecular N_2 present in the combustion air and in the fuel. For pure hydrogen combustion, however, the prompt pathway is not relevant due to the lack of CH radicals in the flame front (Glarborg *et al.*, 2018). In the case of gaseous fuels, which are mostly used in industry, fuel NO is not considered as the amount of fuel-bound nitrogen is negligible. This may change for potential future applications using ammonia as a fuel (Lyon, 1976; Kobayashi *et al.*, 2019). The last two mechanisms are currently under discussion. These mechanisms (Malte and Pratt, 1975; Bozzelli and Dean, 1995) may not be of major importance for natural gas combustion, but their contribution may be relevant for hydrogen and other alternative fuels (Durocher *et al.*, 2021).

B.2.2 NOx emission limits

In the European Union, industrial production plants are required to operate within the framework set out in the Industrial Emissions Directive (IED) 2010/75/EU (European Parliament and the council, 2010). The IED (European Parliament and the council, 2010) use of Best Available Techniques (BAT) as a reference for the granting of permits for industrial installations in order to reduce or prevent emissions to air, thereby reducing the impact of the industry on the environment. BAT are defined as “the most effective and advanced stage in the development of activities and their methods of operation, indicating the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where this is not practicable, to reduce emissions and the impact on the environment as a whole” (European Parliament and the council, 2010). These BAT are listed and described in a series of reference documents (BREF: Best Available Techniques Reference Document) for specific industrial sectors. At Member State level, the IED (European Parliament and the council, 2010) is then transposed into national legislation.

For thermoprocessing plants, the BREFs for the following industrial sectors are considered to be relevant in the framework of the HyInHeat Project:

- Ferrous Metals Processing Industry (FMP) (Aries *et al.*, 2022)
- Non-Ferrous Metals Industries (NFM) (Cusano *et al.*, 2017)

The BREFs also provide Associated Emission Levels (AELs) for different pollutants, including NO_x. These AELs define the range of emission levels to be achieved “under normal operating conditions using the best available techniques or a combination of best available techniques, as described in BAT conclusions” (European Parliament and the council, 2010). Concentrations are defined over an averaging period under specific reference conditions, which may vary between the different BREFs for different industrial sectors.

Table B.2.1 gives an overview of NO_x emission levels for different applications within the ferrous metals processing industry. The BAT-AELs are specified according to the process and to the fuel used. In the case of the BREF FMP (Aries *et al.*, 2022), the BAT-AELs are defined in the unit $mg/m^3_{dry,off\text{-}gas}$ for a reference oxygen content of 3% by volume.

Table B.2.1: Overview of NO_x emissions for different industrial applications within the BREF FMP (Aries et al., 2022) at a reference oxygen concentration of 3 vol% (dry off-gas)

Process	Fuel	Specific process	Unit	BAT-AELs
Hot rolling	Natural Gas	Reheating	mg/m^3_{dry}	New plants: 80 – 200 Existing plants: 100 – 350
		Intermediate heating	mg/m^3_{dry}	100 – 250
		Post heating	mg/m^3_{dry}	100 – 200
	Other fuels	Reheating, intermediate heating, post-heating	mg/m^3_{dry}	100 – 350
Cold rolling	Natural Gas	Feedstock heating	mg/m^3_{dry}	100 – 250
	Other fuels		mg/m^3_{dry}	100 – 300
Wire drawing	N/A	Feedstock heating	mg/m^3_{dry}	100 – 250
Hot dip coating	N/A	Feedstock heating	mg/m^3_{dry}	100 – 300
Batch galvanising	N/A	Kettle heating	mg/m^3_{dry}	70 – 300

Unlike the BREF FMP, the BREF NFM (Cusano *et al.*, 2017) does not mention BAT-AELs. However, NO_x emissions are reported for aluminium melting processes (primary and secondary). For secondary aluminium production, values range from <1 to 340 mg/m^3 for different burner and furnace types (Cusano *et al.*, 2017). For these values, the reference oxygen content, and the state of the off-gas (moist or dry) are not defined. However, the authors recommend the collection of NO_x emission data for future work in order to define BAT-AELs. The data should also include reference conditions for the oxygen content in the off-gas.

B.2.3 NOx measurement methods

EN 14792 (DIN Deutsches Institut für Normung e. V., 2017b) the standard reference method for measuring the NO concentration in the off-gas using chemiluminescence. In this method, NO molecules react with ozone O_3 to form NO_2^*. From its excited state (*), NO_2^* falls back to the ground state and emits radiation that is directly proportional to the NO concentration. The NO concentration can then be determined by measuring the radiation. If NO_x is measured instead of NO, NO_2 must first be catalytically reduced to NO in a separate converter.

The principles for the application of Continuous Emission Monitoring Systems (CEMS) are stated in the EN 15267-1 to -4 (DIN Deutsches Institut für Normung e. V., 2008a, 2009a, 2009b, 2017a) series of standard and in EN 14181 (DIN Deutsches Institut für Normung e. V., 2015). The series describe general methods, certification, calibration, testing and quality assurance procedures. Furthermore, EN 15259 (DIN Deutsches Institut für Normung e. V., 2008b) specifies “requirements for measurement sections and sites and for the measurement objective, plan and report”.

According to EN 14792 (DIN Deutsches Institut für Normung e. V., 2017b), NO_x emissions can be measured from both moist and dry off-gas using an adequate sampling probe system. However, emissions are usually measured from the dry off-gas. For this purpose, the moist off-gas emitted from industrial combustion processes must first be extracted, dried, and filtered in conventional analyser systems. The NO_x concentration is then measured and reported in parts per million (volumetric) of dry off-gas ($ppmv_{dry}$). Eq. B.2.1 is used to convert the measured NO_x concentration $Q_{NO_x,dry}$ to the unit mg/m^3_{dry} at a defined oxygen concentration $y_{O_2,dry,ref}$ given in the BREFs. Here, ρ_{NO_2} = 2.056 kg/m^3 specifies the density of NO_2 and $y_{O_2,dry,M}$ the measured O_2 concentration in the dry off-gas. The oxygen concentration in the oxidizer is given by $x_{O_2,Ox}$. For combustion with air, $x_{O_2,Ox}$ = 0.21.

$$Q_{NO_x,dry,ref}\left[\frac{mg}{m^3_{dry}}\right] = Q_{NO_x,dry}\left[ppmv_{dry}\right]\cdot\left(\frac{x_{O_2,Ox}-y_{O_2,dry,ref}}{x_{O_2,Ox}-y_{O_2,dry,M}}\right)\cdot\rho_{NO_2} \qquad \text{Eq. B.2.1}$$

In the case of oxygen-enriched air or pure oxygen as oxidizer, the BREF FMP (Aries *et al.*, 2022) gives an alternative approach for the conversion of the measured NO_x concentration, Eq. B.2.2. The NO_x concentration is based on a reference CO_2 concentration, considering the constant ratio of NO to CO_2 molecules (Aries *et al.*, 2022). The value $y_{CO_2,dry,M}$ defines the measured CO_2 concentration in the dry off-gas.

$$Q_{NO_x,dry,ref}\left[\frac{mg}{m^3_{dry}}\right] = Q_{NO_x,dry}\left[ppmv_{dry}\right]\cdot\left(\frac{y_{CO_2,dry,ref}}{y_{CO_2,dry,M}}\right)\cdot\rho_{NO_2} \qquad \text{Eq. B.2.2}$$

B.3 Instrumentation

B.3.1 SICK's equipment and requirements

As per the requirement in T4.3 and 4.4, following systems have been designed for the tasks.

The measuring gas probe from the furnace provided by RWTH, will be connected to the sample line, and will be heated to maintain the temperature above dew point. The sample goes to the Hot/wet extractive Analysers MCS 300p and GM32. MCS 300p measures NOx and CO in Mid IR range and near IR for CO_2. The analyser (Figure B.3.1) has a sender unit, sample cell and a receiver unit. The sample inlet and the outlet are equipped in the sample cell which is also heated. The Zirconia sensor for Oxygen measurement is equipped within the system.

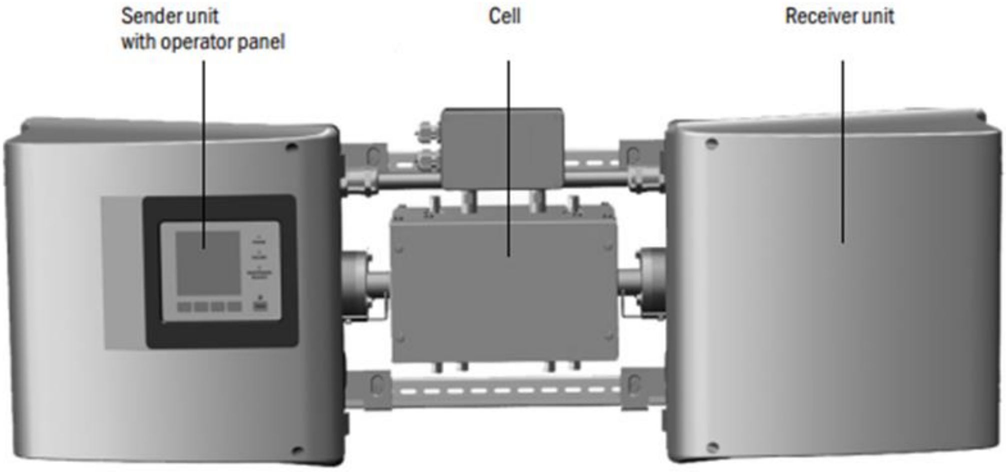

Figure B.3.1: Gas measuring probe

For emission monitoring, Insitu GM32 will be used to measure NO and NO_2 (Figure B.3.2). It measures this component in UV range. Here also, for Oxygen measurement, State of art in situ Zirconium dioxide sensor will be used.

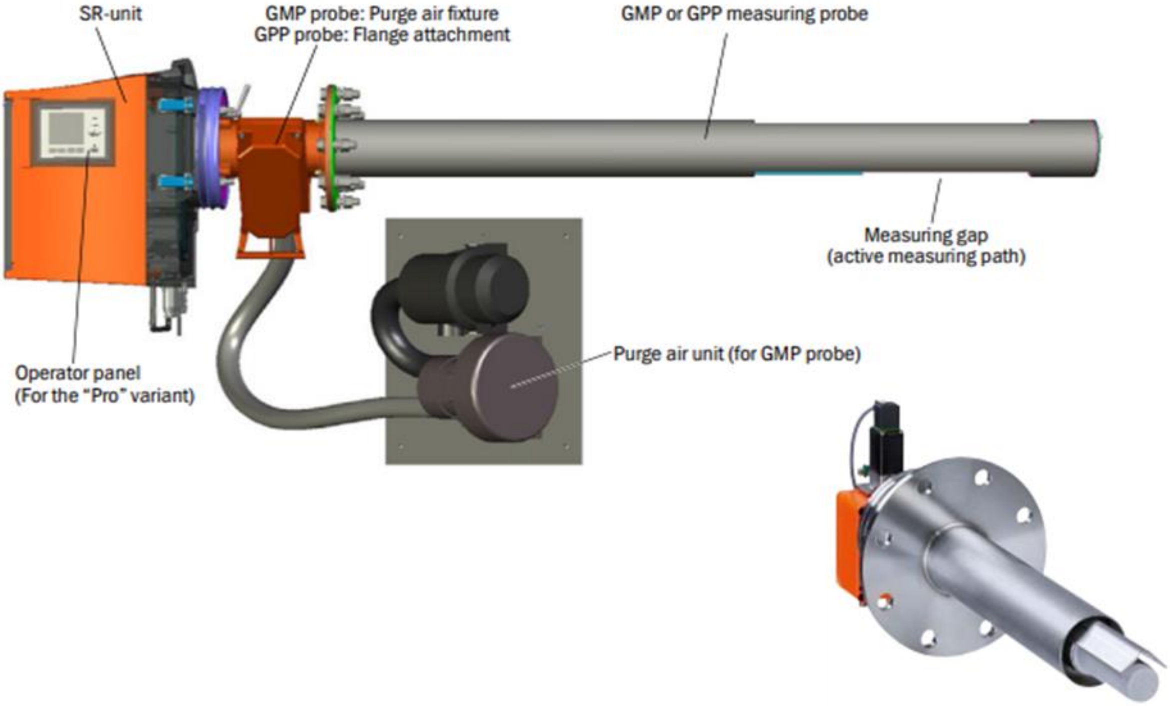

Figure B.3.2: Insitu GM32 device for NO and NO_2 emission measurement

B.3.1.1 Solid state electrochemical cell measurement solution

A sensor based on solid state electrochemical cell with probe will be developed along with a subcontractor which consist of two electrochemical cells made of zirconium dioxide ceramic and is used for the in-situ measurement of oxygen (O_2) and nitrogen oxides NOx (NO and NO_2) directly in the moist flue gas. In conjunction with the NOx Transmitter, the probe can be used for continuous measurement and for combustion control in the systems.

Another sensor and Probe based on a heated electrochemical measuring cell made from zirconium dioxide ceramic ($ZrO2$) Will be developed and used to measure unburned H_2. This Cell will consist of 3 electrodes: O_2 electrode (platinum), H2 electrode (platinum/noble metal) and Reference electrode (platinum). Thus, the Oxygen will be measured by both the sensors as redundant solution.

B.3.1.2 Demonstration installations and requirements

Analysers for combustion control and for emission monitoring will be installed at two demonstrators, SWER and CTEC. The site visits at both the locations have been carried out, discussions have been conducted on locations for analyser installation and the information received is enough to move forward for detail engineering of the system design. The major requirements will be to have a continuous power supply for heated sample line, clean pressurized air for purging, if necessary, etc.

B.3.2 OES equipment

The OES equipment consists of 1. Spectrometer(s) and an industrial PC running Luxmet spectrum collection and analysis software in a closed measurement cabinet, 2. Optical fibre(s), 3. Optical fibre housing, 4. Optional pressurized air equipment in the cabinet for cooling and purging, and 5. Measurement head that will be attached to the furnace's port. If the thermal and mechanical stress conditions allow, instead of a measurement head, the optical fibre can view into the furnace through a glass that does not significantly absorb ultraviolet, visible, and infrared light. An example of the OES set-up for a ladle furnace is illustrated in Figure B.3.3.

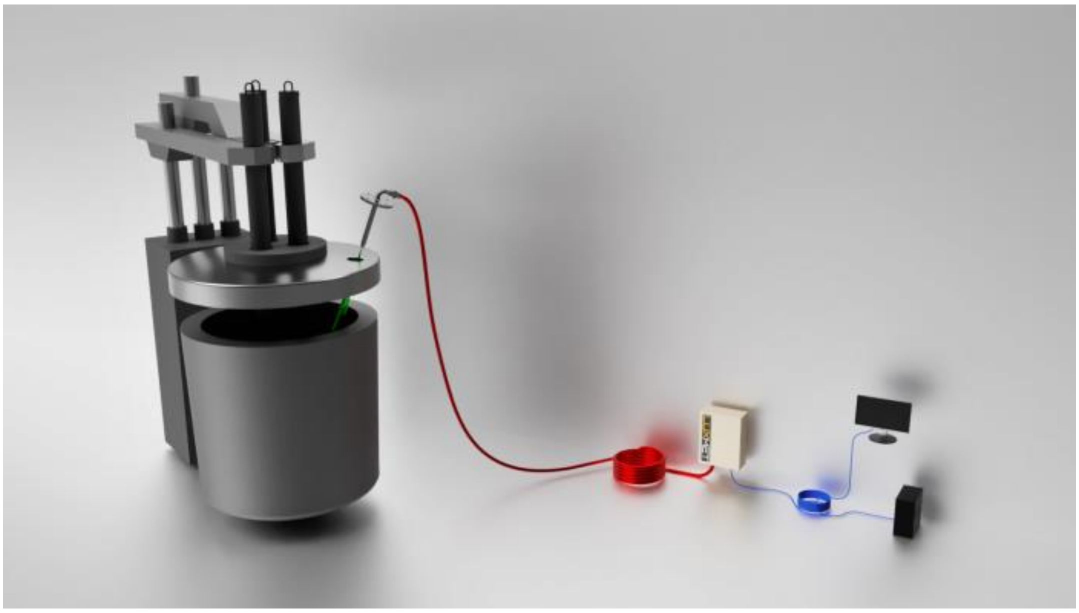

Figure B.3.3: Luxmet's OES equipment at a ladle furnace

The basic principle of an OES spectrometer with a measurement head is presented in Figure B.3.4. For each demonstrator furnace, a way of attaching the measurement head must be designed. The measurement head is purged and cooled with compressed air when the thermal conditions at the measurement location require this. Additional heat/flame protection for the measurement cable (fibre and housing) must be used when the thermal conditions exceed the cable specifications. The maximum length of the measurement cable is typically 15 meters. A user interface for the measurement system for real time monitoring is available via an ethernet connection to the measurement cabinet. Collected spectrum data is stored on the industrial PC hard disk and can be transferred either by using a USB drive or the user interface connection.

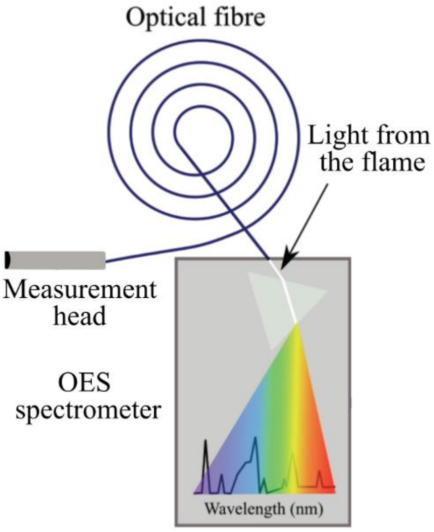

Figure B.3.4: Basic principle of an OES spectrometer with a measurement head

B.3.2.1 Spectrometer specifications

The spectrometer specifications have been assessed based on the literature review, WP4 T4.2 OES measurement campaign at RWTH, and LUX's available spectrometer choices. The optimal wavelength range for H2-burner applications is 230 – 1000 nm, because NO_x optical emissions are prominent below 300 nm. NO is the most important molecule when measuring NO_x compounds. Optical emissions NO molecule can be found in about 230-290 nm wavelength range. However, presumably, NO emission peaks are relatively weak. It is possible that in an industrial environment, they are practically invisible. An alternative method to approximate NO formation in the burning process is to monitor "indicator molecules". In the literature, references can be found that high NH (about 340nm) and CN (about 390 nm) emissions indicate high NO formation. On the other hand, H_2O optical emissions are located near 940 nm. For this purpose, three spectrometers covering 250 – 450 nm, 400 – 860 nm, and 500 – 1100 nm will be used either simultaneously or individually, depending on the wavelength range that is of importance for the said campaign.

One of the most important development aspects of the measurement campaign of T4.2 is related to a spectrometer's capability to collect light, which could limit measurements, especially in the ultraviolet area. Many factors affect the amount of light a spectrometer can detect. For example, the transmission curve of optical fibre, the diameter of optical fibre, the sensitivity of the detector, and the slit size. The optical fibre specifications must be correctly chosen for the used spectrometer and the measured wavelength range. The slit controls the amount of light passed to the spectrometer's detector; the wider the slit, the more light is received. It was found out that the spectrometers' slits should be as wide as possible due to relatively low light emissions from the flame, especially when considering flameless burning. However, a wider slit means a lower resolution of spectra. As a result, the slit's width must be as wide as possible, but still in such a way that sufficient resolution is achieved. Light-gathering lenses can also be used to increase light intensity. This will be taken into consideration when designing the spectrometer specifications for the follow-up measurement campaign in T4.2 and the demonstration campaigns in WP5 and WP6.

B.3.2.2 Demonstration installations and requirements

The OES equipment will be installed at two demonstrators, SWER and CTEC. To facilitate the OES installations at SWER and CTEC furnaces, additional questions were included in the questionnaire. Ports for the optical fibres can already be found at the SWER furnace, whereas the installation of the equipment has to be planned together with CTEC in the third and fourth quarter of 2023. The most important requirements for the OES equipment are 1. The port through which the flame can be seen, 2. Safe locations for the OES measurement cabinet, and 3. Access to pressurized air for cooling of the optical fibre (if needed). The questionnaire and preliminary meetings with CTEC provided sufficient information to proceed with the planning of the demonstrator installations.

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