Examining the Future Environmental Impacts of “Clean” Fuels for Generating Heat

Chan Maureen Botter
MSc Thesis Industrial Ecology, August 2023

Supervisors:
Jeroen Guinée, Leiden University
Paola Ibarra Gonzalez, TU Delft

Executive Summary

Goal and Scope. The decarbonization challenge is especially dire for the energy-intensive industries which worldwide account for a large sum of carbon dioxide emissions. Heat is an essential product demanded by the energy-intensive industries and is currently produced through extensive use of carbon-based fuels including coal, natural gas and oil. Considering the need to meet (inter)national climate targets, these carbon-based fuels must be replaced by cleaner (i.e. less greenhouse gas emitting) alternatives. Biomass, when sourced sustainably, is one such mature alternative yet is still carbon based. For the energy-intensive industries, three of the main non-carbon-based options are: electrification, hydrogen and Iron Fuel Technology™. This research explores the environmental performance of these three alternatives in comparison to natural gas, biomass and each other in two potential future scenarios when implemented in an energy-intensive industry. It also proposes potential ways to reduce environmental impacts and highlights any foreseen (environmental) implications that may occur before large-scale implementation takes place.

Method. The use of ex-ante life cycle assessment allows for the prospective exploration of an upscaled electrification, hydrogen and Iron Fuel Technology™ product system. The life cycle inventory database ecoinvent version 3.9.1 forms the basis for this research in which technology specific processes are modelled by data collected through the inclusion of domain experts and technology developers as well as the completion of desk research. The life cycle impact assessment is based on the European Commission's proposed Product Environmental Footprint and the subsequent standardized set of impact categories included in this research are climate change; ozone depletion; human toxicity, cancer; human toxicity, non-cancer; particulate matter; ionizing radiation; photochemical oxidant formation; acidification; eutrophication, terrestrial; eutrophication, freshwater; eutrophication, marine; ecotoxicity, freshwater; land use; water use; resource use, minerals and metals; and resource use, fossils. Following the life cycle impact assessment, a contribution analysis was completed which highlighted multiple key parameters within processes that were subsequently tested in sensitivity analyses.

Results. This research confirms that electrification, hydrogen and Iron Fuel Technology™ can limit climate change impacts in comparison to natural gas, thereby helping decarbonization efforts and achieve climate targets. From a solely climate change perspective, sustainably sourced biomass is a better alternative to electrification, hydrogen and Iron Fuel Technology™, but it has limited upscaling potential due to the finite availability of sustainable biomass. Considering other impact categories including acidification, freshwater ecotoxicity, marine, terrestrial and freshwater eutrophication, human toxicity cancer and non-cancer, mineral and metal resource use and particulate matter, electrification, hydrogen and Iron Fuel Technology™ all exert more pressure on the environment than steam produced through natural gas. Most of the exerted pressures as seen in the electrification, hydrogen and Iron Fuel Technology™ product systems stem from the assumed electricity mix and the expansion of the electricity network. As a result, some of the impacts, like those associated with expanding the electricity network, are inherently tied to the energy transition.

The comparison between electrification, hydrogen and Iron Fuel Technology™ showed that Iron Fuel Technology™ using scrap iron and waste hydrogen generally performed best except for the impact category human toxicity, cancer. Only when using a fully wind-based electricity mix is Iron Fuel Technology™ outperformed by direct electrification for climate change, fossil resource use, human toxicity cancer, ionizing radiation, land use, and particulate matter. Hydrogen, due to its large electricity demand for water electrolysis, consistently performed the worst throughout all investigated cases and can only be competitive to electrification and Iron Fuel Technology™ based on waste hydrogen when water electrolysis is completed with a fully wind-based electricity mix. The same applies for Iron Fuel Technology™ using green hydrogen.

Discussions. This research has made the first comparison of electrification, hydrogen and Iron Fuel Technology™ considering its implementation in the energy-intensive industries in comparison to natural gas and biomass as well as comparing them among each other. It thereby investigated potential environmental impacts in a possible 2030 and 2050 Dutch future identifying hotspots and key parameters that are highly influential in determining environmental performance through performing ex-ante LCA. It stands out as it investigates a broad range of impact categories when most reviewed studies only focused on a set of impact categories. Consequently, the outcomes of this research can be used to guide research and development, monitor potential problem areas and be used as the basis for evaluation and further research.

However, the limitation of ex-ante life cycle assessment is that it is exploratory in nature and subject to large uncertainties. As “what if” scenarios are examined, this research does not provide any conclusive results and can only be used to provide insights into potential environmental performances of alternatives, to identify environmental hotspots, for debate and to make recommendations for research and development activities. Large uncertainties in the research stem from temporal mismatches in foreground ex-ante data and background dated data, unquantified characterization factors, and slight inconsistencies regarding system boundaries. The largest uncertainty yet may be the development of each product system in time as ex-ante LCA examines and compares a potentially upscaled emergent technology to a mature technology in the present which may also not necessarily be a fair comparison. The underlying availability and quality of the data in this research reflects this. Even though comparison is made at the same assumed technological readiness level, the underlying data of the mature technology is proven to be possible whereas the data of the emerging technologies is assumed based on expected results. The availability and quality of the used data is therefore drastically different and may lead to arbitrary results.

Recommendations. The results of this research suggest reducing material usage, making manufacturing processes of required background products more sustainable (e.g. copper) and decreasing electricity consumption are the most effective ways to limit environmental impacts in the electrification, hydrogen and Iron Fuel Technology™ product systems. Specifically for Iron Fuel Technology™ it is further recommended to source waste hydrogen, produce initial iron fuel from scrap, further improve the circularity of iron fuel and to use ship transport over truck transport whenever possible. For hydrogen, key recommendations include keeping hydrogen losses to a minimum, and technologically improving the electrolyzer and boiler efficiencies. This research also highlighted that differences in case application and assumptions can influence the environmental performances significantly. As a result, it is strongly recommended to further examine electrification, hydrogen and Iron Fuel Technology™ for various end-use applications and under different scenarios.

Conclusions. The results of this research suggest electrification, hydrogen and Iron Fuel Technology™ could all reduce climate change impacts in both 2030 and 2050. However, it is also noted that they are not fully clean alternatives, i.e. that not all environmental impacts are lower in comparison to carbon-based fuels. The completed ex-ante LCA showed higher environmental impacts for multiple impact categories, among others: acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer and mineral and metal resource use among other impact categories. Some of these impacts are a direct result of the assumed 2030 and 2050 scenarios reflecting the transition away from carbon-based fuels sketched in this research. The environmental impacts related to copper associated with an expansion of the electricity network is an example of this. To limit environmental impacts, this research suggests a multitude of redesign recommendations for electrification, hydrogen and Iron Fuel Technology™, primarily focused on increasing efficiencies, limiting electricity demand and decreasing emissions of background processes. Though implementing a set of these redesign recommendations helped decrease environmental impacts for electrification, hydrogen and Iron Fuel Technology™, it was shown to be insufficient to reduce environmental impacts in all impact categories to below the environmental impacts of carbon-based fuels or generally alter the environmental performance of electrification, hydrogen and Iron Fuel Technology™ in comparison with one another. The results therefore indicate that Iron Fuel Technology™ based on scrap iron and waste hydrogen is most preferable among the clean alternatives in decreasing climate change impacts while limiting other environmental impacts in as far as possible. However, it must still be noted that dependent on the specific case, the assumptions used, and which impact categories are prioritized, which technology is best suited may be subject to change.

Perspectives. This research suggests that electrification, hydrogen and Iron Fuel Technology™ can help alleviate climate change impacts to varying degrees depending on the scenario assumed, but that tradeoffs of other environmental impacts will likely arise in the transition away from carbon-based fuels. It should therefore be cautioned that a sole emphasis on tackling climate change impacts, specifically decreasing CO_2 emissions, may result in overlooking potential side effects that may be environmentally harmful. The environmental impacts of any technology must therefore always be holistically examined over multiple impact categories.

Table of Contents

Abbreviations

AC	Acidification [mol H+-Eq]
CC	Climate change [kg CO2-Eq]
CCS	Carbon capture and storage
CH_4	Methane
CO_2	Carbon dioxide
E-boiler	Electric boiler
EAF	Electric arc furnace
EC	Ecotoxicity, freshwater [CTUe]
EF	Eutrophication: freshwater [kg P-Eq]
EHB	European Hydrogen Backbone initiative
EII	Energy-intensive industry
EM	Eutrophication, marine [kg N-Eq]
ET	Eutrophication, terrestrial [mol N-Eq]
FLH	Full load hours
FR	Resource use, fossils [MJ, net calorific value]
GHG	Greenhouse gasses
H-boiler	Hydrogen boiler
IAM	Integrated assessment model
IC	Impact category
IE	Industrial Ecology
IF	Iron Fuel
IF-boiler	Iron Fuel boiler
IFT	Iron Fuel Technology™
IPCC	International Organization for Standardization
IR	Ionising radiation [kBq U235-Eq]
ISO	International Organization for Standardization
KPI	Key performance indicator
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LU	Land use [dimensionless]
MR	Resource use, minerals and metals [kg Sb-eq]
NG-boiler	Natural gas boiler
NOx	Nitrogen oxides
OD	Ozone depletion [kg CFC-11-Eq]
PA	Process alternative
PBL	Planbureau voor de Leefomgeving
PEF	Product environmental footprint
PM	Particulate matter [disease incidence]
PO	Photochemical oxidant formation [kg NMVOC-Eq]
PV	Photovoltaic
R&D	Research and development
RIFT	Renewable Iron Fuel Technology
SDE+	Stimuleringsregeling Duurzame Energieproductie
SDE++	Stimuleringsregeling Duurzame Energieproductie en Klimaattransitie
SSP	Shared socio-economic pathway
TC	Human toxicity, cancer [CTUh]

TNC	Human toxicity, non-cancer [CTUh]
TRL	Technological readiness level
WU	Water use [m3 world eq. deprived]

List of Tables

List of Figures

1. Introduction

In 2015, 195 countries signed the Paris Agreement to limit global warming to 2℃ by 2050, with the aim of keeping it below 1.5℃. In the Netherlands, the government has set the goal of reducing greenhouse gas (GHG) emissions by 55% in 2030 in comparison to its 1990 emissions and to be climate neutral in 2050 (Ministerie van Algemene Zaken, n.d.-f; Ministerie van Economische Zaken en Klimaat, n.d.). The industry and electricity sector together are responsible for 51% of the Dutch carbon dioxide (CO_2) emissions totaling 86.4 MT CO_2/year in 2021 (CBS, 2022). To achieve the Dutch governments reduction goals, these two sectors must decarbonize drastically. Though progress has been made, the Dutch industry must further reduce its emissions by ~30 Mton CO_2 and the electricity sector by 6-20 Mton CO_2 by 2030 (CBS, 2022; Ministerie van Economische Zaken en Klimaat, n.d., 2022; RVO, 2022). With 2030 being less than 7 years away, decarbonization must happen quickly should (inter)national climate targets be achieved.

With the GHG emissions of the industry and electricity sector accounting for such a large share of the total Dutch emissions, these two sectors are key. In this research, the focus will be on energy-intensive industries (EIIs). The energy-intensive industries typically refer to (industrial manufacturing) sectors that demand and consume large amounts of energy such as the iron and steel, mineral, metal, refinery, pulp and paper, food and beverage, and chemical industries, but the term can be broadened to include all large energy consuming sectors like the electricity generation sector (de Bruyn et al., 2020; EIA, 2016; Rehfeldt et al., 2017). When the term EIIs is used in this research, it refers to the broadest extent of the term. The energy-intensive industries are indispensable to Europe's economy and employ millions of people within the EU27 countries (de Bruyn et al., 2020; European Commission, 2019). Currently, they use a variety of fuels and feedstocks (electricity, gas and other fuels) that are largely carbon-based. The use of carbon-based fuels as both energy source and raw material in EIIs results in two types of emissions: emissions that are a direct by-product of production processes, i.e. process emissions, and emissions resulting from the production of energy required for utilities or production processes, i.e. combustion emissions (Andrés et al., n.d.; EIA, 2016). To reduce both types of emissions, carbon-based fuels will need to be replaced with alternative, cleaner fuels with limited to no CO_2 emissions for use as an energy source and feedstock.

As energy comes in various forms and can be used as a feedstock or as fuel, this research specifically focuses on clean fuels for the provision of heat to EIIs. Worldwide, "heat is the largest energy end use" in which "industrial processes are responsible for 51% of the energy consumed for heat" (IEA, 2022b). Two-thirds of the industrial energy demand accounts for industrial heat totaling almost one-fifth of the global energy consumption (Bellevrat & West, 2018). In Europe, heating and cooling accounts for half of the energy demand of the EU28+3[1] (Rehfeldt et al., 2017). The total heating demand of Europe thereby totals 2315.6 TWh of which the Netherlands accounts for approximately 5.5% of this (Rehfeldt et al., 2017). Heat is thus a cornerstone of the energy demanded by EIIs, with coal, natural gas and oil being the dominant fuel sources for the heat demanded in production processes (Roelofsen et al., 2020).

[1] EU28 includes Great Britain before Brexit, and plus three refers to Norway, Switzerland, and Iceland

Heat, however, can come in different temperature ranges. Though ranges may vary slightly, the energy-intensive industries can generally be divided into the following temperature profiles:

- high temperature heat, which refers to heat with a temperature larger than 500°C
- medium temperature heat, which refers to heat in the range of 100-500°C
- low temperature heat, which refers to heat below 100°C (Rehfeldt et al., 2017).

Each industry can require different temperature profiles for meeting its energy demand for which one or multiple applicable solutions may exist. This is case and application specific as this depends on the fuel characteristics, technical feasibility, operational requirements, and economic viability of the solution amongst other factors. Nevertheless, numerous alternative fuels can potentially be applicable to one or multiple of the above-mentioned temperature profiles.

With the need for realizing the energy transition increasing in light of climate change and (inter)national targets, the implementation of clean alternatives for replacing carbon-based fuels for heat provision in EIIs is becoming a must. The term clean energy technologies / alternatives is often used to indicate alternative ways to produce, convert, and store energy other than the conventional carbon-based fuels (i.e. coal, oil, and natural gas) in which "clean" refers to a reduced carbon footprint in comparison to the GHG emissions of carbon-based fuels (Constellation, 2023; IEA, 2020; Linares et al., 2014; Zohuri et al., 2022). Realizing the energy transition, however, is largely dependent on these so-called clean alternatives having the potential to drastically reduce GHG emissions without any adverse environmental side effects. In this research, the term clean alternatives will be used to indicate alternative energy technologies that do not directly emit any CO_2 emissions.

For energy-intensive industries, the clean alternatives are currently limited to electrification and hydrogen. The start-up Renewable Iron Fuel Technology (RIFT) adds to this a third alternative for decarbonizing EIIs: Iron Fuel Technology™ (IFT). Though electrification and hydrogen are acknowledged to be able to contribute to the decarbonization problem to varying degrees in literature, RIFT and existing literature has limitedly researched the environmental benefits of IFT (Bergthorson, 2018; Bergthorson et al., 2015; Honore, 2019; IEA, 2020; Kosmadakis, 2019; Lechtenböhmer et al., 2016; Madeddu et al., 2020; Rahnama Mobarakeh & Kienberger, 2022; Schüwer & Schneider, n.d.; Sorknæs et al., 2022). Therefore, as a result, a comparative examination of the environmental benefits and burdens of these three clean alternatives and to the carbon-based industry incumbents, biomass and gas, can prove beneficial to good policy management, implementation and investment choices.

1.1 Background

In this section further elaboration is given on (i) how each technology works, (ii) what its potential and current state is, (iii) if there are any significant limitations and (iv) the existing literature on the environmental performance of each technology. This is provided for all three clean alternatives (hydrogen, electrification and Iron Fuel Technology™) as well as biomass and natural gas. Natural gas is an often-used fossil fuel for generating heat in the process industry and biomass is the most often non-fossil fuel used (Nederlandse Emissieauthoriteit, 2019; Olsson & Schipfer, 2021). Hence, these two fuels will be included in this research to provide a benchmark for the environmental performance of carbon-based fuels for comparison purposes to the cleaner electrification, hydrogen and Iron Fuel Technology™ alternatives.

1.1.1 Hydrogen

In the transition away from fossil and carbon-based fuels, hydrogen is a prominently discussed potential substitution in the Netherlands. It can be used to provide high-temperature process heat and can be used as both an energy source and feedstock (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019; Neuwirth et al., 2022). The storable characteristics of hydrogen make it a desirable alternative as it allows for storage as a hydrogen molecule or in several related chemicals (Abdalla et al., 2018; Lan et al., 2012). Research has shown that when renewable energy sources are used for hydrogen production, hydrogen can be more favorable in comparison to fossil fuels (Abdalla et al., 2018; Baykara, 2018; Nicoletti et al., 2015). Green hydrogen[2] can be combusted with zero emissions of carbon dioxide and the only byproduct being water vapor (Abdalla et al., 2018). However, limitations of implementing hydrogen at large scale now include the virtually absent production capacity and transport infrastructure (Neuwirth et al., 2022). Green hydrogen also requires a sufficient and guaranteed supply of renewable energy. As such, green hydrogen is currently not yet available and is only being tested in pilots spanning production, distribution networks as well as use cases, e.g. PosHYdon, The Green Village or the implementation in Lochem (Alliander, 2022; de Laat, 2020; *PosHYdon Pilot, Dutch North Sea*, 2022).

Though the green hydrogen market is yet to be developed, the (grey) hydrogen industry has existed for decades and uses hydrogen as a feedstock (Taibi et al., 2018). The estimated value of it represents more than 115 billion USD (Taibi et al., 2018). Of this market, more than 90% of the hydrogen consumption today originates from industrial sectors (Fraile et al., 2015). The largest user is the chemical industry of which the production of ammonia accounts for more than 50% of the industry volume consumption (Fraile et al., 2015). The hydrogen produced to meet current demand is primarily produced via steam methane reforming of natural gas, coal gasification and from cracking of hydrocarbons (Fraile et al., 2015; Taibi et al., 2018). These production methods all emit carbon dioxide during operation and are considered as grey hydrogen (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019). Hydrogen produced from fossil fuels but with the addition of carbon capture and storage (CCS) is referred to as blue hydrogen. Blue hydrogen is seen as a way to transition to a hydrogen economy while green hydrogen is not yet able to be produced at large scale (Hers et al., 2018). However, the ability for a lock-in of fossil fuels, the limited experience with CCS and the potential leaking of captured CO_2 can be reason for societal backlash (Hers et al., 2018). For these reasons, blue hydrogen is not considered to be a long-term sustainable solution (Hers et al., 2018). As a result, there is need for a movement towards green hydrogen eventually.

From an environmental perspective, hydrogen has been shown to emit less GHG emissions than the conventional fossil fuels like natural gas. The Hydrogen Council (2021) investigated

[2] Different colors are used to indicate the production method of hydrogen: grey hydrogen is produced from fossil fuels typically via steam methane reforming, blue hydrogen is fossil fuel based but makes use of carbon capture and storage technology, whereas green hydrogen is produced via water electrolysis using green electricity thereby not producing any direct CO_2 emissions.

GHG emissions of various hydrogen pathways from well-to-use. One pathway showed that when hydrogen produced from natural gas with CCS is transported and consequently used in boilers / furnaces in industry clusters in the United Kingdom, GHG emissions could be reduced to over 80% in 2030 in comparison to natural gas combustion (Hydrogen Council, 2021). This reduction could increase to 90% in 2050 as the electricity required for hydrogen production is assumed to become more sustainable. According to the Hydrogen Council (2021), the grid mix for blue hydrogen production is also the largest contributor to GHG emissions in the value chain. Apart from this specific research, studies into the environmental impact of hydrogen with the end use of industrial heat are absent.

The environmental impact of multiple hydrogen production routes and the use of hydrogen for mobility, however, have been studied extensively, as can be seen in the reviews of, for example, Bhandari et al. (2014) and Valente et al. (2017). The paper of Bhandari et al. (2014) reviews 21 studies that investigate hydrogen production technologies through a life cycle assessment. Life cycle assessment (LCA) is a methodology that allows for the measurement of a product's environmental impacts across all stages of its life cycle and is a common method also seen in existing literature when comparing environmental performance of products. The review finds that impact categories like climate change are often analyzed whereas other categories like those related to toxicity are often not. A full impact assessment is thus often absent. As for the findings of the reviewed LCAs, hydrogen produced through water electrolysis with green sources like wind and hydropower have less environmental impact in comparison to hydrogen production powered by grid electricity mixes or fossil fuels (Bhandari et al., 2014; Hydrogen Council, 2021; Koroneos et al., 2004). It is also noted that the electricity used as input for hydrogen production largely contribute to the environmental performance (Dufour et al., 2012; Hydrogen Council, 2021). As the Hydrogen Council (2021) study only focused on blue hydrogen, but hydrogen produced from green sources by water electrolysis has been shown to have a more beneficial environmental impact in numerous studies, it can be assumed that the use of green instead of blue hydrogen may exert even less pressures on the environment. The 80% emission reduction in 2030 in comparison to natural gas combustion as noted by the Hydrogen Council (2021) could thus potentially be even higher.

Also noticeable in current literature is that in most studies only a part of the life cycle is included in the research, with most studies focusing on XtoGate (Valente et al., 2017). The 'X' signifies the feedstock or energy source production stage whereas the 'gate' often refers to the newly produced / purified hydrogen (Valente et al., 2017). The use and distribution stage of hydrogen is thereby often not included. Whenever the use stage is included, the end use is often mobility (Valente et al., 2017). Most studies with the end use of mobility then consider the distribution of hydrogen to a limited extent, use high-level estimates, or consider truck transport (Bartolozzi et al., 2013; Di Lullo et al., 2022; Hacatoglu et al., 2012; Lucas et al., 2012).

Though the transportation of hydrogen can take place in various forms including gaseous or liquified transport by truck, compressed via pipeline, or in the form of a numerous hydrogen carriers. For energy-intensive industries demanding a stable, large supply, pipeline transport is likely the only realistic option (U.S. Department of Energy, n.d.). In the Netherlands, the future hydrogen network will likely be an expansion and repurposing of the current natural gas pipeline network of which the government plans to connect the larger industrial clusters with together (Gasunie, 2023b). Gasunie, the energy infrastructure company responsible for the gas network in the Netherlands, has already started on the hydrogen network (Gasunie, 2023b). The European Hydrogen Backbone initiative (EHB), a collective of energy infrastructure companies of which Gasunie also takes part in, has also produced multiple reports on the vision of such a hydrogen network connecting various parts of Europe together. However, both Gasunie and the EHB provide no information on the environmental impact of transporting hydrogen. Of the reviewed literature, Di Lullo et al. (2022) provides the only in-depth overview of the associated emissions of each hydrogen transportation method. They find that the transportation of pure hydrogen via pipeline network has one of the lowest GHG emission footprints in comparison to the other potential hydrogen transportation methods such as truck transport and hydrogen carriers (Di Lullo et al., 2022).

Even though a vast amount of literature exists spanning multiple parts of a potential hydrogen supply chain, clear gaps remain in the assessment of the full life cycle impacts of implementing hydrogen for the purpose of creating industrial heat for the energy intensive industries. As literature surrounding the production of hydrogen is relatively large, this research will build on the current (academic) literature and expand this to include the transportation and combustion stage of hydrogen for the end use of provisioning heat to an industrial counterpart.

1.1.2 Electrification

Another decarbonization alternative for the energy-intensive industries is to electrify their processes. Electricity is already a backbone of the energy supply system and a mature technology unlike hydrogen or Iron Fuel Technology™ which still requires extensive technological development. Roelofsen et al. (2020) has found that for the industry's energy use from fuels "it is technically possible to electrify up to half of the industrial fuel consumption today". For instance, for lower temperature heat demands commercial equipment is available, but for temperatures above 1000°C technologies are often still in the research or pilot phase (Roelofsen et al., 2020). Dependent on the specific application, changes for electrification can be as simple as a replacement of parts, e.g. the replacement of a boiler or furnace, or may require an overhaul of the process (Roelofsen et al., 2020).

Within the European and Dutch context, electrification is being considered as a measure to reduce emissions and is often mentioned in roadmap studies (Bert Den Ouden et al., 2017; Gerres et al., 2019; Wiertzema et al., 2020). However, a key consideration to take into account is that electrifying processes is only sustainable if the supplied energy is from renewable sources. Electrification of processes in itself does not guarantee a CO_2 neutral situation (Bert Den Ouden et al., 2017). For large-scale electrification of energy-intensive industries, the generation of renewable electricity would need to increase significantly. One estimation of the complete electrification of the basic materials industry (thus not encompassing all energy-intensive industries) resulted in a required electricity demand of 1713 TWh annually in 2050 (Lechtenböhmer et al., 2016; Wiertzema et al., 2020). To put this into perspective, the current total electricity use of the EU industry totals approximately 1000 TWh (Lechtenböhmer et al., 2016). Hence, a significant increase of (green) electricity will be required if industries choose to electrify their processes.

One of the challenges resulting from increasing the electricity demanded are infrastructural. Congestion of the electricity grid, for example, is a large issue in the Netherlands. Businesses cannot electrify as the current electricity grid has not been designed for meeting industrial demand (de Bruyn et al., 2020). New and expanded electricity grids and additional transformers will be required (de Bruyn et al., 2020). Direct implementation is thus hindered by the need for infrastructure reinforcement. Furthermore, switching to electricity-based processes can leave businesses at a disadvantage due to the associated higher operational expenditures and upfront required investments, e.g. infrastructural or installation costs (de Bruyn et al., 2020). For these reasons, electrification of the industries, though technically possible, is currently not upscaled.

As just mentioned, electrification of the energy-intensive industries is only sustainable when green electricity is the source. There have been numerous studies and reviews completed to identify the environmental impacts of the electricity system separately in its parts: electricity generation technologies, see e.g. Arvesen & Hertwich (2011); Turconi et al. (2013); United Nations Economic Commission for Europe (2021), or the transmission and distribution networks, see e.g. Gargiulo et al. (2017); Harrison et al. (2010); Jorge & Hertwich (2014). Fewer studies take a more holistic and full life cycle approach in which multiple parts of the electricity system are analyzed jointly (Berrill et al., 2016; Hertwich et al., 2015; Kouloumpis et al., 2015). From reviewing these studies it becomes clear that the required infrastructure in the electricity system contributes largely to environmental impacts like mineral resource depletion and has greater land occupation impacts than fossil fuels (Berrill et al., 2016; Turconi et al., 2013). Also impacts from the upstream processes required to generate the electricity are a source of large impacts, e.g. the wind turbine construction, the electricity mix used during manufacturing processes, and the installation and decommissioning stages (Arvesen & Hertwich, 2011; Turconi et al., 2013). As for the use stage of the electricity, most studies are largely focused on the application of electricity in buildings (e.g. Famiglietti et al. (2021); Rinne & Syri (2013); Vechi & Ghis (2018), with relatively few studies focusing on (subsectors of) the energy-intensive industries, e.g. district heating in Nitkiewicz & Sekret (2014). No studies were found to have examined the full life cycle impacts of producing heat directly from electricity via an electric boiler (e-boiler). Similarly, no literature was found to specifically study the environmental impact of e-boilers either. As e-boilers allow for the conversion of (renewable) electricity to heat, they will be key for the energy transition in meeting industrial heat demand in the energy-intensive industries. Studies on heat pumps and conventional boilers have been completed, however these impacts do not translate one-to-one to e-boilers (e.g. Famiglietti et al., 2021; Nitkiewicz & Sekret, 2014; Rinne & Syri, 2013). Hence, this study can contribute to understanding the full life cycle impacts of producing heat directly from electricity via an e-boiler by considering multiple parts of the electricity system.

1.1.3 Iron Fuel Technology™

Iron Fuel Technology™ is a CO_2 free, safe and circular energy technology specifically for district heating, industrial processes and electricity generation plants. It is an alternative for the use of fossil fuels in generating high temperature heat. The foundation of this technology is the rusting and unrusting of iron fuel (iron in powder form), which allows for the storage and release of energy, similar to a rechargeable battery (Renewable Iron Fuel Technology, 2022; RIFT, 2023).

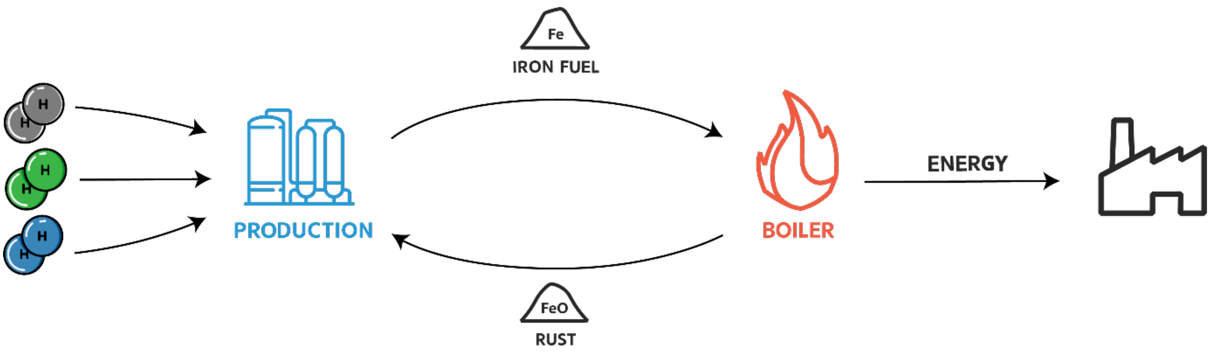

Figure 1: the working principle of Iron Fuel Technology™

The working principle can easily be described in two steps, see Figure 1.

1. Combustion – the release of energy from iron fuel in an iron fuel boiler.
   $4Fe + 3O_2 \rightarrow 2Fe_2O_3$
   The iron fuel (IF) is combusted in a boiler system in which a flame is created that releases energy in the form of heat (~1500°C) with no CO_2 emissions. The only by-product is rust (iron oxide) which gets captured and is reused to form iron fuel again (step 2).
2. Production – the storage of energy in iron fuel in an iron fuel production reactor.
   $Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$
   The rust is transferred into a reactor in which it is produced to iron fuel and water in the form of steam with an excess of hydrogen. The newly produced iron fuel and water are separated out and the hydrogen is recycled within the process to make iron fuel again. This process requires energy, which is transferred from the hydrogen. This energy is released again during combustion in step 1.

Iron Fuel Technology™ is a relatively new technology that has been developed since 2015, with practical exploration largely surrounding the Technical University of Eindhoven and the student team SOLID. In 2020, three ex-members of student team SOLID decided to commercialize the technology and founded start-up Renewable Iron Fuel Technology (RIFT). They have proven and developed the technology further to technological readiness level (TRL) 4/5. It is expected that the technology is ready for commercial implementation in 2025. To date, the environmental impacts of this technology have been studied to a limited extent by some of the involved parties, but results have never been publicized. A standardized assessment such as an LCA has also never been conducted making the developing parties largely unaware of the (future) environmental impacts.

1.1.4 Natural Gas

Natural gas is a gaseous fossil fuel energy source predominantly consisting of methane (CH_4) (U.S. Energy Information Administration, 2022b). It's versatility in storage, transport and ability to be used rapidly in gas-fired plants makes it a desirable fuel (Greenfield, 2023; Shell International, n.d.). In the last decades, natural gas use has grown rapidly worldwide and currently accounts for about a quarter of the global electricity generation (Greenfield, 2023). In the Netherlands, natural gas was first discovered in 1948 at which point there was no market demand nor a gas network. The Groningen gas field, one of the largest in the world, was only tapped in 1959 at which stage the Netherlands became a gas producing country and a societal transition from coal to gas was made (ElementNL, n.d.; Nederlandse Aardolie Maatschappij, n.d.). Today, the Netherlands has extensive gas infrastructure equipped for gas production, transport, and storage (ElementNL, n.d.). However, the winning of gas from the Groningen gas field resulted in numerous earthquakes in the north of the Netherlands leading to damaged houses and societal backlash (ElementNL, n.d.; Ministerie van Algemene Zaken, n.d.-a). In 2018, the Dutch government therefore decided to gradually decrease the winning of gas from the Groningen gas field, which is now set to provide no gas per October 2023 (ElementNL, n.d.; Ministerie van Algemene Zaken, n.d.-a).

In line with reducing CO_2 emissions, the Dutch government has decided to switch to renewable energy sources and therefore eliminate natural gas from the energy mix in so far as possible, a transition which should be completed by 2050. For the energy intensive industries in the Netherlands this is to be achieved through swapping natural gas for alternatives like green electricity, geothermal energy or green hydrogen, as well as capturing CO_2 in empty gas fields and swapping natural gas and oil for biobased feedstocks or reusing raw materials (Ministerie van Algemene Zaken, n.d.-b; Ministerie van Economische Zaken en Klimaat, 2019c). In the lead up to 2050, the role of natural gas will therefore likely gradually decrease with an increase in the quantity of green energy (Gasunie, 2023a). Global demand, however, is expected to increase the coming years only to start falling after 2030 (Greenfield, 2023; Shell International, n.d.). Natural gas will also likely serve as a transition fuel aiding in the integration of renewables and as a replacement for more polluting fossil fuels like coal (Gasunie, 2023a; Greenfield, 2023; Mohammad et al., 2021).

Natural gas is the cleanest hydrocarbon when combusted, producing approximately half the CO_2 emissions of coal when generating electricity (Shell International, n.d.). Other studies communicate similar results in that natural gas performs best in global warming potential and reducing combustion emissions in comparison to hard coal, brown coal, diesel and oil (H. H. Cho & Strezov, 2020; Mac Kinnon et al., 2018; Mohammad et al., 2021; Turconi et al., 2013). The paper of Cho & Strezov (2020) used existing literature studies to compile information from completed life cycle assessments to compare multiple fossil fuels including natural gas. In their review, the global warming potential impact category (i.e. climate change) was the most widely investigated followed by acidification potential (i.e. acidification) whereas other impact categories were studied more limitedly resulting in an incomplete comparison at times (H. H. Cho & Strezov, 2020). The results (an averaged value of the reviewed studies) showed that natural gas generally performed the best from an environmental perspective in comparison to hard coal, brown coal and diesel in producing electricity. However, Cho & Strezov (2020) therein also mentioned that the variation in quality of data, system boundaries and LCIA method limited the ability for a good comparison. Turconi et al. (2013) also clearly state that an "isolated focus on GHG emissions can lead to incorrect conclusions concerning the environmental consequences of electricity generation technologies". Hence, a full life cycle assessment with consistent system boundaries could prove beneficial. All the mentioned and reviewed studies focused on power generation from fossil fuels rather than the end use of heat which is the focus of this research. As the combustion of fossil fuels produces heat which in turn produces electricity, similar trends and comparisons can be expected. Natural gas, as the fossil fuel with the least carbon emissions, can therefore be considered the environmental baseline which the clean alternatives (electrification, hydrogen and Iron Fuel Technology™ should perform better than.

Natural gas is formed from organisms that lived millions of years ago. As a result, the use of natural gas depletes the total resource volume thereby not being replenishable. As of 2018, the worldwide known gas reserves would be sufficient for approximately 50 years (Kuo, 2019). Apart from this, there is the clear limitation that natural gas is also known to negatively impact the environment, for example, by climate change – the reason why this research is also relevant. However, another disadvantage is not as apparent. The increasingly globalized natural gas market has given rise to spot pricing (Greenfield, 2023). As a result, the market has become more volatile and supply shocks can have global implications on prices (Greenfield, 2023). The conflict between Russia and Ukraine in 2022 caused energy prices to skyrocket and endangered natural gas supply security in Europe (Directorate-General for Energy, n.d.; Gasunie, 2022; IEA, 2022a; Ministerie van Algemene Zaken, n.d.-c). The European Union (EU) was dependent on Russian gas for almost 40% of its total gas consumption, highlighting the need for energy independency and security (IEA, 2022a). A topic that is also relevant for all other energy technologies that will be implemented in the future.

1.1.5 Biomass

Whereas fossil fuels make use of organisms that lived long ago, biomass makes use of organisms living more recently (Turgeon & Morse, 2023). It uses the stored chemical energy in living organisms like plants and animals of which the most common used biomass materials are agricultural crops, wood and waste (Turgeon & Morse, 2023; U.S. Energy Information Administration, 2023). These materials can be combusted to produce heat or converted to liquid or gas fuels. Depending on how the biomass is grown and harvested, what type of biomass is sourced, in what time frame it is utilized and what technologies are applied, biomass can be either a renewable or non-renewable source (R. Cho, 2016; Turgeon & Morse, 2023). When the use of biomass releases no new carbon dioxide emissions to the atmosphere as the replanting of harvested biomass ensures an equivalent or higher CO_2 uptake, biomass is renewable (Goldemberg & Teixeira Coelho, 2004; Mckendry, 2002). However, if the contribution of CO_2 emissions released into the atmosphere is larger than the CO_2 sequestrated, a non-renewable case presents itself (Goldemberg & Teixeira Coelho, 2004). A distinction between modern and traditional biomass is also made in which modern biomass is produced sustainably and traditional biomass is not (Goldemberg & Teixeira Coelho, 2004). Modern biomass is seen as a key renewable energy source which can also help achieve climate change goals in the transition away from fossil fuels (Bains et al., 2023; Bridgwater, 2006).

Reviewing literature on the environmental impact of biomass, it is seen to both improve and contribute negatively to environmental issues depending on the specific issue. From a GHG emission perspective, biomass was seen to reduce impacts in comparison to fossil fuels like hard coal, lignite, natural gas and oil for each MWh electricity output (Turconi et al., 2013). In comparison to renewable energy sources such as nuclear energy, hydropower, solar and wind energy, biomass emits more CO_2-equivalent emissions (Turconi et al., 2013). Few studies analyzed the impact to renewable sources, but many studies note similar results on the GHG emissions in comparison to fossil fuels (Caserini et al., 2010; Cherubini & Strømman, 2011; Havukainen et al., 2018; Tonini & Astrup, 2012). Biomass is also seen to reduce other emissions including nitrogen oxides, methane, sulphur oxides and carbon monoxide (Saidur et al., 2011). It thereby also helps "reduce acid rain, soil erosion, water pollution and pressure on landfills, provide wildlife habitat, and help maintain forest health through better management"

(Demirbas, 2005). However, caution is required for increased impacts to land use, water resources, loss of biodiversity and increased deforestation in comparison to both renewable and non-renewable sources (Fthenakis & Kim, 2009; Saidur et al., 2011). It has been emphasized that the production of biomass has "adverse environmental impacts such as biodiversity loss caused by land use changes" (Myllyviita et al., 2012). Biomass also exerts more pressure on acidification and eutrophication impacts than natural gas for energy production (Havukainen et al., 2018). The utilization of biomass seems to bear environmental tradeoffs yet a difficulty in making any generalized comments about the environmental impact of biomass is that the environmental impacts are largely tied to the biomass source. Impacts deriving from the biomass supply were seen to be responsible for the largest contributions to biomass (Turconi et al., 2013). Unfortunately, the associated environmental impacts with using different biomass sources are unclear (Havukainen et al., 2018). Assuming that biomass is carbon neutral is therefore also challenging as it largely depends on "the type, quality and origin of feedstock, as well as the amount and type of co-products" (Havukainen et al., 2018; Turconi et al., 2013). Whether biomass can therefore be considered renewable is therefore often disputed.

Furthermore, some studies only noted impacts deriving from plant operation wherein the upstream impacts of biomass were assumed to have no burdens (Turconi et al., 2013). They assume that the sourced biomass is a waste stream. This, of course, is only sometimes the case, but often biomass will likely be sourced sustainably from forests thereby not being residual nor having no environmental impact. A case study of Denmark showed that "residual domestic biomass resources were insufficient to cover demand for biomass energy thereby requiring additional cultivation of energy crops which caused significant environmental loads" (Tonini & Astrup, 2012). The use of biomass for energy can likely help mitigate climate change impacts but then exert pressures on other parts of the environment. In addition, biomass required for energy increases competition between the energy generation, forest and food production sectors (Turconi et al., 2013). Biomass therein also requires a much larger area of land than other energy sources including harvesting solar energy by photovoltaics (Fthenakis & Kim, 2009). The assumption that biomass has zero burdens is its sourcing is likely incorrect, especially in the longer term (Turconi et al., 2013). However besides environmental pressures it can also create economic and societal disputes if competition between different economic sectors is not managed properly. For each application it must therefore be carefully examined whether the implementation of biomass is sustainable, especially in the long term, or whether adverse (environmental) impacts will outweigh the desired benefits.

1.2 Knowledge Gap

The need to implement sustainable alternatives to decarbonize energy-intensive industries and meet climate targets is clear. Electrification, hydrogen and Iron Fuel Technology™ are three non-carbon-based alternative fuels that allow for the possibility to decarbonize the energy-intensive industries. In the larger picture, it suggests GHG emissions and the subsequent effects on climate change can potentially be limited by implementing any of these three technologies in comparison to carbon-based fuels. However, as has become clear from the previous section is that gaps remain in the understanding of the current and future environmental impacts throughout the life cycle of all three clean technologies as well as natural gas and biomass. First, gaps exist in the analysis of a full life cycle wherein all life cycle stages are considered.

Second, most completed assessments only focused on GHG emissions and climate change impacts leading to a gap in knowledge about the potential environmental impacts of the technologies in other impact categories. Third, there is a gap surrounding the environmental impacts of the specific end use this research focuses on, i.e. providing heat to energy-intensive industries. Fourth, a life cycle assessment on Iron Fuel Technology™ has never been completed. Fifth, the three clean technologies have been limitedly examined in comparison to carbon-based fuels and never to one another. Sixth, as some of the technologies are not yet mature and available at commercial scale, estimations of potential future environmental impacts have also been limitedly completed.

1.3 Research Questions

With the threat of derailing climate targets, a critical assessment of the expected environmental impacts of any potential decarbonization solution must be made to prevent misinformed decision making and investments. Life cycle assessment is a frequently used method to determine the (potential) environmental impacts of products for assisting in (i) identification of improvement opportunities of environmental performance, (ii) decision-making, (iii) selection of environmental performance indicators, and (iv) for marketing purposes (International Organization for Standardization, 2006). The use of LCA is encouraged and is increasingly used in environmental policy in governments and institutions around the world (Guinée et al., 2011). As the energy-intensive industries account for a large emission footprint (inter)nationally and thus are key in the decarbonization challenge, a profound understanding of the environmental impacts of implementing any solution in these industries is vital. As some of the clean technologies are not yet commercially implementable, this research will take a prospective approach (ex-ante LCA explained in section 2.2) and examine the potential future environmental impacts associated with the implementation of hydrogen, electricity and Iron Fuel Technology™ in providing heat to an energy-intensive industry in a future 2030 and 2050 scenario. These three technologies will also be compared to carbon-based fuels, specifically natural gas and biomass. The assessment will be completed through multiple life cycle assessments for all five technologies spanning multiple impact categories to determine whether decarbonization is possible without adverse environmental impacts.

The main research question of this research thereby is:
What are the environmental impacts of electrification, hydrogen and Iron Fuel Technology™ when supplying 1 MWh of steam in 2030 and 2050 in relation to carbon-based fuels and to each other and what redesign recommendations can be made to limit the environmental impacts?

This question can be unpacked into the following sub-questions:

1. How do electrification, hydrogen and Iron Fuel Technology™ perform environmentally in 2030 and 2050 in comparison to carbon-based fuels (natural gas and biomass)?
2. How do electrification, hydrogen and Iron Fuel Technology™ perform environmentally in 2030 and 2050 in comparison to one another?
3. What are the environmental hotspots for electrification, hydrogen and Iron Fuel Technology™?

4. How does the environmental performance of electrification, hydrogen and Iron Fuel Technology™ change when the sensitivity of some parameters are tested as chosen based on the results from sub-question 3?
5. What recommendations can be made for improving the environmental footprint of electrification, hydrogen and Iron Fuel Technology™?
6. What non-environmental factors influence the implementation of electrification, hydrogen and Iron Fuel Technology™ in the future?

As not all three clean technologies are able to have direct flame contact, an indirect medium of heat transfer was chosen namely steam. As all technologies can produce this it allows for a fair comparison. The specific steam temperature (240°C) and pressure (20 bar) as well as size of the boiler system (5-20 MW) are defined based on the requirements of the location of RIFT's pilot plant. This grounds this research by a specific case. The incumbents, biomass and natural gas, have been chosen for comparison material as they are industry wide the most common carbon-based fuels for this type of application and are currently used at the pilot plant location (Nederlandse Emissieauthoriteit, 2019; Olsson & Schipfer, 2021).

1.4 Research Approach

For an overview of the research approach taken in this study, see Figure 2. Though stages are displayed consecutively, overlap and iteration of and between stages was possible. The research could also be divided into two main phases, defined by the activities before (phase 1) and from (phase 2) the execution of the ex-ante LCAs (further elaboration on ex-ante LCA is given in section 2.2).

This research followed an hourglass shape with the division between phase 1 and phase two being the slimmest part. The first phase focused on making the transition from a wealth of information and problems in literature to a researchable and attainable question worth investigating. The information required to conduct a proper assessment to answer the research question was also gathered in this phase as it is a critical part of clearly defining the boundaries of this research. All activities undertaken in phase 1 had to be completed in order to move to phase 2. The second phase first focused on the ex-ante life cycle assessment and the production of results. These results provided the foundation for further exploration into the hotspots and most sensitive parameters of the investigated technologies. This research then tried to put the results into the broader picture by defining redesign recommendations and investigating limitations to both the technologies and this research. The research questions were subsequently answered and areas for future research were defined. Below a more detailed explanation of the main activities completed within each stage is given but refer to the specified sections for further details.

<u>Phase 1:</u>

- *Understanding the research context*: this stage focused on researching the current challenges surrounding decarbonization in the energy-intensive industries and the potential solutions for it. From there a specific, relevant and under investigated problem was defined, namely the limited knowledge of the environmental performances of potential solutions for the energy-intensive industries. A key part of this stage consisted of conducting a detailed literature review and gathering background information by completing desk research. The outcome of this stage is reflected in sections 1.1 and 1.2.

- *Defining research questions & choosing methodologies*: this stage first focused on defining a researchable and attainable question to the chosen problem. The main research question has been defined in the previous section. Subsequently, a research method able to provide an answer to the defined research question was selected, in this case ex-ante life cycle assessment due to the ability to estimate (future) environmental impacts. For further information on life cycle assessment consult Chapter 2.
- *Technology data collection*: this stage was completed simultaneously with the scenario development stage. The technology data collection stage specifically focused on collecting data about each of the five investigated technologies through conducting literature reviews, examining current data within the ecoinvent database and completing interviews with technology developers. This data was used for input to the LCA unit processes as well as for defining the 2030/2050 scenarios, process alternatives and base case. The outcome of the technology data collection stage is primarily seen reflected in the underlying data used in the LCA (see Appendix B and section 4.3) and the distinction between process alternatives (section 3.6).
- *Scenario development*: this stage focused on defining the 2030 and 2050 scenarios. In doing so, the base case and the process alternatives as well as the overall goal and scope of the LCA were further defined. The goal of the LCA has largely been defined at this stage because of the research questions formulated at an earlier stage. However, the base case and scope of the LCA are closely tied to any potential application, in this case the foreseen pilot of RIFT as defined through a combination of desk research and interviews. Hence the scope is the Netherlands in 2030/2050 so the scenarios have been defined by the expected Dutch electricity mix as found in reviewed literature. The goal and scope are handled in Chapter 3 in which the scenarios and the process alternatives are specifically handled in section 3.6. The base case of all process alternatives is further defined in 4.2.

Phase 2:

- *Completing ex-ante LCA*: the focus of this stage was on producing estimates of the environmental performance of each defined process alternative through conducting ex-ante LCAs. Chapter 4 addresses the life cycle inventory whereas Chapter 5 provides the results of the ex-ante LCA including the life cycle impact assessment, the contribution analyses and the sensitivity analyses.
- *Defining redesign recommendations*: in this stage research and development recommendations for improving and limiting the environmental impacts of the investigated technologies were made. These recommendations were based on the results from the sensitivity analyses. For further information refer to Chapter 6.
- *Discussion*: at this stage, a reflection of what this research has achieved including its relevance in the broader sense and any methodological limitations are given. This research then also expanded the examination of each clean technology in a broader sense – from a technical, economic, legislative and societal perspective. It considered the upscaling potential of electrification, hydrogen and Iron Fuel Technology™ while also addressing critical (non-environmental) limitations of these technologies identified through interviews and desk research. For further information, the relevance of this

research is addressed in section 7.1, the limitations are addressed in section 7.2, and the upscaling potential in section 7.3.

- *Conclusion*: finally an answer was provided to the posed research question(s) and recommendations for further research were also made, see Chapter 8.

1.4.1 Research Outline

This report generally follows the research approach as just provided. Deviation exists in what is reported and what the working process was. As a result, this research is structured into eight chapters for clear communication of the work that has been completed. The next chapter (Chapter 2) will explain the methodology of LCA and specifically ex-ante LCA which was followed in this research. In chapter three the goal and scope defining phase of ex-ante LCA will be addressed. Chapter four handles the life cycle inventory phase while chapter five discusses the results of the completed life cycle assessment including the contribution and sensitivity analyses. Chapter six then produces recommendations for redesigning the product systems to reduce the environmental impacts based on the ex-ante LCA results as well as recommendations for actions RIFT can take. Chapter seven then discusses the relevance and limitations of this research as well as the challenges for implementation and upscaling of electrification, hydrogen and Iron Fuel Technology™. Finally, Chapter eight will present the conclusions of this research and the recommendations for further research.

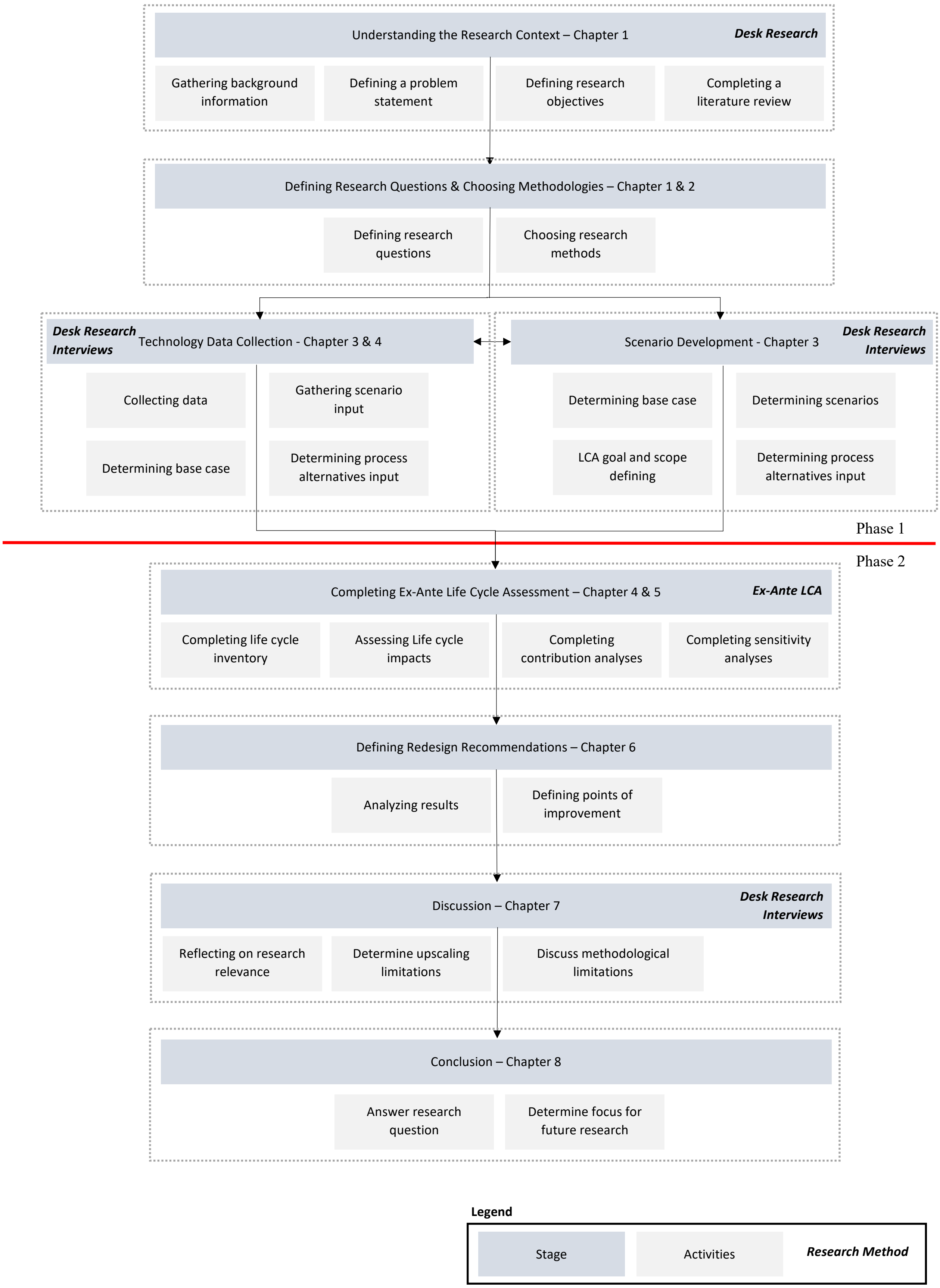

Figure 2: Research approach overview

2. Methodology: (Ex-Ante) Life Cycle Assessment

2.1 Objective and Procedure of Life Cycle Assessments

Life Cycle Assessment (LCA) is defined as the "compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle" (International Organization for Standardization, 2006). LCA is an analytical tool to evaluate environmental impacts of a product along the whole chain and of all processes related to the final consumption of the product, including all stages from extraction of resources through production processes to treatment processes at the end of the product's life (Guinée et al., 2002). 'Product' is interpreted in a broad sense including physical goods as well as services and 'environmental impacts' also encompasses all types of impacts exerted on the environment, including but not limited to land use, emissions or raw material extraction (Guinée et al., 2002). The term 'product system' is therefore often used to encompass all related processes throughout the life cycle leading to the final consumption of the product.

LCA has a standardized methodological framework defined by the International Organization for Standardization (ISO) consisting of four phases: the goal and scope definition, life cycle inventory analysis (LCI), life cycle impact assessment (LCIA) and interpretation, as visualized in Figure 3 (International Organization for Standardization, 2006). The framework outlined in the *ISO 14044 Standard* details the requirements for conducting a proper LCA and will also be followed in this research (International Organization for Standardization, 2006).

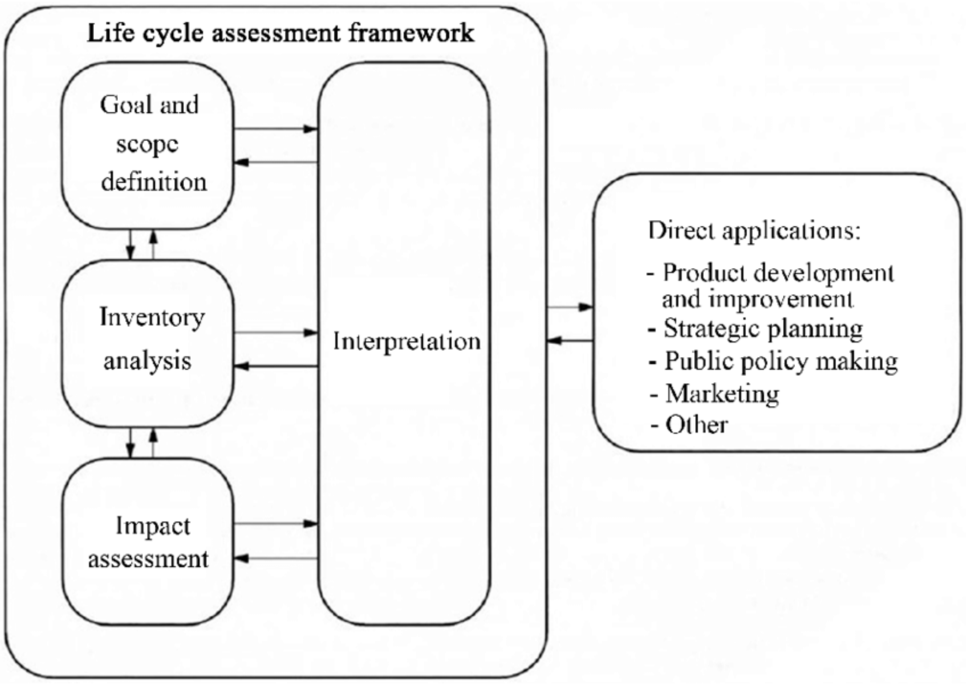

Figure 3: ISO 14040 life cycle assessment framework.

The first phase of LCA is largely related to the subject and the intended use of the study. At this stage the research question, target audience, application, and depth and breadth of the research is defined in relation to the aim of the study. The scope of the research is defined in terms of the temporal, geographical and technological coverage. This results in pinpointing the function, functional unit, alternatives and reference flows of the research. The second phase, the life cycle inventory, is the step in which the product systems and their boundaries are defined, data is collected, and multifunctional processes are dealt with. The calculations result in an inventory of all the quantified environmental in- and outputs throughout each product system. The third phase is the phase of LCA that evaluates the potential impacts of a product system. This evaluation is completed by assigning the life cycle inventory results to an impact category (e.g. climate change) which is quantified through a category indicator (e.g. radiative forcing). The last phase evaluates the results of the LCI and LCIA to check the overall robustness of the study and reach conclusions and recommendations (based on the goal and scope, methods, data, assumptions etc.).

2.2 Ex-ante LCA Explained

LCA studies have largely been ex-post analyses due to the required data for background and foreground processes (Cucurachi et al., 2018). Though these studies provide valuable input, when technologies are already matured, changes come at considerable costs. By applying LCA to future technologies and scenarios at an early stage of development already, alternative policy interventions and claims of environmental sustainability can be tested, and early design improvements and sound investments can be made (Cucurachi et al., 2018). The application of LCA in this manner is termed ex-ante LCA and is defined as studies examining “the scale-up of an emerging technology using likely scenarios of future performance at full operational scale” (Cucurachi et al., 2018). These emergent technologies, typically still at lab or pilot scale, are compared to the evolved incumbent technology as in the current technological landscape (Cucurachi et al., 2018). This, however, gives an unfair comparison as the current technological landscape may also develop with time. The challenge therein lies in modelling consistently across the different product systems as well as modelling both foreground and background future systems (van der Giesen et al., 2020).

As the largest uncertainty is the development in time and the resulting life cycle inventory data that can be used as input, the help of technology developers and other domain experts can be key. As the clean technologies in this case are still at pilot scale (exception: electrification) the projected environmental impacts are only as robust as the assumptions on which the data is based. Where foreground data, as sourced by the LCA practitioner, is often of high uncertainty due to the ex-ante nature, any background data as sourced from existing LCI databases is often not representative of the context of the study (van der Giesen et al., 2020). Corrections to the upstream supply chains are often limitedly possible but should be manipulated for consistent modeling and a fair comparison as “background processes usually make up to 99% of all unit processes in a product system” (van der Giesen et al., 2020). To compensate for this mismatch in time, it is possible to make use of scenarios.

Scenario’s form the backbone of ex-ante LCAs. They are closely tied to the temporal and geographical scope as defined in the research in an attempt to give a more balanced comparison between the emergent and incumbent technologies (van der Giesen et al., 2020). Yet future scenarios are still subject to uncertainty as well. It has been shown that scenarios can be developed and implemented based on the shared socio-economic pathways (SSPs) calculated by integrated assessment models (IAMs) (Mendoza Beltran et al., 2020; van der Giesen et al., 2020). However, IAM based LCI background data is limitedly available and has not been expanded to all background sectors. As such, it is of the essence that assumptions and choices on which temporal mismatches are made are clearly communicated.

Environmental impacts of emergent technologies may also not always be known before commercial roll-out. Furthermore, some impacts may also not be known to contribute to a particular impact category or there may not yet be a suitable impact category. A lack of characterization factors may also leave environmental flows unclassified due to a lack of data and models (van der Giesen et al., 2020).

Ex-ante LCA varies from the standard LCA mostly in that the information is highly uncertain. It also often requires more stakeholder participation and a multitude of disciplines and skills (van der Giesen et al., 2020). Furthermore, the high uncertainty resulting from this type of LCA requires a different approach. Earlier it was mentioned that there can be various purposes for conducting an LCA of which one was for marketing purposes. Considering this, it is important to note that the results of this type of LCA should not be considered as a final result but rather be used as a guidance for debate, evaluation and research and development (R&D).

The ex-ante LCA method deals with the environmental assessment of technologies in a predictive manner such that environmental impact estimations can be made while retaining the ability to influence technological development at relatively low cost. For this reason, this research makes use of this type of LCA. It can provide valuable insight into the ability of an emergent technology to potentially outperform the market-leading competitor, understand where foreseen environmental hotspots are and guide R&D, business case and investment decisions. This research aims to be of aid to RIFT in their development towards commercialization and in its understanding of the potential future environmental impacts of their technology.

This research also addresses some of the challenges inherent to ex-ante LCA as explained in this section. First this research makes use of scenarios, specifically two scenarios – 2030 and 2050. These scenarios define the electricity mix and expansion of the electricity network in line with 2030 and 2050 expectations. The broader technological landscape may also develop toward 2030 and 2050 but this is not considered. The current landscape is reflected in this research. The scenarios, however, are consistently implemented throughout all investigated product systems including the incumbents as this creates a fairer comparison. Furthermore, foreground data was collected with the help of technology developers and domain experts based on expected developments towards 2030 and 2050. Hence, the foreground data is based on performance at mature operational scale resulting in the use of data based on predicted performances for the clean alternatives. The use of the temporal scope of 2030/2050 is not applicable for background processes. As IAM based background LCI data extending to multiple sectors was not available for this research, all background processes do not make use of a 2030/2050 temporal scope for consistency within background data.

3. Goal and Scope Definition

In this chapter the first phase of LCA according to the ISO framework will be addressed. First the goal and geographical, temporal and technological scope of the ex-ante LCA are reported (section 3.1-3.4). Next, the function, functional unit, the alternatives and the reference flows are defined in section 3.5. The chapter then dives deeper into the scenarios that will be used and a more specific description of each of the process alternatives that will be investigated (section 3.6).

3.1 Goal

The goal of this ex-ante LCA is to compare and explore the environmental performance of hydrogen, electrification and Iron Fuel Technology™ to the market incumbents in the provisioning of heat for the energy-intensive industries and to thereby inform technology developers, customers, investors and policy makers of any implications or foreseen environmental issues before large-scale implementation takes place. The alternatives have different value chains exerting various pressures on the environment. By completing a LCA, trade-offs between product systems, processes, and life cycle stages can be identified. As a result thereof designs may be steered, and any environmental burdens or poor investments can be prevented.

3.2 Geographical Scope

This research is based on the pilot and first market RIFT envisions for its product. As such, the life cycle of all alternatives is limited to the Netherlands with data representative of this. Upstream processes, e.g. raw material production, may occur outside of the Netherlands and be imported. Whenever applicable, these processes will reflect the predicted import market of the Netherlands.

3.3 Temporal Scope

The temporal scope of this research is 2030 and 2050. As mentioned earlier, the background processes will not reflect this due to unavailable background LCI data. However, for the foreground processes this temporal scope will be reflected. The two scenarios (further elaborated in section 3.6) define the prospective energy mix and extended electricity network in 2030 and 2050. The electrification product system will therefore build on this with background processes reflecting state-of-the-art data. Both the hydrogen and Iron Fuel Technology™ product systems will also consider the defined scenarios. As they are both not yet commercially and technologically upscaled, for both alternatives a possible future system covering the year 2030 and 2050 are used in the LCA model.

3.4 Technological Scope

The incumbent technology, which will also be used as a benchmark, will be natural gas and biomass. These two fuels have shown to be the most sustainable fuels for generating industrial heat and are currently market standard (Nederlandse Emissieauthoriteit, 2019; Olsson & Schipfer, 2021). As electricity is already a backbone of the current energy system, state-of-the-art data regarding infrastructure, electricity generation technology and e-boilers should suffice. The electricity mix will be adapted to the assumed scenarios accordingly in this research (see section 3.6). For the hydrogen product system, the estimated TRL for producing heat varies, but somewhere around TRL 5 seems realistic (Hers et al., 2018). With that in mind, there are products being developed and tested as well as ongoing literature research on the topic, so data regarding the expected technical parameters used in this research for the hydrogen product system will be sourced from a mix of literature and interviews with manufacturers and experts. For the Iron Fuel Technology™ product system, the data used derives from RIFT's commercial installation designs that meet business case standards. The data will origin from the engineers, manufacturers and suppliers of RIFT. All foreground processes are assumed at commercial scale.

3.5 Function, Functional Unit, Alternatives, Reference Flows

This research concerns itself with the challenge to decarbonize the heat demand of the energy-intensive industries. The function can therefore be defined as the provision of heat for the energy-intensive industries.

As explained in the introduction, there are different grades of heat which also come in different forms, e.g. hot water, steam, hot air. To allow for comparison, the functional unit is defined as the provision of 1 MWh of heat in the form of superheated steam at 240°C and 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry. This is in line with the envisioned pilot of RIFT and based on the client's current energy need.

The clean alternatives under consideration are hydrogen, directly combusted by a hydrogen boiler (h-boiler), electrification, using an industrial electric boiler (e-boiler), and Iron Fuel Technology™, iron fuel combusted in an iron fuel boiler (IF boiler). The alternatives of natural gas, directly combusted by a natural gas boiler (NG boiler), and biomass, wood chips directly combusted in a biomass boiler, will also be included in this research as the market incumbents. The specific configurations of the alternatives will be explained further in section 3.6.

At this temperature scale, a heat pump could potentially also be implemented, but is not being considered because to implement this technology sufficient waste heat is required close to the boiler location at which the heat is needed (Kleefkens & Spoelstra, 2014). In the foreseen pilot of RIFT, the use of a heat pump is practically infeasible and is therefore not considered in this research.

The reference flows that follow from this are:

1. Provision of 1 MWh of heat in the form of superheated steam at 240°C, 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry by a 5-20 MW electric boiler.
2. Provision of 1 MWh of heat in the form of superheated steam at 240°C, 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry by a 5-20 MW hydrogen boiler.

3. Provision of 1 MWh of heat in the form of superheated steam at 240°C, 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry by a 5-20 MW iron fuel boiler.
4. Provision of 1 MWh of heat in the form of superheated steam at 240°C, 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry by a 5-20 MW natural gas boiler.
5. Provision of 1 MWh of heat in the form of superheated steam at 240°C, 20 bar (stack temperature 130°C if applicable) for the supply to an energy-intensive industry by a 5-20 MW biomass boiler.

3.6 Defining Scenarios & Process Alternatives

Earlier the importance of scenarios to ex-ante LCA was already mentioned. "Each scenario that the analyst builds represents a possible future state of the considered technological systems (i.e. the technological system of the emerging technology, and that of the incumbent) with a specific timeframe" (Cucurachi et al., 2018). In building scenarios, there are different starting points and objectives. Three scenario categories – predictive, explorative and normative – can be defined (Börjeson et al., 2006; Höjer et al., 2008). Predictive scenarios are based on forecasting what will happen, explorative scenarios aim to explore what can happen, whereas normative scenarios have a target as starting point and aim to understand how that target can be reached (Höjer et al., 2008). In this study, two different scenarios are examined in an explorative style to understand the "what if". Specifically, what if implementation of an alternative took place in 2030 and 2050.

The scenarios of 2030 and 2050 define the electricity mix and the extent of the expansion of the electricity network. The assumed electricity mix is based on TNO's 'Transform' scenario as seen in Table 1 displaying the electricity sources and their percentage shares for both the 2030 and 2050 scenario (Scheepers, 2022). The extent of the expansion of the electricity network was assumed using a multiplication factor. A factor of 1.5 in 2030 and 2 in 2050. This was estimated based on the ecoinvent documented value and secondary sources (Dones et al., 2007; Franx, 2022; Frischknecht et al., 2007; "In 10 Jaar Het Elektriciteitsnet Verdubbelen, Wat Je Normaal in 40 Jaar Doet," 2023; Jaarbeurs, 2022).

Table 1: Overview of the electricity mix percentage shares based on the TNO Transform electricity scenarios (Scheepers, 2022).

TNO Transform Scenario	2030	2050
Electricity from solar	14.96%	18.87%
Electricity from wind (offshore)	42.38%	60.62%
Electricity from wind (onshore)	19.26%	8.45%
Electricity from natural gas	11.48%	0.05%
Electricity from biomass	1.52%	3.93%
Electricity from waste	1.14%	0.13%
Electricity from nuclear	1.96%	6.67%
Electricity from flue gasses	0.11%	-
Imported electricity	7.13%	1.27%
Electricity from other sources including biogas and hydro	0.05%	0.02%

The use of the word ‘scenario’ sometimes is confused with a specific possible state of an alternative. In this research, a clear distinction is made between ‘scenario’, ‘process alternative’ and ‘product system’ to minimize this confusion. When ‘scenario’ is used this refers to the assumed electricity mix and expansion of the electricity network in either 2030 or 2050. The use of ‘process alternative’ (PA) refers to a specific configuration of an examined alternative. The use of ‘product system’ refers to electrification, hydrogen, Iron Fuel Technology™, natural gas or biomass as a system in its entirety encompassing all specific configurations of the alternative.

In this research, there are 5 alternatives (natural gas, biomass, electricity, hydrogen and Iron Fuel Technology™) of which 3 are referred to as ‘clean alternatives’ as mentioned earlier (electricity, hydrogen and Iron Fuel Technology™). Among the clean alternatives there is one clear limitation for implementing both electricity and hydrogen which is that they require a grid connection. As a result the following market distinction can be made:

1. *Companies that have or can have access to a suitable electricity or hydrogen grid connection[3].*
2. *Companies that do not have and cannot have access to a suitable electricity or hydrogen grid connection.*

In the first case, two different options may occur. If the infrastructure is present, then implementation should be able to take place. If the infrastructure is not yet present but can be, the emissions associated with the construction of the required infrastructure must be considered in the environmental assessment.[4] As a result two different process alternatives can exist for implementing the electrification or hydrogen solution: one requiring the infrastructure construction emissions to be accounted for and one not. In the second case, Iron Fuel Technology™ is the only available alternative as it does not require a grid connection.

For Iron Fuel Technology™, process alternatives can be distinguished based on two factors: the production method of the initial iron fuel and the hydrogen source. The initial iron fuel batch can be produced from primary (iron ore) or secondary (scrap) iron. When production takes place from iron ore it will hereafter be referred to as ‘pig iron’ whereas production from secondary iron will hereafter be referred to as ‘scrap iron’. Box 1 explains the production processes in further detail. The hydrogen source can be waste hydrogen which occurs as a by-product of chemical processes, or hydrogen produced via water electrolysis (hereafter just mentioned as electrolysis). This produces a total of four different process alternatives for IFT.

The last two alternatives, biomass and natural gas, are representative of the market incumbents. As they are already upscaled this research considers only one variant for each alternative for both 2030 and 2050. The biomass process alternative considers sustainable wood chips as the biomass source. This is also in line with the current situation at the pilot location of RIFT.

[3] A grid connection (high voltage electricity line or hydrogen pipeline connection) is necessary for an ample supply of electricity or hydrogen for meeting industrial demand.

[4] A clear distinction in this research is made between the expansion of the electricity network and the construction of infrastructure. The expansion of the electricity network refers to the overall increase in the number of km of electricity lines of all types (e.g. distribution and aerial high voltage direct current lines) as defined by the assumed 2030/2050 scenario whereas the construction of infrastructure refers to any additional electricity / hydrogen infrastructure required to ensure sufficient supply of fuel between the production and boiler location.

Box 1: Initial iron fuel production (primary via blast furnace vs. secondary via electric arc furnace)

There are two main routes for producing iron. The first follows a blast furnace route while the second makes use of an electric arc furnace (EAF) (Lu et al., 2015). In a blast furnace, iron ore is 'reduced' of its oxygen through carbon (specifically as coke) at high temperatures with lime facilitating the smelting process (ArcelorMittal, 2023a; Lu et al., 2015; The Editors of Encyclopaedia Britannica, 2023). This process produces pig iron (molten iron) as a result. The EAF route typically uses scrap steel in which an electric arc melts the scrap to produce liquid iron (ArcelorMittal, 2023c; Wente et al., 2023). Both routes produce slag as a by-product (ArcelorMittal, 2023c). Practically, subsequent processes are required to transform the molten iron into iron fuel, iron in powder form. However, as the specific processes that make iron powder are not available within the ecoinvent database and the products resulting from the blast furnace and electric arc furnace are similar, the two different routes as included in ecoinvent are used as proxies in this research.

All 19 process alternatives are overviewed in Table 2 including whether they are applicable for the 2030 and 2050 scenario. Notice that process alternative D1 does not exist. This is the result of limited hydrogen infrastructure in 2030 (Gasunie, 2023c; Neuwirth et al., 2022; Radowitz, 2022). Table 3 then provides a more detailed overview of the processes included in each process alternative highlighting the differences between them.

Table 2: Process alternatives overview.

	Process Alternative	2030	2050
A	Electrification with a need for infrastructural construction	A1	A2
B	Electrification without the need for any infrastructural construction	B1	B2
C	Hydrogen with a need for infrastructural construction	C1	C2
D	Hydrogen without the need for any infrastructural construction		D2
E	Iron Fuel Technology™ pig iron + hydrogen electrolyzer	E1	E2
F	Iron Fuel Technology™ pig iron + waste hydrogen	F1	F2
G	Iron Fuel Technology™ scrap iron + hydrogen electrolyzer	G1	G2
H	Iron Fuel Technology™ scrap iron + waste hydrogen	H1	H2
I	Natural gas	I1	I2
J	Biomass based on wood chips	J1	J2

Table 3: Detailed overview of included processes in each process alternative.

	Process Alternative[5]													
Process	A1	A2	B1	B2	C1	C2	D2	E1	E2	F1	F2	G1	G2	H1	H2
Additional construction of an electricity / hydrogen network	x	x			x	x									
Hydrogen production via electrolysis					x	x	x	x	x			x	x		
Waste hydrogen										x	x			x	x
Primary initial iron production (pig iron)								x	x	x	x				
Secondary initial iron production (scrap iron)												x	x	x	x

[5] The '1' or '2' signifies whether the process alternative is based on a 2030 ('1') or 2050 scenario ('2'), thus 'A1' refers to process alternative A in 2030 and 'A2' refers to process alternative A in 2050. Applicable to all process alternatives.

4. Life Cycle Inventory

This chapter will cover the second phase of the LCA framework. First the system boundaries will be distinguished in section 4.1 and 4.2. Next the data collection stage will be addressed in section 4.3. Section 4.4 concerns itself with multifunctionality and the subsequent allocation of multifunctional processes. The use of software will be briefly addressed in section 4.5 after which the chapter will conclude with the results of the inventory analysis in section 4.6.

4.1 System Boundaries

In LCA, 3 different types of boundaries are distinguished:

- “The boundary between the product system and the environment system;
- The boundary between processes that are relevant and irrelevant to the product system (cut-off);
- The boundary between the product system under consideration and other product systems (allocation)” (Guinée et al., 2002).

The first two points will be discussed in this section whereas allocation will be discussed in section 4.4.

Economy-Environment System Boundary

Typically the boundary between the environment and economy is defined by the existence of human control over a process (Guinée et al., 2002). This study follows this norm. When heat dissipates in air or water is released from a plant into the environment, this is considered an emission and a flow from the techno- to the ecosphere. These flows form the bridge between the environment and economy and can be beneficial or harmful emissions and uptakes.

Cut-offs

Any cut-offs were consistently applied through all examined product systems. In Table 4, an overview of all cut-offs is shown.

Table 4: overview of cut-offs

Cut-off	Reason
On-site construction emissions of any required infrastructure construction or equipment including any machinery required	On-site construction emissions can be difficult to estimate, and the impacts generated by the machinery are often also omitted in the reviewed literature (Berrill et al., 2016; Delpierre et al., 2021; Turconi et al., 2013). For consistency with other sources they have not been included in this research.
Cooling materials, chemicals and demineralized water required in an e-boiler, h-boiler, IF boiler, NG boiler, and biomass boiler	In all boilers, cooling materials, chemicals and demineralized water are required for the efficient working of the boiler and its steam production. As this is identical for all boilers, this has been cut-off.
The end-of-life stage of the e-boiler, h-boiler, IF boiler, and NG boiler.	As ecoinvent inconsistently in/excludes the end-of-life stage of boilers in processes currently in the database, this stage has not been included for the majority of the boilers to allow for a fairer comparison.

4.2 Base Case & Flowcharts

To gain a quick understanding on what the base-case is and how each process alternative is set up see Box 2. The flow diagrams for each of the process alternatives are visualized in Appendix A, Figures A1 to A14.

Box 2: Base Case PA Set-Up

Each process alternative follows the same set-up: a production location where the fuel is created which is subsequently transported to a boiler location where the heat is produced and required. The transport distance totals 150 km.

The natural gas and biomass PAs differ in that they are modelled with ecoinvent markets. The market process already includes transportation and production in upstream processes. This eliminates the need for foreground process modelling of production and transport processes as in the case of the electricity, hydrogen and IFT process alternatives. Hence, the natural gas and biomass value chains appear differently in Figure 4.

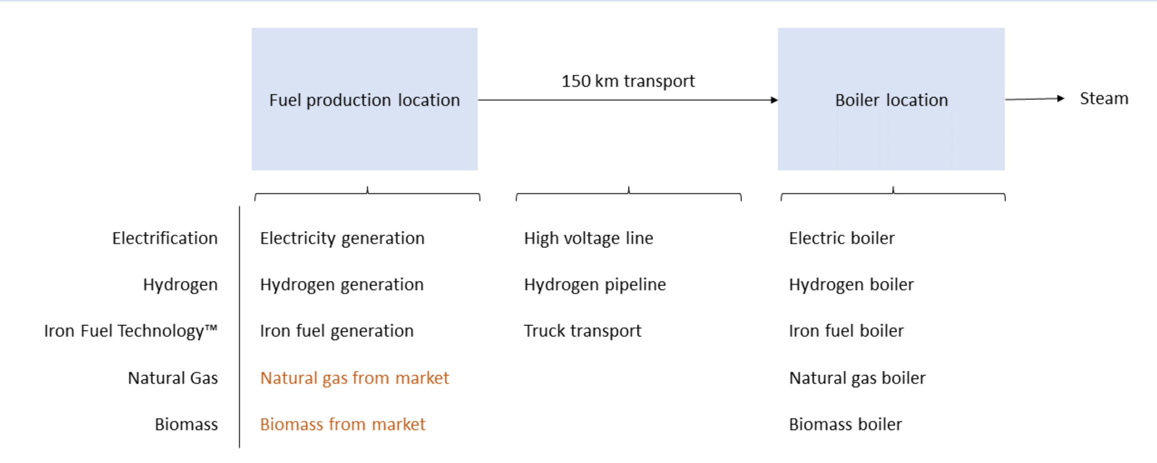

Figure 4: Base-case for process alternatives

4.3 Data Collection

Data collection took place over the time span of three months. For foreground processes, data was collected through literature and interviews with technology developers, suppliers, and manufacturers. Background data was retrieved via the ecoinvent version 3.9.1 database, cut-off model or via the environmental footprint database. Whenever product systems make use of the same processes, e.g. electricity mix, the processes are consistently applied with the same conditions, assumptions and underlying data throughout all product systems. All unit process data including sources, calculations and assumptions is attached in Appendix B. In Table 5, the main data origins and assumptions are overviewed as used in the base case.

Table 5: main data origins and assumptions overviewed for each process alternative.

PA	Data Origin	Key Assumptions
A&B	- Dutch 2030/2050 scenarios created based on TNO ‘transform’ electricity scenario (Scheepers, 2022) - E-boiler manufacturers (B. Averhoff, personal communication, March 1, 2023; J. Jansen, personal communication, March 13, 2023; J. Jansen, personal communication, March 30, 2023; W. Post, personal communication, March 9, 2023; W. Post, personal communication, March 13, 2023; PARAT, 2021; Zander & Ingeström, n.d.)	- Current electricity network as included in ecoinvent is state-of-the-art - No electricity transport losses. - Transformation losses are only accounted for in processes requiring low/medium voltage. - Electricity mix ratio within one category as currently within ecoinvent remains the same (e.g. the shares between types of photovoltaic panels) - Electricity produced from solar is at high voltage in contrast to low voltage - No material losses during network construction - E-boiler runs 8600 full load hours (FLH)
C&D	- Alkaline electrolyzer data sourced from literature (Koj et al., 2017) - Pipeline data derives from the European Hydrogen Backbone initiative (Wang et al., 2021) - Data regarding compressors (energy consumption and material weight) were calculated using Aspen Plus (P. Ibarra Gonzalez, personal communication, April 17, 2023) - H-boiler manufacturers (M. Hinderdael, personal communication, March 16, 2023; M. Hinderdael, personal communication, March 17, 2023; M. Hinderdael, personal communication, March 27, 2023; M. Hinderdael, personal communication, March 31, 2023; M Hoerson, personal communication, March 2, 2023; M Hoerson, personal communication, March 3, 2023; M Hoerson, personal communication, March 17, 2023; M Hoerson, personal communication, March 20, 2023; M Hoerson, personal communication, March 27, 2023)	- Oxygen is released into environment in 2030 and is a byproduct with no economic value in 2050 - The existing hydrogen pipeline network in 2050 is assumed to be equivalent to the extensiveness of today’s Dutch gas network - The compressor is assumed to be fully made of steel. - No material losses during network construction - Hydrogen pipeline operates at maximum capacity - Hydrogen compressor - Hydrogen is 100% pure hydrogen and contains no impurities - 0% hydrogen leakage - Hydrogen boiler runs 8600 FLH - The hydrogen boiler is assumed to consume the least amount of hydrogen in the range provided by the hydrogen boiler manufacturer - The best value for nitrogen oxides emissions by hydrogen boiler were chosen as communicated by hydrogen boiler manufacturer
E, F, G & H	- All data is from RIFT and in line with their energy-mass balances (M. Verhagen, personal communication, April, 2023) - Electric transport data based on Volvo trucks information (AB Volvo, 2022)	- Pig iron produced via a blast furnace (process included in ecoinvent) is assumed to be a good proxy to produce initial iron fuel from iron ore. - Secondary steel production (process included in ecoinvent) is assumed to be a good proxy to produce initial iron fuel from iron scrap via an electric arc furnace. - All PAs consider that the iron fuel lasts for 25 cycles after which it is resold to another market as feedstock. - Water from IFT process can be disposed of in nature in contrast to having to be treated - No losses during IFT transport - Production system runs 8760 FLH - IF boiler runs 8600 FLH

4.4 Multifunctionality and Allocation

Processes that have more than one function are considered multifunctional processes. These processes may generate more than one product or use waste products in their process. There are three types of multifunctional processes: co-production, combined waste processing and recycling processes.

- Co-production processes are defined by having more than one functional outflow, i.e. produce more than 1 good.
- Combined waste processes are defined by having no functional outflows but more than one functional inflows, i.e. process more than 1 waste.
- Recycling processes are defined by having both a functional inflow as an outflow, i.e. produce at least 1 good and process at least 1 waste.

Through four steps, multifunctionality can consistently be recognized: (i) identify the good and waste flows of every process, (ii) identify the functional flows of every process, (iii) identify whether the process is multifunctional and (iv) resolve the problem. To exemplify, these four steps are overviewed in Table 6 for one of the multifunctional processes in this research.

Table 6: example of the four steps for steam production via IF boiler based on pig iron and hydrogen electrolyzer.

Process	Good and Waste Flows	Functional flow(s)	Multifunctional	Solution
Steam production via IF boiler (E1)	Inflows: Transported iron fuel (good), initial iron fuel (good), IF boiler (good), electricity (good) Outflows: steam at 240°C, 20 bar (good), unusable iron oxide, filter (good), unusable iron oxide, cyclic (good), usable iron oxide (good)	Production of steam; production of unusable iron oxide, filter; production of unusable iron oxide, cyclic; production of iron oxide	Yes, co-production process	Economic allocation

Multifunctionality must be resolved as a decision is required on which of the environmental interventions must be allocated to the functional unit produced by the system. Multifunctional processes can be dealt with in numerous ways including system expansion, substitution and partitioning (allocation). In this study, economic allocation is used. Economic allocation is the most desirable partitioning method as mentioned by Guinée et al. (2002). As some multifunctional unit processes have different units, it is also the only partitioning method able to be used in this study.

There are 3 foreground multifunctional co-production processes in this study. Two processes are in the Iron Fuel Technology™ process alternatives, namely the iron fuel production and steam production via iron fuel boiler process. For these processes the current (2023) monetary value when reselling the unusable iron fuel / oxide to another market forms the input to the allocation calculations. In process alternative C2 and D2, the production of hydrogen via electrolysis produces oxygen as a by-product and it is therefore also a co-production process. The oxygen is assumed to have no economic value as the main function for completing hydrogen electrolysis is for generating hydrogen and a clear perspective on the potential economic value of the produced oxygen is also currently lacking (Kato et al., 2005; Maggio et al., 2022; Terlouw et al., 2022). As a result, all environmental impacts are still allocated to the produced hydrogen.

4.5 Software

OpenLCA has been used in this study as the software of choice. As a user-friendly, open-access software it provides the ability for RIFT to further use and develop the created LCA model after the completion of this research. Due to its functions for incorporating scenarios and parametrization, it is also easy to adapt for testing environmental impacts for future projects with different parameters.

4.6 Results of Inventory Analysis

At the end of the inventory analysis phase, a complete life cycle inventory table was calculated outlining all biosphere and technosphere flows of each process alternative. These are recorded in Appendix C.

5. Results

This chapter focuses on the results as produced through the completion of various analyses. First, an explanation of which impact categories were selected is given in section 5.1. The following three sections then relay the results as produced by the life cycle impact assessment (section 5.2), the contribution analysis (section 5.3) and the sensitivity analysis (section 5.4).

5.1 Selection of Impact Categories

The purpose of life cycle impact assessment is to assess the contribution of the life cycle inventory results to a selection of impact categories (European Commission, 2021). In this study, it was chosen to adhere to the standardized set of impact categories as defined by the product environmental footprint (PEF). The PEF is a framework based on LCA that the European Commission has proposed as a way to standardize companies' assessment of evaluating life cycle environmental performance (Directorate-General for Environment, n.d.; Quist, 2023). The impact categories included in the PEF are climate change (total) (CC); ozone depletion (OD); human toxicity, cancer (TC); human toxicity, non-cancer (TNC); particulate matter (PM); ionizing radiation (IR); photochemical oxidant formation (PO); acidification (AC); eutrophication, terrestrial (ET); eutrophication, freshwater (EF); eutrophication, marine (EM); ecotoxicity, freshwater (EC); land use (LU); water use (WU); resource use, minerals and metals (MR); and resource use, fossils (FR) (European Commission, 2021). These impact categories will thus also be examined in this research.

5.2 LCIA Results

In Table 7, the results per MWh of superheated steam produced at 240°C, 20 bar are visualized for each of the examined process alternatives. For each impact category, process alternatives are given relative to the largest value represented by the value '1' and the lowest value which can be '0'. The following formula was used to calculate these values for each impact category[6]:

$$z_i = \frac{x_i - min(x)}{\max(x) - \min(x)}$$

The use of colors aids in the quick identification of the most and least impactful process alternatives with red signifying the most impactful PAs, green the best performing PAs and white highlighting the middle of the scale. In Table 8 a quick overview of the best performing alternative, the best clean performing alternative and the worst performing process alternative for each examined impact category is displayed for the easy spotting of trends. The gas and biomass boiler process alternatives are representative of the baseline as the incumbent technologies.

[6] All tables that show results relative to the largest value were calculated using this formula.

Table 7: LCIA results of all process alternatives for each impact category shown relative to the largest impact value per impact category.

Impact Category	A1	B1	A2	B2	C1	C2	D2	E1	F1	E2	F2	G1	H1	G2	H2	I1	I2	J1	J2
Acidification	0.50	0.50	0.60	0.60	0.83	1.00	0.99	0.78	0.22	0.90	0.24	0.72	0.16	0.84	0.17	0.06	0.06	0.62	0.62
Climate change	0.51	0.51	0.22	0.22	0.82	0.36	0.36	0.87	0.32	0.45	0.21	0.76	0.21	0.34	0.10	1.00	1.00	0.09	0.09
Ecotoxicity, freshwater	0.50	0.50	0.61	0.61	0.81	1.00	0.99	0.75	0.21	0.87	0.20	0.76	0.22	0.88	0.21	0.02	0.02	0.11	0.12
Resource use, fossils	0.62	0.62	0.44	0.44	0.99	0.70	0.70	0.96	0.30	0.69	0.22	0.88	0.22	0.61	0.14	1.00	1.00	0.09	0.09
Eutrophication, freshwater	0.63	0.63	0.54	0.54	1.00	0.86	0.85	0.93	0.26	0.81	0.24	0.84	0.17	0.73	0.15	0.01	0.01	0.08	0.07
Eutrophication, marine	0.24	0.24	0.23	0.23	0.38	0.38	0.37	0.40	0.15	0.39	0.14	0.35	0.09	0.34	0.09	0.09	0.09	1.00	1.00
Eutrophication, terrestrial	0.23	0.23	0.26	0.26	0.38	0.41	0.41	0.39	0.14	0.42	0.14	0.34	0.09	0.36	0.09	0.09	0.09	1.00	1.00
Human toxicity, cancer	0.20	0.20	0.25	0.25	0.33	0.40	0.40	0.50	0.28	0.55	0.29	0.94	0.72	1.00	0.73	0.03	0.03	0.13	0.13
Human toxicity, non-cancer	0.48	0.48	0.63	0.63	0.77	1.00	0.99	0.64	0.13	0.82	0.16	0.65	0.14	0.83	0.17	0.01	0.01	0.14	0.14
Ionising radiation	0.34	0.34	0.63	0.63	0.53	1.00	0.99	0.44	0.08	0.81	0.14	0.44	0.08	0.81	0.15	0.00	0.01	0.04	0.05
Land use	0.13	0.13	0.26	0.26	0.21	0.41	0.41	0.21	0.07	0.36	0.09	0.21	0.06	0.36	0.09	0.00	0.00	1.00	1.00
Resource use, minerals and metals	0.48	0.48	0.62	0.62	0.76	1.00	0.99	0.62	0.11	0.80	0.14	0.62	0.11	0.81	0.15	0.00	0.00	0.02	0.02
Ozone depletion	0.48	0.48	0.25	0.25	0.81	0.44	0.43	0.74	0.20	0.42	0.13	0.68	0.14	0.36	0.07	1.00	1.00	0.04	0.03
Particulate matter formation	0.31	0.31	0.40	0.40	0.50	0.65	0.64	0.71	0.38	0.82	0.39	0.63	0.30	0.74	0.31	0.04	0.04	1.00	1.00
Photochemical oxidant formation	0.30	0.30	0.29	0.29	0.49	0.48	0.47	0.60	0.28	0.57	0.25	0.47	0.14	0.43	0.12	0.18	0.18	1.00	1.00
Water use	0.00	0.00	0.00	0.00	1.00	1.00	1.00	0.01	0.00	0.01	0.00	0.01	0.00	0.01	0.00	0.53	0.53	0.00	0.00

A1: Steam production through e-boiler, 2030, with infrastructural construction; A2: Steam production through e-boiler, 2050, with infrastructural construction; B1: Steam production through e-boiler, 2030, without infrastructural construction; B2: Steam production through e-boiler, 2050, without infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; C2: Steam production through h-boiler, 2050, with infrastructural construction; D2: Steam production through h-boiler, 2050, without infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; E2: Steam production through IF boiler, 2050, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; F2: Steam production through IF boiler, 2050, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; G2: Steam production through IF boiler, 2050, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen; H2: Steam production through IF boiler, 2050, iron scrap + waste hydrogen; I1: Steam production through gas boiler, 2030; I2: Steam production through gas boiler, 2050; J1: Steam production through biomass boiler, 2030; J2: Steam production through biomass boiler, 2050.

Table 8: Overview of the best, best clean alternative and worst performing process alternatives for each examined impact category

	Best performing PA	Best performing clean PA	Worst performing PA
Acidification	Gas boiler, 2030	IF boiler, 2030, iron scrap + waste hydrogen	H-boiler, 2050, incl. network construction
Climate Change	Biomass boiler, 2050	IF boiler, 2050, iron scrap + waste hydrogen	Gas boiler, 2030
Ecotoxicity, freshwater	Gas boiler, 2030	IF boiler, 2050, pig iron + waste hydrogen	H-boiler, 2050, incl. network construction
Eutrophication, freshwater	Gas boiler, 2050	IF boiler, 2050, iron scrap + waste hydrogen	H-boiler, 2030, incl. network construction
Eutrophication, marine	IF boiler, 2050, iron scrap + waste hydrogen	IF boiler, 2050, iron scrap + waste hydrogen	Biomass boiler, 2030/2050
Eutrophication, terrestrial	Gas boiler, 2030	IF boiler, 2050, iron scrap + waste hydrogen	Biomass boiler, 2030/2050
Human toxicity, cancer	Gas boiler, 2030	E-boiler, 2030, excl. network construction	IF boiler, 2050, iron scrap + hydrogen electrolyzer
Human toxicity, non-cancer	Gas boiler, 2030	IF boiler, 2030, pig iron + waste hydrogen	H-boiler, 2050 incl. network construction
Ionizing radiation	Gas boiler, 2030	IF boiler, 2030, pig iron + waste hydrogen	H-boiler, 2050, incl network construction
Land use	Gas boiler, 2030	IF boiler, 2030, iron scrap + waste hydrogen	Biomass boiler, 2050
Ozone depletion	Biomass boiler, 2050	IF boiler, 2050, iron scrap + waste hydrogen	Gas boiler, 2030
Particulate matter	Gas boiler, 2030	IF boiler, 2030, iron scrap + waste hydrogen	Biomass boiler, 2030/2050
Photochemical oxidant formation	IF boiler, 2050, iron scrap + waste hydrogen	IF boiler, 2050, iron scrap + waste hydrogen	Biomass boiler, 2030/2050
Resource use, fossils	Biomass boiler, 2050	IF boiler, 2050, scrap iron + waste hydrogen	Gas boiler, 2030
Resource use, minerals and metals	Gas boiler, 2030	IF boiler, 2030, pig iron + waste hydrogen	H-boiler, 2050, incl network construction
Water use	IF boiler, 2050, pig iron + waste hydrogen	IF boiler, 2050, pig iron + waste hydrogen	All hydrogen process alternatives

To decarbonize, GHG emissions must be reduced in the energy intensive industries. As derived from the LCIA climate change impact category results, all hydrogen, electrification and Iron Fuel Technology™ process alternatives perform better in this regard in comparison to natural gas combustion, see PAs A1-H2 in comparison to I1 and I2 in Table 7. To address the problem faced by the energy-intensive industries, hydrogen, electrification and Iron Fuel Technology™ can thus all contribute to a decrease in emissions in comparison to natural gas. Noticeable is that both biomass PAs (J1 and J2) have the lowest climate change scores. When biomass origins from sustainably harvested sources, the associated carbon emissions during combustion are balanced by a carbon uptake in sequestration in wood earlier in the chain and the resulting GHG emissions are limited (U.S. Energy Information Administration, 2022a). From a purely GHG emission and climate change perspective, sustainably sourced biomass would thus be a better solution than hydrogen, electrification or Iron Fuel Technology™.

A decrease in CO_2-equivalent emissions can also be seen between 2030 and 2050, see climate change impact category of PAs 1 vs. 2. A main difference between all process alternatives of 2030 and 2050 is the different electricity mix assumed. The electricity mix, as in the TNO Transform scenario on which the mix is based, is led by more renewable sources in 2050 than in 2030, refer back to Table 1 for specific shares of each electricity source in each scenario. The consequent environmental impacts are seen to decrease CO_2-equivalent emissions, as well as decrease impacts in the categories of fossil resource use, freshwater eutrophication, ozone depletion, marine eutrophication, photochemical oxidant formation and water use, as seen in the difference between A1 and A2 in Table 7 for example. However, the switch to more renewable energy sources increases the environmental impacts of acidification, freshwater ecotoxicity, cancer and non-cancer human toxicity, ionizing radiation, mineral and metal resource use, and particulate matter. In focusing on the specific decarbonization problem, it is thus important to note that impacts may be transferred to exert pressure on other parts of the environment.

From a holistic examination of the results, gas and biomass PAs tend to perform well in many of the studied impact categories as seen in Table 8. One or both fuels outperform the hydrogen, electrification and Iron Fuel Technology™ process alternatives in multiple impact categories. Also noticeable is that when gas performs the worst biomass performs the best or vice versa, as can be seen in the impact categories of climate change, fossil resource use, marine and terrestrial eutrophication, land use, ozone depletion, and particulate matter in Table 8. Gas performs the best in the categories of acidification, freshwater ecotoxicity, freshwater eutrophication, terrestrial eutrophication, human toxicity cancer, human toxicity non-cancer, ionizing radiation, land use, particulate matter, and mineral and metal resource use, whereas biomass performs the best in the categories of climate change, ozone depletion and fossil resource use. As no process alternative performs best in all impact categories, which process alternative performs best overall depends on which impact category (or categories) is (or are) prioritized.

Table 8 also clearly highlights that natural gas generally performs well except for climate change, ozone depletion and fossil resource use. This relates to the fossil fuel nature of natural gas and the subsequent emissions it produces when combustion takes place. Having completed a literature review on all technologies (section 1.1), it is noteworthy to mention that the high climate change impact score of natural gas in comparison to biomass, electrification and hydrogen can be seen reflected in completed studies, yet the low environmental impacts of natural gas in other impact categories has been limitedly publicized and only in comparison to other fossil fuels and biomass (Berrill et al., 2016; H. H. Cho & Strezov, 2020; Hydrogen Council, 2021; Turconi et al., 2013). The results as seen in Table 7 and 8 showing the low impacts of natural gas in comparison to electrification, hydrogen and IFT, therefore raises the question whether natural gas needs complete phasing out or whether it could not act as a useful supplementary fuel in combination with cleaner alternatives. The latter could potentially limit significant environmental tradeoffs.

Between the clean alternatives, overall the Iron Fuel Technology™ process alternatives using waste hydrogen (F1, F2, H1 & H2) perform the best, apart from the human toxicity, cancer, impact category for H1 and H2. The electrification process alternatives generally score somewhere in the middle of each of the impact categories, as indicated by the predominantly white color in Table 7. The process alternatives including hydrogen production via electrolysis (thus all hydrogen process alternatives and Iron Fuel Technology™ process alternatives sourcing hydrogen from an electrolyzer; C1, C2, D2, E1, E2, G1, and G2) are often among the worst performers in each of the examined impact categories as seen in the impact categories of acidification, climate change, freshwater ecotoxicity, fossil resource use, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, human toxicity non-cancer, ionizing radiation, land use, mineral and metal resource use, ozone depletion, particulate matter, and photochemical oxidant formation. This is linked to the large consumption of electricity required to produce hydrogen and the materials required to construct the electrolyzer plant.

The impact category water use is worth pointing out as the results may not be as obvious. Both the natural gas (I1 & I2) and hydrogen process alternatives (C1, C2, & D2) display large impacts because they produce water as a byproduct during the combustion process whereas this is not the case with the other fuels. As hydrogen produces more water than natural gas, it thus also performs relatively poorer.

Also noticeable is that the construction of additional required infrastructure for both the hydrogen and electricity PAs have negligible impact on all impact categories as can be seen in the minimal differences between A1 and B1, A2 and B2, and C2 and D2 in Table 7. From an environmental perspective, the need for constructing additional infrastructure between the production and boiler location, specifically the aerial high voltage direct current lines and the hydrogen pipeline spanning the 150 km distance for electrification and hydrogen respectively, is thus not seen as a barrier.

Key Takeaways

Of these results, two concluding comments can be made. First, these results show that there are tradeoffs to be made as no one technology performs well in every impact category. Take biomass, for example, it performs best in the climate change impact category so from a CO_2 reduction perspective this would be the go-to option. However, it is detrimental for the environment in increasing eutrophication of marine and terrestrial life, exerts large land use impacts and emits the most particulate matter and photochemical oxidants in comparison to the other process alternatives. If we give more value to reducing impacts other than extracting fossil resources, emitting greenhouse gases and destroying the ozone layer, natural gas would be the best performing process alternative as in these other impact categories, natural gas has the lowest environmental impacts. Taking only the cleaner alternatives into consideration, the IFT process alternative based on iron scrap and waste hydrogen (H1/2) performs well with the exception for the emissions of cancerous human toxins. It can also be decided that a middle of the road is taken for which the IFT pig iron and waste hydrogen PA or any of the e-boiler process alternatives would be a possible choice. Depending on what impact category more value is given to, the answer of which process alternative is best may differ.

The results from the LCIA also show that some key processes can be identified that can be largely impactful to multiple impact categories, namely the electricity mix, the hydrogen sourced for the IF production process and the initial iron fuel production process. This is seen through the large difference between the 2030 and 2050 scenarios and the differences seen between the Iron Fuel Technology™ process alternatives. This provides insight into parameters that require more thorough investigation. The next section will therefore dive deeper into the contribution of (individual) processes toward each process alternative and impact category.

5.3 Contribution Analysis

The process alternatives have key differences in the scenario (2030/2050), the hydrogen source in case of the IFT process alternatives, the initial iron fuel production method and the in/exclusion of infrastructure construction, as seen in Table 3 in section 3.6. As derived from the LCIA results, only some of these key differences lead to a large change in the observed results. As such we can focus the contribution analysis on only a set of the studied process alternatives as the requirement for additional infrastructure construction between the production and boiler location has limited impact.

The process alternatives that will be examined more closely in this chapter are: steam production through e-boiler, 2030, including network construction (A1); steam production through e-boiler, 2050, including network construction (A2); steam production through h-boiler, 2030, including network construction (C1); steam production through IF-boiler, 2030, pig iron + hydrogen electrolyzer (E1); steam production through IF-boiler, 2030, pig iron + waste hydrogen (F1); steam production through IF-boiler, 2030, scrap iron + hydrogen electrolyzer (G1) and steam production through IF-boiler, 2030, scrap iron + waste hydrogen (H1). To examine the contributions in relation to the difference in assumed scenario (and subsequent electricity mix) A1 and A2 are chosen, keeping the need for infrastructure construction the same. To further examine the contributions to the hydrogen system, C1 is studied. No other hydrogen process alternatives are studied as the need for extra infrastructure was derived to be negligible from the LCIA results and the difference of the 2030/2050 scenario is already studied in A1 and A2. As for the Iron Fuel Technology™ process alternatives, all 2030 process alternatives are examined to understand more clearly the difference between a change in the initial iron fuel production method and a varying hydrogen source. In general, all process alternatives used for the contribution analysis are based on the year 2030 (exception A2 for understanding the effect of the 2030/2050 scenario) as the used background processes are likely to be closer to today's technological state. Hence less uncertainty is present in the background processes in comparison to 2050 based PAs.

An additional contribution analysis into the steam production through gas boiler, 2030 (I1) and steam production through biomass boiler, 2030 (J1) was completed but these results are in Appendix D as they are not critical for answering the research questions defined. Noteworthy to mention is that environmental impacts for both I1 and J1 occur mainly at the steam production process, i.e. the process in which the fuel is combusted and heat is created.

In this research, 3 different types of contribution analyses were completed. The first analysis focused on the individual process contributions by examining all processes that contributed at least 1% to any impact category. This identified individual processes that were hotspots. Next, the contributions of processes collectively to an individual impact category were investigated by grouping processes into one of 8 groups:

1. Agriculture, forestry and fishing processes,
2. Mining and quarrying processes
3. Manufacturing processes
4. Electricity, gas, steam and air conditioning supply processes
5. Water supply, sewerage, waste management and remediation processes
6. Construction processes

7. Transportation and storage processes
8. Other processes

For a more detailed overview of what processes fall into which group see Appendix C. By grouping processes, a quick analysis of the type of processes contributing to different impact categories was able to be made. Lastly an economic flow contribution analysis was completed to understand where most of the total upstream or downstream impacts derived from. Throughout this section, the reader can identify which analysis is referred to by the use of the following specific key words: 'individual' refers to the individual process contribution analysis, 'group' refers to the grouped processes contribution analysis and 'upstream' refers to the economic flow contribution analysis. In this section, results are visually shown mainly from the grouped contribution analysis, but the results of the individual process contribution analysis and economic flow contribution analysis can be found in Appendix C.

5.3.1 Electricity-Based Process Alternatives A1 and A2

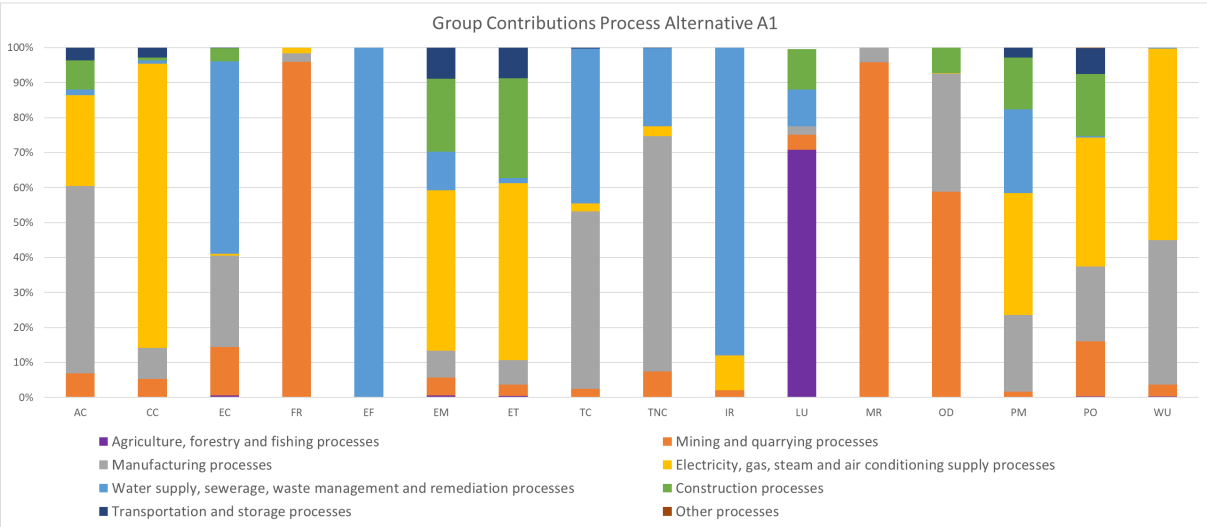

Figure 5: Group process contributions to process alternative A1 – steam production via e-boiler, 2030, including network construction. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

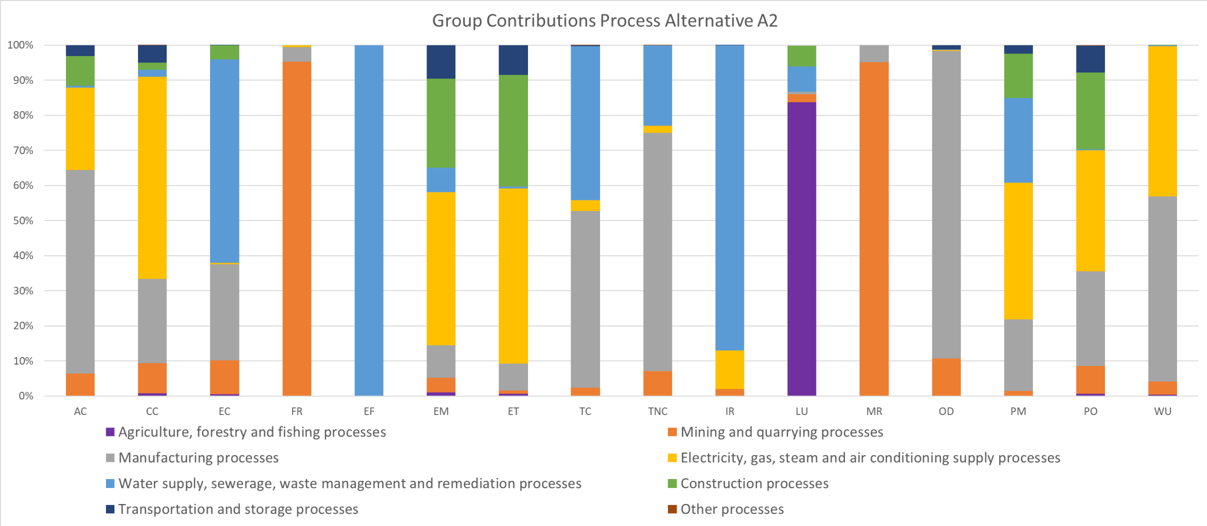

Figure 6: Group process contributions to process alternative A2 – steam production via e-boiler, 2050, including network construction. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

As can be seen in Figures 5 and 6, multiple impact categories show visual differences between the process alternatives A1 (steam production via e-boiler, 2030, including network construction) and A2 (steam production via e-boiler, 2050, including network construction) in the percentage contribution of each group. The ozone depletion impact category is a good example of this as it shows large visual differences between A1 and A2. In A1, mining related processes are dominant contributors (59%) and manufacturing processes account for less (34%) whereas in A2 manufacturing processes are dominant contributors (88%) and mining processes account for less of the total group contribution (11%). This is also seen reflected on an individual process level. All individual process contributions can be found in Appendix C while an example extract is shown in Table 9. To exemplify, petroleum and gas production processes (mining processes) together account for 55% in A1 but only account for 3% in A2 whereas the production of purified terephthalic acid (manufacturing process) increases from 15% to 30% from A1 to A2. The decrease in mining process contributions in this case is the result of a decrease of natural gas in the electricity mix toward 2050 whereas the increase of manufacturing processes is the result of an expanded electricity network, both the result of the assumed 2030/2050 scenarios. A similar trend is seen in the photochemical oxidant formation impact category where impacts stemming from mining activities decrease while manufacturing activity impacts increase from A1 to A2.

Table 9: Individual processes contributing >1% to the total ozone depletion impacts for A1.

Contributing process	Impact result	Unit	% of total
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - NO	2.45E-06	kg CFC-11-Eq	40%
petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - NL	7.20E-07	kg CFC-11-Eq	12%
purified terephthalic acid production | purified terephthalic acid | Cutoff, U - RoW	7.03E-07	kg CFC-11-Eq	12%
transport, pipeline, onshore, long distance, natural gas | transport, pipeline, onshore, long distance, natural gas | Cutoff, U - RU	2.60E-07	kg CFC-11-Eq	4%
trichloromethane production | trichloromethane | Cutoff, U - RoW	2.29E-07	kg CFC-11-Eq	4%

petroleum and gas production, offshore | natural gas, high pressure | Cutoff, U - RU	1.76E-07	kg CFC-11-Eq	3%
purified terephthalic acid production | purified terephthalic acid | Cutoff, U - RER	1.66E-07	kg CFC-11-Eq	3%
chlorodifluoromethane production | chlorodifluoromethane | Cutoff, U - RoW	1.45E-07	kg CFC-11-Eq	2%
trichloromethane production | trichloromethane | Cutoff, U - RER	1.07E-07	kg CFC-11-Eq	2%
chlor-alkali electrolysis, membrane cell | sodium hydroxide, without water, in 50% solution state | Cutoff, U - RoW	9.86E-08	kg CFC-11-Eq	2%
transport, pipeline, offshore, long distance, natural gas | transport, pipeline, offshore, long distance, natural gas | Cutoff, U - NO	9.15E-08	kg CFC-11-Eq	2%
vinyl chloride production | vinyl chloride | Cutoff, U - RoW	9.11E-08	kg CFC-11-Eq	1%
refrigerant R134a production | refrigerant R134a | Cutoff, U - RoW	9.01E-08	kg CFC-11-Eq	1%
coking | coke | Cutoff, U - RoW	8.99E-08	kg CFC-11-Eq	1%
transport, pipeline, offshore, long distance, natural gas | transport, pipeline, offshore, long distance, natural gas | Cutoff, U - RU	7.72E-08	kg CFC-11-Eq	1%
chlorodifluoromethane production | chlorodifluoromethane | Cutoff, U - NL	6.68E-08	kg CFC-11-Eq	1%
chlor-alkali electrolysis, membrane cell | chlorine, gaseous | Cutoff, U - RoW	6.63E-08	kg CFC-11-Eq	1%

Whereas the impact categories of ozone depletion and photochemical oxidant formation showed large group contribution differences, other impact categories show relatively little visual differences between the groups contributing to process alternatives A1 and A2, as can be seen in the impact categories of human toxicity cancer, human toxicity non-cancer and freshwater ecotoxicity in Figures 5 and 6. On an individual process level, the same processes are also seen to contribute similar quantities. To exemplify, in the impact category of human toxicity cancer the treatment of electric arc furnace slag totals 15% in A1 and 14% in A2 and the smelting of copper concentrate totals 24% in 2030 and 25% in 2050. While closer examining what causes this little difference between the process alternatives, it was found that approximately half of the upstream emissions can be traced back to the distribution network for all three impact categories. The emissions tracing back to the electricity network infrastructure come from the materials required for it, mostly copper as an important element for the electricity network infrastructure as the electricity lines are copper based. The small difference as seen in the toxicity impact categories between A1 and A2 here can thus be explained by the expansion of the electricity network toward 2050 inherent to the assumed 2030/2050 scenarios. In Figure 7, the upstream impacts for the impact category of freshwater ecotoxicity of A1 are shown, it displays that a large portion of the upstream impacts are accounted to the distribution network. All upstream impacts for any impact category can be generated through the OpenLCA model as explained in Appendix C.

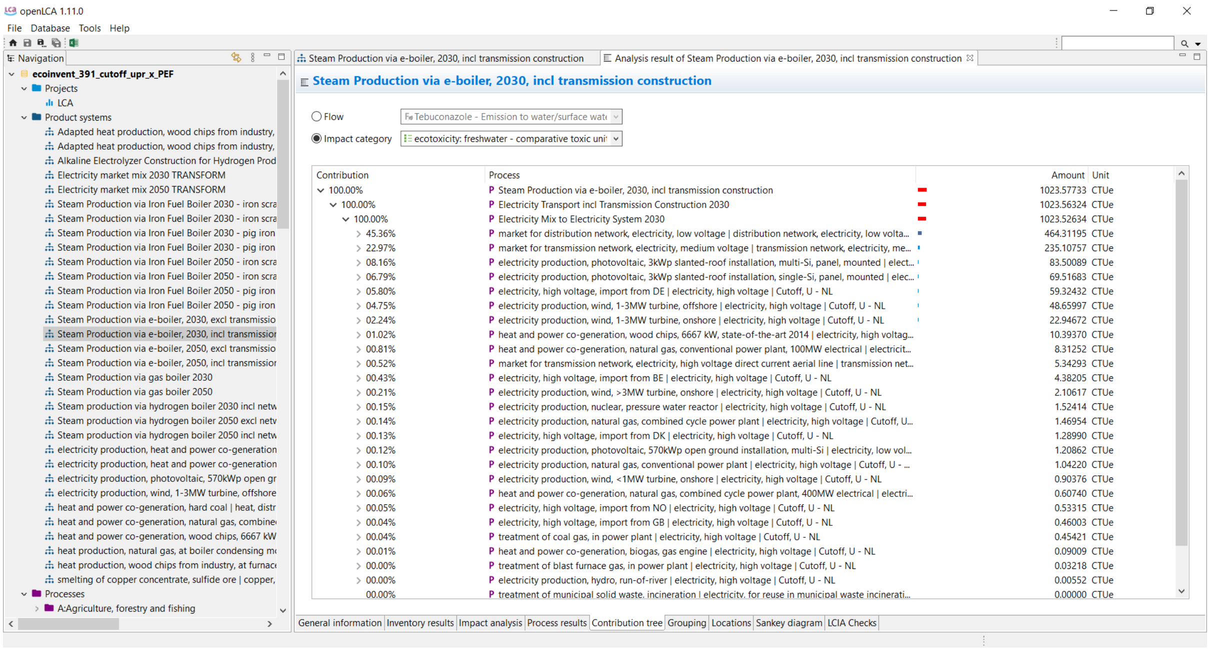

Figure 7: Upstream contributions for the impact category of freshwater ecotoxicity of A1.

Similar to the impact categories of human toxicity cancer and human toxicity non-cancer, the impact category of particulate matter at group level visually also shows little differences, see Figures 5 and 6. On an individual process level, the top five most contributing processes have a slight variation in their percentage contribution from A1 to A2, but the processes remain the same and the total percentage contribution of the top five processes also remains similar. As a result, the difference between A1 to A2 in the impact category of particulate matter is limited.

The largest contributors to acidification are manufacturing processes, as seen by the large portion of grey in Figures 5 and 6. On an individual process level, specifically the smelting of copper concentrate is seen to be a large contributor accounting for at least 46% in process alternative A1 and 50% in process alternative A2. This increase is both relative but also absolute increasing by more than 30%. Many activities related to copper are seen to contribute to multiple impact categories. This again is related to the electricity network. For the impact category of mineral and metal resource use, 76% of both A1 and A2 contributions stem from copper mine operations. When examining the mining of copper as a resource from the ground more than 75% of the resource uptake traces back to the use of copper in the distribution network.

The impact category fossil resource use also finds most of the individual process contributions related to mining activities. Here, however, impacts are largely dominated by the individual processes of petroleum and gas production, uranium production and uranium mine operation. Whereas in A1 the petroleum and gas production processes account for 46% of emissions, this decreases to 3% in A2. Uranium production and uranium mine operation, on the other hand, increase from 10% and 9% to 25% and 23% respectively. This increase in contribution of uranium-based processes is the result of an increased share of nuclear energy in the electricity mix by approximately 4.5% from the 2030 to 2050 scenario. Likewise, the decreasing contribution of the petroleum and gas production process is the result of an approximately 11%

decrease in share of natural gas in the electricity mix from 2030 to 2050. Refer back to Table 1 in section 3.6 to see the shares of each energy source in the 2030 / 2050 scenario.

Generally, the different electricity mix inherent to the 2030 and 2050 scenario, a main difference between the process alternatives A1 and A2, results in both small and large differences in total contributions in multiple categories. To exemplify, the process of heat and power cogeneration by natural gas contributes to climate change by a total of 27% in the 2030 scenario whereas this reduces drastically to 4% in the 2050 scenario in line with the decreasing share of natural gas toward 2050. The electricity production by lignite follows the same trend in that it reduces from contributing 9% in 2030 to a mere 4% in 2050. Interesting to note is that the electricity production by lignite has Germany as the geographical scope and is the result of imported electricity. In the assumed scenarios, the total share of imported electricity will decrease from 2030 to 2050 (7% to 1%). Therefore a small amount of imported electricity from Germany (0.7% of the total assumed electricity mix in 2050) can have a significant environmental impact (4% of the relative climate change total contributions in 2050). This highlights that a trace amount of fossil fuel-based electricity can relatively contribute a lot. It also shows that the electricity sources used in countries from which the Netherlands imports energy must not be considered negligible.

The effect of the assumed energy mix can also be seen reflected in other impact categories. In the water use impact category, the largest upstream process contributor of A1 is hydro electricity production whereas electricity production from nuclear power is the largest process contributor in A2. This is again in line with the assumed electricity mix of the scenarios as nuclear energy increases from an electricity mix share of just below 2% to well over 6% in 2050 whereas the share of hydropower decreases by 60%.

From Figures 5 and 6 it can also be seen that the impact categories of marine eutrophication and terrestrial eutrophication show similar group contributions. This is also reflected in the individual process contributions with heat and power cogeneration from wood chips and blasting processes among the largest contributors in both impact categories. Noteworthy is to mention that for marine eutrophication, heat and power cogeneration by natural gas was the 2nd largest contributor in A1 (9%). However, in A2 this process contributes less than 1%. This again reflects the electricity mix where in the assumed 2050 scenario natural gas only accounts for 0.5% of the total electricity mix. Similarly the increase in biomass produced electricity from 2030 (1.5%) to 2050 (~4%) is seen in that heat and power cogeneration from wood chips (biomass) is the largest single process contributor in A2 accounting for 20%, but only accounts for 8% in A1.

Most processes contributing to freshwater eutrophication and ionizing radiation are processes related to water supply, sewage, waste management and remediation as seen by the largely blue color for these two impact categories in Figures 5 and 6. The treatment of tailings or spoil from mines account for the largest individual process contributions to both impact categories. For freshwater eutrophication, the treatment of sulfidic tailings from copper mines and the treatment of spoil from lignite mining together account for 83% of the total emissions in both A1 and A2. For the ionizing radiation impact category, the treatment of tailings from uranium milling and the treatment of spent nuclear fuel together account for 83% of the emissions in

A1 and for 81% of the emissions in A2. Whereas the treatment of sulfidic tailings from copper mines relates to the electricity network, the other individual processes relate to the electricity mix as part of the assumed scenarios.

The land use impact category is the only impact category in which the group agriculture, forestry and fishing processes are a dominant group contributor. Hardwood and softwood forestry together account for most of the individual process contributions (65% in A1 and 79% in A2). It can also be seen that more land use impacts origin from agriculture, forestry and fishing processes in A2 than in A1, also reflected in Figures 5 and 6. This is largely the result of the increase in biomass produced electricity from 2030 to 2050.

Key Takeaways

The contribution analysis showed that depending on the impact category the hotspots may vary. However, a few individual process hotspots can be identified over multiple impact categories: smelting of copper concentrate, copper mine operations and the treatment thereof, petroleum and gas production processes, heat and power cogeneration from wood chips and blasting processes. These hotspots are related to two things: the different electricity mix and the expansion of the electricity network, both inherent to the assumed 2030 and 2050 scenario. The smelting of copper concentrate, copper mine operations and the treatment thereof, and the blasting processes are related to the electricity network expansion whereas the petroleum and gas production processes and heat and power cogeneration from wood chips are related to the electricity mix.

To start with the electricity mix part, the increase of biomass toward 2050, though percentage wise relatively small, has a significant impact on the impact categories of terrestrial eutrophication, land use and particulate matter. To exemplify, the upstream contributions of biomass electricity increase from 13% to 31% from A1 to A2 for the impact category terrestrial eutrophication, from 59% to almost 80% for land use and from about 9% to 17% for particulate matter. Similarly, nuclear produced electricity increases toward 2050 for which the upstream impacts of ionizing radiation in 2030 total 49% but significantly dominate in 2050 with nuclear upstream impacts accounting for 90% of the total contributions. Now the impacts of nuclear and biomass generated electricity may jump out, yet the impacts of offshore wind and solar produced electricity also contribute. In Table 8 and 9, an overview of the percentage upstream impacts per energy source and by the electricity network are shown for each impact category for both 2030 and 2050. It easily displays how the change in electricity mix changes the relative contribution of impacts by each energy source. This can be clearly seen in how the impacts associated with natural gas significantly decrease toward 2050 in line with the large decrease of natural gas as a percentage share of the electricity mix, for example. Comparing this with the assumed energy source shares (Table 1, section 3.6), the conclusion can be made that the electricity mix is a large determinant in potentially reducing environmental impacts in multiple impact categories.

The second hotspot, the expansion of the electricity network, impacts the environment as it requires additional copper. As a result, individual processes such as the smelting of copper concentrate, copper mine operations and the treatment thereof as well as blasting processes will increase. This has a direct impact on impact categories like acidification, terrestrial eutrophication, and cancer and non-cancer human toxicity. Though these processes are partly fed by fossil fuels, the processes themselves also emit a range of emissions. Specifically for the impact categories acidification, terrestrial eutrophication and cancer and non-cancer human toxicity the following emissions need to be targeted: ammonia, nitrogen oxides, sulfur dioxide, arsenic ion, cadmium II, lead II, mercury II, nickel II, chromium VI and carbon disulfide. As the expansion of the electricity network is a definitive requirement for successfully achieving the energy transition, it is more important to look at how the emissions of these processes can be decreased.

Table 10: Percentage relative upstream emissions of the assumed electricity mix in 2030 per energy source and the electricity network as shown for each impact category.

2030	AC	CC	EC	FR	EF	EM	ET	TC	TNC	IR	LU	MR	OD	PM	PO	WU
Electricity network	57.79%	8.58%	68.85%	5.51%	41.49%	24.96%	29.48%	56.77%	76.84%	2.28%	15.89%	79.05%	14.38%	41.30%	28.24%	10.41%
Electricity from solar	16.18%	12.70%	15.07%	8.87%	12.47%	17.55%	16.57%	11.33%	12.41%	4.69%	7.82%	14.86%	17.61%	22.32%	18.82%	37.45%
Electricity from wind (offshore)	6.05%	5.74%	4.75%	3.66%	3.80%	8.39%	7.16%	15.93%	4.43%	1.02%	2.55%	3.76%	1.60%	11.38%	8.41%	6.23%
Electricity from wind (onshore)	2.58%	2.49%	2.54%	1.73%	1.82%	3.65%	3.30%	7.30%	1.75%	0.50%	5.56%	1.47%	0.91%	5.91%	4.14%	2.20%
Electricity from natural gas	5.74%	47.57%	1.11%	45.17%	0.81%	18.17%	17.76%	2.78%	0.92%	0.27%	1.24%	0.40%	57.73%	2.93%	21.98%	8.29%
Electricity from biomass	4.21%	0.68%	1.02%	0.45%	0.34%	8.84%	13.29%	1.65%	1.21%	0.21%	59.47%	0.03%	2.19%	8.81%	7.28%	1.39%
Electricity from waste	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity from nuclear	0.15%	0.11%	0.15%	11.93%	0.11%	1.07%	0.26%	0.15%	0.10%	49.40%	0.07%	0.04%	0.04%	1.37%	0.26%	4.71%
Electricity from flue gasses	0.17%	1.55%	0.04%	0.09%	0.10%	0.34%	0.33%	0.90%	0.00%	0.00%	0.04%	0.00%	0.11%	0.17%	0.45%	0.03%
Imported electricity	7.07%	20.53%	6.45%	22.58%	39.03%	16.98%	11.75%	3.13%	2.33%	41.63%	7.34%	0.40%	5.42%	5.72%	10.39%	29.30%
Electricity from other sources	0.05%	0.03%	0.01%	0.01%	0.01%	0.03%	0.08%	0.01%	0.00%	0.00%	0.02%	0.00%	0.00%	0.06%	0.03%	0.00%

Table 11: Percentage relative upstream emissions of the assumed electricity mix in 2050 per energy source and the electricity network as shown for each impact category.

2050	AC	CC	EC	FR	EF	EM	ET	TC	TNC	IR	LU	MR	OD	PM	PO	WU
Electricity network	64.28%	26.78%	74.67%	10.43%	64.72%	33.78%	36.00%	62.41%	79.39%	1.62%	11.02%	80.83%	37.58%	42.22%	38.91%	14.50%
Electricity from solar	16.99%	37.41%	15.42%	15.85%	18.36%	22.42%	19.09%	11.76%	12.11%	3.18%	5.12%	14.34%	43.41%	21.54%	24.47%	49.24%
Electricity from wind (offshore)	7.21%	19.16%	5.52%	7.43%	6.36%	12.16%	9.36%	18.75%	4.90%	0.78%	1.89%	4.11%	4.49%	12.46%	12.40%	9.30%
Electricity from wind (onshore)	0.95%	2.54%	0.90%	1.08%	0.94%	1.62%	1.33%	2.64%	0.59%	0.13%	1.27%	0.50%	0.79%	1.99%	1.88%	1.01%
Electricity from natural gas	0.01%	0.49%	0.00%	0.28%	0.00%	0.08%	0.07%	0.01%	0.00%	0.00%	0.00%	0.00%	0.51%	0.01%	0.10%	0.04%
Electricity from biomass	9.07%	4.13%	2.13%	1.63%	1.03%	23.16%	31.39%	3.52%	2.42%	0.29%	79.87%	0.07%	11.07%	17.42%	19.40%	3.75%
Electricity from waste	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Electricity from nuclear	0.42%	0.89%	0.41%	57.58%	0.44%	3.69%	0.82%	0.41%	0.26%	90.04%	0.13%	0.09%	0.29%	3.56%	0.90%	16.71%
Electricity from flue gasses	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Imported electricity	1.04%	8.54%	0.94%	5.70%	8.12%	3.06%	1.92%	0.47%	0.31%	3.98%	0.68%	0.04%	1.89%	0.78%	1.92%	5.44%
Electricity from other sources	0.02%	0.03%	0.00%	0.00%	0.00%	0.01%	0.03%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.00%

Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

5.3.2 Hydrogen-Based Process Alternative C1

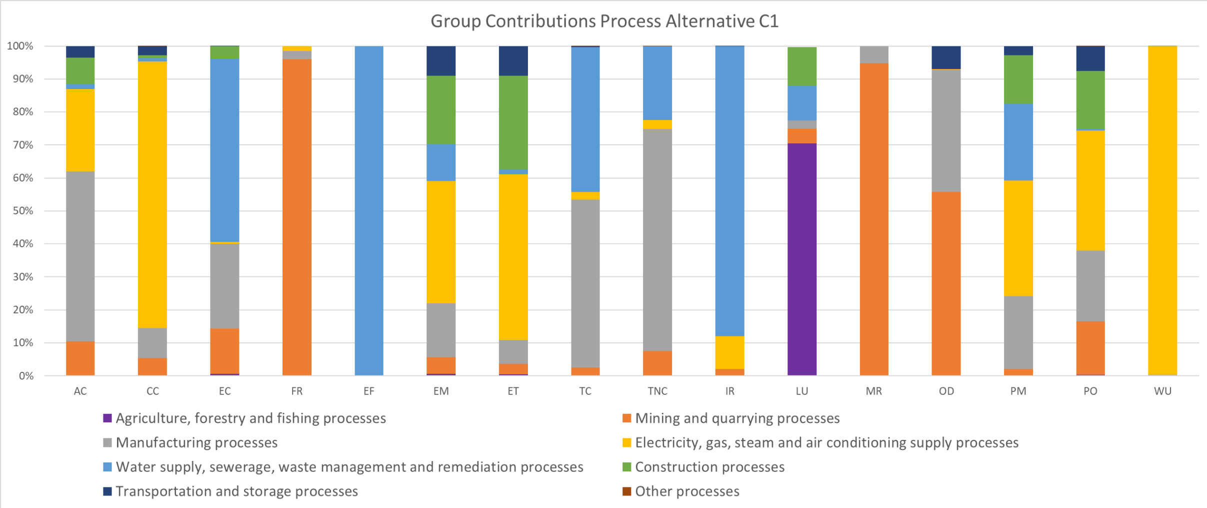

Figure 8: Group process contributions to process alternative C1 - steam production via h-boiler, 2030, including network construction. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

Examining Figures 5 and 8, it can be seen that the group contributions appear very similar. All the environmental impacts for process alternative steam production via h-boiler, 2030, including network construction (C1) originate for at least 92% from the upstream impacts of the assumed 2030 electricity mix required to produce hydrogen. As a result, the individual processes contributing the most to the process alternative A1 (steam production through e-boiler, 2030, including network construction) as examined earlier are the same as the processes contributing to process alternative C1. To exemplify, the individual processes contributing the most to acidification in A1 is the smelting of copper accounting for 46% whereas this is slightly lower in C1 accounting for 43%. Similar individual process contributions are seen for all impact categories except for water use.

The reason why the water use impact category is different is because the combustion of hydrogen produces water in the form of steam as part of the chemical reaction. This steam is released into the environment together with other flue gasses leading to an increase in the deprived m^3 of water worldwide. As a result, the individual process of producing steam by a hydrogen boiler (the combustion process of hydrogen) contributes 99% of the total impacts registered. Important to note is that the steam as a result of the reaction is a waste stream and different from the indirect heat production via steam as per the reference flow.

The minority share of upstream impacts that are not associated with the assumed electricity scenario can be linked to the electrolyzer's construction and the materials required for the electrolysis process such as potassium hydride and deionized water. The electrolyzer is constructed of numerous materials of which nickel and tetrafluoroethylene are two materials that are seen to significantly contribute in some impact categories such as acidification and ozone depletion.

5.3.3 Iron Fuel Technology™-Based Process Alternatives E1, F1, G1 & H1

The IFT process alternatives can be distinguished by the source of hydrogen and the initial iron fuel production method used. This subsection will therefore be divided into two. First, the contribution differences because of the source of hydrogen will be addressed after which the contributions as a result of the initial iron fuel production method will be discussed.

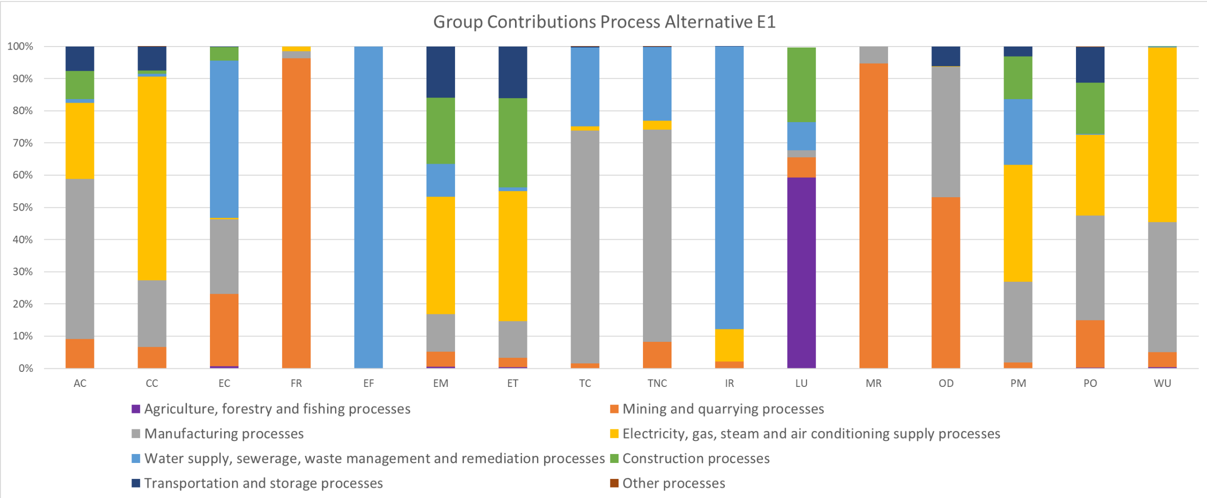

Figure 9: Group process contributions to process alternative E1 – steam production via IFT boiler, 2030, pig iron + hydrogen electrolyzer. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use

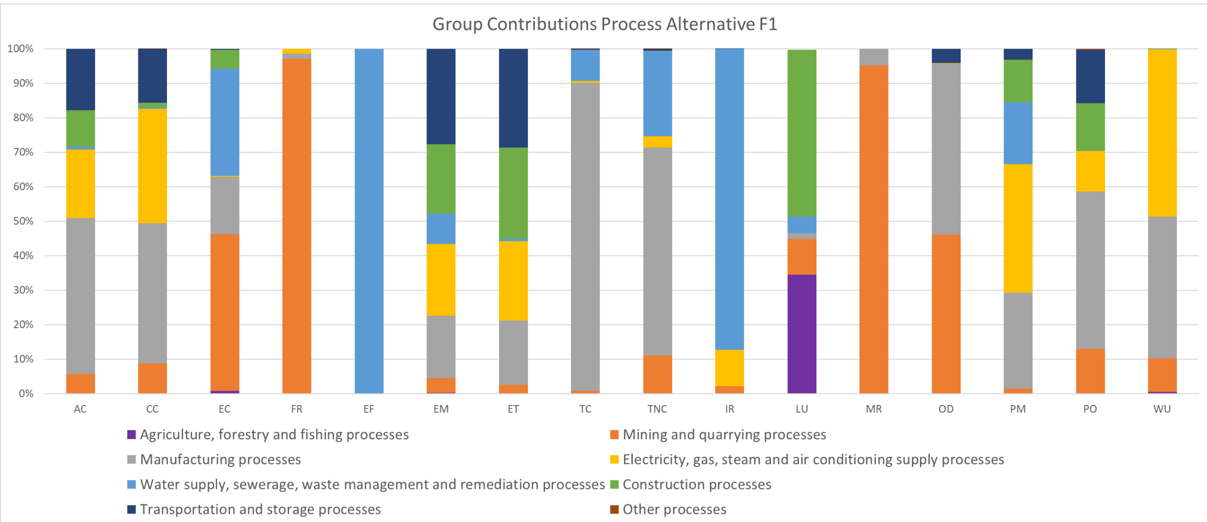

Figure 10: Group process contributions to process alternative F1 – steam production via IFT boiler, 2030, pig iron + waste hydrogen. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

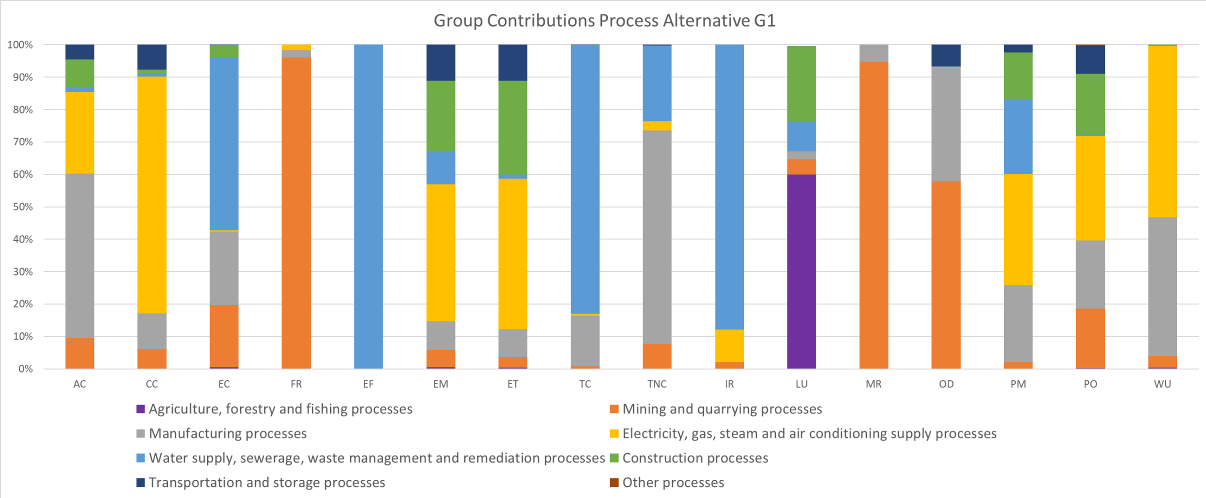

Figure 11: Group process contributions to process alternative G1 – steam production via IFT boiler, 2030, scrap iron + hydrogen electrolyzer. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

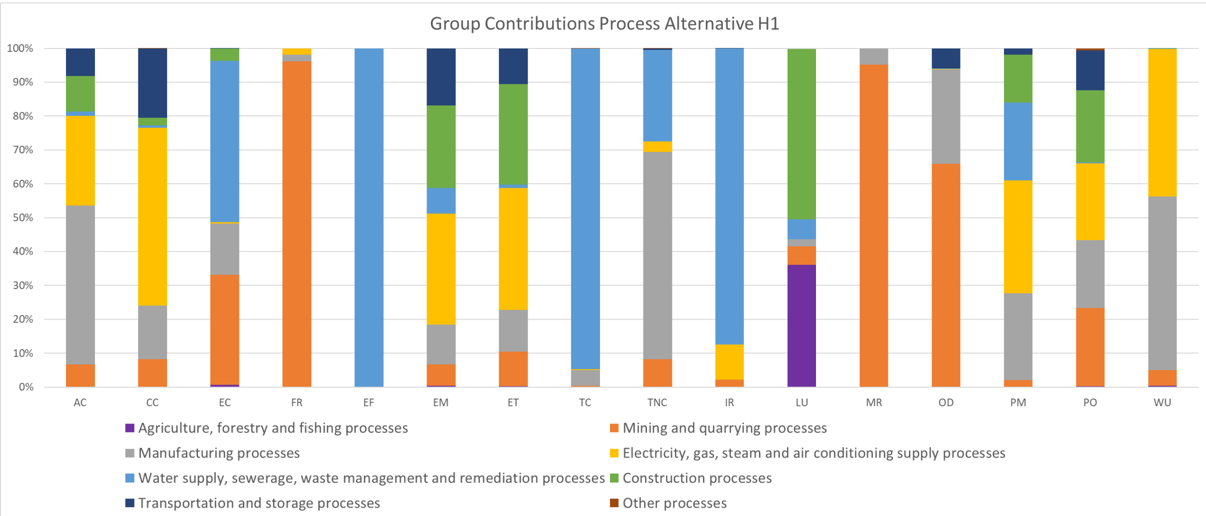

Figure 12: Group process contributions to process alternative H1 – steam production via IFT boiler, 2030, scrap iron + waste hydrogen. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

Source of hydrogen

To reiterate, the difference between E1 and F1 as well as G1 and H1 is the source of hydrogen with E1 and G1 having hydrogen sourced from an electrolyzer fed by the assumed 2030 electricity market mix and F1 and H1 using waste hydrogen. The contribution analysis into C1 (steam production through h-boiler, 2030, including network construction) showed that most impacts derive from the electricity mix used to produce hydrogen, thus when that hydrogen is used in Iron Fuel Technology™, the impacts are further transferred. As a result, this is reflected in process alternative E1 (steam production through IFT boiler, 2030, pig iron + hydrogen electrolyzer) which has for all impact categories a large majority overlap with the individual processes contributing the most to the process alternative A1 (steam production through e-boiler, 2030, including network construction). At least 80% of the upstream impacts of E1 derive from the assumed 2030 electricity market mix and the connected upstream processes for all impact categories except for climate change, marine eutrophication, terrestrial eutrophication, and human toxicity cancer. As a result, with the exception of those impact categories, the group contributions are quite similar between E1 and A1, as seen when comparing Figures 9 and 5. For the impact categories of climate change, marine eutrophication, and terrestrial eutrophication 17-18% of the upstream impacts derive from the process of primary iron production while for the impact category human toxicity cancer this sums to 45% of the total emissions. Similarly, for G1 (steam production through IF boiler, 2030, scrap iron + hydrogen electrolyzer) more than 80% of the upstream impacts derive from the assumed 2030 electricity market mix and the connected upstream processes for all impact categories except two: cancer human toxicity and particulate matter. The group contributions of G1 and A1 are hence also quite similar as seen between Figures 11 and 5.

Greater relative upstream impacts related to pig iron production in F1 in comparison to E1 can be seen in the impact category of climate change. When examining the contributions to E1 (steam production through IF boiler, 2030, pig iron + electrolyzer) for the impact category of climate change the top three individual contributing processes are heat and power cogeneration by natural gas (21%), pig iron production (9%) and electricity production by lignite (7%). In the case of F1 (steam production through IF boiler, 2030, pig iron + waste hydrogen), the largest individual contributor to climate change is the process of pig iron production accounting for 24% of the total emissions after which freight transport by lorry accounts for 11% of the total emissions. The upstream impacts from the pig iron production are thus a heavier contributor in F1 in comparison to E1. This can be explained by the absence of the impacts related to hydrogen produced by an electrolyzer and thereby the associated electricity consumption because of the use of waste hydrogen in F1. To further elaborate, in comparison to the approximately 80% of the upstream impacts deriving from the assumed 2030 electricity mix and the connected upstream processes for most impact categories for E1, most impact categories in F1 have only approximately 25-50% of the total impact deriving from the upstream processes of the assumed electricity mix. This is also reflected in visual differences in group contributions between E1 and F1 as seen in Figures 9 and 10. With less upstream impacts from the assumed 2030 scenario, the proportion of impacts stemming from upstream processes related to pig iron production are larger in F1, with most of the impact categories totaling 34-57% of the total environmental impacts. Several impact categories in F1 display extreme cases of the proportion between impacts stemming from the assumed electricity mix vs. the pig iron production. The impact category human toxicity cancer, for example, accounts 80% of its impacts from upstream processes related to pig iron production whereas the impact category of ionizing radiation only accounts 6% to this. Corresponding to this, cancerous human toxin emissions stemming from the electricity mix are a mere ~15% of the total emissions whereas this is about 90% in the ionizing radiation impact category. Hence when the relative contribution of the assumed electricity mix is high, environmental impacts are similar to those seen in process alternative A1 and the group contributions appear similar, as seen in the ionizing radiation impact category in Figures 10 and 5. However, when the relative contribution of the upstream impacts related to pig iron production are high, activities related to the manufacturing of coke and iron sinter (processes related to pig iron production) have higher impacts. High upstream impacts related to pig iron production can also be seen reflected in the photochemical oxidant formation and marine eutrophication impact categories in F1.

Other noticeable differences between the sourcing of hydrogen are that the relative group contributions of transportation processes are higher in F1 in comparison to E1, as seen in the impact categories of acidification, climate change, marine eutrophication and terrestrial eutrophication in Figures 9 and 10. Sea freight transport by bulk carrier is the largest individual contributing process in the impact categories of terrestrial eutrophication, marine eutrophication and acidification accounting for 13%, 13% and 11% of the total impacts respectively in F1. The absolute contribution of transportation processes, however, is higher in E1 in comparison to F1. This is the result of the upstream transportation processes associated with the electrolyzer. A similar trend is seen between G1 (Figure 11) and H1 (Figure 12) in the impact categories of acidification, climate change and marine eutrophication.

Another interesting point to note is that the process of road construction is the largest individual process contributor to all four process alternatives in the impact category of land use. The impact also significantly increases from E1/G1 (pig iron process alternatives) to F1/H1 (scrap iron process alternatives) from accounting 15-16% to 41-42% of the total land use changes. This is reflected in Figures 9-12 in the group contribution increase of the construction processes. Also seen in the land use impact category is that the group contribution of the agriculture, forestry and fishing processes group decreases from E1/G1 to F1/H1. On an individual process level, this is seen in the decrease of hardwood and softwood forestry logging with a relative decrease of 9-10% in hardwood forestry logging and by a 13-14% decrease in softwood forestry logging from E1/G1 to F1/H1. The absolute contribution of the road construction process is lower in F1/H1 in comparison to E1/G1, in line with the general trend that F1/H1 exerts less environmental impacts than E1/G1 as seen in Table 7 in section 5.2.

Initial Iron Fuel Production Method

Moving on to the differences between the initial iron fuel production method pig iron (E1/F1) vs. scrap iron (G1/H1), it must first be said that in most impact categories the use of iron scrap is more environmentally friendly than the use of pig iron. For multiple impact categories (freshwater ecotoxicity, human toxicity non-cancer, ionizing radiation, land use, mineral and metal resource use) this is not the case, but the differences are minimal. Only one impact category, human toxicity cancer shows a very clear difference between the two production methods in which the use of iron scrap does not perform better. To investigate the hotspots of the two different production methods, we take a closer look at this impact category, human toxicity cancer.

For G1 and H1 (the IFT scrap iron process alternatives), the treatment of electric arc furnace slag is seen to total 73% and 91% of the contributions respectively. To provide some context, electric arc furnace slag is a by-product created by the combination of lime, silicates and oxides which floats on top of the molten iron/steel during the production process (Mineral Products Association, n.d.). The liquid slag, often containing impurities, is separately discharged from the desired molten iron/steel and further processed and treated (Mineral Products Association, n.d.). The electric arc furnace is central to the production of iron/steel, allowing for the ability to produce iron and steel products with green electricity. The treatment of the slag, however, seems to be a hotspot when producing initial iron fuel from scrap iron.

The individual process contributing the most to human toxicity cancer for the pig iron alternatives (E1 and F1) is the process of coking. Coke plays an important part in the production of pig iron as it serves two functions: to provide the heat for melting the ore and as reductor for removing the oxygen from the iron ore thus creating pure iron (ArcelorMittal, 2023b). The coking process is the process of heating coal such that impurities are removed, and a substance known as coke is left over consisting of almost pure carbon (ArcelorMittal, 2023b). In process alternative E1, 51% of the total impacts are a direct result of the coking process whereas this increases to 82% in F1. Hence the relative upstream impacts related to pig iron production are greater in F1 in comparison to E1. This relates to the absence of the impacts related to hydrogen produced by an electrolyzer. The absolute contribution of the coking process, however, is lower in F1 in comparison to E1. This is in line with the general trend that F1 exerts less environmental impacts than E1 as seen in Table 5. Depending on which initial iron fuel production method is used, either the process of coking or the treatment of electric arc furnace slag will thus be a hotspot in the process alternative.

Another notable point as a result of the differing two initial iron fuel production methods is the increased water use by the manufacturing processes in H1 (steam production through IF boiler, 2030, iron scrap + waste hydrogen) in comparison to F1 (steam production through IF boiler, 2030, pig iron + waste hydrogen). This stems from the water required to produce initial iron fuel by an electric arc furnace, accounting for 15% of the total impacts of water usage. A similar difference is also seen between process alternatives E1 (steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer) and G1 (steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer).

Lastly, some impact categories are largely unaffected by a change in the initial iron fuel production method. The impact categories of human toxicity non-cancer, mineral and metal resource use and land use are examples of this. These impact categories have the same processes contributing most of the impacts with individual processes deviating +/- 1% between E1 and G1 as well as F1 and H1. As a result, the grouped contribution graphs appear very similar. This, however, does not mean that individual processes do not increase or decrease. It must be noted that the amount of iron ore mining for example does decrease when switching to the scrap based initial iron fuel production method from contributing 0.0034% of total material resource use in H1 to 0.089% in F1. However this is completely overshadowed by other mining activities, namely copper mining due to the impacts associated with the assumed 2030 scenario.

To summarize, a large portion of the impacts for all four process alternatives still stem from the assumed 2030 scenario, both the electricity mix and the expansion of the electricity network. Then depending on whether the initial iron fuel production method is based on scrap iron or on pig iron, the hotspot will either be the treatment of electric arc furnace slag or the coking process respectively. Transportation impacts pose a relatively limited impact with the exception of several impact categories, namely acidification, climate change, marine and terrestrial eutrophication, and photochemical oxidant formation.

5.4 Sensitivity Analysis

5.4.1 Chosen Parameters

The parameters tested in the sensitivity analyses are chosen based on two reasons: they were shown to be hotspots as derived from the contribution analyses results or there were economic, technical and/or application related reasons which RIFT expressed making the parameters important to study. Table 12 provides an overview of all the sensitivity parameters that will be tested. The process alternatives that will take part in the sensitivity analysis are steam production through e-boiler 2030 including network construction (A1), steam production through h-boiler 2030 including network construction (C1), steam production through IF boiler 2030, pig iron + H electrolyzer (E1), steam production through IF boiler 2030, pig iron + waste hydrogen (F1), steam production through IF boiler, 2030, scrap iron + electrolyzer (G1), steam production through IF boiler, 2030, scrap iron + waste hydrogen (H1). These six PAs are chosen as they have already been examined more closely in the contribution analysis, are likely to be more resembling of today's technological state as 2030 based PAs and because these alternatives provide the necessary breadth to answer research sub-question 4 sufficiently. The following paragraphs will explain the reason for choosing each parameter in more detail.

Table 12: Sensitivity parameters tested.

Parameter	Base-case	Sensitivity 1	Sensitivity 2	Sensitivity 3
Electricity mix of production phase of electricity, hydrogen and IFT	TNO scenarios for 2030 (and 2050)	100% offshore wind	100% open-ground solar	
Hydrogen leakage (C1 only)	0%	5%	10%	15%
Hydrogen quantity required for combustion in a h-boiler (C1 only)	~31 kg/MWh	33 kg/MWh		
Electricity consumption of IF production system (E1, F1, G1, H1 only)	~476 kW/t IF	388 kW/t IF	604 kW/t IF	
FLH boilers	8600	1000	3000	
FLH iron fuel production (E1, F1, G1, H1 only)	8760	3000	4500	
FLH electrolyzer (C1 only)	8300	3000	4500	
Transport distance	150	500	1000	5000
Transport method (E1, F1, G1, H1 only)	Truck	Ship		

<u>Electricity mix of production phase of electricity, hydrogen and IFT</u>

From the completed contribution analysis, it becomes clear that the assumed 2030/2050 scenarios (defined by the electricity mix and the expansion of the electricity network) are a key determinant for both impact categories and process alternatives. As a result, testing different possible compositions of the electricity mix is interesting for comparison to the base case and for determining whether other compositions can be more environmentally beneficial. The largest portion of the impacts for the clean alternatives derive from the use of electricity at the production stage, i.e. production of electricity/hydrogen/iron fuel.[7,8] By changing the

[7] Important to note is that the electricity mix of the initial iron fuel production is not included in this sensitivity analysis. Hence the upstream initial iron fuel production impacts (both via the iron scrap / pig iron route) remain the same.

[8] The electricity mix of the production stage would likely not influence the market incumbents, biomass and natural gas. This is because the contribution analysis showed that there is a relatively limited electricity demand throughout the value chain and most of the environmental impacts of these two fuels do not occur at the front end but rather at the combustion stage.

electricity mix at this stage, a comparison of the different electricity mix compositions across the clean process alternatives can be made to understand whether it may impact the favorability of one alternative over another from an environmental perspective. The two analyzed compositions are 100% offshore wind and 100% open-ground solar energy by photovoltaic panels. This relates to real life cases as offshore wind is expected to be one of the main drivers for producing renewable energy in the Netherlands, and specifically many projects are based on offshore wind farms in the North Sea in combination with energy initiatives including hydrogen production projects (Radowitz, 2022). As for solar energy, initiatives are underway to import large quantities from more sun blessed areas like the south of Europe and the north of Africa (Hers et al., 2018; *Import van Waterstof*, n.d.).

Hydrogen leakage

Sensitivity analyses will also be completed on the potential hydrogen that is leaked into the environment. In the base case, it is assumed that no hydrogen is leaked anywhere. However, many authors acknowledge that leakage occurs and will occur in multiple parts of a future hydrogen energy system from production to end use (Fan et al., 2022; Ocko & Hamburg, 2022; Tromp et al., 2003). What the extent of the leakage currently is and what it will become in the future is unknown with numbers varying for each part of the system as well as economy wide. As a result, a sensitivity analysis will be run with a 5, 10 and 15% hydrogen leakage. This is in line with current estimates of potential hydrogen leakages in multiple parts of a future system (Fan et al., 2022; *STUDY: Emissions of Hydrogen Could Undermine Its Climate Benefits; Warming Effects Are Two to Six Times Higher Than Previously Thought*, 2022; Tromp et al., 2003).

Quantity of hydrogen required for combustion in a h-boiler

Uncertainty is also present in the amount of hydrogen required for hydrogen combustion and subsequent steam production, as this is strongly dependent on the boiler's design (M. Derksen, personal communication, 30 March 2023). During data collection, a hydrogen boiler manufacturer provided a range for the amount of hydrogen required for combustion. Currently, the base case considers the lower end of the given range. Therefore a sensitivity analysis will be conducted to consider the impact when a larger amount of hydrogen would be required. It is expected that the environmental impact would be higher as an increase in the required hydrogen would translate into an increased electricity input.

Electricity consumption of IF production system

As the electricity mix has been shown to be a large source of environmental impacts and a determinant of the environmental performance of the process alternatives, any way to decrease the electricity consumption will be positive on a PAs performance. RIFT has indicated that the electricity consumption of the IF production system can range between 388 to 604 kWh per ton of produced IF. The base case currently takes the middle road, so to understand whether a decrease or increase can substantially change the environmental performance of the IFT PAs in comparison to the other alternatives a sensitivity analysis will be completed on this.

Number of FLH of boiler, IF production system and electrolyzer

Sensitivity analyses will also be run on the amount of full load hours (FLH) which the boilers, iron fuel production system and electrolyzer run. This sensitivity analysis is important for two reasons. The first is that renewable energy is not always available and in order to be sustainable, they may need to adapt to when renewable energy is available. Hence, base load (8600 FLH) may not be achievable for these systems. The second reason is economical, if a system operates less hours, the capital investment required often becomes a significant part of the final product's cost (Lehner & Hart, 2021). The question is whether a change in FLH also changes the environmental performance significantly. Boilers can be run base load, peak load or as back-up which loosely translates into how many FLH are run per year. As for the values chosen for the FLH sensitivity analysis of the iron fuel production and hydrogen production system, they are based on the typical and estimated FLHs of the availability of renewable energy and the FLH that other studies have used (Hanif et al., 2022; Lehner & Hart, 2021).

<u>Transport distance and method</u>
The last sensitivity analyses to be completed are related to transport. The base case is assumed based on the RIFT pilot which covers 150 km. However, when the distance increases, the environmental impact that transportation processes exert on the environment may change. As each of the three technologies makes use of a different transportation method, it is important to understand the sensitivity of what additional travelling distance does in comparison to its competitors. Specifically for the Iron Fuel Technology™ process alternatives, the transportation method of using a ship in comparison to a truck has also been tested.

5.4.2 Results of the Sensitivity Analyses

In this section the main results of the completed sensitivity analyses will be highlighted, for further elaboration on each completed sensitivity analysis refer to Appendix E.

A change in the electricity mix at the production stage from the base case to a purely solar electricity mix generally showed impacts increasing whereas a switch to a purely wind electricity mix showed impacts decreasing, see Table 13 (values are shown relative to the largest impact denoted by a '1' while colors help visually indicate this with red signifying the largest impacts, green the least and white the middle). A contribution analysis specifically into the background electricity mix in comparison to the base case indicated similar results (see Appendix E). Slight discrepancies between results of the contribution analysis and Table 13 are the result of the relative upstream impacts accounted to the electricity mix by a process alternative. To exemplify, in C1 (h-boiler, 2030, including network construction) it is seen that the five impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer and non-cancer all have upstream impacts from the distribution network accounting for at least ~30% of the total impacts in that impact category. As such the electricity mix used for the hydrogen production process can account for as little as 40.6%. A switch in the mix therefore makes less of a difference in these impact categories. In contrast, for the impact categories of climate change, fossil resources and ionizing radiation, the electricity mix to the production stage of C1 accounts for at least 85% of the upstream impacts hence being more sensitive to changes. Similar trends were seen in other PAs though generally the electricity mix is a highly sensitive parameter.

Table 13: Sensitivity analysis results of electricity mix presented relative to the largest impact per impact category.

Impact Category	**A1**			**C1**			**E1**			**F1**			**G1**			**H1**		
	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar
Acidification	0.42	0.30	0.61	0.70	0.52	1.00	0.66	0.51	0.90	0.19	0.17	0.22	0.61	0.46	0.84	0.13	0.11	0.17
Climate change	0.59	0.13	0.53	0.94	0.23	0.86	1.00	0.43	0.93	0.37	0.29	0.36	0.87	0.30	0.80	0.24	0.16	0.23
Ecotoxicity, freshwater	0.42	0.34	0.62	0.69	0.56	1.00	0.64	0.53	0.89	0.18	0.16	0.21	0.65	0.54	0.89	0.18	0.17	0.22
Resource use, fossils	0.63	0.09	0.39	1.00	0.17	0.63	0.97	0.31	0.67	0.30	0.21	0.26	0.89	0.23	0.60	0.23	0.13	0.18
Eutrophication, freshwater	0.60	0.30	0.63	0.95	0.49	1.00	0.88	0.51	0.92	0.25	0.19	0.25	0.80	0.43	0.84	0.16	0.11	0.17
Eutrophication, marine	0.47	0.21	0.63	0.76	0.35	1.00	0.80	0.48	1.00	0.30	0.25	0.33	0.69	0.37	0.89	0.19	0.14	0.22
Eutrophication, terrestrial	0.47	0.22	0.63	0.75	0.36	1.00	0.79	0.48	0.99	0.29	0.24	0.32	0.69	0.37	0.88	0.18	0.14	0.21
Human toxicity, cancer	0.20	0.19	0.27	0.32	0.30	0.43	0.48	0.47	0.57	0.27	0.27	0.28	0.92	0.90	1.00	0.70	0.70	0.71
Human toxicity, non-cancer	0.48	0.42	0.63	0.77	0.67	1.00	0.64	0.56	0.82	0.12	0.11	0.15	0.65	0.57	0.84	0.14	0.13	0.16
Ionising radiation	0.63	0.03	0.19	1.00	0.07	0.31	0.82	0.07	0.27	0.15	0.04	0.07	0.83	0.08	0.27	0.16	0.05	0.07
Land use	0.05	0.01	0.64	0.07	0.02	1.00	0.07	0.03	0.81	0.02	0.02	0.13	0.07	0.03	0.81	0.02	0.02	0.13
Resource use, minerals and metals	0.45	0.40	0.63	0.72	0.64	1.00	0.58	0.51	0.81	0.10	0.09	0.13	0.59	0.52	0.81	0.11	0.10	0.14
Ozone depletion	0.46	0.08	0.61	0.77	0.19	1.00	0.71	0.24	0.89	0.19	0.12	0.22	0.65	0.18	0.83	0.14	0.07	0.16
Particulate matter	0.29	0.20	0.55	0.47	0.33	0.87	0.68	0.56	1.00	0.36	0.35	0.41	0.60	0.48	0.92	0.28	0.27	0.33
Photochemical oxidant formation	0.39	0.19	0.57	0.63	0.32	0.91	0.77	0.52	1.00	0.35	0.32	0.39	0.60	0.35	0.83	0.18	0.14	0.21
Water use	0.00	0.00	0.01	0.99	0.98	1.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00

A1: Steam production through e-boiler, 2030, with infrastructural construction
C1: Steam production through h-boiler, 2030, with infrastructural construction
E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer
F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen
G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer
H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

Changes in the electricity mix also highlighted which process alternatives consumed the largest quantities of electricity in the production stage as these were generally more red. Process alternative C1 has the largest electricity consumption and hence performs poorest in most impact categories. As a result decreasing electricity consumption is generally beneficial. This was also seen in a reduction of electricity consumption in the IF production system. For the electrolyzer based PAs (E1 & G1) an approximately 2% decrease was found for all impact categories whereas for the waste hydrogen-based PAs (F1 & H1) a generally higher percentage (2.7-15.3%) decrease was found for the investigated impact categories. This result can be clarified due to the larger relative impacts accounted to the electricity consumption of the IF production system in F1 and H1.

Similarly, limiting the hydrogen losses and reducing the amount of hydrogen required for steam generation positively affects the environment. This relates to a reduction in the amount of hydrogen required throughout the value chain and the subsequent electricity consumption required for hydrogen production. Specifically for hydrogen losses, the sensitivity analysis results show a systematic decrease for all impact categories. This is the result of hydrogen losses only being modelled at the transportation phase leading to a compensation of losses through increased production of hydrogen. In a real-life situation, hydrogen could also leak in the final end-use process meaning that the modelled losses in this research may not be an accurate portrayal of the more complex practical reality. The water use impact category follows a different decrease rate as the other investigated impact categories because 99% of the contributions to the water use impact category stem from the steam production process via a hydrogen boiler, thus hydrogen losses modelled at the transportation phase are relatively unimportant. Noteworthy is to mention that hydrogen leakages into the environment, which are known to contribute to climate change, are not characterized in any impact category (Derwent et al., 2006; *EF Reference Package 3.1*, 2022; Ocko & Hamburg, 2022). As a result, the effect of hydrogen leakage on climate change, and potentially other impact categories as well, is not fully reflected by the sensitivity analysis results.

As for the number of FLH of a boiler, electrolyzer or the IF production system, the more FLH run annually the lower the environmental impacts. Box 3 explains this further. Whereas for boilers and iron fuel production system the number of FLH made limited impact (<1% for any impact category), changing the number of FLH of an electrolyzer showed larger differences, specifically for the impact categories of acidification and ozone depletion. This can be explained by two reasons: (i) the relative environmental impacts accounted to the construction of the hydrogen electrolyzer are higher for these two impact categories and (ii) the electrolyzer consists of a multitude of materials that are not present in boilers and in the IF production system including nickel, polytetrafluoroethylene and multiple acids among other materials. As a result, the number of FLH of the electrolyzer should be optimized to reduce environmental pressures.

Box 3: FLH explained

Full load hours refer to the number of hours that a system (e.g. machinery, boilers) runs annually. The maximum number of FLH a system can run annually is 8760 hours. FLH have an influence as it is a key determinant in the "amount" of system required for the production process for which the system is designed. The following equation describes this:

$$\text{the amount of system required for a process} = \frac{(\text{the amount of product produced by the system})}{(\text{FLH})(\text{lifetime of the system})(\text{capacity of the system})}$$

To exemplify with two problems, a boiler produces 1 MWh of heat and can run either 6000 FLH or 1000 FLH annually. It has a lifetime of 20 years and a capacity of 2 MWh of heat.

$$\text{the amount of system required for a process with 6000 FLH} = \frac{(1)}{(6000)(20)(2)} = 4.2x10^{-6}$$

$$\text{the amount of system required for a process with 1000 FLH} = \frac{(1)}{(1000)(20)(2)} = 2.5x10^{-5}$$

As becomes clear from these two examples is that less FLH will translate to an underutilization of the system. This results in the system depreciating over less hours run and the environmental impacts associated with the system will be higher for each hour the system runs.

Lastly, as far as transportation goes, the larger the distance travelled, the higher the environmental impacts become, as seen in Table 14 (values are shown relative to the largest impact denoted by a '1' while colors help visually indicate this with red signifying the largest impacts, green the least and white the middle). However, a change in distance for process alternatives A1 and C1 makes a much smaller difference whereas for the IFT process alternatives E1, F1, G1 and H1, the potential environmental impact can drastically increase when the distance changes. To understand why this is the case see Box 4. Noteworthy is that when transport distance changes, the best performing alternative can switch as C1, E1 and G1 perform better or worse in multiple impact categories depending on which cases you compare together, examine Table 14 impact category acidification for an example.

Specifically for IFT, ship transport would be recommended over truck transport from an environmental perspective whenever both options are possible as ship transport reduces environmental impacts across all impact categories, as seen in Table 15 (values are shown relative to the largest impact denoted by a '1' while colors help visually indicate this with red signifying the largest impacts, green the least and white the middle). The difference between short (150 km) and long (5000 km) distance transport by ship can also be considered negligible for all process alternatives. This is the result of the large quantities a ship can transport, the same principle as described in Box 4.

Table 14: Sensitivity analysis results of varying transport distance presented relative to largest impact.

IC	A1				C1				E1				F1				G1				H1			
	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km
AC	0.32	0.32	0.32	0.32	0.53	0.53	0.53	0.53	0.50	0.53	0.59	1.00	0.14	0.18	0.23	0.65	0.46	0.49	0.54	0.96	0.10	0.14	0.19	0.61
CC	0.18	0.18	0.18	0.18	0.29	0.29	0.29	0.29	0.30	0.36	0.43	1.00	0.11	0.16	0.24	0.81	0.27	0.32	0.39	0.96	0.07	0.12	0.20	0.77
EC	0.20	0.20	0.20	0.20	0.33	0.33	0.33	0.34	0.31	0.36	0.43	1.00	0.09	0.14	0.21	0.78	0.31	0.36	0.43	1.00	0.09	0.14	0.21	0.78
FR	0.21	0.21	0.21	0.21	0.33	0.33	0.33	0.33	0.32	0.37	0.44	1.00	0.10	0.15	0.22	0.78	0.30	0.34	0.41	0.97	0.07	0.12	0.19	0.76
EF	0.52	0.52	0.52	0.52	0.83	0.83	0.83	0.83	0.77	0.79	0.81	1.00	0.21	0.23	0.25	0.45	0.70	0.71	0.74	0.93	0.14	0.16	0.18	0.38
EM	0.21	0.21	0.21	0.21	0.33	0.33	0.33	0.34	0.35	0.40	0.47	1.00	0.13	0.18	0.25	0.78	0.31	0.35	0.42	0.95	0.08	0.13	0.20	0.73
ET	0.22	0.22	0.22	0.22	0.35	0.35	0.35	0.35	0.37	0.42	0.48	1.00	0.13	0.18	0.25	0.77	0.32	0.37	0.43	0.95	0.09	0.13	0.20	0.72
TC	0.17	0.17	0.17	0.17	0.28	0.28	0.28	0.28	0.42	0.43	0.46	0.62	0.23	0.25	0.27	0.44	0.80	0.81	0.83	1.00	0.61	0.63	0.65	0.82
TNC	0.49	0.49	0.49	0.49	0.77	0.77	0.77	0.77	0.64	0.67	0.70	0.99	0.13	0.15	0.19	0.47	0.65	0.68	0.71	1.00	0.14	0.16	0.20	0.49
IR	0.62	0.62	0.62	0.62	0.98	0.98	0.98	0.98	0.80	0.82	0.84	0.99	0.15	0.16	0.18	0.34	0.81	0.82	0.84	1.00	0.15	0.17	0.19	0.35
LU	0.12	0.12	0.12	0.12	0.19	0.19	0.19	0.19	0.19	0.25	0.33	1.00	0.06	0.12	0.20	0.88	0.19	0.25	0.33	1.00	0.06	0.12	0.20	0.87
MR	0.63	0.63	0.63	0.63	1.00	1.00	1.00	1.00	0.81	0.81	0.83	0.93	0.14	0.15	0.16	0.26	0.82	0.83	0.84	0.94	0.15	0.16	0.17	0.27
OD	0.30	0.30	0.30	0.30	0.51	0.51	0.51	0.51	0.47	0.50	0.56	1.00	0.12	0.16	0.22	0.66	0.43	0.47	0.52	0.96	0.09	0.13	0.18	0.63
PM	0.08	0.08	0.08	0.08	0.14	0.14	0.14	0.14	0.20	0.25	0.34	1.00	0.10	0.16	0.25	0.92	0.17	0.23	0.31	0.98	0.08	0.14	0.22	0.89
PO	0.14	0.14	0.14	0.14	0.22	0.22	0.22	0.22	0.27	0.33	0.40	1.00	0.13	0.18	0.25	0.86	0.21	0.27	0.34	0.94	0.06	0.12	0.19	0.80
WU	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00

Abbreviations: IC: impact category; A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen; AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

Table 15: Sensitivity analysis results of varying the transport method (IFT PAs tested only) presented relative to largest impact.

IC	**E1**			**F1**			**G1**			**H1**			**A1**	**C1**
	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	Base Case
AC	0.94	0.91	0.91	0.27	0.24	0.24	0.86	0.83	0.83	0.19	0.16	0.16	0.60	1.00
CC	1.00	0.93	0.93	0.37	0.30	0.30	0.87	0.80	0.80	0.24	0.17	0.17	0.59	0.94
EC	0.93	0.86	0.86	0.26	0.19	0.19	0.94	0.87	0.87	0.27	0.20	0.20	0.61	1.00
FR	0.97	0.91	0.91	0.30	0.24	0.24	0.89	0.83	0.83	0.23	0.16	0.16	0.63	1.00
EF	0.93	0.92	0.92	0.26	0.25	0.25	0.84	0.83	0.83	0.17	0.16	0.16	0.63	1.00
EM	1.00	0.94	0.94	0.37	0.31	0.31	0.86	0.81	0.81	0.23	0.18	0.18	0.59	0.94
ET	1.00	0.95	0.95	0.36	0.31	0.31	0.87	0.82	0.82	0.23	0.18	0.18	0.59	0.95
TC	0.53	0.52	0.52	0.29	0.29	0.29	1.00	0.99	0.99	0.77	0.76	0.76	0.22	0.35
TNC	0.83	0.82	0.82	0.16	0.15	0.15	0.85	0.83	0.83	0.18	0.16	0.16	0.63	1.00
IR	0.82	0.81	0.81	0.15	0.14	0.14	0.83	0.82	0.82	0.16	0.15	0.15	0.63	1.00
LU	0.98	0.85	0.85	0.31	0.18	0.18	0.97	0.84	0.84	0.30	0.17	0.17	0.63	1.00
MR	0.81	0.80	0.80	0.14	0.14	0.14	0.82	0.82	0.82	0.15	0.15	0.15	0.63	1.00
OD	0.91	0.88	0.88	0.24	0.21	0.21	0.84	0.81	0.81	0.18	0.14	0.14	0.60	1.00
PM	1.00	0.87	0.87	0.53	0.41	0.41	0.88	0.76	0.76	0.42	0.29	0.29	0.43	0.70
PO	1.00	0.92	0.92	0.46	0.37	0.37	0.78	0.70	0.70	0.23	0.15	0.15	0.50	0.81
WU	0.01	0.01	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.00	0.00	0.00	0.00	1.00

Abbreviations: IC: impact category; A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen; AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

Box 4: Transport Changes Explained

The required "amount" of transport infrastructure is derived by the following equation:

$$\frac{(distance\ required\ to\ travel)}{(quantity\ transportable\ by\ the\ transportation\ method)(lifetime)} \qquad (1)$$

As a result, if a specific transport method (e.g. electricity network or hydrogen pipeline) can transport large quantities the transport footprint and the associated emissions will be relatively small even over long distances. When a mode of transport has limited transport capacity, several of the same transport modes will need to be used in parallel to fulfill the quantity demanded (e.g. multiple trucks) and the subsequent environmental impact can increase.

Key Takeaways

The sensitivity analysis results have indicated that some parameters are more sensitive to determining the environmental performance of a process alternative than others. Table 16 overviews all parameters investigated and their sensitivity.

Table 16: Overview of all parameters and their sensitivity to change. A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

	Sensitivity					
Parameter	A1	C1	E1	F1	G1	H1
Electricity mix for production phase of electricity, hydrogen & IFT	High	High	High	High	High	High
Hydrogen leakage	-	High	-	-	-	-
Hydrogen quantity required for hydrogen combustion	-	High	-	-	-	-
Electricity consumption of IF production system	-	-	Limited	Medium	Limited	Medium
FLH boilers	Limited	Limited	Limited	Limited	Limited	Limited
FLH iron fuel production	-	-	Limited	Limited	Limited	Limited
FLH electrolyzer	-	Limited	Limited	-	Limited	-
Transport distance	Limited	Limited	High	High	High	High
Transport method (ship/truck)	-	-	High	High	High	High

Considering all investigated parameters, Table 17 (values are shown relative to the largest impact denoted by a '1' while colors help visually indicate this with red signifying the largest impacts, green the least and white the middle) shows the best performance each PA can achieve based on changing the parameters tested. It shows that natural gas still performs better in the impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer, human toxicity non-cancer, ionizing radiation, land use, mineral and metal resource use, and particulate matter than any of the other (clean) alternatives. From a climate change perspective, H1 (steam production through IF boiler, 2030, scrap iron and waste hydrogen) now performs best. It also performs best in the impact categories of fossil resource use, marine eutrophication, terrestrial eutrophication, ozone depletion, and photochemical oxidant formation. Considering limiting extreme environmental impacts, generally, A1 (steam production through e-boiler, 2030, including network infrastructure), F1 (steam production through IF boiler, 2030, pig iron and waste hydrogen) and H1 perform well. The PAs requiring hydrogen from an electrolyzer (C1, E1 and G1) still perform the worst. This again highlights that tradeoffs in the transition away from carbon-based fuels are likely and limiting electricity consumption of electrolysis is highly key.

Table 17: Best possible configurations for the clean alternatives[9].

IC	Best A1	Best C1	Best E1	Best F1	Best G1	Best H1	I1 base case	J1 base case
AC	0.58	1.00	0.91	0.25	0.81	0.15	0.10	1.00
CC	0.11	0.20	0.30	0.17	0.18	0.06	1.00	0.09
EC	0.60	1.00	0.85	0.18	0.86	0.20	0.03	0.17
FR	0.09	0.17	0.22	0.12	0.14	0.04	1.00	0.09
EF	0.61	1.00	0.99	0.33	0.82	0.16	0.03	0.15
EM	0.11	0.18	0.21	0.09	0.16	0.04	0.09	1.00
ET	0.11	0.18	0.21	0.09	0.16	0.04	0.09	1.00
TC	0.21	0.34	0.51	0.28	1.00	0.77	0.03	0.14
TNC	0.63	1.00	0.80	0.13	0.81	0.15	0.02	0.21
IR	0.36	0.86	0.57	0.15	0.64	0.22	0.09	1.00
LU	0.03	0.05	0.05	0.01	0.04	0.01	0.00	1.00
MR	0.63	1.00	0.78	0.11	0.79	0.13	0.01	0.02
OD	0.09	0.20	0.21	0.08	0.15	0.03	1.00	0.04
PM	0.21	0.35	0.49	0.26	0.41	0.18	0.04	1.00
PO	0.15	0.25	0.35	0.19	0.21	0.05	0.18	1.00
WU	0.00	1.00	0.00	0.00	0.00	0.00	0.54	0.00

Abbreviations: IC: impact category; A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen; AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

[9] A1 considers a wind-based electricity mix, highest FLH of boiler, and 150km transport distance. C1 considers a wind-based electricity mix, highest FLH of boiler and electrolyzer, higher combustion efficiency, no hydrogen losses, and 150km transport distance. E1/G1 considers a wind-based electricity mix, highest FLH of boiler, IF production system and electrolyzer, lowest electricity consumption of IF production system, and 150km ship transport distance. F1/H1 considers a wind-based electricity mix, highest FLH of boiler and IF production system, lowest electricity consumption of IF production system, and 150km ship transport distance.

6. Redesign Recommendations to Reduce Environmental Impacts

The environmental impacts of each process alternative have been studied extensively in this research and the analysis showed that several processes can be considered hotspots. The advantage of ex-ante LCA and its explorative nature of estimating future environmental impacts before technologies are mature allows for recommendations to redesign the system to reduce potential environmental impacts. As such, this chapter focuses on recommendations to reduce the environmental impacts of all three clean product systems and guide technology developers into areas for research and development based on the ex-ante LCA results. The first sections will provide redesign recommendations for electrification, hydrogen and Iron Fuel Technology™ in general (sections 6.1, 6.2 and 6.3 respectively). Subsequently, advice to RIFT will be given on what they can do to reduce the environmental impact of Iron Fuel Technology™ moving forward (section 6.4).

6.1 Recommendations to Improve the Electricity Product System

The electricity product system showed two hotspots: the electricity mix and the expansion of the electricity network, both related to the assumed 2030/2050 scenarios. In line with achieving climate and energy targets, the electricity mix is expected to change toward an increased share of renewables of mostly wind and solar energy and a significant expansion of the electricity network will need to be realized. The resulting environmental impacts of these two actions are therefore an inherent side effect to the energy transition.

The first recommendation would be to choose the electricity mix wisely. The electricity system is the backbone of today's energy system and it will likely only gain a more important role in the future. If anything, this study has highlighted how the environmental impacts from the electricity system transfer to every other product system that is reliant on electricity, emphasizing that the energy sources making up the electricity mix are key. While completing the contribution analysis into electricity scenarios (Appendix E), wind produced electricity showed to be an energy source with relatively limited environmental impacts across the board whereas a large share of solar produced electricity will likely have certain environmental impacts increasing. Referring back to Table 13, solar produced electricity showed an increase of impacts in the categories of marine and terrestrial eutrophication, land use, ozone depletion, particulate matter, photochemical oxidant formation and water use in comparison to the base case electricity scenario (consisting of a variety of energy sources) that is also more fossil fuel based. Comparing these results with other studies, similar conclusions can be drawn from literature. Multiple studies indeed show that wind has limited impacts in comparison with other electricity sources and similarly solar electricity does in cases also show increased impacts in impact categories like land use and mineral and metal resource use comparison to a grid energy mix or fossil fuels (Alam & Xu, 2023; Arvesen & Hertwich, 2012; Hertwich et al., 2015; Marashli et al., 2022; United Nations Economic Commission for Europe, 2021a; Varun et al., 2009). That said, the data of the processes of both the wind and solar produced electricity from ecoinvent are quite dated. To exemplify, the solar produced electricity process data was last updated in 2015 and since then photovoltaic technologies have advanced further with efficiencies now reaching well over 22% (International Renewable Energy Agency, n.d.; Svarc, 2023). Furthermore, the recycling of photovoltaic (PV) panels is currently not considered to the extent it could be as multiple materials are not yet recycled in ecoinvent such as silicone, nickel, copper and other impact intensive materials. Considering all this, the environmental impact of the renewable electricity sources, in particular from solar energy, may actually be lower than what is presented in this study. Nevertheless, the likelihood that a switch from a largely carbon-based fuel energy system to a renewable energy system will provide tradeoffs in other impact categories is very plausible.

Now to decrease these side effects in the transition to more renewable electricity sources, the best course of action is to decrease the environmental impacts of the hotspots of each renewable energy source whenever possible. Though a specific study on the impact of each electricity source has not been completed as it falls outsides the scope of this study, one general recommendation can be made: investigate ways to reduce the production process emissions of the materials required for PV installations and wind turbines. The impact of wind and solar produced electricity does not originate from the electricity production process itself in contrast to carbon-based fuels but rather from the upstream production processes required to construct the PV installation and the wind turbine. As a result, the environmental impacts associated with solar and wind produced electricity are indirect impacts stemming from the associated (production and mining) processes of the materials and chemicals used like silicon, trichloromethane and terephthalic acid, as well as aluminum, concrete, steel and copper. To help reduce impacts associated with renewable electricity production, the environmental impacts related to manufacturing and mining activities must thus be addressed. This recommendation also holds for impacts related to non-renewable sources of electricity production like biomass.

The last recommendation regarding the electricity mix is to be aware of the electricity source of imported electricity. In this research, it has been shown that trace amounts of fossil fuel based imported electricity production (e.g. lignite) was responsible for a relatively large total contribution to several impact categories. Hence, regardless of whether electricity is produced domestically or elsewhere, the energy source is key in determining the environmental impact score and thus the origin of imported electricity should also be considered.

Moving on to the expansion of the electricity network, one key hotspot was identified: copper. Copper is an essential material in the electricity network meaning that environmental impacts related to copper will be inherent to the energy transition. The contribution results identified specifically three processes related to copper: copper mine operation and beneficiation, smelting of copper concentrate and the treatment of sulfidic tailings from copper mines. All processes occur at the front end of the copper production process so this is where developments to decrease emissions should be focused. In recent years, developments have been made and the players within the copper industry are committing to achieving more sustainable practices (Davey, 2022). Numerous companies around the world are also becoming more transparent in reporting their environmental, social and economic performances (Northey et al., 2013). Some of the developments and recommendations to improve the environmental performance in the copper processes include increased automation, increased recycling, and sourcing electricity from renewable energy sources (Codelco, n.d.; Durrant et al., 2022; Moreau et al., 2021; Tankard & Chuah, 2020). To achieve environmental targets, companies, governments and other collectives will still need to take further steps to improve environmental performance throughout the copper supply chain. It is expected that the demand for copper will only increase further because of its key role in the energy transition and related societal developments like electric mobility, thus decreasing environmental impacts along the copper supply chain is crucial (E. Valente & Yameogo, 2021).

6.2 Recommendations to Improve the Hydrogen Product System

One of the main results of this research is that the total environmental impacts of the hydrogen system are for the majority directly linked to the impacts from the electricity system. This stems from the large use of electricity required for producing hydrogen. This result is in line with conclusions of reviewed literature (Dufour et al., 2012; Hydrogen Council, 2021). The recommendation that follows from this is to decrease the energy consumption as much as possible at this stage. Current alkaline electrolyzers typically operate around 50 kWh / kg H_2 or higher which is what this study also considers (Collins, 2022). However, the evolution of electrolyzer efficiency can potentially be increased with some companies claiming to be able to reach much higher efficiencies reducing the energy consumption to 41.5 kWh / kg H_2 (Collins, 2022). The use of different types of electrolyzers such as solid oxide electrolyzers can also reduce primary electricity need to around 40 kWh / kg H_2 (Jaeger & deBiasi, 2022; Pavan et al., 2023). Improvement is thus plausible, but these technologies are currently still in development and will also need to be evaluated on their environmental performance (Pavan et al., 2023).

With hydrogen boilers still being in the technological development phase, the quantity of hydrogen required for combustion and thus the generation of heat at a specific temperature and pressure can still vary. A higher required quantity of hydrogen translates to more electricity input at the front end thereby increasing the environmental impacts. It is therefore strongly recommended that boiler manufacturers engineer towards affordable energy-efficient boilers.

Losses are typically undesirable and in the case of hydrogen losses can also significantly increase environmental impacts. Though leakage of hydrogen is only modelled within the transportation stage in this study, leakage can occur at any stage of the supply chain. Limiting leakage losses is therefore strongly recommended to decrease the amount of hydrogen not utilized and to not (in)directly stimulate any environmental impacts such as the increase of greenhouse gases. Though a certain degree of (leakage) losses generally occurs within every energy system, losses can be reduced by safe handling and good practices.

What is potentially easier to ensure is to optimize the number of full load hours run by the electrolyzer. As seen during the sensitivity analysis, a reduction in the FLH would increase the construction impacts accounted to the electrolyzer. To make the most effective use of resources, it is thus advised to operate the electrolyzer at the maximum number of full load hours whenever possible and design for a long lifetime. What is important to consider is that the electrolyzer should ideally run on renewable energy sources as this reduces the environmental impacts in multiple impact categories in comparison to a more predominant carbon-based electricity mix.

6.3 Recommendations to Improve the Iron Fuel Technology™ Product System

In Table 18, an overview of key parameters of the IFT system are displayed. This subsection will provide recommendations for improving the environmental performance of the IFT system across multiple impact categories following the listed parameters in Table 18.

Table 18: overview of key parameters in the IFT product system.

Parameter	Sensitivity to change	Examined in this study
Hydrogen source	High	Yes
Initial iron fuel source	High	Yes
Circularity	Potentially high	No
Price of unusable iron fuel / iron oxide	Potentially high	No
Electricity mix at production stage	High	Yes
Electricity consumption at production stage	Limited	Yes
Transport distance	Medium	Yes
Transport method	Medium	Yes
FLH of boiler	Limited	Yes
FLH of production system	Limited	Yes

This study investigated four different IFT system process alternatives that differed in the source of hydrogen (utilizing waste hydrogen or electrolysis produced hydrogen) and the initial iron fuel production method (utilizing pig iron based on a blast furnace production route or scrap iron based on an electric arc furnace production route). Regarding the source of hydrogen, this study recommends using waste hydrogen instead of hydrogen produced through electrolysis. In this research, the utilization of waste hydrogen did not carry any upstream impacts. Hence, the upstream impacts associated with the production of hydrogen through electrolysis and the associated electricity mix are eliminated when choosing to utilize waste hydrogen. Theoretically, the impacts of waste hydrogen may not be entirely impact free, though they are likely lower than producing hydrogen from green electricity through electrolysis.

Regarding the initial iron fuel production method the recommendation is slightly more complex. This study has indicated that the use of secondary iron (scrap iron) in comparison to primary iron (pig iron) sees environmental benefits in the impact categories of acidification, climate change, fossil resource use, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, land use, ozone depletion, particulate matter and photochemical oxidant formation. However, it more detrimental to the environment in the impact categories of freshwater ecotoxicity, human toxicity cancer and non-cancer, ionizing radiation, material resource use and water use. To reduce climate change impacts with the least number of adverse environmental impacts, it is advised to make use of secondary iron and to reduce the side impacts in the other impact categories as much as possible. Among the impact categories in which secondary iron performs more poorly than primary iron, the human toxicity cancer impact category stands out as it shows the most significant difference. The treatment of electric arc furnace slag is responsible for more than 90% of the total impacts to human toxicity cancer thus reducing emissions here, specifically the emission of hexavalent chromium (chromium VI) to water, would be most efficient. The leaching of hexavalent chromium is a known ecological issue and has been researched over the years with potential solutions following, e.g. to control the cooling regime of the slag (Engström et al., 2010; Li & Xue, 2019; Sakai et al., 2013; Tossavainen et al., 2007). The production of hexavalent chromium also decreases the potential for utilizing the produced slag which could be used in sustainable road applications, the construction industry, or for wastewater treatments among other applications (Li & Xue, 2019; Sukmak et al., 2023; Teo et al., 2020). Innovative ways to increase the recyclability of the electric arc furnace slag and prevent leaching of hexavalent chromium would also contribute to decreasing freshwater ecotoxicity impacts. Another recommendation to decrease side effects of secondary iron in multiple impact categories is to focus on reducing the impacts related to copper, see section 6.1. A completely different recommendation is to source initial iron fuel as a waste product from an existing production process – titanium oxide production. This potential source of initial iron fuel was not investigated within this study but can potentially be interesting. As a waste product, it can potentially eliminate any impacts related to the upstream emissions of the initial iron fuel production thereby decreasing environmental impacts of IFT substantially.

As the initial iron fuel production method accounts for a part of the upstream emissions in every impact category, one way to limit environmental impacts is by better utilizing the initial iron fuel. The Iron Fuel Technology™ is a circular process meaning that the initially produced iron fuel is used multiple times cyclically before being discarded due to its unsuitability for technical reasons. If the number of cycles the initial iron fuel can make before needing to be discarded can increase, the quantity of initial iron fuel required throughout the product system will decrease. As a result, the environmental impacts associated with the upstream emissions of the initial iron fuel production method will decrease due to the lower quantity required per MWh of steam generated. Though this parameter has not been investigated in this study, it is expected that a significant increase from the 25 cycles currently assumed can make a large difference environmentally. This is especially the case for impact categories where the initial iron fuel production method accounts for a relatively high upstream contribution. Hence, it is recommended that the usability of the iron fuel is technologically optimized to last more cycles.

In the modelled IFT foreground product system there are two multifunctional processes, namely the steam generation process by IF boiler (the IF combustion process) and the IF production process. Multifunctional processes require allocation, as explained in section 3.2.4, and economic allocation was chosen in this study. The economic value of each produced product in the multifunctional processes reflects the current (2023) monetary value of what that product is paid for on the market. As this monetary value is likely to fluctuate in the future, it is recommended to track this well. To exemplify why, should the monetary value of a MWh of steam produced increase (e.g. the price of energy increases) relatively to the price of iron fuel / oxide sold to other markets then the environmental impacts accounted to the MWh of steam produced will increase. As a result, the total environmental impacts of a MWh of steam produced will increase across all impact categories. Inherent to multifunctional processes that are allocated by economic value are that the environmental impacts can shift depending on the percentage impact that each product is allocated.

Earlier the recommendation as to the source of hydrogen was discussed. The IFT product system is closely linked with both the hydrogen and electricity product system in general. The use of hydrogen and electricity required as inputs to the production process of iron fuel transfer the impacts related to the production processes of hydrogen and electricity to the IFT product system. As a result, the electricity mix used during the production stage and the source of the hydrogen are key in determining environmental performance. The results of this study therefore suggest choosing a wind-based electricity supply for the production stage as it is the most beneficial for all IFT PAs environmental performance. As the facilities of all three clean alternatives are assumed at the same location in this study, a switch in the electricity supply benefits all production processes and the subsequent environmental impacts significantly. In case hydrogen is not sourced from a waste stream but rather from an electrolysis production process, a wind-based electricity mix will greatly benefit the environmental impact of the hydrogen utilized within the IFT system. Inherent to this is the recommendation to limit electricity consumption to a minimum. The sensitivity analysis conducted in this study showed some improvements when electricity consumption of the IF production system was decreased, but it is without doubt that any increase in electricity consumption will exert more undesirable pressures on the environment.

Regarding transport, it is first recommended to use ship transport over truck transport whenever both methods are an option. Second, long transport distance should ideally be completed by a ship as long-distance road transport can have significant impacts on the environment. For very long distances, the impacts will increase so significantly that from an environmental perspective, other fuels can become more interesting.

Lastly, the results of this study would recommend in favor of running the maximum number of full load hours for both the production system and boiler. Though the construction impacts of the boiler and production system are seen to be negligible in this study, in line with utilizing the most out of every resource spent it is advised to optimize the operational hours run.

Considering all the recommendations made, some of them will be easier to implement then others and they will also be subject to technical, economic and physical constraints. To exemplify, the used hydrogen source will be dependent on market availability, quantities required and economic viability among other parameters. If there is an insufficient amount of waste hydrogen in a specific location / market then even though it would be environmentally more beneficial to use waste hydrogen, this will not be an option. Similarly, it may turn out that under specific circumstances hydrogen produced by electrolysis can be cheaper to use than waste hydrogen. A dilemma of whether economic or environmental performance is more important will then arise. As environmental performance is not the only determinant in successful implementation of an alternative, section 7.3 will elaborate further on the possibility to upscale all three clean alternatives and discuss any foreseen challenges that may arise as a result.

6.4 Recommendations to RIFT

RIFT, as the technology developer of the iron fuel production and boiler systems can best exert control on the processes and products which they develop themselves. In this research these are the foreground processes of the iron fuel production and steam generation via IF boiler process as defined in the IFT process alternatives. There are 6 key recommendations which RIFT's team can steer towards either technically or from a business perspective to reduce environmental impacts of their technology in so far as possible:

1. Focus on increasing the cyclicity of the iron fuel.

2. Decrease the electricity consumption of both the boiler and production system to the furthest extent possible.
3. Decrease the amount of resources (e.g. steel) used in both the boiler and production system to the furthest extent possible.
4. Source electricity produced through wind power for operating production and boiler systems.
5. Implement IFT in markets with a large potential for using waste hydrogen.
6. Implement IF production and boiler systems at locations having access to waterways.

Impacts from upstream processes such as the impacts related to the initial iron fuel production as well as the treatment processes of electric arc furnace slag have been shown to also contribute significantly to the environmental performance of Iron Fuel Technology™. The recommendation is thereby to source initial iron fuel produced from scrap iron and choose to partner with supply chain market players that aim to produce their products with the lowest environmental impacts. By choosing who RIFT will and will not partner with and demanding their partners conform to the best environmental standards among the market's competitors, RIFT can exert power in making upstream and downstream processes more sustainable. This must not be underestimated because in contrast to the market incumbents biomass and natural gas, environmental impacts of IFT are largely associated with background processes and not directly with the combustion of the fuel.

7. Discussion

This chapter will reflect on this research. Section 7.1 first reflects on the achievements of this research and its relevance. Section 7.2 then addresses the limitations of this research integrating the consistency and completeness check as part of the interpretation phase of the LCA framework defined by ISO. Up until now, this research has also largely concerned itself with only the environmental performance of the investigated alternatives thus section 7.3 will look broader by examining non-environmental barriers and limitations to the upscaling of the clean alternatives.

7.1 Reflection & Relevance

This research has made the first comparison of electrification, hydrogen and Iron Fuel Technology™ considering its implementation in the energy-intensive industries in comparison to natural gas and biomass as well as comparing them among each other. It thereby investigated potential impacts in a possible 2030 and 2050 Dutch future identifying hotspots and key parameters that are highly influential in determining environmental performance. The outcomes of this research can be used to guide R&D, monitor potential problem areas and be used as the basis for evaluation and further research. As such, this research is highly relevant scientifically, societally and to the field of Industrial Ecology.

From a scientific point of view, it stands out as it investigates a broad range of impact categories when most reviewed studies only focused on a set of impact categories. It is also the first study of its kind to perform an ex-ante LCA of the implementation of electrification, hydrogen, Iron Fuel Technology™, biomass and natural gas transparently and extensively for steam generation specific for an energy-intensive industry application. Consequently, the results point to further important areas of exploration for both the technologies and for further research.

Societally, this research suggests that the investigated three clean alternatives all have lower climate change impacts than natural gas and can subsequently help in achieving Dutch climate targets. It however also points out that other environmental impacts may become more prominent potentially leading to different environmental challenges in the future. The results of this research may therefore add to the knowledge surrounding the three clean alternatives and serve as input for a broader conversation for multiple actors in improving the environmental performance of the investigated technologies.

This research was conducted as part of the Master Industrial Ecology (IE). "Industrial ecology is committed to preserving embedded energy and materials as much as possible and accounting for them across their lifecycles" (Clini et al., 2008). This research focused on this by taking a systematic and lifecycle perspective on the industrial metabolism of the investigated technological product systems through conducting life cycle assessment. It used technical data as the basis to understand the broader environmental performance to address a societal problem and the potential solutions thereby integrating technical, environmental and the social perspective on sustainability. Whereas most reviewed studies focused on ex-post LCAs, this research took a novel approach in seeking to determine potential environmental impacts through ex-ante LCA. It thereby also demonstrates that the use of ex-ante LCA can be successfully applied to identify potential environmental impacts before large-scale implementation of energy technologies has taken place.

Reflecting on the entire process, more time spent on the data collection and modelling phase could have been beneficial. Data is an integral part of LCA and as it dictates the results better verification of data would have been useful to indicate the level of uncertainty of the produced results. Currently, there is also a limited view on how uncertain the results are from a technological point of view. If direct integration of the technological foundation (physical reactions, formulas etc.) which produced the input data for this research and any LCA software was possible by for example linking Microsoft Excel with LCA software, this research could (i) better indicate the sensitivity of technological parameters and the subsequent uncertainties that follow and (ii) allow for the ability to more easily run different applications and cases which were now inherent to the inputted data. To the researcher's best knowledge, this direct integration of multiple software is currently not possible, but further integration of formulas and data parametrization could have been applied to the existing model.

7.2 Limitations

This section addresses limitations of the research conducted. Limitations can stem from choices made by the researcher and those inherent to the use of specific methods, in this case the use of ex-ante LCA. Both types will be addressed here. The first subsection focuses on the limitations of ex-ante LCA and the use thereof (subsection 6.3.1), followed by the limitations of the used data (subsection 6.3.2), system boundaries (subsection 6.3.3), and modelling choices (subsection 6.3.4) by the researcher.

7.2.1 Limitations of ex-ante LCA

First, it is important to stress the nature of the limitations inherent to ex-ante LCA. The results of this study should not be considered as a final result but rather be used as a guidance for debate, evaluation and R&D development. This study has provided valuable insight into the ability of process alternatives to potentially outperform any of the other examined process alternatives from an environmental perspective, has shed light on where foreseen environmental hotspots are and has made recommendations into research and development activities. However, the largest uncertainty in this study is the development of each product system in time. Hence, the results as presented in this study are still subject to considerable changes.

Furthermore, one of the greatest challenges of ex-ante LCA is that there is the consistent modelling of both foreground and background future systems often leading to a mismatch in temporal scope (van der Giesen et al., 2020). The use of scenarios can help alleviate this, and it has helped this research in the foreground processes. However, as no LCI data extending all background sectors was available, for temporal consistency background processes were not adapted to the 2030 / 2050 scope. Through the consistent use of shared ecoinvent background processes, consistent life cycle stage modelling of foreground processes and the completion of sensitivity analyses on most hotspot processes the impact of this inconsistency was reduced. In addition to the temporal scope, a similar annotation can be made on the geographical scope with background processes having a more regional or global reach whereas foreground processes were specifically tailored to the Dutch scope.

It should also be highlighted that the models of the underlying impact assessment (including characterization factors) have some limitations. Some characterization factors have left environmental flows unclassified due to a lack of data and models (van der Giesen et al., 2020). This is the case with the modelled emissions of hydrogen for example. Within the PEF impact assessment hydrogen emissions have not been classified to contribute to any impact category. However, hydrogen has been known to contribute indirectly to for example climate change for over 20 years and the GWP for hydrogen has been defined to be 5.8 over a 100-year time horizon (Derwent et al., 2006; Kurmayer, 2021; Raga Mexico et al., 2007). An Intergovernmental Panel on Climate Change (IPCC) document shed light on the reasons why indirect radiative effects are not considered. The reasons being that the uncertainties surrounding "the indirect GWPs are generally much higher than for the direct GWPs" and that the GWP of the emission is often location and time bound (Raga Mexico et al., 2007). As a result, the IPCC concludes that "the usefulness of the global mean GWPs to inform policy decisions can be limited" (Raga Mexico et al., 2007). The document does also state "the issue may need to be reconsidered as inventory guidelines are revised" (Raga Mexico et al., 2007). Though inventory guidelines do not appear to have been revised given the absence of a characterization factor in the most updated PEF impact assessment, the inclusion of hydrogen as a characterized environmental intervention seems important. With the general notion that hydrogen will play a key role in provisioning energy in the future resulting in an extensive hydrogen system, large hydrogen leakages throughout the value chain can be detrimental for the environment (Ministerie van Economische Zaken en Klimaat, 2019d). "When these atmospheric effects are taken into account, the climate benefits of replacing fossil fuels with hydrogen becomes less clear" … "even when hydrogen is produced from renewable electricity" an expert cautions (Kurmayer, 2021). The example of hydrogen emissions into the environment is just one example. Unfortunately, OpenLCA does not produce a list of all environmental interventions that are not characterized, unlike other LCA software programs. Hence it is not known how many unquantified environmental flows there are in this research. It is therefore likely that the environmental impacts of each of the process alternatives as seen in this study may not be a complete portrayal of all future environmental impacts.

7.2.2 Limitations of the Data Collected

As the largest uncertainty in this study is the development of each product system in time, the help of technology developers and other domain experts has been critical during multiple phases throughout the completion of this study. Foreground processes were largely modelled by the researcher and based on primary and secondary data whereas background processes were based on the LCA database ecoinvent. Data gathered for the electricity, hydrogen and IFT process alternatives was largely gathered from primary sources whereas the biomass and natural gas process alternatives were largely based on existing ecoinvent data. Though this does not necessarily signify any cause for large inconsistencies, data can potentially be of a different accuracy and reliability. A similar issue concerns the level of detail and extensiveness of the data. To exemplify, some sources provided a better level of detail in the bill of materials whereas other used data made use of expected ranges. Certain materials, processes and their associated impacts may therefore come more profound to the foreground or fall into the shadows, thereby obscuring a more accurate assessment.

Both points are not considered to be a large inconsistency with regards to this study for two reasons. First, data of the ecoinvent processes can also originate from primary sourced data like data received from manufacturers or conducted interviews (ecoinvent, n.d.). Second, this study aimed to examine potential future technologies in an assumed landscape meaning that data is inherently uncertain as it is ex-ante in nature. To mitigate any large inconsistencies should data be inaccurate or unreliable, the sensitivity analyses completed on processes with known large contributions and/or uncertainty also helped understand the bandwidth of a process alternative's sensitivity and help draw more informed and credible conclusions.

The larger question concerning this is whether the comparison between existing mature technologies and emerging technologies is even fair. Though the comparison is made at the same TRL, in this research at commercial scale, the underlying data of the mature technology is proven to be possible whereas the data of the emerging technologies is assumed based on expected results. The availability and quality of the used data is therefore also drastically different. The availability and quality is almost guaranteed in the case of mature technologies while assumptions are the basis for data of the emerging technologies. The notion that this assessment is not a final result and that decisions cannot be made based on the results of this research is therefore vital also in relation to the data. Refer back to section 7.2.1 and section 2.2 for a clear understanding of ex-ante LCA and its limitations.

The last limitation concerning data results from using ecoinvent version 3.9.1 as database. Several ecoinvent processes are based on outdated data, some data even going back to before the turn of the century. Hence, all used background processes represent processes before 2023 and none represent the desired 2030 / 2050 temporal scope. To exemplify, the natural gas mix of the Netherlands in ecoinvent still has a part of its natural gas sourced from Russia. However, the sourcing of Russian gas has decreased in the last years and is thus not representative anymore of the state-of-the-art and likely not of the future. Similarly, some of the identified hotspots, for example those related to the copper production process, make use of data that has not been updated since 2009 (Classen et al., 2009). Since then, improvements to the copper production process may have reduced environmental impacts but this will not be reflected in the identified hotspots of this research. Through consistent use of shared background processes the inconsistency between process alternatives was limited and the used background data is therefore consistent. Hence, no hotspots will be identified in one process alternative that are out of proportion with another process alternative. However, caution must still be exercised as some of the identified hotspots may have shifted or may no longer be the main contributor to an examined process alternative.

7.2.3 Limitations of the System Boundaries Used

In life cycle assessment, the aim is to include all life cycle stages of any product system. In this research, the decision was made to leave out the end-of-life stage of the capital goods in foreground processes. This choice was made for two reasons. First, construction and waste disposal of capital goods has been omitted in a portion of the reviewed life cycle assessments. Second, recycling and waste treatment of capital goods is currently inconsistently included within ecoinvent with some processes including all parts and other processes not including all parts. To model in the most consistent way, the end-of-life stage of any capital goods was not modelled. To exemplify the second point, a biomass heat production process included within the ecoinvent database includes the end-of-life stage including the steel used for constructing the boiler/furnace. A similar process, namely a gas heat production process included within the ecoinvent database, includes some waste streams but not for any of the steel used. This is notable as steel is one of the largest materials that make up a boiler. As all boilers, except for the biomass boiler, are modelled by the researcher with mostly primary data, the biomass boiler was the only boiler in this research that has an end-of-life stage included. A quick examination into the contribution of the waste disposal process from the ecoinvent biomass heat production process showed that the treatment of scrap steel was responsible for less than 0.04% of the total impacts to any impact category. Hence, this small inconsistency across the alternatives can be considered negligible. It also does not interfere in any way with the goal and scope of this study. The same principle applies to the production system and transportation infrastructure.

Another notable point regarding system boundaries is that this research cut-off all the on-site impacts related to the construction of any primary modelled infrastructure, i.e. IF production system, electrolyzer and all boilers except the biomass boilers. As a result, all machinery, heat, electricity, and materials required during the construction of capital goods have not been considered. Adding process data to include the impacts related to the construction of foreground modelled infrastructure as well as the end-of-life stage of the foreground processes would make this research more complete. Frischknecht et al. (2007) have previously also completed an analysis confirming that capital goods can substantially contribute to environmental impacts for certain impact categories including freshwater ecotoxicity or human toxicity thereby reinforcing the statement that the inclusion of all life cycle stages of the capital good is beneficial for the completeness of the study.

7.2.4 Limitations of the Modelling Choices Made

There is one noteworthy point in which the model used in the completed ex-ante LCA does not mirror the real-life situation. This concerns the modelling of hydrogen leakage in the hydrogen product system. Hydrogen leakage, which can and does occur at multiple stages along the supply chain, has only been modelled in this research during the transportation stage. This overestimates the losses of hydrogen at the front end while underestimating the losses after the transportation stage. As this study is explorative in nature it does not undermine the credibility of the study, but it is important to note it does not reflect the practical situation.

7.3 Upscaling of Clean Alternatives

This research has largely focused on the environmental aspect of the investigated alternatives until now. However, when an emergent technology wants to breakthrough more than only the environmental performance is a barrier and technical, economic, physical, legislative and social constraints come into play. In this section, the aim is to consider what other known challenges can hinder the potential breakthrough of the clean alternatives in the next coming years. Subsection 7.3.1 will start with biomass as an example of the barriers it encountered while upscaling throughout the Netherlands. The following subsection (subsection 7.3.2) will then focus on the challenges in expanding the use of electricity. Subsections 7.3.3 and 7.3.4 will subsequently focus on upscaling hydrogen and Iron Fuel Technology™ respectively. The chapter will then end with a reflection on whether there is a silver bullet (subsection 7.3.5).

7.3.1 Learnings from Biomass

The Dutch government views biomass as key to making the economy more sustainable and combatting climate change (Ministerie van Economische Zaken en Klimaat, 2019a). Back in 2003, the Dutch government started subsidizing the use of wood pellets for energy production (van der Wal, 2021). The use of biomass, specifically wood pellets, has been a largely debated topic in the Netherlands (Milieu Centraal, n.d.-a). Biomass, when sourced from sustainable sources and releasing no new CO_2 emissions into the atmosphere, can be a renewable source of energy (Goldemberg & Teixeira Coelho, 2004; Mckendry, 2002). It can potentially have key benefits such as providing CO_2 neutral energy but cutting wood can negatively impact biodiversity of forests in which the trees grow, contaminate soil quality, and increase the particulate matter and nitrogen emissions released during combustion (Hakkenes, 2020; Milieu Centraal, n.d.-a). Moreover, large quantities of biomass imported to the Netherlands result in additional CO_2 emissions from transport (Hakkenes, 2020; van Poppel & Bol, 2020). Reports also concluded that links between forest losses and the use of wood pellets for energy production in the Netherlands were found (Kuepper, 2021; van der Wal, 2021). In 2020, after widespread attention in the media and public outcries, the Dutch government therefore decided to limit the use of biomass for energy production and stop providing subsidies to the use of wood pellets for energy production (van der Wal, 2021).

The example of biomass provides a few key learnings. One of the problems that a widespread upscaling of biomass proved is that it was not as sustainable as it was made out to be. The combustion of wood results in more GHG emissions than the combustion of coal and a new tree is not immediately replaced by one that is cut (Gibbens, 2021; Hakkenes, 2020; Tonini & Astrup, 2012; van der Wal, 2021). Furthermore, the supply of sustainably harvested biomass is limited (Tonini & Astrup, 2012). Planbureau voor de Leefomgeving (PBL) expects that the availability of sustainable biomass will become problematic after 2030 though reports suggest it is already problematic (Kuepper, 2021; Ministerie van Economische Zaken en Klimaat, 2019a; van der Wal, 2021). Sustainability assessments can help recognize these types of problems and assessments before implementation (ex-ante) takes place and aid in early recognition of problems, highlighting why this research can also be of use.

The stimulation of the increased use of biomass also resulted in intensifying deforestation practices and decreasing biodiversity (Swart et al., 2020). The legislation and stimulating subsidies provided by the Dutch government, including Stimuleringsregeling Duurzame Energieproductie (SDE+) subsidy, embraced the use of biomass (Ministerie van Algemene Zaken, n.d.-d). The SDE+ subsidy scheme has strict criteria in which companies must demonstrate that the biomass comes from sustainable origins. The question is rather whether the rules are (and were) complied with (Milieu Centraal, n.d.-a). Reports suggest not and the implementation of stimulating subsidies likely worsened the situation (Kuepper, 2021; van der Wal, 2021). It highlights that legislation is an important and highly influential tool that can help promote upscaling as it did with the rapidly increasing market share of biomass, but that it can also stimulate a bad situation (Milieu Centraal, n.d.-a).

For successful upscaling, a good social image of a technology must also not be underestimated. The Dutch government's decision to reverse the expanded use of biomass was made after much negative publicity and attention in the public and media spheres (Hakkenes, 2020; Timmer, 2020; van der Wal, 2021). Societal backing or backlash on technologies can influence political decision making and the acceptance or rejection of technologies.

The biomass example highlights that upscaling is a multifaceted problem. The ability for a technology to upscale requires much more than a limited environmental footprint. It also requires political, legislative, and social support apart from technical and economic feasibility.

7.3.2 Upscaling Electricity

The Dutch climate agreement states that 70% of all electricity in 2030 should come from renewable sources such as offshore wind, onshore wind and by solar panels and parks (Ministerie van Economische Zaken en Klimaat, 2019b). The increased production of renewable electricity, however, has already created pressure on the electricity network. In combination with the rise of electricity demanded (e.g. more construction of houses, higher demand for electric car charging stations, increased use of heat pumps for heat demand, use of electric cooking) the pressure on the electricity network has increased so much that some areas in the Netherlands do not have the ability to extend new or extra capacity to businesses ("In 10 Jaar Het Elektriciteitsnet Verdubbelen, Wat Je Normaal in 40 Jaar Doet," 2023). The electricity network has not been designed for decentralized energy production, the large growing demand for electricity and for meeting industrial demand (de Bruyn et al., 2020; KiesZon, 2023). The network is only able to transport certain capacities which no longer fulfill the required capacities foreseen – the electricity network is congested. To decongest, the electricity network will need to be expanded.

The aim is to double the capacity of the electricity network towards 2030 ("In 10 Jaar Het Elektriciteitsnet Verdubbelen, Wat Je Normaal in 40 Jaar Doet," 2023). It will require thousands of kilometers of additional electricity cables, larger capacity electricity stations, and hundreds of new electricity transformer houses (Franx, 2022; Jaarbeurs, 2022). First, the expansion of the electricity network takes time and is difficult to realize when there are large staff shortages (Rooijers, 2023). Then there is societal backlash of residents who do not wish to have extra transformer houses in their neighborhoods (Rubio, 2022; van den Broek, 2022). It must also be noted that the expansion of the electricity network is not a cheap undertaking with TenneT, the Dutch high-voltage network operator, expecting to invest 8 billion Euro annually for the next decade (Monique, 2023). PwC concluded that the three largest Dutch regional network operators (Liander, Stedin and Enexis) and TenneT will collectively need to invest 102 billion Euro in energy infrastructure up until 2050 (PricewaterhouseCoopers Advisory, 2021; Rodenburg, 2021). The expansion of the electricity network will not be an easy endeavor.

Besides expanding the electricity network, the generation of renewable energy must significantly increase. This requires new windmills and solar panels to be installed. At the start of this research an estimation of the electricity demand of a fully electrified basic materials industry was made which would require almost double the current EU industry electricity demand (Lechtenböhmer et al., 2016; Wiertzema et al., 2020). Should large parts of the energy-intensive industries thus electrify their processes, the electricity demanded would need to increase substantially. Though wind at sea is considered a key pillar of realizing the energy transition and is expected to be the largest renewable energy source of the Netherlands in the future, renewable energy from windmills and solar panels on land will also significantly contribute to the electricity mix towards 2030 (Ministerie van Algemene Zaken, 2022; Ministerie van Economische Zaken en Klimaat, 2019b; NWEA, 2023). However there is fierce opposition by Dutch residents in installing new renewable electricity generation on land (Janssen, 2021; Louwes, 2021; Nauta, 2018; Renes, 2021; van Dijk, 2023; van Dongen & van Mersbergen, 2018; van Zeggelaar, 2018; Walhout, 2023). Citizens feel that windmills ruin the landscape, cause noise nuisance and cause shadow flicker (Hettema & Lammers, 2023; van Dongen & van Mersbergen, 2018). Similarly, citizens oppose the construction of solar parks due to visual pollution and dazzling glares (Renes, 2021; Walhout, 2023). Regardless of resident opposition, the new windmills and solar parks often continue to be developed (Grol, 2020; Tiekstra, 2023; *Vergunning Voor Zonnepark Juridisch Vaak Lastig Aan Te Vechten*, 2023). Earlier in the case of biomass, societal influence was seen to drastically affect the implementation of a technology. This case, however, exemplifies that societal opposition alone will not hinder implementation and upscaling as the consensus and support for renewable electricity is present. The transition to more renewable electricity is supported by many citizens they would just prefer windmills and solar panels not to be placed in their backyard (Nauta, 2018; Renes, 2021; Walhout, 2023).

An increase in renewable energy production will also lead to an increased dependency on the weather. As a result, flexibility in the energy system will need to be created through storage, conversion to energy carriers, and/or the in- and export of electricity with other countries for example (Ministerie van Economische Zaken en Klimaat, 2019b). Especially if industries electrify their processes, a reliable supply of electricity is necessary. Important to realize is that each type of energy storage and the various energy carriers that will be required for a stable electricity system all have their individual sets of difficulties that will arise during upscaling.

Assuming that upscaling of the electricity network occurs across the value chain and that industrial electricity demand can be met for businesses in the future, the question of how much of the energy-intensive industries can be electrified remains. At the start of this research in section 1.1.2, it was mentioned that it was technically possible for half of the industries running on fuel to electrify their processes (Roelofsen et al., 2020). This concerns the industries requiring lower temperature heat demands which can already decarbonize, e.g. by e-boilers (Roelofsen et al., 2020; Rootzén et al., n.d.). Meeting temperatures above 1000℃ by direct electrification, however, is still a (technological) challenge (Roelofsen et al., 2020; Rootzén et al., n.d.). The steel, cement and chemical industries account for a large majority of this high temperature heat demand (Rehfeldt et al., 2017; Rootzén et al., n.d.). For these sectors, the direct electrification possibilities are therefore more limited and other technical solutions like hydrogen combustion that can more easily reach high temperatures may be better suited (Rootzén et al., n.d.). Assuming all process heating demands up until 500℃ in the Netherlands can be electrified, then according to Rehfeldt et al. (2017) 46.1 TWh can be electrified, approximately 41% of the total Dutch process heat demanded. Unfortunately, no study can say precisely how large the electrification potential is but that there is a large potential for electrification of energy-intensive industries is well acknowledged (Bühler et al., 2023; Hers et al., 2021; Huismans & Voswinkel, 2023; Rootzén et al., n.d.; Sorknæs et al., 2022).

It is great that electrification potential exists, but this has only taken into consideration what is technically feasible. Bühler et al. (2023) found that even though electric boilers are readily available there was limited economic feasibility in the Danish climate (Sorknæs et al., 2022). The cost of transitioning to electricity-based processes also gives businesses high initial investment costs (de Bruyn et al., 2020; Huismans & Voswinkel, 2023). In the Netherlands, electrification of the industries is seen as a key step to reducing CO_2 in the industries for which a roadmap has been set up (Hers et al., 2021). One of the actions it lays out to promote the economic feasibility of applying available electrification technologies before 2030 is to extend and improve accessibility to financial incentives (including Stimuleringsregeling Duurzame Energieproductie en Klimaattransitie (SDE++) subsidies) (Hers et al., 2021). Instruments like these will be crucial, but they will only be successful in combination with a good approach that will quickly upscale the electricity network, increase renewable energy production and ensure sufficient availability of clean electricity in the future (Hers et al., 2021).

7.3.3 Upscaling Hydrogen

Large scale use of hydrogen would first require a large increase in hydrogen production. In the Netherlands approximately 10 billion cubic meters of hydrogen is currently produced annually of which 80% is produced from natural gas, i.e. grey hydrogen (Milieu Centraal, n.d.-b). The other 20% is waste hydrogen originating from the chemical industries as by-product (Milieu Centraal, n.d.-b). In line with climate neutral objectives, there are only a limited number of production routes of hydrogen: green hydrogen through electrolysis, waste hydrogen from industrial gasses, hydrogen from nuclear energy and hydrogen produced from biomass and waste (Nationaal Waterstof Programma, 2022). The capacity to produce hydrogen sustainably is virtually absent (Milieu Centraal, n.d.-b; Neuwirth et al., 2022). Blue hydrogen, i.e. hydrogen produced by natural gas making use of CCS, is seen to help aid the transition to large scale hydrogen usage as long as there is also an insufficient supply of green electricity for green hydrogen production (Milieu Centraal, n.d.-b). The Dutch government’s aim is to focus as much as possible on green hydrogen (Ministerie van Economische Zaken en Klimaat, 2019d). By 2030, 3-4 GW of electrolysis capacity should be installed, but this has recently been increased to 8 GW electrolysis capacity by 2032 (Ministerie van Algemene Zaken, n.d.-e; Ministerie van Economische Zaken en Klimaat, 2019d). The Netherlands is seen as a good location for green hydrogen production as it has the potential for large renewable electricity generation from offshore wind of the North Sea (Ministerie van Economische Zaken en Klimaat, 2019d). An increase in green hydrogen production can, however, only be realized in combination with an increase in renewable energy. If the electricity required for hydrogen production cannot be used at the expense of electrification and decarbonizing the existing electricity consumption, then the renewable electricity supply must increase further (Nationaal Waterstof Programma, 2022). The challenges associated with increasing the renewable electricity supply were handled in the previous subsection (subsection 7.3.2).

Other limitations of upscaling hydrogen include the required transport infrastructure (Milieu Centraal, n.d.-b; Neuwirth et al., 2022). In the Netherlands, the future hydrogen network will connect the larger industrial clusters together by repurposing the existing gas infrastructure

(Gasunie, 2023b; Ministerie van Algemene Zaken, n.d.-e). It is expected that in the coming years the use of natural gas transport will decrease allowing for a transition to hydrogen transport (Gasunie, 2023b). From 2025 onwards, the national hydrogen network will open in sections (Gasunie, 2023b). 85% of the national hydrogen network is expected to consist of repurposed natural gas infrastructure (Gasunie, 2023b). There is also a larger vision in which a hydrogen network connects various parts of Europe together (Wang et al., 2021). However, the construction of hydrogen infrastructure, including the repurposing of the existing natural gas network, is expected to cost 1.5 billion Euro according to Gasunie (Gasunie, 2023c; Milieu Centraal, n.d.-b). These costs must be added on top of the investments required for expanding the electricity network, both the transport infrastructure and the additional renewable energy production required.

Furthermore, during conversion of electricity to hydrogen, approximately 25% of the energy is lost (Milieu Centraal, n.d.-b). Further transport and storage can lead to an additional 10% losses (Lerma, 2021). Depending on the end use, the further losses then vary between 13 to 50% (Deloitte, 2023). For ballpark comparison, “about 12% of the original fossil energy is lost between oil wells and filling stations for transportation” (Bossel & Eliasson, n.d.). Should hydrogen replace fossil fuels for this specific application, losses would be significantly higher (Bossel & Eliasson, n.d.). For heat production purposes, direct electrification is in any case more favorable in comparison to a hydrogen-based system as it prevents considerable energy losses (Sorknæs et al., 2022). In comparison to Iron Fuel Technology™, hydrogen losses are likely higher, but this is case and application dependent[10]. Studies therefore agree that “from an energy system perspective, the direct use of hydrogen for industrial processes should only be applied where no alternative solution exists” (Deloitte, 2023; Sorknæs et al., 2022). In that case, hydrogen, though it may have significant energy losses, may be the only option.

From a societal perspective, hydrogen as a key to decarbonization seems to have been embraced by the public. There is a profound understanding of the societal need to implement hydrogen and it is generally positively handled in the media (Armstrong, 2022; Gosman et al., 2021). Some have safety concerns regarding the use of hydrogen and the ecological impacts (Gosman et al., 2021; van Bokkum, 2023; van Renselaar, 2023). Others also question the ability for the cost of hydrogen to drop and the large energy losses throughout the value chain (Armstrong, 2022; de Bruijn et al., 2022; Smelik, 2023; “Staar Je Niet Blind Op Waterstof,” 2022; “Waterstof Is Dure En Inefficiënte Oplossing,” 2023; van Renselaar, 2023). Good public opinion has been known to be vital for acceptance of technologies for which in the case of hydrogen the jury is still out as it has not yet been adopted.

Technologically, hydrogen combustion is possible. However, due to the high temperature flame created during combustion, large amounts of nitrogen oxides (NOx) are formed. Three types of NOx can be distinguished: fuel NOx, prompt NOx and thermal NOx. Fuel NOx occurs when combustion of a fuel consisting of nitrogen takes place, which is not the case in natural gas or hydrogen (National Energy Technology Laboratory, 2022). Prompt NOx, typically the

[10] Assuming a 25% energy loss during electrolysis, a further 15-25% loss during IF production, 0.01% loss during storage, and a 5-15% loss at the boiler, the electricity to heat efficiency of IFT with electrolysis is approximately 48-60% (Renewable Iron Fuel Technology, 2022). Assuming 25% energy losses during electrolysis, 10% during transport and storage, 13-50% losses at end-use, the electricity to heat efficiency of hydrogen is approximately 34-58%.

least significant, occurs when nitrogen in the air directly reacts with the fuel creating a cyanide group which is subsequently converted into NOx (National Energy Technology Laboratory, 2022). Lastly, thermal NOx, occurring in most high-temperature combustion applications, is the result of direct oxidation of free nitrogen in the air (National Energy Technology Laboratory, 2022). Depending on the temperature, residence time (time in the boiler system) and oxygen content thermal NOx formation is largely determined (National Energy Technology Laboratory, 2022). In the case of hydrogen, thermal NOx is the most dominant. This is problematic for two reasons. First, NOx emissions are environmentally impactful and are a key emission contributor to multiple impact categories including acidification, terrestrial eutrophication, photochemical oxidant formation, marine eutrophication, and particulate matter. It also indirectly contributes to climate change but is not quantified for the climate change impact category (Raga Mexico et al., 2007). Second, the high emissions often exceed the environmental permit limits. In the Netherlands, environmental permits dictate that natural gas plants may not exceed 70 mg NOx/nm^3 with some locations having even lower emission limits like 40 mg NOx/nm^3 (Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 2023; Rijkswaterstaat, n.d.-a, n.d.-b). To comply with existing Dutch permits, hydrogen boilers may not exceed the assigned threshold which results in the implementation of hydrogen boilers often being impossible. The NOx emission limits are higher in other countries but in the Netherlands there is an issue regarding the emissions of nitrogen (EPA, 2023; Ministry of the Environment, 2021). "Many companies, like Siemens, claim that several of their turbines are already capable of 100% hydrogen… [but] such turbines are not marketable because the unmitigated NOx emissions are too high" (National Energy Technology Laboratory, 2022). Depending on the boiler's design, the use of hydrogen can increase NOx emissions by eight times in comparison with natural gas (Ilbas et al., 2005; National Energy Technology Laboratory, 2022). Interestingly, the NOx emission range as provided by a hydrogen boiler manufacturer for this research (the lowest value being used in the completed ex-ante LCA) also did not comply with the Dutch permit threshold (70 mg NOx/nm^3). Challenges in relation to decreasing NOx emissions (also while maintaining high turbine efficiencies) has been extensively researched in the past decades and continue to be researched today (National Energy Technology Laboratory, 2022). According to interviewed boiler experts, it is difficult to get hydrogen boilers to comply with the existing natural gas allowed NOx emissions. To decrease NOx emissions, the boiler must be designed differently and/or the flame temperature must be decreased (M. Derksen, personal communication, 30 March 2023; National Energy Technology Laboratory, 2022). Hence, there is still technical work to be done on this before implementation of hydrogen boilers in any energy intensive industry can take place.

To finish this discussion with the upscaling potential market wise, the answer is that this is not very clear. First, a transport network will need to be present to ensure business have a steady supply of (green) hydrogen. The national hydrogen network that was mentioned earlier is expected to be fully operational from 2030 onward thereby connecting the 5 large industrial clusters of the Netherlands (Eemshaven, Noordzeekanaalgebied, Rotterdam, Zeeland en Limburg) (Gasunie, 2023c). However, this leaves all business that are not located within one of the 5 large industrial clusters behind. The so-called 6th industrial cluster refers to all the businesses spread out through the Netherlands not located within one of the 5 industrial clusters, including energy-intensive industries like the paper and pulp, ceramic and the textile industry, which together account for approximately 30% of the CO_2 emissions of the total

Dutch industries (*Het 6e Industriecluster: Waterstofbackbone En Energie Infrastructuur*, 2022). The CO_2 reduction potential of hydrogen if completely upscaled will thus not reach these businesses before 2030.

Furthermore, the demand of hydrogen in 2030, has been estimated to be approximately 125-213 PJ solely for industrial applications on the coast of the Netherlands with an additional 25-40 PJ demand estimated for the industrial cluster Chemelot (Limburg, consisting mostly of chemical applications) (Ministerie van Economische Zaken en Klimaat, 2019d). Assuming 8 GW of electrolysis capacity is installed by 2030 (two years earlier than the targeted ambition)[11], then this can lead to a total of 5.1 GW of installed capacity of hydrogen boilers if all electrolysis capacity were to be used (Ministerie van Algemene Zaken, n.d.-e; Ministerie van Economische Zaken en Klimaat, 2019d). Comparing this with the foreseen demand, (150-253 PJ which translates to 6.9-11.7 GW), it is likely that there will be shortages of green hydrogen. The limited supply of green hydrogen at that point in time will likely cause an important discussion as to how it will be divided (Milieu Centraal, n.d.-b). Should hydrogen be implemented, applications with temperatures higher than 600°C seem likely targets as other alternatives are limited (Ministerie van Economische Zaken en Klimaat, 2019d; Rootzén et al., n.d.). For example, the use of renewable hydrogen to produce ammonia and other basic chemicals as well as for hydrogen direct reduction in the iron and steel industry are potential applications which currently lack many other alternatives (Rootzén et al., n.d.). The process heating market requiring temperatures above 500°C is estimated to be 66.5 TWh in the Netherlands, totaling approximately 59% of the process heat demanded annually (Rehfeldt et al., 2017). The potential market is therefore significant. Whether hydrogen will be implemented in any part of this market, however, will depend on a multitude of factors including overcoming technical challenges, economic viability, and increased renewable energy supply among others.

7.3.4 Upscaling Iron Fuel Technology™

A main advantage of Iron Fuel Technology™ in upscaling is that it does not require any additional transport infrastructure unlike electrification and hydrogen. However, for RIFT to upscale Iron Fuel Technology™ the first challenge will be to prove they can meet all technical and economic conditions so that they can outperform carbon-based fuels and other clean alternatives. According to RIFT's management the first insights have shown promising results and all key performance indicators (KPIs) will be proven by 2025 when commercial implementation is set to take place. Through two projects set to take place in 2024/2025 they will scale up and optimize the systems ahead of commercial roll out. They will also require legislative and political support of which subsidies to cover the green premium will help maximum scale up of IFT. Lastly, as seen in other technologies, social acceptance, especially of residents living in close proximity to the system, is key. On all these fronts RIFT and her partners will need to work in order for successful upscaling of the Iron Fuel Technology™.

As a result of the investigation into the environmental performance of Iron Fuel Technology™ in comparison to the other investigated alternatives, two key recommendations followed (implement IFT in markets with large potential for using waste hydrogen and source initial iron fuel from market players that produce it from scrap and as sustainably as possible) for which

[11] Assuming 50 kWh of electricity is required for each kg of hydrogen produced, 6000 FLH run annually, and for every MWh steam 31 kg of hydrogen is required. For full calculation see Appendix G.

the question arises whether the market is large enough to accommodate an upscaled implementation of IFT. The first pertains to the market size of the hydrogen and the second to the market size of the scrap iron, calculations are in Appendix G.

First, the Netherlands currently produces approximately 2 billion cubic meters waste hydrogen originating from the chemical industries as by-product (Milieu Centraal, n.d.-b). Assuming a density of hydrogen of 0.08375 kg/m^3 and 6000 FLH annually, if all waste hydrogen in the Netherlands would be used RIFT would be able to install IFT systems totaling 1.1 GW capacity. Worldwide, assuming the same density and FLH, 99 GW system capacity (2022 numbers) could be installed if all by-product hydrogen is used (Bermudez et al., 2023). RIFT's aim is to reduce 1 Gigaton CO_2 by 2050 which would require them to install approximately 550 GW capacity. The waste hydrogen market is therefore not large enough to cover their aimed for installed capacities meaning that large scale green hydrogen production will be essential for IFT's upscaling in the long-term. Furthermore, there generally are three purposes for by-product hydrogen (Connelly et al., 2019; Freund & Sánchez, 2022). First, by-product hydrogen can be reintegrated back into processes of the same or nearby located company and thus be used on site (Connelly et al., 2019; Freund & Sánchez, 2022). Examples of this type of reuse and industrial symbiosis are numerous, e.g. Houston Ship Channel, Ulsan eco-industrial park, and Kwinana industrial area (Ehrenfeld & Gertler, 1997; Harris, 2007; Laughlin & Freund, 2022; Mendez-Alva et al., 2021; Park et al., 2019). Second, by-product hydrogen is vented or flared (Connelly et al., 2019; Freund & Sánchez, 2022). This often relates to "hydrogen's well known supply-and-demand problem" which requires a stable supply and a buyer, often one being missing (Laughlin & Freund, 2022). Third, by-product hydrogen can be sold as merchant hydrogen, i.e. "hydrogen generated on site or in a central production facility and sold to a consumer by pipeline, bulk tank, or cylinder truck delivery" (Connelly et al., 2019). Only in the first case when by-product hydrogen is used on site is it not potentially available for IFT use. Unfortunately there is no specific indication of the proportion of each end use of by-product hydrogen though there seems to be an indication that by-product hydrogen used on site is the main end-use (Connelly et al., 2019; Laughlin & Freund, 2022). This reinforces the notion that green hydrogen sourcing will be crucial for IFT's success.

To verify this notion, a simple calculation can be executed knowing that the Dutch government has goals to install 8 GW electrolysis capacity by 2032 (Ministerie van Algemene Zaken, n.d.-e; Ministerie van Economische Zaken en Klimaat, 2019d). Assuming 8 GW of electrolysis capacity is installed by 2030 (2 years earlier than the target) and fully used for IFT, it would allow for 5.9 GW of installed capacity of IFT[12]. This is more than the hydrogen boiler as calculated earlier (5.1 GW) as there are less energy losses in IFT. Comparing this to the foreseen goals of RIFT and the realistic prospect that not all hydrogen produced will be used for IFT purposes, it is plausible that the electrolysis capacity will be insufficient. Hence, a similar situation will likely occur as mentioned earlier in that an important discussion will arise as to the division of the limited supply of green hydrogen (Milieu Centraal, n.d.-b). In the long term, upscaling of electrolysis (and renewable energy) production will thus be essential for the success of Iron Fuel Technology™.

[12] Assuming 50 kWh of electricity is required for each kg of hydrogen produced, 6000 FLH run annually, and 27 kg of hydrogen is required for every MWh steam produced through IFT. For the full calculation see Appendix G.

As for the scrap iron market, the 2022 market size was estimated at 624.5 million metric tons with the projected market value in 2033 to increase to 1050 million metric tons (Jha, 2023). This translates to the ability to install 371,726 GW of installed capacity worldwide, assuming 6000 FLH and all scrap being used. The use of scrap iron in producing iron fuel applicable for IFT should therefore not be a barrier in upscaling.

7.3.5 The Silver Bullet

Reviewing all that has been investigated, no one silver bullet stands out. Instead this research rather makes obvious that the silver bullet lies in using a mix of energy sources. As seen in the results of the LCIA as well as the contribution and sensitivity analyses, different process alternatives performed better or worse depending on the investigated impact category. To really benefit the environment, a more holistic view will need to be taken across impacts of multiple impact categories instead of merely focusing on a set of alternatives that focus on reducing impact in one impact category, namely climate change. This means that natural gas, for example, does not by definition need to be an undesirable energy source if used to specific limits as it provides better environmental results in specific impact categories like acidification, land use and eutrophication in comparison to the clean alternatives. Of course, consideration and mitigation of other non-environmental aspects must then also be taken, e.g. reducing societal opposition due to gas winning and subsequent earthquakes taking place as introduced in section 1.1.4. A holistic view of all aspects including those non-environmental must thus be taken. Biomass too, for example, can be considered but the upscaling potential of it is limited, and caution must be taken in the source of the biomass used. Another consideration that must be noted is that the upscaling of renewable energy sources will take time and large-scale availability of renewables and hydrogen will likely only be available after 2030 (Radowitz, 2022). For Iron Fuel Technology™ this means that waste hydrogen will likely be the main source of hydrogen available in the first years of commercial implementation (2025 onwards) and securing supply contracts will be crucial. The use of waste hydrogen is also an effective way to reduce environmental impacts in the short term when implementing IFT and helps upcycle by-products in the spirit of circular economy. A keynote for all technologies is that this is a race against the clock for both the technologies and relieving climate issues. Whichever technology can cross the finish line the first (and upscale the fastest) will likely stand the best chance to win the largest market shares which may not necessarily be the one with the least environmental impacts. Very simply said, if the technology is not implementable in a specific case (application or business), then the technology is not really in the running in any sense.

8. Conclusion & Further Research

This chapter is split in two sections. Section 8.1 will provide the conclusion of this research by recapping the main takeaways of this research, answering the sub-research questions and the main research question. Section 8.2 will provide recommendations for further research.

8.1 Conclusion

In the introduction the idea of "clean" alternatives was introduced (i.e. alternative ways to produce, convert, and store energy other than the conventional carbon fuels in which "clean" refers to a reduced carbon footprint in comparison to the GHG emissions of carbon-based fuels) (Constellation, 2023; IEA, 2020; Linares et al., 2014; Zohuri et al., 2022). In this research, the term clean alternatives was used to refer to electrification, hydrogen and Iron Fuel Technology™, alternatives that do not directly emit any CO_2 emissions. These three alternatives all have the potential to decarbonize the energy-intensive industries, accounting for more than half of the total Dutch CO_2 emissions thereby being able to substantially help meet Dutch climate goals (CBS, 2022). Heat, the focus of this research, is a cornerstone of the EIIs and the total heat demand of the EIIs in the Netherlands is 112.7 TWh annually (Rehfeldt et al., 2017). However, realizing decarbonization goals and making the energy transition is largely dependent on any alternative having the potential to drastically reduce GHG emissions without causing any adverse environmental side effects. One of the large gaps in existing literature examining the environmental performances of the three clean alternatives as well as natural gas and biomass was that a full environmental assessment including impacts other than GHG emissions and climate change was often lacking. This research therefore focused on examining multiple impact categories and made contributions to existing literature through completing a comparative environmental assessment of the potential future impacts of using electrification, hydrogen, Iron Fuel Technology™, natural gas and biomass for generating heat in the energy-intensive industries. Specifically, the following research question was defined: *What are the environmental impacts of electrification, hydrogen and Iron Fuel Technology™ when supplying 1 MWh of steam in 2030 and 2050 in relation to carbon-based fuels and to each other and what redesign recommendations can be made to limit the environmental impacts?*

To answer this question, life cycle assessment, a widely used standardized method for assessing environmental impacts along the whole life cycle chain as defined in the *ISO 14044 standard*, was chosen as a suitable methodology for this research. With some of the investigated technologies not yet commercially available, specifically ex-ante LCA was conducted which differs from regular LCA in the focus on exploring future environmental impacts of emergent technologies rather than conducting ex-post analyses.

Before handling the main research question, first all sub-research questions will be handled, starting with the first: *how do electrification, hydrogen and Iron Fuel Technology™ perform environmentally in 2030 and 2050 in comparison to carbon-based fuels (natural gas and biomass)?* The ex-ante LCA results showed that electrification, hydrogen and Iron Fuel Technology™ can all reduce climate change impacts in comparison to natural gas in both 2030 and 2050, thus helping meet Dutch decarbonization climate goals. In comparison to sustainably sourced biomass, the LCIA assessment showed that electrification, hydrogen and Iron Fuel

Technology™ for both 2030 and 2050 all have higher climate change impacts[13]. Similarly, the three clean alternatives all show larger impacts than biomass in the impact categories of freshwater ecotoxicity, fossil resource use, freshwater eutrophication, human toxicity cancer, ionizing radiation, mineral and metal resource use, and ozone depletion. Biomass then also performs better than all hydrogen process alternatives and the IFT process alternatives sourcing hydrogen from an electrolyzer in acidification, better than all process alternatives except the 2030 IFT process alternative based on pig iron and waste hydrogen in human toxicity non-cancer, and better than all hydrogen and electrification process alternatives in the water use impact category. In comparison to natural gas, all clean alternatives for both 2030 and 2050 also perform worse in the impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, terrestrial eutrophication, human toxicity cancer, human toxicity non-cancer, ionizing radiation, land use, mineral and metal resource use, and particulate matter. Only three impact categories were noted in which a clean process alternative performs better than natural gas and biomass. The first is marine eutrophication wherein the 2050 IFT process alternative based on scrap iron and waste hydrogen is the only process alternative that outperforms natural gas and biomass. The second is in the impact category of photochemical oxidant formation where both the 2030 and 2050 IFT process alternatives based on scrap iron and waste hydrogen perform better than natural gas and biomass. The third, and last, is in the water use impact category where all 2030 and 2050 IFT process alternatives based on waste hydrogen perform better than biomass and natural gas. The results indicated that electrification, hydrogen and IFT process alternatives based on electrolyzer sourced hydrogen did not outperform both natural gas and biomass in any impact category. Moreover, the LCIA results show that for the impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity non-cancer, ionizing radiation, mineral and metal resource use and water use, one of the hydrogen process alternatives performs worst among all examined alternatives whereas for the human toxicity cancer impact category this is the case for the 2050 IFT process alternative based on scrap iron and hydrogen sourced from an electrolyzer. Some of the electrification, hydrogen and Iron Fuel Technology™ process alternatives can perform better than one of the two carbon-based fuels in the majority of the examined impact categories (i.e. acidification, climate change, fossil resource use, marine eutrophication, terrestrial eutrophication, human toxicity non-cancer, land use, ozone depletion, particulate matter, photochemical oxidant formation, and water use), but they generally do not perform better than both natural gas and biomass and the performance is highly dependent on the specific process alternative.

Next, the second sub-research question is answered: *How do electrification, hydrogen and Iron Fuel Technology™ perform environmentally in 2030 and 2050 in comparison to one another?* The results of the LCIA indicate that generally the 2030 and 2050 Iron Fuel Technology™ process alternatives based on waste hydrogen performed best among the clean process alternatives. The 2030 and 2050 IFT process alternatives based on scrap iron and waste hydrogen perform well with the exception for the emissions of cancerous human toxins, whereas the 2030 and 2050 IFT process alternative based on pig iron and waste hydrogen perform well and in contrast do not perform poorly in any impact category. Specifically, the 2030 IFT process alternative based on scrap iron and waste hydrogen performed best in the impact categories of acidification, land use and particulate matter. The 2050 IFT process

[13] This is only applicable for sustainably sourced biomass from wood chips as biomass sourced from other sources will likely present different results.

alternative based on scrap iron and waste hydrogen performed best in climate change, fossil resource use, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, ozone depletion and photochemical oxidant formation. The 2030 IFT process alternative based on pig iron and waste hydrogen performed best in the impact categories of human toxicity non-cancer, ionizing radiation and mineral and metal resource use. Lastly, the 2050 IFT process alternative based on pig iron and waste hydrogen performed best in the impact categories of freshwater ecotoxicity and water use. The impact category of human toxicity cancer is also the only impact category wherein electrification performs better than all the IFT process alternatives. All 2030 and 2050 electrification process alternatives generally perform somewhere in the middle, not performing the best nor the worst among all clean process alternatives. All hydrogen process alternatives and IFT process alternatives based on hydrogen sourced from an electrolyzer, however, generally perform the worst. The results of this research revealed a strong link between the electricity consumption and the environmental impacts noted. The larger the electricity consumption of a process alternative was, the higher the environmental impacts tended to be. The production of hydrogen through electrolysis demands high electricity consumption resulting in the highest environmental footprints among the clean alternatives. Hence, all process alternatives requiring hydrogen produced through electrolysis generally showed high environmental impacts. Comparing the hydrogen and IFT electrolyzer based process alternatives, hydrogen PAs performed worse in most impact categories. Only for the impact categories of climate change, marine eutrophication, terrestrial eutrophication, human toxicity cancer particulate matter and photochemical oxidant formation this is not applicable. The results of this research suggest that when comparing electrification, hydrogen and Iron Fuel Technology™, it can be concluded that IFT waste hydrogen-based process alternatives show the best environmental performance followed by electrification process alternatives, IFT electrolyzer based process alternatives and lastly hydrogen process alternatives.

To answer the third sub-research question (*What are the environmental hotspots for electrification, hydrogen and Iron Fuel Technology™?*), the environmental impacts of electrification, hydrogen and Iron Fuel Technology™ were mostly traced back to the assumed 2030 and 2050 scenarios, specifically the electricity mix and the expansion of the electricity network. While the expansion of the electricity network is inherent to the upscaling of renewable energy production, the electricity mix can be altered and thus room for reducing impacts exists. All three product systems generally had a strong link to the assumed 2030 and 2050 scenarios resulting in largely overlapping hotspots for all three clean alternatives. Some of the impactful individual processes related to the 2030 and 2050 scenarios were the individual processes of: blasting, treatment of by-products from mining processes, copper smelting, copper mine operations, petroleum and gas production processes and heat and power cogeneration from wood chips. The smelting of copper, the copper mine operations and the treatment of copper mine tailings, and the blasting processes are related to the electricity network expansion whereas the gas production processes and the heat and power cogeneration from wood chips are related to the electricity mix. Specifically for the hydrogen product system a small portion of impacts were also seen to stem from the electrolyzer, both from the construction of the system and the materials required during the electrolysis process. For the IFT product system a portion of the environmental impacts also stemmed from the initial iron fuel production. Depending on whether primary iron or secondary iron was used to produce the initial iron fuel, impacts stemmed from either the coking process or the treatment of electric arc furnace slag respectively. The relative share of the impacts associated with the initial iron fuel production were more dominant in the waste hydrogen based IFT process alternatives as no impacts were assumed to be related to the sourcing of waste hydrogen. Important to note is that all environmental impacts for all three clean alternatives originate from background processes (i.e. indirect environmental impacts) in contrast to the carbon-based fuels in which emissions are mostly direct. As such, the three clean alternatives are largely dependent on background sectors, such as the copper and steel industries, for improving their environmental performance.

As a result of exploring the contributions to electrification, hydrogen and Iron Fuel Technology™ the electricity mix was found to be a key parameter of the assumed 2030 and 2050 scenarios influential for all three clean alternatives. Subsequently, sub-question 4 builds on this: *How does the environmental performance of electrification, hydrogen and Iron Fuel Technology™ change when the sensitivity of some parameters are tested as chosen based on the results from sub-question 3?* A sensitivity analysis that switched the 2030 assumed base case electricity mix to a fully wind powered electricity mix, showed direct electrification outperforming IFT process alternatives in the impact categories of climate change, fossil resource use, human toxicity cancer, ionizing radiation, land use, and particulate matter. Hydrogen and the IFT electrolyzer based process alternatives, which generally performed worst in all examined cases and variations, could also become competitive when electrolysis is completed with wind-based electricity. For all three clean alternatives, using a fully wind-based electricity mix showed the least amount of environmental pressures exerted.

Other sensitivity parameters tested were the number of FLH of the IF production system, electrolyzer and the boilers, different electricity consumptions of the IF production system, the amount of hydrogen leakage, the quantity of hydrogen required for combustion in a h-boiler, various transport distances and transport method. These parameters were chosen in cooperation with RIFT as a result of their importance for technical, economic or case applicability reasons. The results of these sensitivity analyses indicated that limiting the hydrogen losses and reducing the amount of hydrogen required for steam generation positively affected the environment as a result of the reduced electricity consumption. Similarly, a reduced electricity consumption of the IF production system limited environmental impacts. As for the number of FLH of a boiler, electrolyzer or the IF production system, the more FLH run annually the lower the environmental impacts. Lastly, larger transport distances were shown to increase environmental impacts and a switch to ship transport decreased environmental impacts of IFT process alternatives. When implementing the sensitivity analysis results to test for the best possible configuration for each examined clean alternative, some of the results remained similar to those noted in sub-question 1 and 2. Though the environmental impacts for all three clean alternatives decreased, natural gas still performed better in the impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer, human toxicity non-cancer, ionizing radiation, land use, mineral and metal resource use, and particulate matter than any of the clean alternatives. However, considering climate change impacts, the 2030 steam production through IF boiler process alternative based on scrap iron and waste hydrogen now performed best. It also performed best in the impact categories of fossil resource use, marine eutrophication, terrestrial eutrophication, ozone depletion, and photochemical oxidant formation, but still had significant impacts in the human toxicity, cancer impact category. To limit extreme environmental impacts, the 2030 steam production through IF boiler process alternative based on pig iron and waste hydrogen showed to be a generally well performing process alternative as did the 2030 steam production through e-boiler including network infrastructure process alternative. The process alternatives requiring hydrogen from an electrolyzer (the hydrogen and IFT electrolyzer based PAs) still performed the worst. The results suggest that though some parameters showed to be highly sensitive, it was not able to change environmental impacts sufficiently to change the environmental performance of the clean alternatives to below the environmental impact of the carbon-based fuels in all impact categories or change the standing between the clean alternatives themselves when different parameters were applied.

The completed sensitivity analyses also pointed at suggestions for improving the environmental impacts of the clean alternatives thereby providing the possibility to answer sub-question 5: *What recommendations can be made for improving the environmental footprint of electrification, hydrogen and Iron Fuel Technology™?* Examining all the results, it was seen that decreasing the electricity consumption throughout the value chain is key for all three clean alternatives. In contrast to carbon-based fuels, the environmental impacts of electrification, hydrogen and Iron Fuel Technology™ are mostly upstream and not a direct result of the process in which the fuel is converted to heat (typically the combustion process). As a result, reducing the material usage and making the manufacturing processes of required background products, e.g. wind turbines for electricity generation, more sustainable will help reduce environmental impacts. This also applies to the copper mining, beneficiation and smelting processes as copper was shown to be the most impactful product required for the electricity network expansion. Though this is important for all three product systems, for the electricity product system tackling background emissions is the only way to limit environmental impacts. Specifically for hydrogen, reducing hydrogen losses to a minimum will be essential and any technological improvements to the electrolyzer as well as the boiler efficiency can also greatly reduce environmental impacts. For Iron Fuel Technology™ it is recommended to source waste hydrogen and produce initial iron fuel from scrap as it reduced impacts in most of the impact categories in comparison to using pig iron and hydrogen produced by an electrolyzer. Other recommendations to improve the environmental footprint of IFT are to further develop the circularity of the fuel and to use ship transport over truck transport whenever possible. In general, all three clean alternatives still showed room for improving their environmental performances though they are largely dependent on background processes.

Assuming that electrification, hydrogen and Iron Fuel Technology™ can and will reduce their environmental footprint satisfactory, upscaling any of the three technologies is still a multifaceted problem. Sub-research question 6 relates to this: *What non-environmental factors influence the implementation of electrification, hydrogen and Iron Fuel Technology™ in the future?* To start, all three clean alternatives are dependent on an increased expansion of the electricity network and a larger supply of renewable electricity. Current outlooks for the Netherlands indicate that this can potentially be a bottleneck as businesses may not have a sufficient electricity network connection, the supply of renewable electricity may fall short of the expected demand, there are staff shortages, high associated costs and societal opposition. This can subsequently lead to a restricted implementation of any of the three clean alternatives in energy-intensive industries towards 2030. Similarly, as IFT cannot solely rely on sourcing waste hydrogen, the hydrogen source will need to come from green hydrogen produced domestically or abroad. Estimates completed in this research based on the Dutch government's targets show that there will likely be insufficient green hydrogen in 2030 in the Netherlands, likely severely hindering upscaling of both hydrogen and IFT. Parallel to this, technological innovation is still required to maximize the potential market implementation as e-boilers are currently not available for high temperature heat demands, hydrogen boilers must limit NOx emissions to below environmental permit thresholds and Iron Fuel Technology™ must prove its ability to perform according to required economic and technical KPIs. The (financial) incentive for businesses to implement any of the three technologies must also be present in which political and societal support is often helpful. The successful implementation of electrification, hydrogen and Iron Fuel Technology™ is a race against the clock considering climate change impacts but it is the culmination of technical, economic, societal, political as well as environmental aspects that is required.

To return to the main research question, the results of this research point out that electrification, hydrogen and Iron Fuel Technology™ all could reduce climate change impacts in both 2030 and 2050. However, it also suggests that when switching from natural gas or biomass to one of the cleaner alternatives trade-offs will arise, some impacts which are inherently tied to making a transition to renewables. The impacts related to copper associated with the expansion of the electricity network in the assumed 2030 and 2050 scenarios is an example of this. Furthermore, results of the ex-ante LCA show that when generating steam electrification, hydrogen and Iron Fuel Technology™ are not fully clean alternatives, i.e. that not all environmental impacts are lower in comparison to carbon-based fuels as shown by higher impacts of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer and mineral and metal resource use among other impact categories. This research therefore casts doubt on whether the term "clean" is not misleading as the current definition is focused only on a reduction of GHG emissions in comparison to carbon-based fuels and does not indicate anything about other environmental impacts increasing. To limit environmental impacts, this research suggests a multitude of redesign recommendations for electrification, hydrogen and Iron Fuel Technology™, primarily focused on increasing efficiencies, limiting electricity demand and decreasing emissions in background processes. Examining electrification, hydrogen and Iron Fuel Technology™ in relation to both carbon-based fuels and to one another, implementing a set of these redesign recommendations was shown to be insufficient to reduce environmental impacts in all impact categories to below the environmental impacts of carbon-based fuels or drastically alter the environmental performance of electrification, hydrogen and Iron Fuel Technology™ in comparison with one another. The results therefore indicate that Iron Fuel Technology™ based on scrap iron and waste hydrogen is most preferable among the clean alternatives from an environmental perspective in decreasing climate change impacts while limiting other environmental impacts in as far as possible. It must however be cautioned that a sole emphasis on tackling climate change impacts, specifically decreasing CO_2 emissions, may overshadow the possible side effects that a transition towards alternative energy sources will bring, potentially creating other environmental crises. A holistic view should therefore be kept at all times.

As a final note, it must be clear that the intention of this research is not to eliminate any of the investigated technologies or push forward one alternative. The nature of this research and the completed ex-ante LCA was to explore “what if” scenarios. The results are thus not a final result but serve as an informed guidance to provide valuable insights into the environmental performances of process alternatives, to identify any potential problematic areas and hotspots and make recommendations for research and development. The underlying data, assumptions and model are subject to uncertainty and can result in different results when they change in light of new developments and research that may occur in the future.

8.2 Recommendations for Further Research

This research also identifies further areas of research. One main area of research concerns investigating a potential mix of energy sources supplying heat for energy intensive industry applications that could complement each source to overall decrease impacts across multiple impact categories. Natural gas, for example, was shown to have limited environmental impacts in categories like acidification, freshwater ecotoxicity, marine, terrestrial and freshwater eutrophication, non-cancer and cancer human toxicity, mineral and metal resource use and particulate matter. A complementary mix that reduces impacts across multiple impact categories may be more environmentally beneficial than a mix that solely focuses on one impact category.

This study also noted that the environmental performance is dependent on the application. This research was based on one specific pilot case, but other applications call for different assumptions and parameters to be considered which can change results. Further exploration into the environmental performance of the investigated alternatives with different end applications and temperature profiles should be completed.

Another important development for further research which would have substantially improved this research is to generate and make available background LCI data of possible futures. Background scenarios based on the SSPs calculated by IAMs have been developed and implemented before (Mendoza Beltran et al., 2020; van der Giesen et al., 2020). However, these do not cover all background sectors which thereby limits the possibility for a better assessment of background hotspots. In general, further research should be completed with updated background and foreground data to investigate whether the results from this research are still applicable or whether different environmental hotspots and results are identified.

The ecoinvent database used as the basis for background processes in this research shows multiple limitations including their inconsistent modelling across processes with a similar function and the use of outdated data. As a result, a list of improvement recommendations for ecoinvent based on the researcher’s use of ecoinvent processes can be found in Appendix F.

Lastly, the current exclusion of indirect environmental impacts, particularly related to emissions of hydrogen, in impact assessment models should be re-evaluated. Especially in the context of ex-ante LCA and determining future impacts, unquantified flows (especially when they are known to contribute to environmental issues) can distort environmental impacts leading to potentially undesirable environmental pressures in the future.

9. References

AB Volvo. (2022, January 4). *Volvo's heavy-duty electric truck is put to the test: excels in both range and energy efficiency*. https://www.volvogroup.com/en/news-and-media/news/2022/jan/news-4153093.html

Abdalla, A. M., Hossain, S., Nisfindy, O. B., Azad, A. T., Dawood, M., & Azad, A. K. (2018). Hydrogen production, storage, transportation and key challenges with applications: A review. In *Energy Conversion and Management* (Vol. 165, pp. 602–627). Elsevier Ltd. https://doi.org/10.1016/j.enconman.2018.03.088

Alam, E., & Xu, X. (2023). Life cycle assessment of photovoltaic electricity production by mono-crystalline solar systems: a case study in Canada. *Environmental Science and Pollution Research*, *30*(10), 27422–27440. https://doi.org/10.1007/s11356-022-24077-3

Alliander. (2022). *Pilots met waterstof*. https://www.alliander.com/nl/energietransitie/pilots-met-waterstof-2/

Andrés, K., Scheepers, M., van den Brink, R., & Smokers, R. (n.d.). *DE ENERGIETRANSITIE MOET SNELLER DIT IS NODIG OM DE KLIMAAT DOELSTELLINGEN TE HALEN maart 2022*.

ArcelorMittal. (2023a). *Blast furnace*. https://corporate.arcelormittal.com/about/making-steel/making-iron-steel-blast-furnace?chapter=Making%20iron%20&%20steel

ArcelorMittal. (2023b). *Coking Plant*. https://corporate.arcelormittal.com/about/making-steel/raw-materials-coking-plant#:~:text=To%20make%20steel%20in%20a,only%20the%20pure%20iron%20behind

ArcelorMittal. (2023c). *Electric arc furnace*. https://corporate.arcelormittal.com/about/making-steel/making-iron-steel-electric-arc-furnace#:~:text=These%20furnaces%20are%20typically%20charged,in%20an%20integrated%20steel%20plant.

Armstrong, J. (2022, June 4). *Is de mening van het publiek over waterstof van belang?* https://ee-ip.org/nl/article/is-de-mening-van-het-publiek-over-waterstof-van-belang-6466

Arvesen, A., & Hertwich, E. G. (2011). Environmental implications of large-scale adoption of wind power: A scenario-based life cycle assessment. In *Environmental Research Letters* (Vol. 6, Issue 4). Institute of Physics Publishing. https://doi.org/10.1088/1748-9326/6/4/045102

Arvesen, A., & Hertwich, E. G. (2012). Assessing the life cycle environmental impacts of wind power: A review of present knowledge and research needs. In *Renewable and Sustainable Energy Reviews* (Vol. 16, Issue 8, pp. 5994–6006). https://doi.org/10.1016/j.rser.2012.06.023

Bains, P., Moorhouse, J., & Hodgsen, D. (2023, July 11). *Bioenergy*. IEA. https://www.iea.org/energy-system/renewables/bioenergy

Bartolozzi, I., Rizzi, F., & Frey, M. (2013). Comparison between hydrogen and electric vehicles by life cycle assessment: A case study in Tuscany, Italy. *Applied Energy*, *101*, 103–111. https://doi.org/10.1016/j.apenergy.2012.03.021

Baykara, S. Z. (2018). Hydrogen: A brief overview on its sources, production and environmental impact. *International Journal of Hydrogen Energy*, *43*(23), 10605–10614. https://doi.org/10.1016/j.ijhydene.2018.02.022

Bellevrat, E., & West, K. (2018, January 23). *Clean and efficient heat for industry*. IEA. https://www.iea.org/commentaries/clean-and-efficient-heat-for-industry

Bergthorson, J. M. (2018). Recyclable metal fuels for clean and compact zero-carbon power. In *Progress in Energy and Combustion Science* (Vol. 68, pp. 169–196). Elsevier Ltd. https://doi.org/10.1016/j.pecs.2018.05.001

Bergthorson, J. M., Goroshin, S., Soo, M. J., Julien, P., Palecka, J., Frost, D. L., & Jarvis, D. J. (2015). Direct combustion of recyclable metal fuels for zero-carbon heat and power. *Applied Energy*, *160*, 368–382. https://doi.org/10.1016/j.apenergy.2015.09.037

Bermudez, J. M., Evangelopoulou, S., & Pavan, F. (2023, July 10). *Hydrogen*. IEA. https://www.iea.org/energy-system/low-emission-fuels/hydrogen

Berrill, P., Arvesen, A., Scholz, Y., Gils, H. C., & Hertwich, E. G. (2016). Environmental impacts of high penetration renewable energy scenarios for Europe. *Environmental Research Letters*, *11*(1). https://doi.org/10.1088/1748-9326/11/1/014012

Bert Den Ouden, B., Lintmeijer, N., Van, J., Ce, A., Maarten, D., Harry, A., Marit Van Lieshout, C., Klop, E., Waggeveld, R., & Grift, J. (2017). *Electrification in the Dutch process industry: In-depth study of promising transition pathways and innovation opportunities for electrification in the Dutch process industry*.

Bhandari, R., Trudewind, C. A., & Zapp, P. (2014). Life cycle assessment of hydrogen production via electrolysis – a review. *Journal of Cleaner Production*, *85*, 151–163. https://doi.org/10.1016/J.JCLEPRO.2013.07.048

Börjeson, L., Höjer, M., Dreborg, K. H., Ekvall, T., & Finnveden, G. (2006). Scenario types and techniques: Towards a user's guide. *Futures*, *38*(7), 723–739. https://doi.org/10.1016/j.futures.2005.12.002

Bossel, U., & Eliasson, B. (n.d.). *Energy Hydrogen Economy*. Retrieved July 16, 2023, from https://afdc.energy.gov/files/pdfs/hyd_economy_bossel_eliasson.pdf

Bridgwater, T. (2006). Biomass for energy. *Journal of the Science of Food and Agriculture*, *86*(12), 1755–1768. https://doi.org/10.1002/jsfa.2605

Bühler, F. ; M., Holm, F. ;, Elmegaard, B., Bühler, F., & Holm, F. M. (2023). *Potentials for the electrification of industrial processes in Denmark*. POLAND.

Caserini, S., Livio, S., Giugliano, M., Grosso, M., & Rigamonti, L. (2010). LCA of domestic and centralized biomass combustion: The case of Lombardy (Italy). *Biomass and Bioenergy*, *34*(4), 474–482. https://doi.org/10.1016/j.biombioe.2009.12.011

CBS. (2022). *Welke sectoren stoten broeikasgassen uit?* https://www.cbs.nl/nl-nl/dossier/dossier-broeikasgassen/welke-sectoren-stoten-broeikasgassen-uit-

Cherubini, F., & Strømman, A. H. (2011). Life cycle assessment of bioenergy systems: State of the art and future challenges. In *Bioresource Technology* (Vol. 102, Issue 2, pp. 437–451). https://doi.org/10.1016/j.biortech.2010.08.010

Cho, H. H., & Strezov, V. (2020). A Comparative Review on the Environmental Impacts of Combustion-Based Electricity Generation Technologies. In *Energy and Fuels* (Vol. 34, Issue 9, pp. 10486–10502). American Chemical Society. https://doi.org/10.1021/acs.energyfuels.0c02139

Cho, R. (2016, October 19). *Is Biomass Really Renewable?* Columbia Climate School. https://news.climate.columbia.edu/2011/08/18/is-biomass-really-renewable/

Classen, M., Althaus, H.-J., Blaser, S., Scharnhorst EMPA, W., Matthias Tuchschmid, D., Jungbluth, N., & Faist Emmenegger, M. (2009). *Life Cycle Inventories of Metals*. www.ecoinvent.ch

Clini, C., Musu, I., & Lodovica Gullino, M. (2008). *Sustainable Development and Environmental Management*. Springer.

Codelco. (n.d.). *Advancing our 2030 targets in Sustainable Development Commitments*. Retrieved June 25, 2023, from https://www.codelco.com/sites/site/edic/base/port/avances_sustentabilidad_ingles.html

Collins, L. (2022, August 2). *"World's cheapest green hydrogen" | Start-up with ultra-efficient electrolyser to develop pilot factory after securing $29m*. Recharge News. https://www.rechargenews.com/energy-transition/worlds-cheapest-green-hydrogen-start-up-with-ultra-efficient-electrolyser-to-develop-pilot-factory-after-securing-29m/2-1-1270403

Connelly, E., Elgowainy, A., Ruth, M., Vickers, J., Randolph, K., Levi, P., Kim, T.-Y., Zhang, K., Burgunder, A., Rustagi, N., Joseck, F., Miller, E., & Satyapal, S. (2019). *DOE Hydrogen and Fuel Cells Program Record 19002: Current Hydrogen Market Size: Domestic and Global*. https://www.hydrogen.energy.gov/pdfs/19002-hydrogen-market-domestic-global.pdf

Constellation. (2023). *What is Clean Energy?* https://www.constellation.com/energy-101/energy-innovation/what-is-clean-energy.html#:~:text=The%20use%20of%20clean%20energy,during%20the%20electricity%20generating%20process.

Cucurachi, S., van der Giesen, C., & Guinée, J. (2018). Ex-ante LCA of Emerging Technologies. *Procedia CIRP*, *69*, 463–468. https://doi.org/10.1016/j.procir.2017.11.005

Davey, R. (2022, March 22). Working Towards a Sustainable Copper Mining Industry. *AZO Mining*. https://www.azomining.com/Article.aspx?ArticleID=1647

de Bruijn, E., van Doesburg, H., Hoogcarspel, J., & Spek, T. (2022, January 12). Opinie: 'Echt, zonder kernenergie gaat de groene energietransitie niet lukken.' *Het Parool*. https://www.parool.nl/columns-opinie/opinie-echt-zonder-kernenergie-gaat-de-groene-energietransitie-niet-lukken~bd103adc/

de Bruyn, S., Jongsma, C., Kampman, B., Görlach, B., & Thie, J.-E. (2020). *Energy-intensive industries Challenges and opportunities in energy transition*.

de Laat, P. (2020). *Overview of Hydrogen Projects in the Netherlands*. https://www.topsectorenergie.nl/sites/default/files/uploads/TKI%20Gas/publicaties/Overview%20Hydrogen%20projects%20in%20the%20Netherlands_0.pdf

Deloitte. (2023). *Assessment of green hydrogen for industrial heat*. https://www2.deloitte.com/content/dam/Deloitte/us/Documents/Advisory/us-advisory-assessment-of-green-hydrogen-for-industrial-heat.pdf

Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A., & Cucurachi, S. (2021). Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *Journal of Cleaner Production*, *299*, 126866. https://doi.org/10.1016/J.JCLEPRO.2021.126866

Demirbas, A. (2005). Potential applications of renewable energy sources, biomass combustion problems in boiler power systems and combustion related environmental issues. In *Progress in Energy and Combustion Science* (Vol. 31, Issue 2, pp. 171–192). Elsevier Ltd. https://doi.org/10.1016/j.pecs.2005.02.002

Derwent, R., Simmonds, P., O'Doherty, S., Manning, A., Collins, W., & Stevenson, D. (2006). Global environmental impacts of the hydrogen economy. *International Journal of Nuclear Hydrogen Production and Applications*, *1*(1), 57. https://doi.org/10.1504/ijnhpa.2006.009869

Di Lullo, G., Giwa, T., Okunlola, A., Davis, M., Mehedi, T., Oni, A. O., & Kumar, A. (2022). Large-scale long-distance land-based hydrogen transportation systems: A comparative techno-economic and greenhouse gas emission assessment. *International Journal of Hydrogen Energy*, *47*(83), 35293–35319. https://doi.org/10.1016/j.ijhydene.2022.08.131

Directorate-General for Energy. (n.d.). *Secure gas supplies*. Retrieved July 5, 2023, from https://energy.ec.europa.eu/topics/energy-security/secure-gas-supplies_en

Directorate-General for Environment. (n.d.). *Environmental Footprint methods*. Retrieved May 11, 2023, from https://green-business.ec.europa.eu/environmental-footprint-methods_en

Dones, R., Bauer, C., Bolliger, R., Burger, B., Heck, T., Röder, A., Faist, M., Frischknecht, R., Jungbluth, N., & Tuchschmid, M. (2007). *Life Cycle Inventories of Energy Systems: Results for Current Systems in Switzerland and other UCTE Countries*. http://www.ecoinvent.org/

Dufour, J., Serrano, D. P., Gálvez, J. L., González, A., Soria, E., & Fierro, J. L. G. (2012). Life cycle assessment of alternatives for hydrogen production from renewable and fossil sources. *International Journal of Hydrogen Energy*, *37*(2), 1173–1183. https://doi.org/10.1016/j.ijhydene.2011.09.135

Durrant, A., Dai, Y., & Shang, K. (2022, June 21). Sustainable smelting: how green can it go? *Wood Mackenzie*. https://www.woodmac.com/news/opinion/sustainable-smelting-how-green-can-it-go/

ecoinvent. (n.d.). *FAQs*. Retrieved July 27, 2023, from https://ecoinvent.org/offerings/faqs/#1629117984500-2bc4b532-2240

EF reference package 3.1. (2022). European Commission. https://eplca.jrc.ec.europa.eu/LCDN/developerEF.xhtml

Ehrenfeld, J., & Gertler, N. (1997). Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg. *Journal of Industrial Ecology*, *1*(1), 67–79. https://doi.org/10.1162/jiec.1997.1.1.67

EIA. (2016). *International Energy Outlook 2016*. www.eia.gov

ElementNL. (n.d.). *Alles over aardgas*. Retrieved July 5, 2023, from https://www.onsaardgas.nl/alles-over-aardgas/

Engström, F., Adolfsson, D., Yang, Q., Samuelsson, C., & Björkman, B. (2010). Crystallization behaviour of some steelmaking slags. *Steel Research International*, *81*(5), 362–371. https://doi.org/10.1002/srin.200900154

EPA. (2023, July 13). *Nitrogen Oxides (NOx) Control Regulations*. https://www3.epa.gov/region1/airquality/nox.html#:~:text=The%20EPA%20established%20the%20statewide,from%20sources%201990%20emissions%20rate

European Commission. (2019). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE EUROPEAN COUNCIL, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS The European Green Deal* (Issue COM(2019) 640 final). https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0640

European Commission. (2021). *Understanding Product Environmental Footprint and Organisation Environmental Footprint methods*.

Famiglietti, J., Toppi, T., Pistocchini, L., Scoccia, R., & Motta, M. (2021). A comparative environmental life cycle assessment between a condensing boiler and a gas driven absorption heat pump. *Science of the Total Environment*, *762*. https://doi.org/10.1016/j.scitotenv.2020.144392

Fan, Z., Sheerazi, H., Bhardwaj, A., Corbeau, A.-S., Longobardi, K., Castañeda, A., Merz, A.-K., Caleb, D. R., Woodall, M., Agrawal, M., & Orozco-Sanchez, S. (2022). *HYDROGEN LEAKAGE: A POTENTIAL RISK FOR THE HYDROGEN ECONOMY*. https://energypolicy.columbia.edu/about/partners.

Fraile, D., Lanoix, J.-C., Maio, P., Rangel, A., & Torres, A. (2015). *Overview of the market segmentation for hydrogen across potential customer groups, based on key application areas*.

Franx, L. (2022, April 11). Liander gaat elektriciteitsnet in vijf Nederlandse provincies uitbreiden. *Tweakers*. https://tweakers.net/nieuws/195444/liander-gaat-elektriciteitsnet-in-vijf-nederlandse-provincies-uitbreiden.html

Freund, S., & Sánchez, D. (2022). Green hydrogen market and growth. In *Machinery and Energy Systems for the Hydrogen Economy* (pp. 605–635). Elsevier. https://doi.org/10.1016/B978-0-323-90394-3.00001-1

Frischknecht, R., Althaus, H.-J., Bauer, C., & Heck, T. (2007). The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. *The International Journal of Life Cycle Assessment* , *12*(1). https://doi.org/10.1065/lca2007.02.309

Frischknecht, R., Tuchschmid, M., Faist-Emmenegger, M., Bauer, C., & Dones, R. (2007). *Strommix und Stromnetz*. http://www.ecoinvent.org/

Fthenakis, V., & Kim, H. C. (2009). Land use and electricity generation: A life-cycle analysis. In *Renewable and Sustainable Energy Reviews* (Vol. 13, Issues 6–7, pp. 1465–1474). https://doi.org/10.1016/j.rser.2008.09.017

Fuel Cells and Hydrogen 2 Joint Undertaking. (2019). *Hydrogen roadmap Europe : a sustainable pathway for the European energy transition*. https://doi.org/10.2843/249013

Gargiulo, A., Girardi, P., & Temporelli, A. (2017). LCA of electricity networks: a review. In *International Journal of Life Cycle Assessment* (Vol. 22, Issue 10, pp. 1502–1513). Springer Verlag. https://doi.org/10.1007/s11367-017-1279-x

Gasunie. (2022, February 28). *Gasunie zet extra stappen om leveringszekerheid van gas in Nederland en Europa veilig te stellen*. https://www.gasunie.nl/nieuws/gasunie-zet-extra-stappen-om-leveringszekerheid-van-gas-in-nederland-en-europa-veilig-te-stellen

Gasunie. (2023a). *Aardgas*. https://www.gasunie.nl/expertise/aardgas

Gasunie. (2023b). *Waterstofnetwerk Nederland*. https://www.gasunie.nl/projecten/waterstofnetwerk-nederland

Gasunie. (2023c, June 27). *Landelijk waterstofnetwerk gaat van start in Rotterdam*. https://www.gasunie.nl/nieuws/landelijk-waterstofnetwerk-gaat-van-start-in-rotterdam#:~:text=Dit%20landelijke%20waterstofnetwerk%2C%20dat%20ongeveer,Duitsland%20en%20Belgi%C3%AB%2C%20met%20elkaar.

Gerres, T., Chaves Ávila, J. P., Llamas, P. L., & San Román, T. G. (2019). A review of cross-sector decarbonisation potentials in the European energy intensive industry. *Journal of Cleaner Production*, *210*, 585–601. https://doi.org/10.1016/j.jclepro.2018.11.036

Gibbens, S. (2021, November 15). Europa gebruikt omstreden 'hernieuwbare' brandstof: bomen uit de VS. *National Geographic*. https://www.nationalgeographic.nl/europa-gebruikt-omstreden-hernieuwbare-brandstof-bomen-uit-de-vs

Goldemberg, J., & Teixeira Coelho, S. (2004). Renewable energy - Traditional biomass vs. modern biomass. *Energy Policy*, *32*(6), 711–714. https://doi.org/10.1016/S0301-4215(02)00340-3

Gosman, K., Hartman, K., Hein, J., Huijsinga, M., & Kluver, L. (2021). *Offshore Elektrolyse*. https://vissersbond.nl/wp-content/uploads/2023/07/3.-Offshore-Elektrolyse-Een-onderzoek-naar-de-publieke-opinie-NET-Shell.pdf

Greenfield, C. (2023, July 11). *Natural Gas*. IEA. https://www.iea.org/energy-system/fossil-fuels/natural-gas

Grol, C. (2020, October 2). Windpark Veenkolonien van verzet naar verdrietige berusting. *Financieel Dagblad*. https://fd.nl/weekend/1355616/windpark-veenkolonien-van-verzet-naar-verdrietige-berusting

Guinée, J. B., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., de Koning, A., van Oers, L., Wegener Sleeswijk, A., Suh, S., Udo de Haes, H. A., de Bruijn, H., van Duin, R., & Huijbregts, M. A. J. (2002). *Handbook on Life Cycle Assessment, Operational Guide to the ISO Standards*. Kluwer Academic Publishers.

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science and Technology*, *45*(1), 90–96. https://doi.org/10.1021/es101316v

Hacatoglu, K., Rosen, M. A., & Dincer, I. (2012). Comparative life cycle assessment of hydrogen and other selected fuels. *International Journal of Hydrogen Energy*, *37*(13), 9933–9940. https://doi.org/10.1016/j.ijhydene.2012.04.020

Hakkenes, E. (2020, July 2). Hoe biomassa van belofte een bedreiging werd. *Trouw*. https://www.trouw.nl/duurzaamheid-economie/hoe-biomassa-van-belofte-een-bedreiging-werd~bb57a12b/

Hanif, M. A., Nadeem, F., Tariq, R., & Rashid, U. (2022). Future energy options: an overview. In *Renewable and Alternative Energy Resources* (pp. 113–169). Elsevier. https://doi.org/10.1016/b978-0-12-818150-8.00009-5

Harris, S. (2007). Industrial Symbiosis in the Kwinana Industrial Area (Western Australia). *Measurement and Control*, *40*(8), 239–244. https://doi.org/10.1177/002029400704000802

Harrison, G. P., Maclean, E. (Ned) J., Karamanlis, S., & Ochoa, L. F. (2010). Life cycle assessment of the transmission network in Great Britain. *Energy Policy*, *38*(7), 3622–3631. https://doi.org/10.1016/j.enpol.2010.02.039

Havukainen, J., Nguyen, M. T., Väisänen, S., & Horttanainen, M. (2018). Life cycle assessment of small-scale combined heat and power plant: Environmental impacts of different forest biofuels and replacing district heat produced from natural gas. *Journal of Cleaner Production*, *172*, 837–846. https://doi.org/10.1016/j.jclepro.2017.10.241

Hers, S., Oliveira Machado dos Santos, C., Lamboo Sam, van Dril, T., Raadschelders, J., Mallon, W., de Ronde, M., Goemans, C., de Klerk, I., Tonneijck, S., van Dijk, H., Kreiter, R., de Haans, A., & ten Cate, A. (2021). *Elektrificatie: cruciaal voor een duurzame industrie*.

Hers, S., Scholten, T., van der Veen, R., van de Water, S., Leguijt, C., & Rooijers, F. (2018). *Waterstofroutes Nederland: Blauw, groen en import*. www.ce.nl

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2015). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America*, *112*(20), 6277–6282. https://doi.org/10.1073/pnas.1312753111

Het 6e industriecluster: Waterstofbackbone en energie infrastructuur. (2022). https://www.knb-keramiek.nl/media/269105/2022-172-position-paper-6e-cluster.pdf

Hettema, B., & Lammers, J. (2023, March 8). Nog meer windmolens op land dan gepland? Er zijn alternatieven om klimaatdoelen te halen, blijkt uit onderzoek. *Een Vandaag*. https://eenvandaag.avrotros.nl/item/nog-meer-windmolens-op-land-dan-gepland-er-zijn-alternatieven-om-klimaatdoelen-te-halen-blijkt-uit-onderzoek/

Höjer, M., Ahlroth, S., Dreborg, K. H., Ekvall, T., Finnveden, G., Hjelm, O., Hochschorner, E., Nilsson, M., & Palm, V. (2008). Scenarios in selected tools for environmental systems analysis. *Journal of Cleaner Production*, *16*(18), 1958–1970. https://doi.org/10.1016/j.jclepro.2008.01.008

Honore, A. (2019). *Decarbonization and industrial demand for gas in Europe*. https://doi.org/10.26889/9781784671396

Huismans, M., & Voswinkel, F. (2023, July 11). *Electrification*. IEA. https://www.iea.org/energy-system/electricity/electrification

Hydrogen Council. (2021). *Hydrogen decarbonization pathways A life-cycle assessment*. www.hydrogencouncil.com.

IEA. (2020). *Energy Technology Perspectives 2020*. https://www.iea.org/reports/energy-technology-perspectives-2020

IEA. (2022a). *A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas*. https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas

IEA. (2022b, September 27). *Heating*. IEA. https://www.iea.org/fuels-and-technologies/heating

Ilbas, M., Yilmaz, I., Veziroglu, T. N., & Kaplan, Y. (2005). Hydrogen as burner fuel: Modelling of hydrogen-hydrocarbon composite fuel combustion and NOx formation in a small burner. *International Journal of Energy Research*, *29*(11), 973–990. https://doi.org/10.1002/er.1104

Import van Waterstof. (n.d.). Port of Rotterdam. Retrieved July 17, 2023, from https://www.portofrotterdam.com/nl/haven-van-de-toekomst/energietransitie/lopende-projecten/waterstof-rotterdam/import-van-waterstof

In 10 jaar het elektriciteitsnet verdubbelen, wat je normaal in 40 jaar doet. (2023, January 30). *Verkeerskunde*. https://www.verkeerskunde.nl/artikel/in-10-jaar-het-elektriciteitsnet-verdubbelen-wat-je-normaal-in-40-jaar-doet

International Organization for Standardization. (2006). *ISO 14040:2006 Environmental management—life cycle assessment—principles and framework*. https://www.iso.org/standard/37456.html

International Renewable Energy Agency, T. (n.d.). *Future of Solar Photovoltaic*.

Jaarbeurs. (2022, March 28). SNEL TOENEMENDE VRAAG NAAR ELEKTRICITEIT VERHOOGT DRUK OP UITBREIDING ELEKTRICITEITSNET. *Maakindustrie Nieuws*. https://www.maakindustrie.nl/nieuws/energie/snel-toenemende-vraag-naar-elektriciteit-verhoogt-druk-op-uitbreiding-elektriciteitsnet/

Jaeger, H., & deBiasi, V. (2022, November 2). *NEEDED: ELECTROLYZERS PRODUCING CHEAP, GREEN, HYDROGEN*. Gas Turbine World. https://gasturbineworld.com/electrolyzers-green-hydrogen/#:~:text=In%20the%20real%20world%2C%20the,conversion%20efficiency%20of%20about%2060%25

Janssen, L. (2021, February 23). Verzet tegen windpark Venray groeit: ‘De mensen voelen zich niet serieus genomen.’ *De Limburger*. https://www.limburger.nl/cnt/dmf20210223_95391854

Jha, S. N. (2023, March). *Steel Scrap Market*. Fact.MR. https://www.factmr.com/report/steel-scrap-market

Jorge, R. S., & Hertwich, E. G. (2014). Grid infrastructure for renewable power in Europe: The environmental cost. *Energy*, *69*, 760–768. https://doi.org/10.1016/j.energy.2014.03.072

Kato, T., Kubota, M., Kobayashi, N., & Suzuoki, Y. (2005). Effective utilization of by-product oxygen from electrolysis hydrogen production. *Energy*, *30*(14), 2580–2595. https://doi.org/10.1016/j.energy.2004.07.004

KiesZon. (2023). *Wat zijn de oplossingen om congestie te verminderen?* https://www.kieszon.nl/kennisbank/bericht/congestie/

Kleefkens, O., & Spoelstra, S. (2014). *R&D on Industrial Heat Pumps*.

Koj, J. C., Wulf, C., Schreiber, A., & Zapp, P. (2017). Site-dependent environmental impacts of industrial hydrogen production by alkalinewater electrolysis. *Energies*, *10*(7). https://doi.org/10.3390/en10070860

Koroneos, C., Dompros, A., Roumbas, G., & Moussiopoulos, N. (2004). Life cycle assessment of hydrogen fuel production processes. *International Journal of Hydrogen Energy*, *29*(14), 1443–1450. https://doi.org/10.1016/j.ijhydene.2004.01.016

Kosmadakis, G. (2019). Estimating the potential of industrial (high-temperature) heat pumps for exploiting waste heat in EU industries. *Applied Thermal Engineering*, *156*, 287–298. https://doi.org/10.1016/j.applthermaleng.2019.04.082

Kouloumpis, V., Stamford, L., & Azapagic, A. (2015). Decarbonising electricity supply: Is climate change mitigation going to be carried out at the expense of other environmental impacts? *Sustainable Production and Consumption*, *1*, 1–21. https://doi.org/10.1016/j.spc.2015.04.001

Kuepper, B. (2021). *Dutch Wood Pellet Imports Is Dutch Biomass Burning Contributing to Forest Loss in Baltic States?* https://www.greenpeace.org/static/planet4-netherlands-stateless/2021/06/7c0ec271-wood-pellets-nl-210603-final.pdf

Kuo, G. (2019, May 23). *When Fossil Fuels Run Out, What Then?* MAHB. https://mahb.stanford.edu/library-item/fossil-fuels-run/

Kurmayer, N. J. (2021, October 19). *Scientists warn against global warming effect of hydrogen leaks*. Euractiv. https://www.euractiv.com/section/energy/news/scientists-warn-against-global-warming-effect-of-hydrogen-leaks/

Lan, R., Irvine, J. T. S., & Tao, S. (2012). Ammonia and related chemicals as potential indirect hydrogen storage materials. In *International Journal of Hydrogen Energy* (Vol. 37, Issue 2, pp. 1482–1494). https://doi.org/10.1016/j.ijhydene.2011.10.004

Laughlin, R. B., & Freund, S. (2022). Economics of hydrogen fuel. *Machinery and Energy Systems for the Hydrogen Economy*, 305–330. https://doi.org/10.1016/B978-0-323-90394-3.00012-6

Lechtenböhmer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy*, *115*, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110

Lehner, F., & Hart, D. (2021). The importance of water electrolysis for our future energy system. In *Electrochemical Power Sources: Fundamentals, Systems, and Applications Hydrogen Production by Water Electrolysis* (pp. 1–36). Elsevier. https://doi.org/10.1016/B978-0-12-819424-9.00008-2

Lerma, A. (2021, September 16). *Hydrogen Fuel Cell Efficiency: How Does it Compare to Lithium-Ion?* https://www.fluxpower.com/blog/hydrogen-fuel-cell-efficiency-how-does-it-compare-to-lithium-ion#:~:text=In%20order%20to%20produce%20hydrogen,converting%20the%20hydrogen%20into%20electricity.

Li, W., & Xue, X. (2019). Emission reduction research and formation of hexavalent chromium in stainless steel smelting: Cooling rate and boron oxide addition effects. *Process Safety and Environmental Protection*, *122*, 131–143. https://doi.org/10.1016/J.PSEP.2018.11.025

Linares, N., Silvestre-Albero, A. M., Serrano, E., Silvestre-Albero, J., & García-Martínez, J. (2014). Mesoporous materials for clean energy technologies. In *Chemical Society Reviews* (Vol. 43, Issue 22, pp. 7681–7717). Royal Society of Chemistry. https://doi.org/10.1039/c3cs60435g

Louwes, W. (2021, June 7). Omwonenden in actie tegen zonnepark bij Het Rutbeek: "Het geeft sociale spanning." *RTV Oost*. https://www.rtvoost.nl/nieuws/1961282/omwonenden-in-actie-tegen-zonnepark-bij-het-rutbeek-het-geeft-sociale-spanning

Lu, L., Pan, J., & Zhu, D. (2015). Quality requirements of iron ore for iron production. In *Iron Ore: Mineralogy, Processing and Environmental Sustainability* (pp. 476–504). Elsevier Inc. https://doi.org/10.1016/B978-1-78242-156-6.00016-2

Lucas, A., Neto, R. C., & Silva, C. A. (2012). Impact of energy supply infrastructure in life cycle analysis of hydrogen and electric systems applied to the Portuguese transportation sector. *International Journal of Hydrogen Energy*, *37*(15), 10973–10985. https://doi.org/10.1016/j.ijhydene.2012.04.127

Mac Kinnon, M. A., Brouwer, J., & Samuelsen, S. (2018). The role of natural gas and its infrastructure in mitigating greenhouse gas emissions, improving regional air quality, and renewable resource integration. In *Progress in Energy and Combustion Science* (Vol. 64, pp. 62–92). Elsevier Ltd. https://doi.org/10.1016/j.pecs.2017.10.002

Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K. A., Krüger, C., & Luderer, G. (2020). The CO2reduction potential for the European industry via direct electrification of heat supply (power-to-heat). *Environmental Research Letters*, *15*(12). https://doi.org/10.1088/1748-9326/abbd02

Maggio, G., Squadrito, G., & Nicita, A. (2022). Hydrogen and medical oxygen by renewable energy based electrolysis: A green and economically viable route. *Applied Energy*, *306*. https://doi.org/10.1016/j.apenergy.2021.117993

Marashli, A., Gasaymeh, A. M., & Shalby, M. (2022). Comparing the Global Warming Impact from Wind, Solar Energy, and Other Electricity Generating Systems through Life Cycle Assessment Methods (A Survey). *International Journal of Renewable Energy Research*, *12*(2), 899–920. https://doi.org/10.20508/ijrer.v12i2.13010.g8474

Mckendry, P. (2002). Energy production from biomass (part 1): overview of biomass. *Bioresource Technology*, *83*(1), 37–46.

Mendez-Alva, F., Cervo, H., Krese, G., Van Eetvelde, G., & Ene Cervo, H. (2021). Industrial symbiosis profiles in energy-intensive industries: Sectoral insights from open databases. *Journal of Cleaner Production*, *314*. https://doi.org/10.1016/j.jclepro.2021.128031ï

Mendoza Beltran, A., Cox, B., Mutel, C., van Vuuren, D. P., Font Vivanco, D., Deetman, S., Edelenbosch, O. Y., Guinée, J., & Tukker, A. (2020). When the Background Matters: Using Scenarios from Integrated Assessment Models in Prospective Life Cycle Assessment. *Journal of Industrial Ecology*, *24*(1), 64–79. https://doi.org/10.1111/jiec.12825

Milieu Centraal. (n.d.-a). *Biomassa*. Retrieved July 15, 2023, from https://www.milieucentraal.nl/klimaat-en-aarde/energiebronnen/biomassa/

Milieu Centraal. (n.d.-b). *Waterstof*. Retrieved July 16, 2023, from https://www.milieucentraal.nl/klimaat-en-aarde/energiebronnen/waterstof/

Mineral Products Association. (n.d.). *Electric arc furnace carbon steel slag (EAF)*. Retrieved May 29, 2023, from https://www.mineralproducts.org/Mineral-Products/Slag/Electric-arc-furnace-carbon-steel-slag.aspx

Ministerie van Algemene Zaken. (n.d.-a). *Afbouw gaswinning Groningen*. Retrieved July 5, 2023, from https://www.rijksoverheid.nl/onderwerpen/gaswinning-in-groningen/afbouw-gaswinning-groningen#:~:text=De%20bevingen%20hebben%20onder%20meer,stopt%20de%20gaswinning%20in%20Groningen.

Ministerie van Algemene Zaken. (n.d.-b). *Maatregelen Klimaatakkoord per sector*. Retrieved July 5, 2023, from https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/klimaatakkoord/maatregelen-klimaatakkoord-per-sector

Ministerie van Algemene Zaken. (n.d.-c). *Reducing dependence on Russia*. Retrieved July 5, 2023, from https://www.government.nl/topics/gas/reducing-dependence-on-russia

Ministerie van Algemene Zaken. (n.d.-d). *Rijksoverheid stimuleert ontwikkeling bio-energie*. Retrieved July 15, 2023, from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/bio-energie

Ministerie van Algemene Zaken. (n.d.-e). *Stimulering gebruik van waterstof*. Retrieved July 16, 2023, from https://www.rijksoverheid.nl/onderwerpen/duurzame-energie/overheid-stimuleert-de-inzet-van-meer-waterstof

Ministerie van Algemene Zaken. (n.d.-f). *Voortgang klimaatdoelen*. Retrieved July 5, 2023, from https://www.rijksoverheid.nl/onderwerpen/klimaatverandering/voortgang-klimaatdoelen

Ministerie van Algemene Zaken. (2022, September 16). *Nederland maakt ambitie wind op zee bekend: 70 gigawatt in 2050*. https://www.rijksoverheid.nl/actueel/nieuws/2022/09/16/nederland-maakt-ambitie-wind-op-zee-bekend-70-gigawatt-in-2050

Ministerie van Binnenlandse Zaken en Koninkrijksrelaties. (2023). *Activiteitenbesluit milieubeheer*. Overheid.Nl. https://wetten.overheid.nl/BWBR0022762/2022-09-21#Hoofdstuk3

Ministerie van Economische Zaken en Klimaat. (n.d.). *Wat is het doel van het Klimaatakkoord?* Retrieved October 25, 2022, from https://www.klimaatakkoord.nl/klimaatakkoord/vraag-en-antwoord/wat-is-het-doel-van-het-klimaatakkoord

Ministerie van Economische Zaken en Klimaat. (2019a). *Klimaatakkoord Hoofdstuk Biomassa*. https://www.klimaatakkoord.nl/themas/biomassa/documenten/publicaties/2019/06/28/klimaatakkoord-hoofdstuk-biomassa

Ministerie van Economische Zaken en Klimaat. (2019b). *Klimaatakkoord Hoofdstuk Elektriciteit*. https://www.klimaatakkoord.nl/elektriciteit

Ministerie van Economische Zaken en Klimaat. (2019c). *Klimaatakkoord hoofdstuk Industrie*. https://www.klimaatakkoord.nl/industrie/documenten/publicaties/2019/06/28/kliimaatakkoord-hoofdstuk-industrie

Ministerie van Economische Zaken en Klimaat. (2019d). *Klimaatakkoord hoofdstuk Waterstof*. https://www.klimaatakkoord.nl/themas/waterstof/documenten/publicaties/2019/06/28/klimaatakkoord-hoofdstuk-waterstof

Ministerie van Economische Zaken en Klimaat. (2022). *Klimaatnota 2022*. https://www.rijksoverheid.nl/documenten/publicaties/2022/11/01/klimaatnota-2022

Ministry of the Environment. (2021, July 12). *Guideline A-9: NOx Emissions from Boilers and Heaters*. https://www.ontario.ca/page/guideline-9-nox-emissions-boilers-and-heaters

Mohammad, N., Mohamad Ishak, W. W., Mustapa, S. I., & Ayodele, B. V. (2021). Natural Gas as a Key Alternative Energy Source in Sustainable Renewable Energy Transition: A Mini Review. In *Frontiers in Energy Research* (Vol. 9). Frontiers Media S.A. https://doi.org/10.3389/fenrg.2021.625023

Monique. (2023, March 14). TenneT verwacht 8 miljard euro per jaar te investeren in uitbreiding elektriciteitsnet. *Industrielinqs*. https://industrielinqs.nl/tennet-verwacht-8-miljard-euro-per-jaar-te-investeren-in-uitbreiding-elektriciteitsnet/

Moreau, K., Laamanen, C., Bose, R., Shang, H., & Scott, J. A. (2021). Environmental impact improvements due to introducing automation into underground copper mines. *International Journal of Mining Science and Technology*, *31*(6), 1159–1167. https://doi.org/10.1016/j.ijmst.2021.11.009

Myllyviita, T., Holma, A., Antikainen, R., Lähtinen, K., & Leskinen, P. (2012). Assessing environmental impacts of biomass production chains - Application of life cycle assessment (LCA) and multi-criteria decision analysis (MCDA). *Journal of Cleaner Production*, *29–30*, 238–245. https://doi.org/10.1016/j.jclepro.2012.01.019

Nationaal Waterstof Programma. (2022). *Routekaart Waterstof*. www.nationaalwaterstofprogramma.nl

National Energy Technology Laboratory. (2022). *A LITERATURE REVIEW OF HYDROGEN AND NATURAL GAS TURBINES: CURRENT STATE OF THE ART WITH REGARD TO PERFORMANCE AND NO X CONTROL A LITERATURE REVIEW OF HYDROGEN AND NATURAL GAS TURBINES: CURRENT STATE OF THE ART WITH REGARD TO PERFORMANCE AND NOX CONTROL*. https://netl.doe.gov/sites/default/files/publication/A-Literature-Review-of-Hydrogen-and-Natural-Gas-Turbines-081222.pdf

Nauta, M. (2018, July 4). Omwonenden mega-zonnepark met handen in het haar: "Wie is er nog voor ons?" *RTV Noord*. https://www.rtvnoord.nl/nieuws/196169/omwonenden-mega-zonnepark-met-handen-in-het-haar-wie-is-er-nog-voor-ons

Nederlandse Aardolie Maatschappij. (n.d.). *Historie van aardgas en aardolie*. Retrieved July 5, 2023, from https://www.nam.nl/gas-en-olie/aardgas/historie-van-aardgas-en-olie.html

Nederlandse Emissieauthoriteit. (2019). *Feiten en cijfers over emissiehandel in Europa en Nederland*.

Neuwirth, M., Fleiter, T., Manz, P., & Hofmann, R. (2022). The future potential hydrogen demand in energy-intensive industries - a site-specific approach applied to Germany. *Energy Conversion and Management*, *252*. https://doi.org/10.1016/j.enconman.2021.115052

Nicoletti, G., Arcuri, N., Nicoletti, G., & Bruno, R. (2015). A technical and environmental comparison between hydrogen and some fossil fuels. *Energy Conversion and Management*, *89*, 205–213. https://doi.org/10.1016/j.enconman.2014.09.057

Nitkiewicz, A., & Sekret, R. (2014). Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Conversion and Management*, *87*, 647–652. https://doi.org/10.1016/j.enconman.2014.07.032

Northey, S., Haque, N., & Mudd, G. (2013). Using sustainability reporting to assess the environmental footprint of copper mining. *Journal of Cleaner Production*, *40*, 118–128. https://doi.org/10.1016/j.jclepro.2012.09.027

NWEA. (2023, June 22). *Wind op Zee, Kernenergie en Waterstof: 3 nieuwe Informatiekaarten*. https://klimaatweb.nl/nieuws/wind-op-zee-kernenergie-en-waterstof-3-nieuwe-informatiekaarten/

Ocko, I. B., & Hamburg, S. P. (2022). Climate consequences of hydrogen emissions. *Atmospheric Chemistry and Physics*, *22*(14), 9349–9368. https://doi.org/10.5194/acp-22-9349-2022

Olsson, O., & Schipfer, F. (2021). *Decarbonizing industrial process heat: the role of biomass*. https://www.ieabioenergy.com/wp-content/uploads/2022/02/Role-of-biomass-in-industrial-heat.pdf

PARAT. (2021). *High Voltage Electrode Boiler*. https://www.parat.no/media/eigabtot/parat-ieh-english-2021.pdf

Park, J., Park, J., & Park, H. (2019). Scaling-Up of Industrial Symbiosis in the Korean National Eco-Industrial Park Program: Examining Its Evolution over the 10 Years between 2005–2014. *Journal of Industrial Ecology*, *23*(1), 197–207. https://doi.org/10.1111/jiec.12749

Pavan, F., Bermudez, J. M., Evangelopoulou, S., & Bennett, S. (2023, July 10). *Electrolysers*. IEA. https://www.iea.org/energy-system/low-emission-fuels/electrolysers

PosHYdon pilot, Dutch North Sea. (2022). Neptune Energy. https://www.neptuneenergy.com/esg/poshydon-hydrogen-pilot

PricewaterhouseCoopers Advisory. (2021). *De energietransitie en de financiële impact voor netbeheerders*. https://www.netbeheernederland.nl/_upload/RadFiles/New/Documents/20210407-Finaal%20rapport%20Project%20FIEN.pdf

Quist, Z. (2023, February 14). *Product Environmental Footprint (PEF) – A Complete Overview*. Ecochain. https://ecochain.com/knowledge/product-environmental-footprint/#:~:text=The%20PEF%20is%20based%20on,and%20comparable%20Life%20Cycle%20Assessment

Radowitz, B. (2022, September 9). “Don’t expect large-scale application of hydrogen until after 2030” | TenneT CEO. *Recharge*.

Raga Mexico, G., Nakajima, T., Ramanathan, V., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D., Haywood, J., Lean, J., Lowe, D., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van, R., Solomon, C., Qin, D., … Averyt, K. (2007). *Changes in Atmospheric Constituents and in Radiative Forcing*.

Rahnama Mobarakeh, M., & Kienberger, T. (2022). Climate neutrality strategies for energy-intensive industries: An Austrian case study. In *Cleaner Engineering and Technology* (Vol. 10). Elsevier Ltd. https://doi.org/10.1016/j.clet.2022.100545

Rehfeldt, M., Fleiter, T., & Toro, F. (2017). A bottom-up estimation of heating and cooling demand in the European industry. *Energy Efficiency*, *11*(5), 1057–1082. https://doi.org/10.1007/s12053-017-9571-y

Renes, J. (2021, June 25). Aanhoudend verzet tegen zonnepark bij Vollenhove: “Als ik nu niet in actie kom, krijg ik later spijt.” *RTV Oost*. https://www.rtvoost.nl/nieuws/1981555/aanhoudend-verzet-tegen-zonnepark-bij-vollenhove-als-ik-nu-niet-in-actie-kom-krijg-ik-later-spijt

Renewable Iron Fuel Technology. (2022). *Iron Fuel Technology*.

RIFT. (2023). *Technology*. https://www.ironfueltechnology.com/technology/

Rijkswaterstaat. (n.d.-a). *Activiteitenbesluit 3.2.1*. Retrieved July 16, 2023, from https://www.infomil.nl/onderwerpen/lucht-water/stookinstallaties/kleine-en/emissiegrenswaarden/activiteitenbesluit/

Rijkswaterstaat. (n.d.-b). *Emissiegrenswaarden*. Retrieved July 16, 2023, from https://www.infomil.nl/onderwerpen/lucht-water/stookinstallaties/kleine-en/emissiegrenswaarden/

Rinne, S., & Syri, S. (2013). Heat pumps versus combined heat and power production as CO2 reduction measures in Finland. *Energy*, *57*, 308–318. https://doi.org/10.1016/j.energy.2013.05.033

Rodenburg, S. (2021, April 15). "Netbeheerders hebben tot 2050 100 miljard nodig voor energietransitie." *RTL Nieuws*. https://www.rtlnieuws.nl/economie/artikel/5225507/netbeheerders-100-miljard-2050-energietransitie-rapport-pwc

Roelofsen, O., Somers, K., Speelman, E., & Witteveen, M. (2020). *Plugging in: What electrification can do for industry*.

Rooijers, E. (2023, February 28). Nog jarenlang wachtlijsten voor aansluiting op het stroomnet. *Financieel Dagblad*. https://fd.nl/bedrijfsleven/1468954/nog-jarenlang-wachtlijsten-voor-aansluiting-op-het-stroomnet

Rootzén, J., Wiertzema, H., Brolin, M., & Fahnestock, J. (n.d.). *Electrify everything! Challenges and opportunities associated with increased electrification of industrial processes*.

Rubio, I. (2022, June 28). En ineens staat er een enorm transformatorhuisje voor je deur: 'Wen er maar aan, gaat steeds vaker gebeuren.' *AD*. https://www.ad.nl/wonen/en-ineens-staat-er-een-enorm-transformatorhuisje-voor-je-deur-wen-er-maar-aan-gaat-steeds-vaker-gebeuren~a378007c/?referrer=https%3A%2F%2Fwww.google.com%2F&cb=fb33379dd756a88d81cbd70ce4842cc7&auth_rd=1

RVO. (2022, June 27). *Ontwikkeling broeikasgasemissies in Nederland*. https://dashboardklimaatbeleid.nl/

Saidur, R., Abdelaziz, E. A., Demirbas, A., Hossain, M. S., & Mekhilef, S. (2011). A review on biomass as a fuel for boilers. In *Renewable and Sustainable Energy Reviews* (Vol. 15, Issue 5, pp. 2262–2289). https://doi.org/10.1016/j.rser.2011.02.015

Sakai, Y., Yabe, Y., Takahashi, M., Iizuka, A., Shibata, E., & Nakamura, T. (2013). Elution of hexavalent chromium from molten sewage sludge slag: Influence of sample basicity and cooling rate. *Industrial and Engineering Chemistry Research*, *52*(10), 3903–3909. https://doi.org/10.1021/ie303354j

Scheepers, M. (2022). *EEN KLIMAATNEUTRAAL ENERGIESYSTEEM VOOR NEDERLAND*.

Schüwer, D., & Schneider, C. (n.d.). *Electrification of industrial process heat: long-term applications, potentials and impacts*.

Shell International. (n.d.). *Natural gas and its advantages*. Retrieved July 5, 2023, from https://www.shell.com/energy-and-innovation/natural-gas/natural-gas-and-its-advantages.html

Smelik, J. (2023, February 9). 'Energieverlies bij waterstof'. *De Telegraaf*. https://www.telegraaf.nl/watuzegt/602330273/energieverlies-bij-waterstof

Sorknæs, P., Johannsen, R. M., Korberg, A. D., Nielsen, T. B., Petersen, U. R., & Mathiesen, B. v. (2022). Electrification of the industrial sector in 100% renewable energy scenarios. *Energy*, *254*. https://doi.org/10.1016/j.energy.2022.124339

Staar je niet blind op waterstof. (2022, April 21). *Trouw*. https://www.trouw.nl/opinie/staar-je-niet-blind-op-waterstof~b17a4352/

STUDY: Emissions of Hydrogen Could Undermine Its Climate Benefits; Warming Effects Are Two to Six Times Higher Than Previously Thought. (2022, July 19). Environmental Defense Fund. https://www.edf.org/media/study-emissions-hydrogen-could-undermine-its-climate-benefits-warming-effects-are-two-six

Sukmak, P., Sukmak, G., De Silva, P., Horpibulsuk, S., Kassawat, S., & Suddeepong, A. (2023). The potential of industrial waste: Electric arc furnace slag (EAF) as recycled road construction materials. *Construction and Building Materials*, *368*, 130393. https://doi.org/10.1016/J.CONBUILDMAT.2023.130393

Svarc, J. (2023, June 22). Most Efficient Solar Panels 2023. *Clean Energy Reviews*. https://www.cleanenergyreviews.info/blog/most-efficient-solar-panels

Swart, F., Visschers, M., & Vollenbroek, J. (2020, November 26). Kappen van oerbossen voor Nederlandse biomassa is géén "fake-nieuws." *BNNVARA*. https://www.bnnvara.nl/joop/artikelen/kappen-van-oerbossen-voor-nederlandse-biomassa-is-geen-fake-nieuws

Taibi, E., Miranda, R., Vanhoudt, W., Winkel, T., Lanoix, J.-C., & Barth, F. (2018). *Hydrogen from renewable power: Technology outlook for the energy transition*. www.irena.org

Tankard, W., & Chuah, H. H. (2020, December 15). 5 Ways The Copper Industry Can Improve Economics And Sustainability. *Forbes*. https://www.forbes.com/sites/woodmackenzie/2020/12/15/5-ways-the-copper-industry-can-improve-economics-and-sustainability/?sh=3319a33c6820

Teo, P. Ter, Zakaria, S. K., Salleh, S. Z., Taib, M. A. A., Sharif, N. M., Seman, A. A., Mohamed, J. J., Yusoff, M., Yusoff, A. H., Mohamad, M., Masri, M. N., & Mamat, S. (2020). Assessment of electric arc furnace (EAF) steel slag waste's recycling options into value added green products: A review. In *Metals* (Vol. 10, Issue 10, pp. 1–21). MDPI AG. https://doi.org/10.3390/met10101347

Terlouw, T., Bauer, C., McKenna, R., & Mazzotti, M. (2022). Large-scale hydrogen production via water electrolysis: a techno-economic and environmental assessment. *Energy and Environmental Science*, *15*(9), 3583–3602. https://doi.org/10.1039/d2ee01023b

The Editors of Encyclopaedia Britannica. (2023, July 23). *Blast Furnace*. Britannica. https://www.britannica.com/technology/blast-furnace

Tiekstra, J. (2023, April 12). Raad van State laat omstreden windparken doorgaan. *Binnenlands Bestuur*. https://www.binnenlandsbestuur.nl/ruimte-en-milieu/raad-van-state-laat-omstreden-windparken-toch-doorgaan

Timmer, E. (2020, May 18). De ecologische ramp achter biomassa. *De Telegraaf*. https://www.telegraaf.nl/nieuws/316198030/de-ecologische-ramp-achter-biomassa

Tonini, D., & Astrup, T. (2012). LCA of biomass-based energy systems: A case study for Denmark. *Applied Energy*, *99*, 234–246. https://doi.org/10.1016/j.apenergy.2012.03.006

Tossavainen, M., Engstrom, F., Yang, Q., Menad, N., Lidstrom Larsson, M., & Bjorkman, B. (2007). Characteristics of steel slag under different cooling conditions. *Waste Management*, *27*(10), 1335–1344. https://doi.org/10.1016/j.wasman.2006.08.002

Tromp, T. K., Shia, R.-L., Allen, M., Eiler, J. M., & Yung, Y. L. (2003). Potential Environmental Impact of a Hydrogen Economy on the Stratosphere. *Science*, *300*(5626), 1740–1742. https://doi.org/10.1126/science.1085169

Turconi, R., Boldrin, A., & Astrup, T. (2013). Life cycle assessment (LCA) of electricity generation technologies: Overview, comparability and limitations. In *Renewable and Sustainable Energy Reviews* (Vol. 28, pp. 555–565). Elsevier Ltd. https://doi.org/10.1016/j.rser.2013.08.013

Turgeon, A., & Morse, E. (2023, June 7). *Biomass Energy*. National Geographic Society. https://education.nationalgeographic.org/resource/biomass-energy/

United Nations Economic Commission for Europe. (2021a). *Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources*.

United Nations Economic Commission for Europe. (2021b). *Life Cycle Assessment of Electricity Generation Options*. https://unece.org/sites/default/files/2021-10/LCA-2.pdf

U.S. Department of Energy. (n.d.). *Hydrogen Delivery*. Energy.Gov. Retrieved July 27, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-delivery

U.S. Energy Information Administration. (2022a, November 7). *Biomass explained*. https://www.eia.gov/energyexplained/biomass/biomass-and-the-environment.php#:~:text=Burning%20either%20fossil%20fuels%20or,a%20carbon%2Dneutral%20energy%20source

U.S. Energy Information Administration. (2022b, December 27). *Natural gas explained*. https://www.eia.gov/energyexplained/natural-gas/

U.S. Energy Information Administration. (2023, June 30). *Biomass explained*.

Valente, A., Iribarren, D., & Dufour, J. (2017). Life cycle assessment of hydrogen energy systems: a review of methodological choices. In *International Journal of Life Cycle Assessment* (Vol. 22, Issue 3, pp. 346–363). Springer Verlag. https://doi.org/10.1007/s11367-016-1156-z

Valente, E., & Yameogo, T. (2021, October 1). *How the copper mining sector can be competitive in the long term*. https://www.ey.com/en_ca/mining-metals/long-term-competitiveness-in-the-copper-mining-sector

van Bokkum, M. (2023, February 20). Toezichthouder: kans op grote incidenten met waterstof in havens. *NRC*. https://www.nrc.nl/nieuws/2023/02/20/veiligheidsproblemen-met-ammoniak-in-rotterdamse-haven-vertragen-energietransitie-a4157651?t=1689523797

van den Broek, S. (2022, May 23). Er komen 1000 nieuwe elektriciteitshuisjes aan: "Weg uitzicht." *AT5*. https://www.at5.nl/artikelen/215248/er-komen-1000-nieuwe-elektriciteitshuisjes-aan-weg-uitzicht

van der Giesen, C., Cucurachi, S., Guinée, J., Kramer, G. J., & Tukker, A. (2020). A critical view on the current application of LCA for new technologies and recommendations for improved practice. *Journal of Cleaner Production*, *259*. https://doi.org/10.1016/j.jclepro.2020.120904

van der Wal, S. (2021). *Wood pellet damage*. https://www.somo.nl/wood-pellet-damage/

van Dijk, B. (2023, June 23). Stop maar met bouwen van windmolens op land. *Financieel Dagblad*. https://fd.nl/economie/1479910/stop-maar-met-bouwen-van-windmolens-op-land

van Dongen, A., & van Mersbergen, S. (2018, March 31). Er komen nog veel meer windmolens bij - ook op land. *AD*. https://www.ad.nl/economie/er-komen-nog-veel-meer-windmolens-bij-ook-op-land~a7411d43/

van Poppel, J., & Bol, R. (2020, August 30). Zonder biomassa haalt Nederland zijn klimaatdoelen niet. Hoe werkt het, en hoe duurzaam is het? *De Correspondent*. https://decorrespondent.nl/11466/zonder-biomassa-haalt-nederland-zijn-klimaatdoelen-niet-hoe-werkt-het-en-hoe-duurzaam-is-het/1e68bb29-7b9e-09aa-0e70-9e006d03fe2c#:~:text=Vaste%20biomassa&text=Het%20gaat%20vooral%20om%20reststromen,voor%20energieopwekking%20uit%20andere%20landen.

van Renselaar, B. (2023, March 19). Het waterstofsprookje zal de energietransitie niet oplossen. *Financieel Dagblad*. https://fd.nl/opinie/1470709/het-waterstofsprookje-zal-de-energietransitie-niet-oplossen

van Zeggelaar, D. (2018, October 8). Omwonenden buitengebied starten petitie tegen zonnepark. *Ede Stad*. https://www.edestad.nl/lokaal/lokaal/124885/omwonenden-buitengebied-starten-petitie-tegen-zonnepark-496954

Varun, Bhat, I. K., & Prakash, R. (2009). LCA of renewable energy for electricity generation systems-A review. In *Renewable and Sustainable Energy Reviews* (Vol. 13, Issue 5, pp. 1067–1073). https://doi.org/10.1016/j.rser.2008.08.004

Vechi, M., & Ghisi, E. (2018). Evaluation of Water Heating Systems Through Life Cycle Assessment. *European Journal of Sustainable Development*, *7*(3). https://doi.org/10.14207/ejsd.2018.v7n3p131

Vergunning voor zonnepark juridisch vaak lastig aan te vechten. (2023, February 14). https://www.dekempenaer.nl/kennis/vergunning-voor-zonnepark-juridisch-vaak-lastig-aan-te-vechten/

Walhout, R. (2023, April 5). Verzet tegen zonnepark bij Westerlee: "Onze backyard is vol." *RTV Noord*. https://www.rtvnoord.nl/nieuws/1011124/verzet-tegen-zonnepark-bij-westerlee-onze-backyard-is-vol

Wang, A., Jens, J., Mavins, D., Moultak, M., Schimmel, M., Van Der Leun, K., Peters, D., & Buseman, M. (2021). *Analysing future demand, supply, and transport of hydrogen*. https://transparency.entsog.eu/

Waterstof is dure en inefficiënte oplossing. (2023, March 5). *BN DeStem*. https://www.bndestem.nl/opinie/waterstof-is-dure-en-inefficiente-oplossing~a788c194/?referrer=https%3A%2F%2Fwww.google.com%2F&cb=117c46def5f493af68f8b9514ef26220&auth_rd=1

Wente, E. F., Nutting, J., Wondris, E. F., & The Editors of Encyclopaedia Britannica. (2023, May 18). *Steel*. Britannica. https://www.britannica.com/technology/steel/additional-info#contributors

Wiertzema, H., Svensson, E., & Harvey, S. (2020). Bottom–Up Assessment Framework for Electrification Options in Energy-Intensive Process Industries. *Frontiers in Energy Research*, *8*. https://doi.org/10.3389/fenrg.2020.00192

Zander & Ingeström. (n.d.). *Hot water and steam boilers*. Retrieved March 1, 2023, from https://www.zeta.se/siteassets/zander--ingestrom/elpannor/dokument-elpannor/hot-water-and-steam-boilers_en.pdf

Zohuri, B., Mossavar-Rahmani, F., & Behgounia, F. (2022). Today's fast-paced technology. In *Knowledge is Power in Four Dimensions: Models to Forecast Future Paradigm* (pp. 347–370). Elsevier. https://doi.org/10.1016/b978-0-323-95112-8.00011-8

10. Appendix A

For the sake of readability, environmental in- and outflows have been omitted and only the input flows to foreground processes from background processes are displayed (blue arrows and lines indicate background inputs to foreground processes). If a red or orange line is shown then this is done for clarity, these are normal flows but due to visualization issues they were overlapping with other flows.

A1/A2

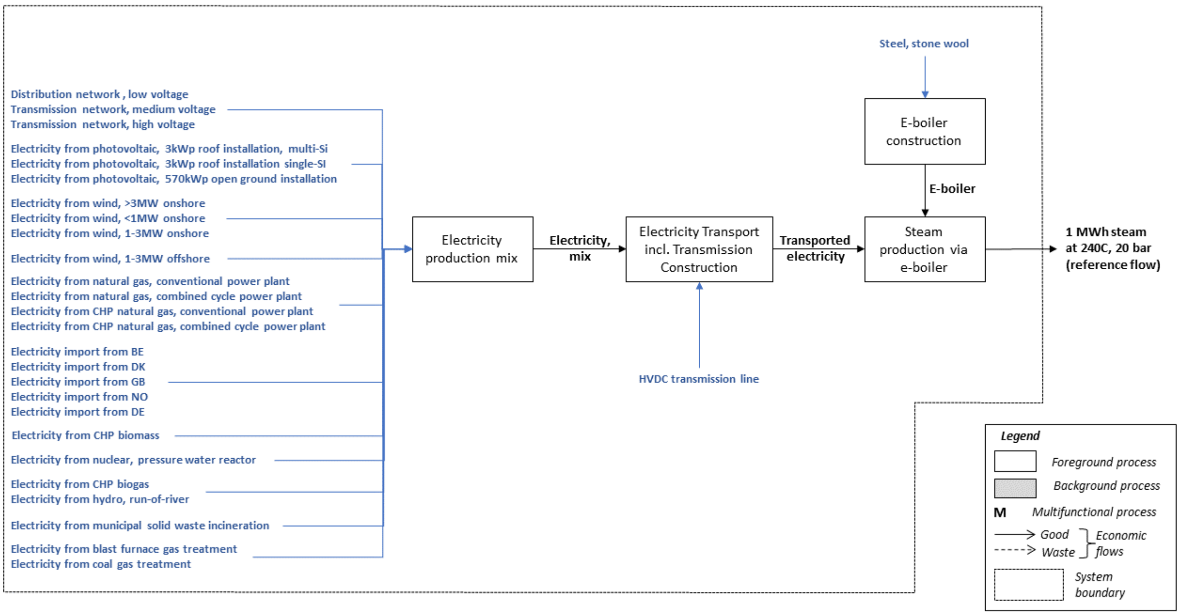

Figure A1: flowchart of steam production via e-boiler including transmission construction 2030 and 2050.

B1/B2

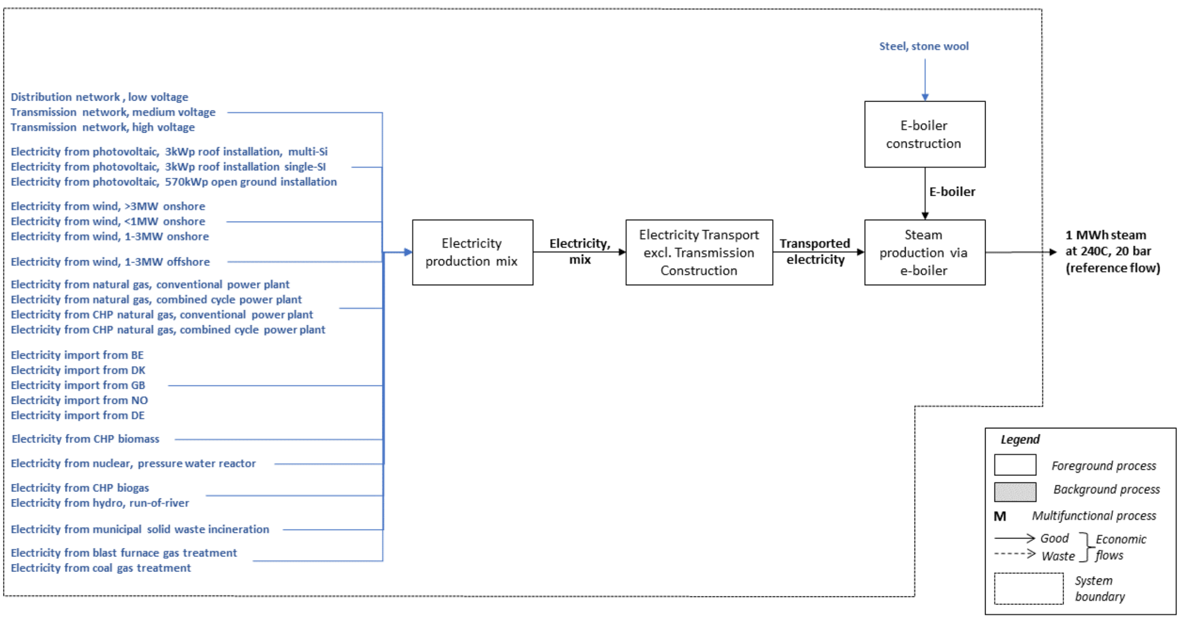

Figure A2: flowchart of steam production via e-boiler excluding transmission construction 2030 and 2050.

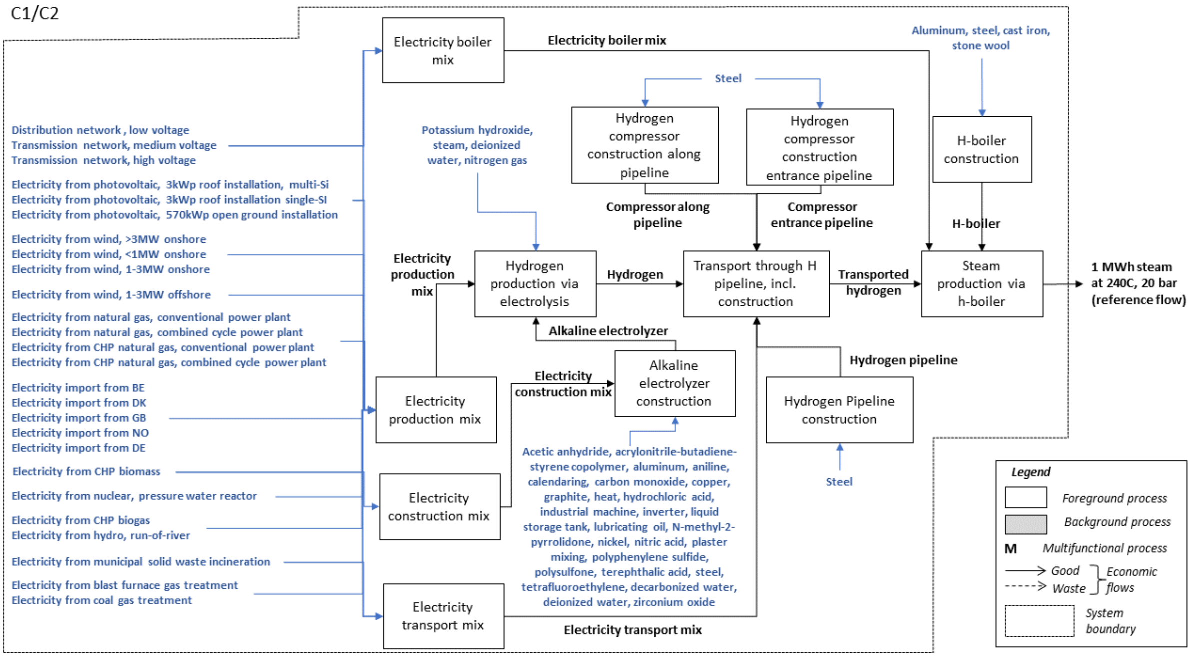

Figure A3: flowchart of steam production via h-boiler including network construction 2030 and 2050.

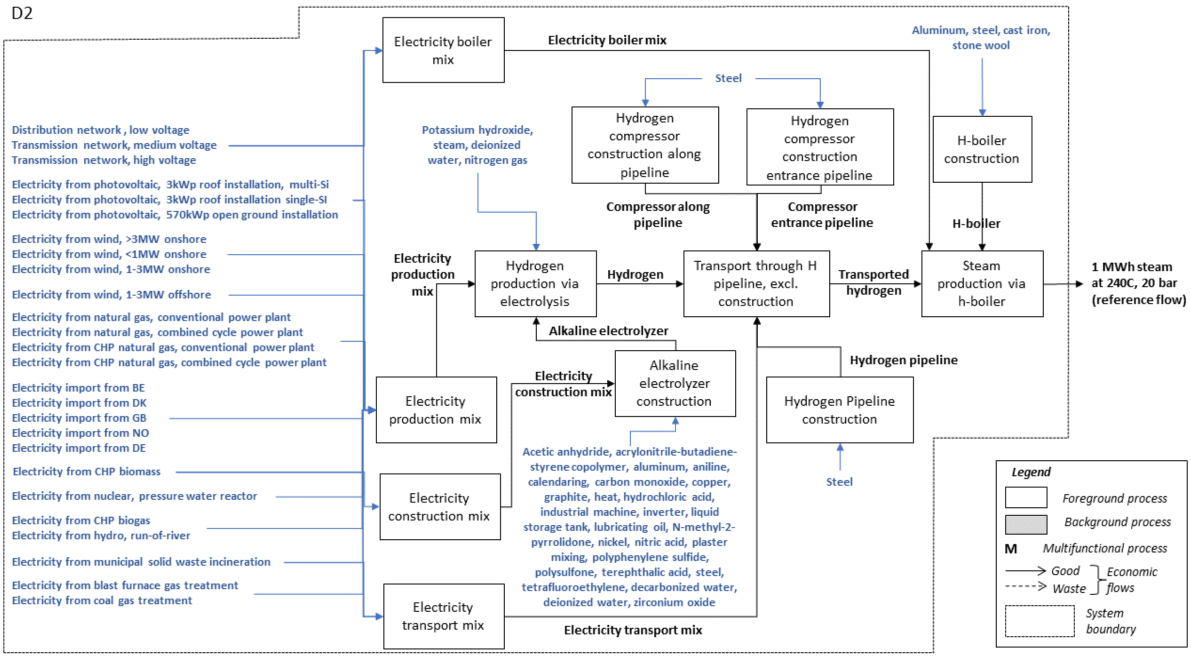

Figure A4: flowchart of steam production via h-boiler excluding network construction 2030 and 2050.

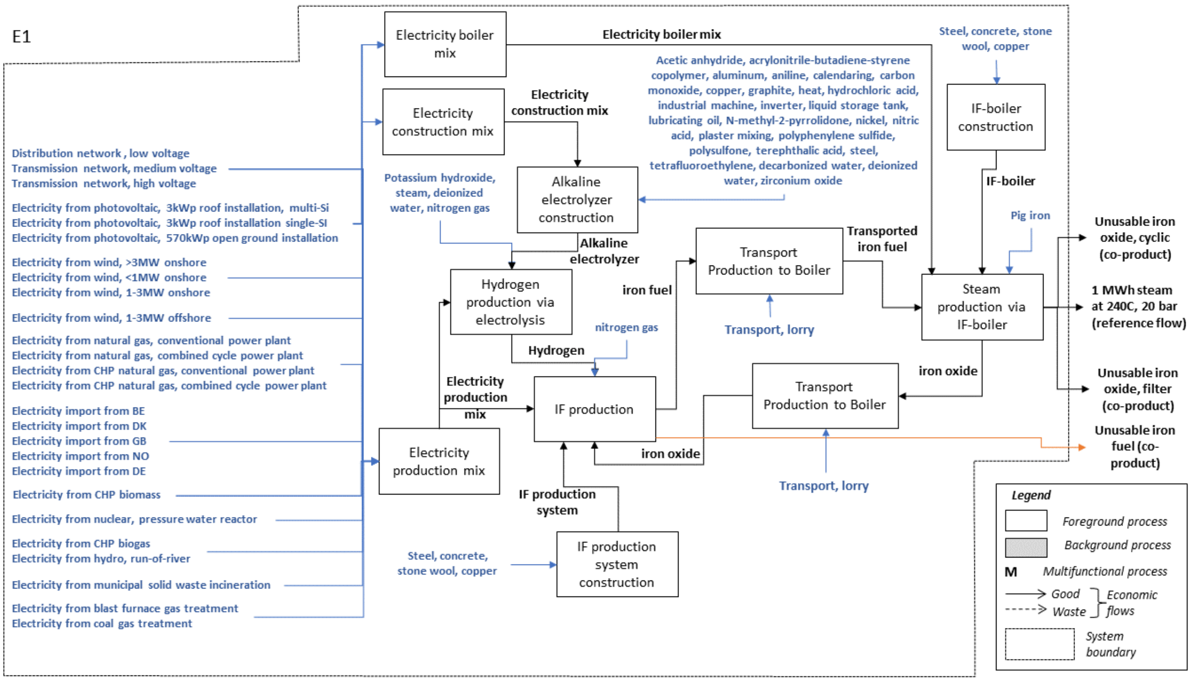

Figure A5: flowchart of steam production via IF-boiler, pig iron + hydrogen electrolyzer 2030.

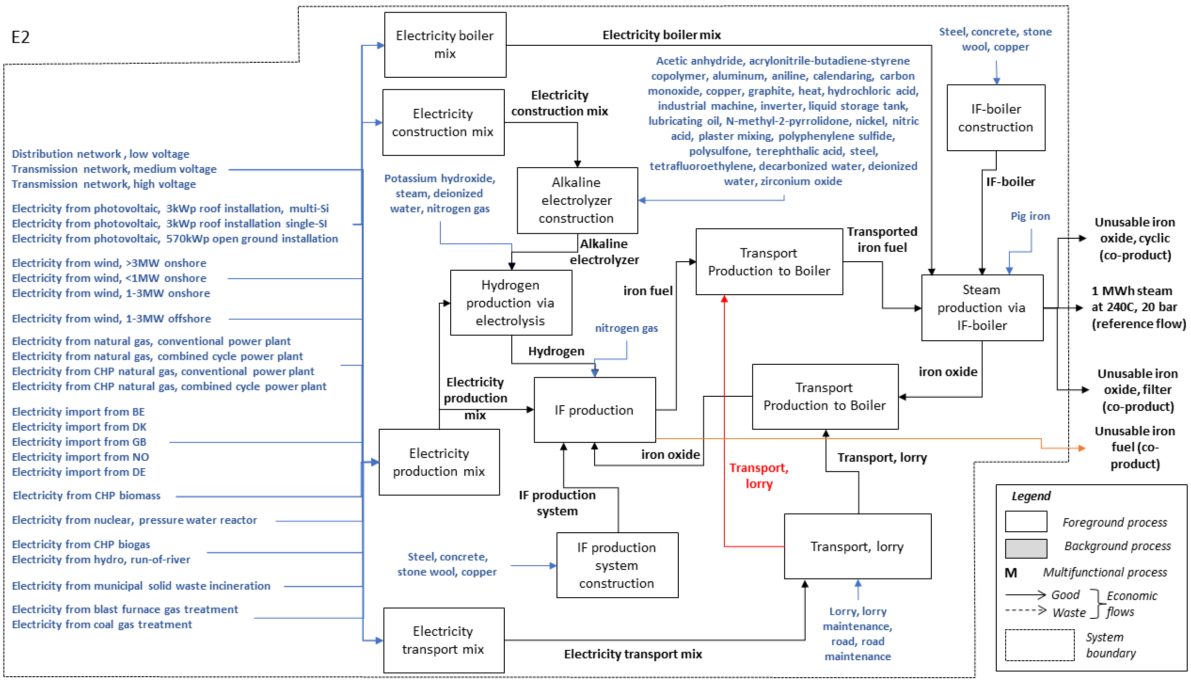

Figure A6: flowchart of steam production via IF-boiler, pig iron + hydrogen electrolyzer 2050.

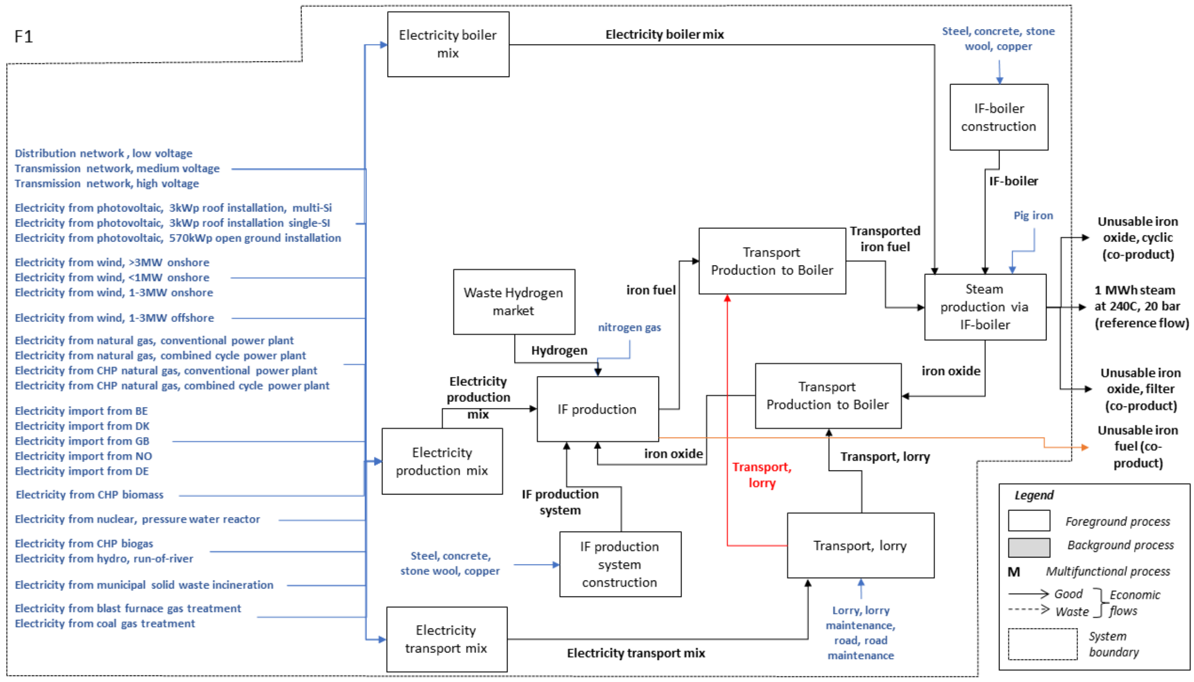

Figure A7: flowchart of steam production via IF-boiler, pig iron + waste hydrogen 2030.

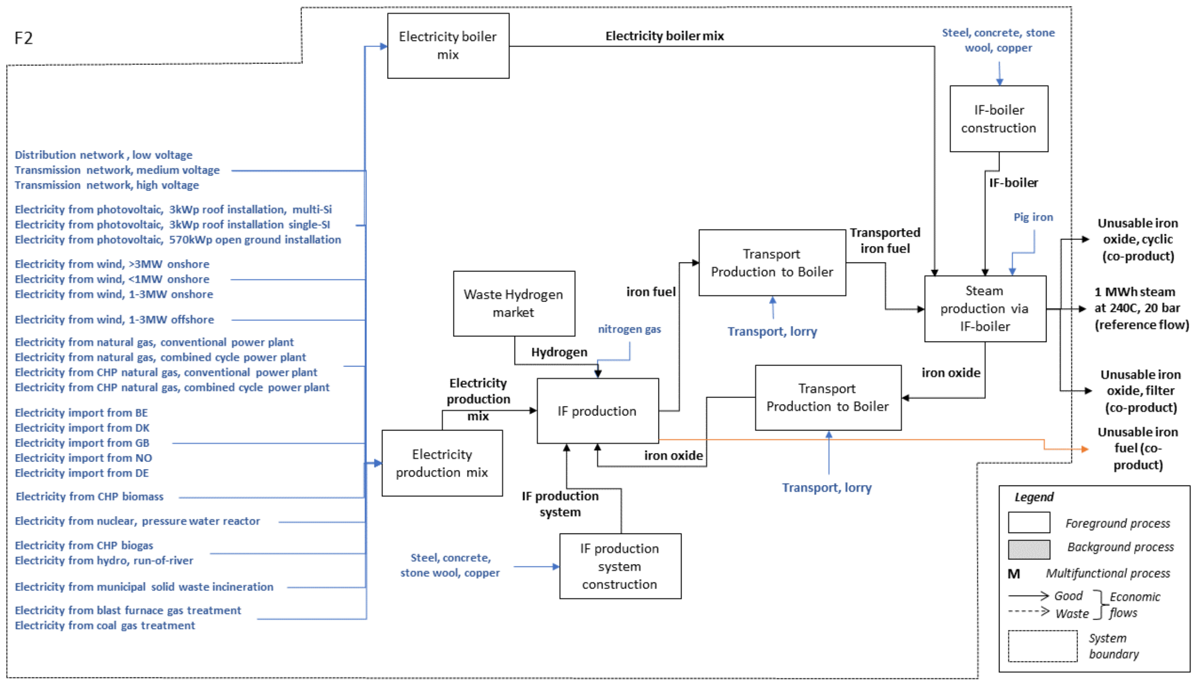

Figure A8: flowchart of steam production via IF-boiler, pig iron + waste hydrogen 2050.

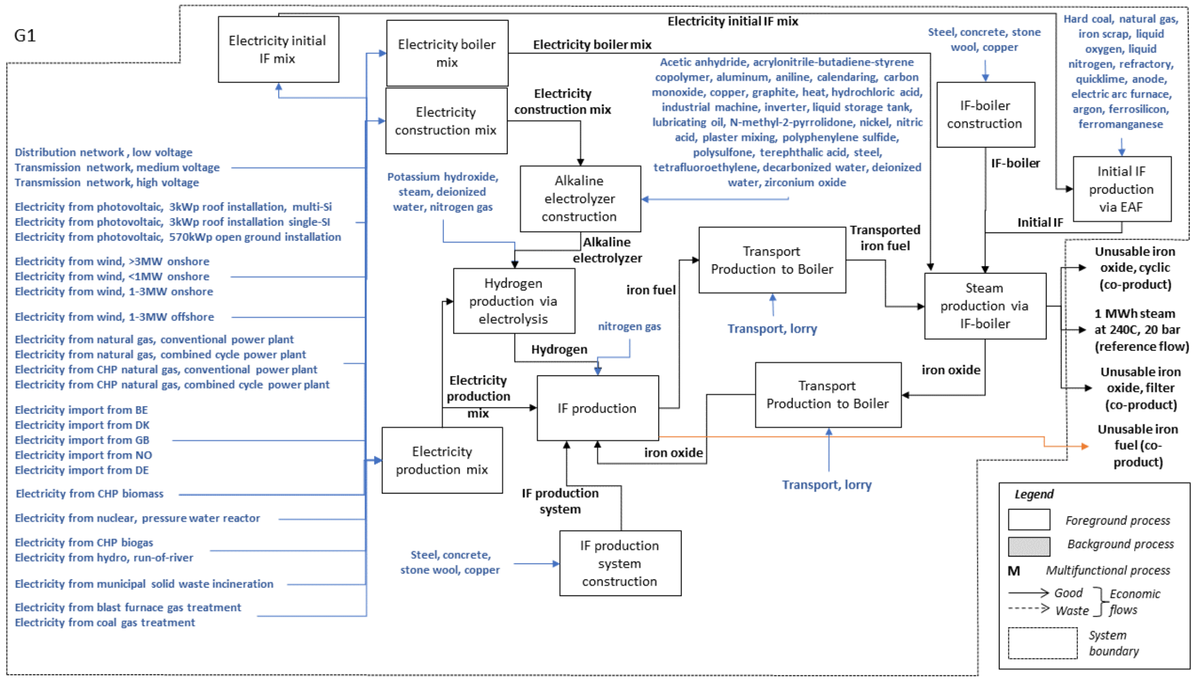

Figure A9: flowchart of steam production via IF-boiler, scrap iron + hydrogen electrolyzer 2030.

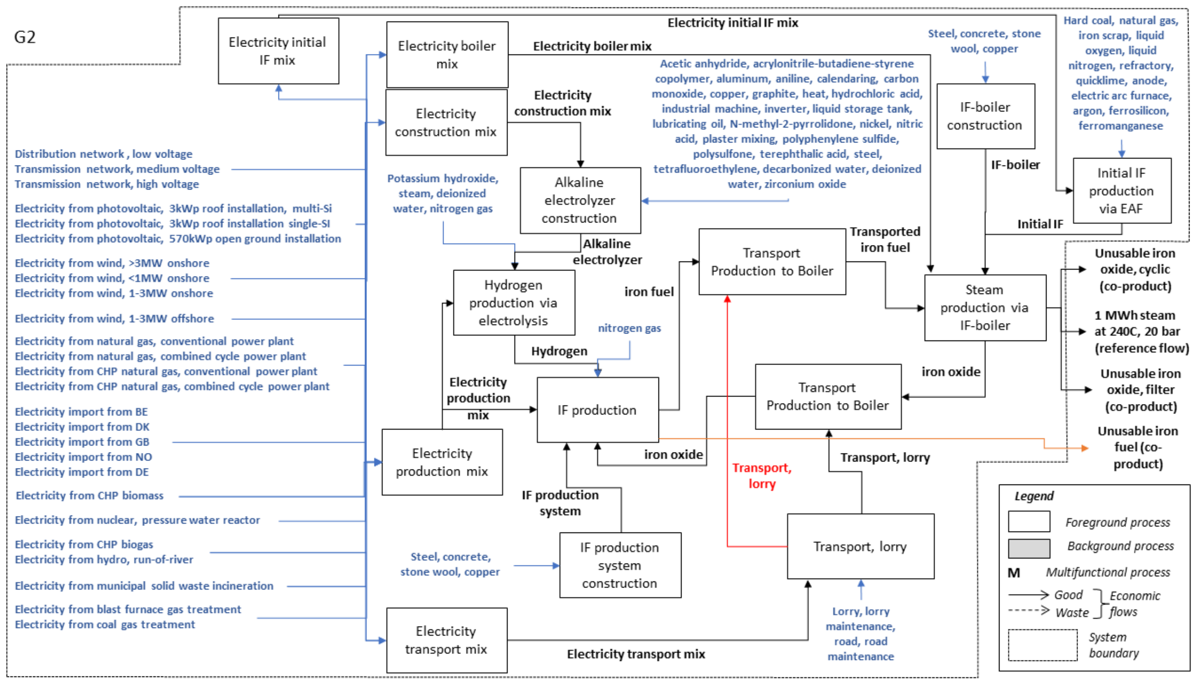

Figure A10: flowchart of steam production via IF-boiler, scrap iron + hydrogen electrolyzer 2050.

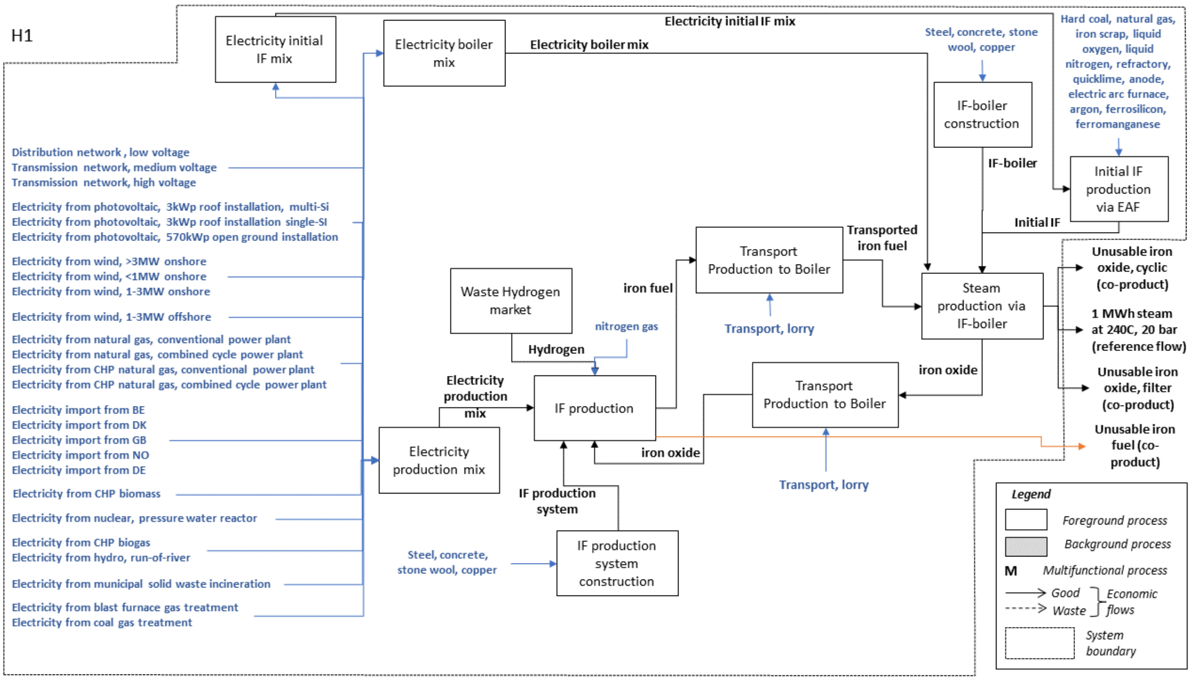

Figure A11: flowchart of steam production via IF-boiler, scrap iron + waste hydrogen 2030.

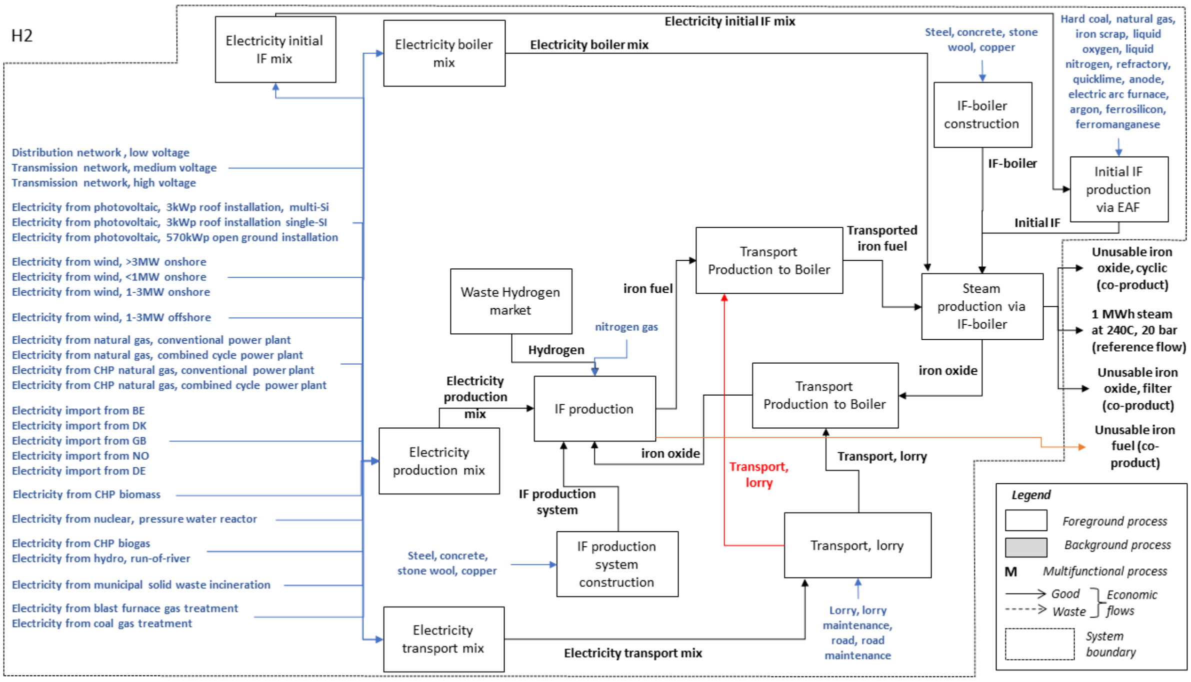

Figure A12: flowchart of steam production via IF-boiler, scrap iron + waste hydrogen 2050.

I1/I2

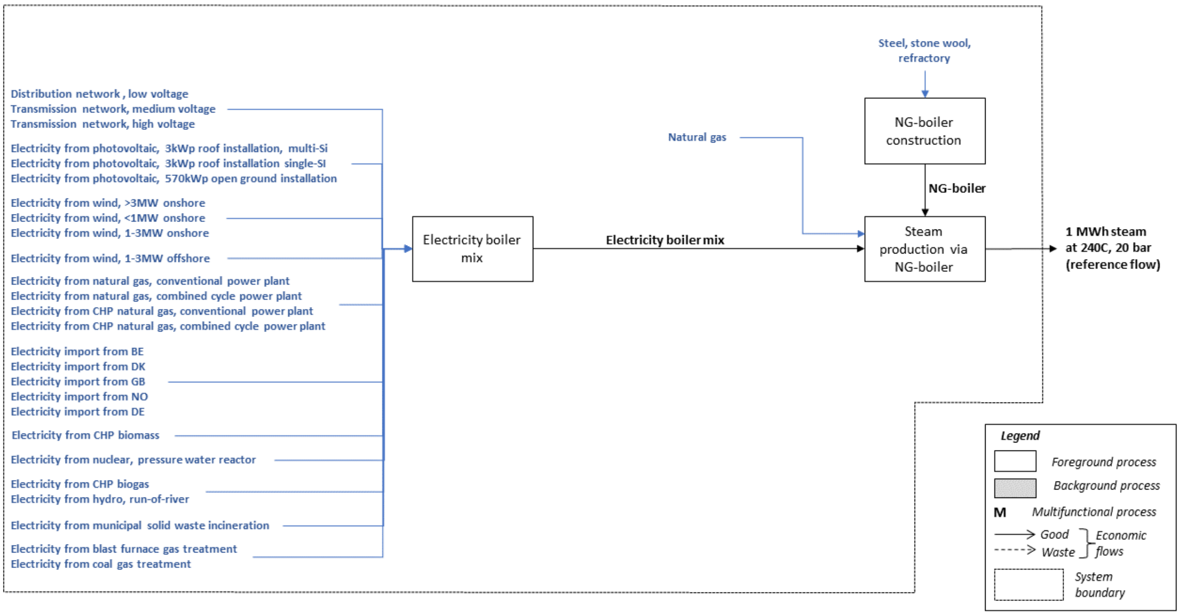

Figure A13: flowchart of steam production via NG-boiler 2030 and 2050.

J1/J2

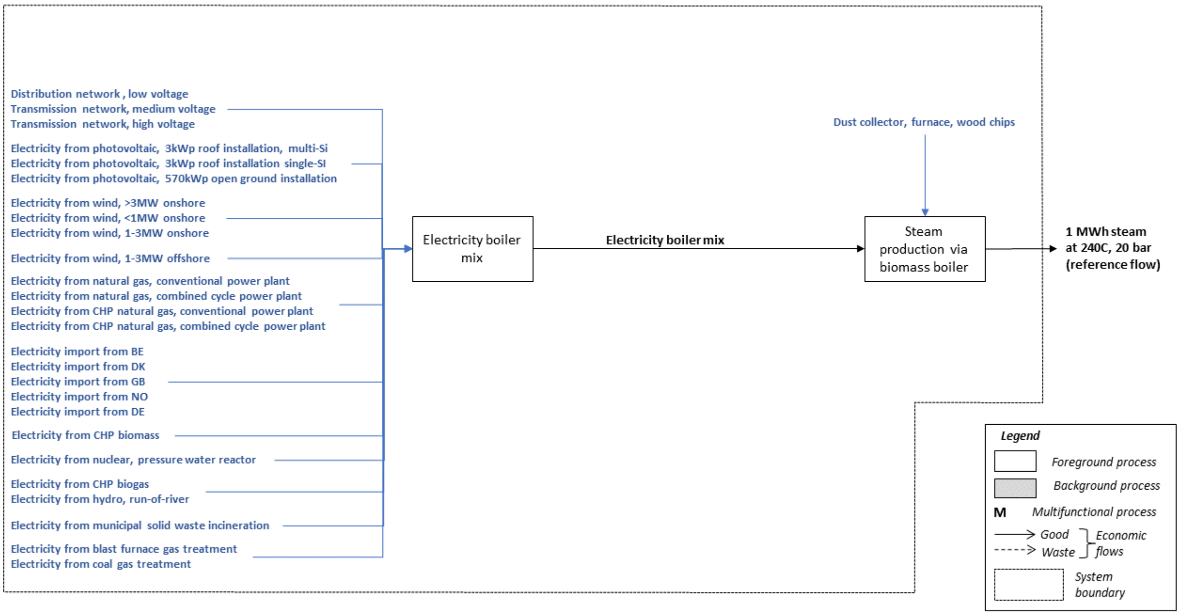

Figure A14: flowchart of steam production via biomass boiler 2030 and 2050.

11. Appendix B

All data is noted within Appendix_B.xlsx as included in the zip-file. The multiple sheets included shows all economic and environmental inflows and outflows of the foreground (and in exceptions background processes) for which data is gathered. The first sheet titled ‘explanation sheet’ explains what can be found in each sheet and has direct links to each tab.

12. Appendix C

All results are in Appendix_C.xlsx as included in the zip-file. The multiple sheets included show LCI, LCIA, contribution and sensitivity results as well any other sheets that process data for any of the tables / figures in this research. The first sheet titled 'explanation sheet' explains what can be found in each sheet and has direct links to each tab.

The only results that are not included are the upstream contributions of each process. These results are embedded within OpenLCA and are difficult to export. Hence, a quick guide has been made. The OpenLCA model is also attached in the zip-file.

OpenLCA allows a user to run an in-depth analysis of a product system as seen in Figure C1 below.

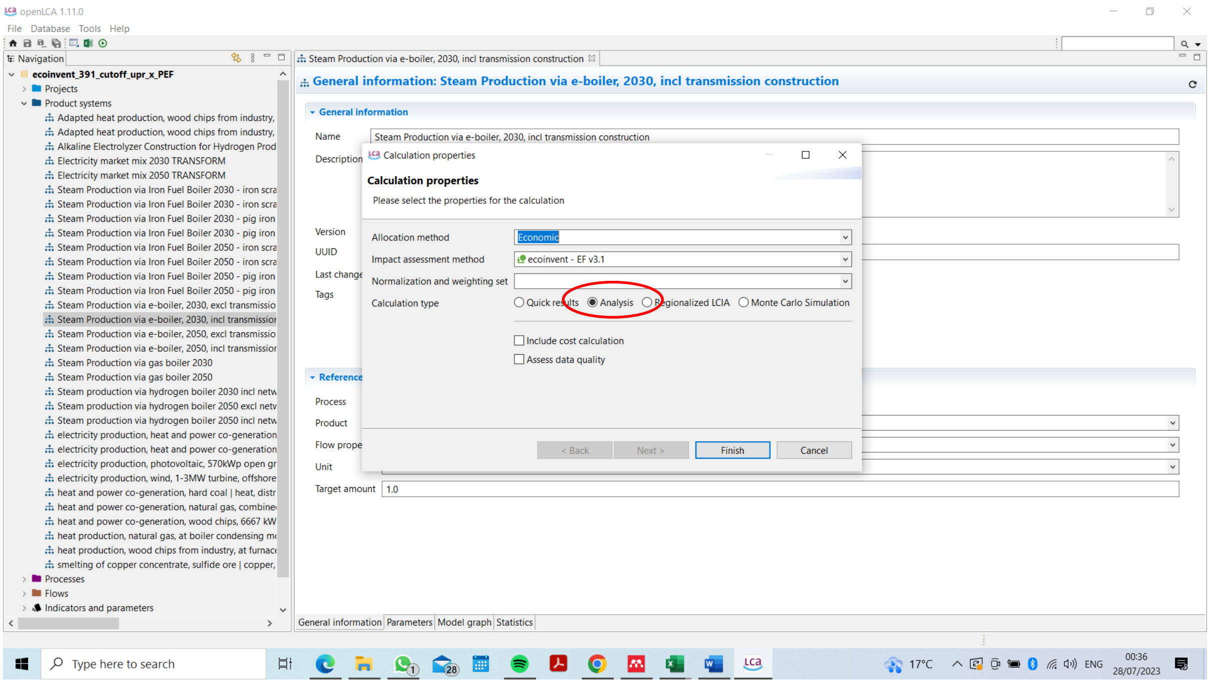

Figure C1: after hitting the 'calculate' button when a product system is selected, choose the calculation type 'analysis'.

One of the tabs that you can view is the contribution tree. This can show the upstream environmental impacts per flow and per impact category and provides it as a percentage per process. Essentially it is the economic flow contribution completed for you to a large extent. By expanding the tree, you are able to view all upstream environmental impacts for each process.

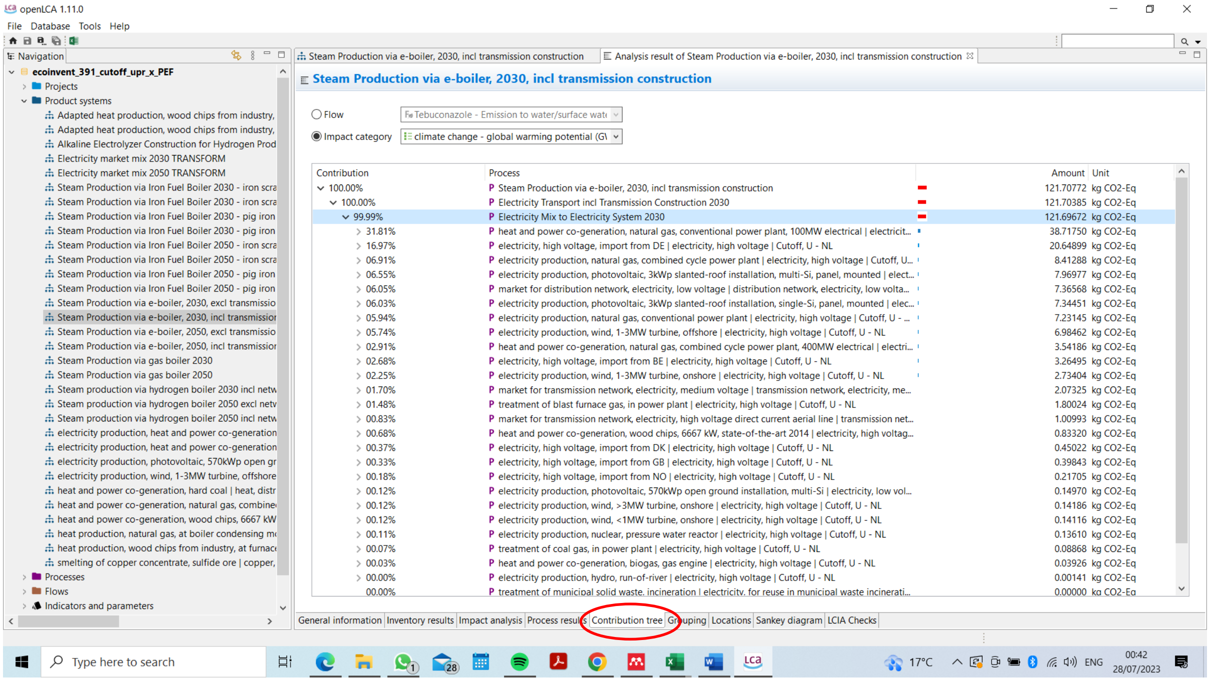

Figure C2: navigate to the 'contribution tree' tab, choose a flow or impact category and expand the tree to see results.

13. Appendix D

This appendix includes the contribution analysis results of steam production via natural gas boiler, 2030 process alternative (I1) and the steam generation via biomass boiler, 2030 process alternative (J1).

Process Alternative I1

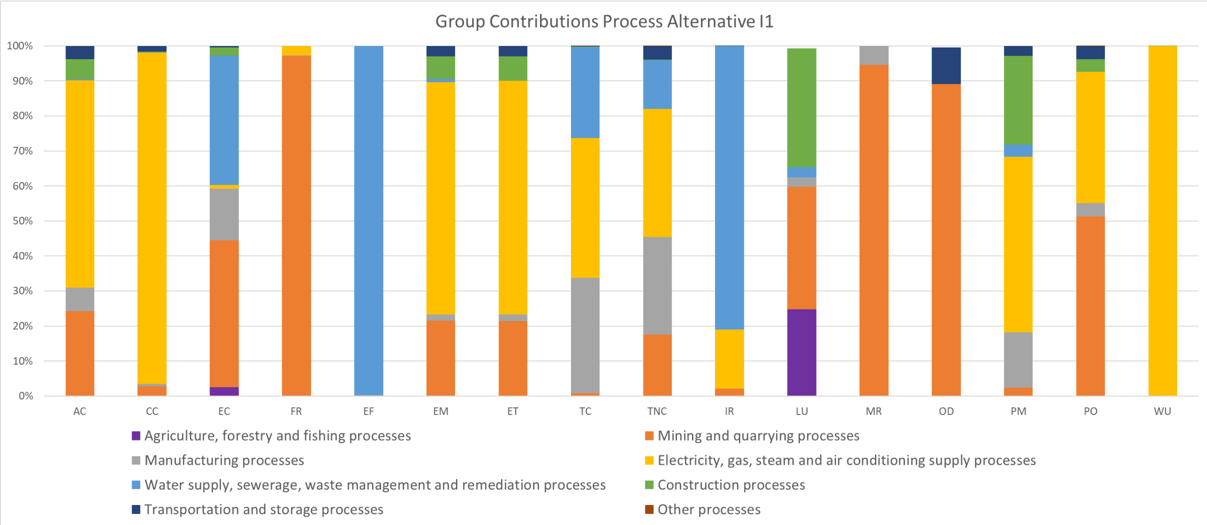

Figure D1: Group process contributions to process alternative I1 – steam production via natural gas boiler, 2030. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

One of the largest process contributors throughout multiple impact categories is the steam production via gas boiler process in which combustion of the natural gas takes place. This process is responsible for the majority share of impacts in the impact categories of water use (99%), climate change (88%) terrestrial eutrophication (54%), and marine eutrophication (53%). It also contributes substantially as one of the top 2 individual most contributing processes in the impact categories of acidification (45%), photochemical oxidant formation (29%), particulate matter (31%), human toxicity non-cancer (31%) and human toxicity cancer (38%). The steam production via natural gas boiler process is labeled under the electricity, gas, and air conditioning supply group and the yellow color is certainly present as reflected in Figure D1.

Another individual process that can be considered a hotspot is the petroleum and gas production process. This process is an upstream process in which the petroleum and gas is produced prior to its combustion for steam production. This process contributes 23% of the total impacts towards acidification, is responsible for 95% of the fossil resource footprint, contributes 20% to the impacts causing marine eutrophication, and totals 89% of the total contributions in the impact category of ozone depletion.

Other processes that are large contributors to specific impact categories that do not also contribute to other impact categories are overviewed in Table D1 for reference (only processes contributing more than 20% of the total impacts for any impact category were noted).

Table D1: Overview of processes with large contributions (>20%) to specific impact categories for process alternative I1

Impact Category	Large Contributing Processes	Contribution [%]
Freshwater Ecotoxicity	Treatment of water discharge from petroleum/natural gas extraction	25%
Ionizing Radiation	Treatment of tailings from uranium milling	64%
Photochemical Oxidant Formation	Natural gas venting from petroleum/natural gas production	41%
Freshwater Eutrophication	Treatment of spoil from hard coal mining	43%
Mineral and Metal Resource Use	Copper mine operation and beneficiation	67%
Human Toxicity, non-cancer	Sweet gas burned in gas turbine	22%
Human Toxicity, cancer	Coking	30%

Process Alternatives J1

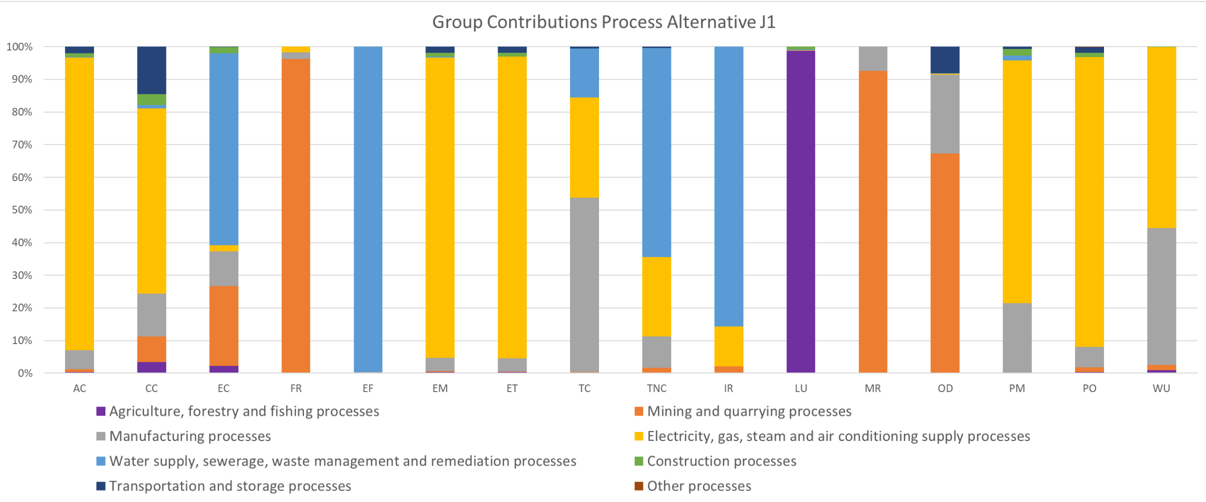

Figure D2: Group process contributions to alternative J1 – steam production via biomass boiler, 2030. Abbreviations: AC: acidification; CC: climate change; EC: ecotoxicity, freshwater; FR: resource use, fossils; ET: eutrophication, terrestrial; EM: eutrophication, marine; TC: human toxicity, cancer; TNC: human toxicity, non-cancer; IR: ionizing radiation; LU: land use; MR: resource use, minerals and metals; OD: ozone depletion; PM: particulate matter; PO: photochemical oxidant formation; and WU: water use.

The main hotspot for the 2030 biomass boiler process alternative is the steam production process itself, thus the production by steam by wood chips. It contributes 86% of the total emissions to acidification, 14% to climate change, 40% to water use, 91% to terrestrial eutrophication, 87% to photochemical oxidant formation, 91% to marine eutrophication, 73% to particulate matter, 23% to non-cancer human toxicity, and 30% to human toxicity cancer. Next to the steam production process, the petroleum and gas production process is a large contributor to the impact categories of fossil resource use (38%) and ozone depletion (61%), whereas the treatment of wood ash mixture contributes significantly to freshwater ecotoxicity (45%) and human toxicity non-cancer (58%).

Next to this, no significant hotspots were identified to contribute to any of the impact categories. However, some processes did contribute largely to a specific impact category and are recorded in Table D2.

Table D2: Overview of processes with large contributions to specific impact categories for process alternative J1

Impact Category	Large Contributing Process(es)	Contribution [%]
Land Use	Softwood forestry logging	85%
Ionizing Radiation	Treatment of tailings from uranium milling	68%
Freshwater Eutrophication	Treatment of spoil from lignite mining	46%
Mineral and Metal Resource Use	Copper mine operation and beneficiation	64%

14. Appendix E

14.1 Results of the Variation in Electricity Mix to the Production Stages

Table E.1 shows the impacts of each electricity scenario and process alternative per impact category relative to the largest impact in that category. The color coding displays the largest impacts as red and the smallest impacts as green with white signifying the middle of the scale. It can be visually spotted that for most impact categories the 100% solar electricity scenario has the largest impacts whereas the 100% wind electricity has the least impacts. To dive deeper into where the impacts of the solar and wind electricity scenario originate from, a contribution analysis was completed into the two used electricity production processes – the electricity production process by an open ground 570kWp photovoltaic installation and the electricity production process by a 1-3MW offshore wind turbine, see Box E1. These two electricity scenarios were then compared to the electricity mix as based on the TNO scenario. This provides a better foundation to understand the results seen in Table E1. Important to note is that this contribution analysis only examines the production of electricity and is therefore further upstream in comparison to the process alternatives' reference flows.

Table E1: Sensitivity analysis results of electricity mix presented relative to the largest impact per impact category

Impact Category	E-boiler 2030, incl. network construction [A1]			H-boiler 2030, incl. network construction [C1]			IF boiler 2030, pig + H electrolyzer [E1]			IF boiler 2030, pig + waste H [F1]			IF boiler 2030, scrap + H electrolyzer [G1]			IF boiler 2030, scrap + waste H [H1]		
	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar	Base Case	100% wind	100% solar
Acidification	0.42	0.30	0.61	0.70	0.52	1.00	0.66	0.51	0.90	0.19	0.17	0.22	0.61	0.46	0.84	0.13	0.11	0.17
Climate change	0.59	0.13	0.53	0.94	0.23	0.86	1.00	0.43	0.93	0.37	0.29	0.36	0.87	0.30	0.80	0.24	0.16	0.23
Ecotoxicity, freshwater	0.42	0.34	0.62	0.69	0.56	1.00	0.64	0.53	0.89	0.18	0.16	0.21	0.65	0.54	0.89	0.18	0.17	0.22
Resource use, fossils	0.63	0.09	0.39	1.00	0.17	0.63	0.97	0.31	0.67	0.30	0.21	0.26	0.89	0.23	0.60	0.23	0.13	0.18
Eutrophication, freshwater	0.60	0.30	0.63	0.95	0.49	1.00	0.88	0.51	0.92	0.25	0.19	0.25	0.80	0.43	0.84	0.16	0.11	0.17
Eutrophication, marine	0.47	0.21	0.63	0.76	0.35	1.00	0.80	0.48	1.00	0.30	0.25	0.33	0.69	0.37	0.89	0.19	0.14	0.22
Eutrophication, terrestrial	0.47	0.22	0.63	0.75	0.36	1.00	0.79	0.48	0.99	0.29	0.24	0.32	0.69	0.37	0.88	0.18	0.14	0.21
Human toxicity, cancer	0.20	0.19	0.27	0.32	0.30	0.43	0.48	0.47	0.57	0.27	0.27	0.28	0.92	0.90	1.00	0.70	0.70	0.71
Human toxicity, non-cancer	0.48	0.42	0.63	0.77	0.67	1.00	0.64	0.56	0.82	0.12	0.11	0.15	0.65	0.57	0.84	0.14	0.13	0.16
Ionising radiation	0.63	0.03	0.19	1.00	0.07	0.31	0.82	0.07	0.27	0.15	0.04	0.07	0.83	0.08	0.27	0.16	0.05	0.07
Land use	0.05	0.01	0.64	0.07	0.02	1.00	0.07	0.03	0.81	0.02	0.02	0.13	0.07	0.03	0.81	0.02	0.02	0.13
Resource use, minerals and metals	0.45	0.40	0.63	0.72	0.64	1.00	0.58	0.51	0.81	0.10	0.09	0.13	0.59	0.52	0.81	0.11	0.10	0.14
Ozone depletion	0.46	0.08	0.61	0.77	0.19	1.00	0.71	0.24	0.89	0.19	0.12	0.22	0.65	0.18	0.83	0.14	0.07	0.16
Particulate matter	0.29	0.20	0.55	0.47	0.33	0.87	0.68	0.56	1.00	0.36	0.35	0.41	0.60	0.48	0.92	0.28	0.27	0.33
Photochemical oxidant formation	0.39	0.19	0.57	0.63	0.32	0.91	0.77	0.52	1.00	0.35	0.32	0.39	0.60	0.35	0.83	0.18	0.14	0.21
Water use	0.00	0.00	0.01	0.99	0.98	1.00	0.01	0.00	0.02	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00

Box E1: Contribution analysis into electricity scenario.

The contribution analysis into solar electricity showed that the upstream impacts related to the construction of the photovoltaic panels and the mounting system were seen to be responsible for contributing the largest environmental impacts to the solar produced electricity. Most of the impact categories accounted for 58-84% and 11-30% of the total impacts to the photovoltaic panels and the mounting system respectively. Four impact categories stand out in which the percentage contribution shows a different trend. The land use impact category showed that most impacts derived from the mounting system (97.6%) in contrast to the photovoltaic construction (1.8%). The exact opposite was seen for the ozone depletion and water use impact categories where the construction of the PV panel (94.5% and 92.6%) contributed more in comparison to the mounting system (4.5% and 6% respectively). In the impact category human toxicity cancer the contribution was more balanced with the construction of the mounting system accounting for 40.5% and the construction of the PV panels totaling 44.9% of the total impacts. Examining individual process contributions, processes like silicone production, aluminum production and the smelting of copper concentrate are contributors to multiple impact categories.

Comparing the solar produced electricity to the base case electricity mix, Table E2 shows that the base case produced electricity displays larger impacts in all impact categories except for marine eutrophication, terrestrial eutrophication, land use, ozone depletion, particulate matter, photochemical oxidant formation and water use. In these impact categories, solar produced electricity has a higher environmental impact. This can be derived back to the impacts resulting from chemicals like silicon, trichloromethane and terephthalic acid, as well as (fossil based) processes required in far upstream background processes.

Table E2: Overview of the life cycle impact analysis results of the base case 2030, wind and solar electricity scenarios per kWh of electricity produced.

Impact Category	Unit	Base Case Electricity Mix 2030	Wind	Solar
Acidification	mol H+-Eq	7.30E-04	1.00E-04	6.40E-04
Climate change	kg CO2-Eq	1.20E-01	1.63E-02	9.84E-02
Ecotoxicity, freshwater	CTUe	1.01E+00	1.13E-01	7.95E-01
Resource use, fossils	MJ, net calorific value	2.17E+00	1.88E-01	1.22E+00
Eutrophication, freshwater	kg P-Eq	7.70E-05	6.92E-06	4.93E-05
Eutrophication, marine	kg N-Eq	1.00E-04	2.00E-05	1.10E-04
Eutrophication, terrestrial	mol N-Eq	1.12E-03	1.90E-04	1.17E-03
Human toxicity, cancer	CTUh	1.76E-10	6.63E-11	1.37E-10
Human toxicity, non-cancer	CTUh	7.14E-09	7.46E-10	3.87E-09
Ionising radiation	kBq U235-Eq	2.86E-02	6.90E-04	7.78E-03
Land use	dimensionless	1.08E+00	6.47E-02	1.47E+01
Resource use, minerals and metals	kg Sb-Eq	6.78E-06	6.01E-07	4.12E-06
Ozone depletion	kg CFC-11-Eq	6.01E-09	2.28E-10	7.07E-09
Particulate matter	disease incidence	4.83E-09	1.30E-09	7.11E-09
Photochemical oxidant formation	kg NMVOC-Eq	3.60E-04	7.07E-05	4.20E-04
Water use	m3 world eq. deprived	5.49E-02	8.08E-03	1.46E-01

Earlier it was mentioned that from Table E1, it could be seen that the solar electricity scenario performs worst in most impact categories, even more poorly than the base case. From Table E2, it was just shown that when only examining the electricity scenario only some impact categories showed solar electricity performing worse than the base case electricity mix. Comparing the two tables, it is noteworthy that when considering the process alternatives, the solar electricity scenario only performs better than the base case in three impact categories: climate change, fossil resources and ionizing radiation. It raises the question why when solar produced electricity is swapped out for the base case electricity mix the impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer and non-cancer are not performing better. The reason why these latter impact categories are not seen to perform better when included in the process alternative chains is because other impacts from other parts of the value chain are seen to relatively contribute a significant part. These impacts therefore outweigh any benefit to the electricity used. To exemplify, in C1 (h-boiler, 2030, including network construction) it is seen that the five impact categories of acidification, freshwater ecotoxicity, freshwater eutrophication, human toxicity cancer and non-cancer all have upstream impacts from the distribution network accounting for at least ~30% of the total impacts in that impact category. As such the electricity mix used for the hydrogen production process can account for as little as 40.6%. A change in the electricity mix therefore certainly makes a difference in the environmental performance, but to a lesser extent. Looking at the three impact categories that do perform better for the PA C1, i.e. climate change, fossil resources and ionizing radiation, here the electricity mix to the production stage accounts for at least 85% of the upstream impacts. Hence, a change in the electricity mix will make a significant difference to the environmental performance. Similar trends are seen in all the other process alternatives.

Moving on to the 100% wind electricity scenario, from both tables it becomes clear that this electricity mix performs the best environmentally. The impacts related to the electricity generated by a wind turbine are almost all accounted to the production process of the wind turbine made of stationary and moving parts. These parts are made of materials like glass fiber reinforced plastic, steel, copper and concrete. The associated upstream production process emissions of these materials are the largest source of the limited environmental impacts of electricity generated through a wind turbine. No emissions are directly related to the production of electricity by a wind turbine.

Circling back to Table E1, process alternative F1 and H1 generally perform best among all the alternative systems, whereas C1, E1 and G1 generally perform worst. The change in the electricity scenario highlights which process alternatives consume the largest quantities of electricity in the production stage as these are generally more red. Process alternative C1 has the largest electricity consumption and performs poorest in most impact categories. It is interesting to note that when taking a closer look at C1 and G1, the solar scenario performs worse in C1 in comparison to G1 whereas the wind scenario performs better. The consumed electricity during the production stage in both process alternatives does not change, however, as the impacts related to the production of electricity via wind considerably decrease, the environmental impact of other parts of the life cycle chain become more dominant. During the contribution analysis of C1 in the previous section, impacts in C1 were seen to largely stem from the electricity consumption used to produce hydrogen, whereas impacts in G1 were also seen to derive from the initial iron fuel production from scrap among other processes. In G1, the impacts resulting from, for example, the initial iron fuel production are seen to weigh relatively heavy when the impact of the electricity consumption is decreased significantly in the wind scenario. The decrease is so significant that in most impact categories it results in tipping the environmental performance in favor of heat produced by a hydrogen boiler in the case of wind produced hydrogen. It can be concluded that the electricity mix at the production stage is a highly sensitive parameter.

14.2 Results of the Variation in Hydrogen Leakage – Hydrogen PA only

Interesting to see from Table E3 is that when looking at the result of an increase of hydrogen leakage in C1, the impacts scale linearly the same for all impact categories except for the impact category water use. To explain why the water use does not scale the same, it is important to remember that 99% of the contributions to the water use impact category stem from the steam production process via a hydrogen boiler, i.e. the final process resulting in the reference flow. As this process combusts a fixed amount of hydrogen producing a fixed amount of water, this process is unaffected by any leakage of hydrogen occurring prior in the chain. In this study, the leakage of hydrogen is modelled during the transportation phase. Hence, there is a limited impact on the water use impact category because of this modelled leakage of hydrogen. In a real-life situation, hydrogen could also leak in the final end-use process meaning that this modelling may not be a completely accurate portrayal of the more complex practical reality.

Table E3: Sensitivity analysis results of a variation in the percentage of hydrogen leakage, results are shown relative to largest impact.

Impact Category	Unit	H-boiler 2030, incl. network construction [C1]			
		Base Case	5% leakage	10% leakage	15% leakage
Acidification	mol H+-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Climate change	kg CO2-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Ecotoxicity, freshwater	CTUe	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Resource use, fossils	MJ, net calorific value	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Eutrophication, freshwater	kg P-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Eutrophication, marine	kg N-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Eutrophication, terrestrial	mol N-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Human toxicity. cancer	CTUh	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Human toxicity, non-cancer	CTUh	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Ionising radiation	kBq U235-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Land use	dimensionless	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Resource use, minerals and metals	kg Sb-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Ozone depletion	kg CFC-11-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Particulate matter	disease incidence	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Photochemical oxidant formation	kg NMVOC-Eq	8.51E-01	8.95E-01	9.45E-01	1.00E+00
Water use	m3 world eq. deprived	9.99E-01	9.99E-01	1.00E+00	1.00E+00

The way in which the hydrogen leakage is modelled currently, results in an increased production of hydrogen to compensate the hydrogen leaked to the environment during transport. This results in a systematic increase of hydrogen at the front end of the life cycle chain and explains the results seen in Table E3. However, it does not explain why the impact to climate change also scales linearly. The leakage of hydrogen into the environment is known to cause indirect warming effects through reacting with hydroxyl radicals leading to increased concentrations of greenhouse gases (Derwent et al., 2006; Ocko & Hamburg, 2022). (Derwent et al., 2006) state that hydrogen has a global warming potential of 5.8 over a 100-year horizon, but this is not seen reflected in the graphs. The reason why this effect is not shown in Table 10 is because there is no characterization factor for hydrogen in any of the impact categories in the LCIA method of PEF version 3.1 (*EF Reference Package 3.1*, 2022). As a result, the effect of hydrogen leakage on climate change, and potentially other impact categories as well, is not fully reflected here.

As the electricity consumption at the production stage has been shown to be of importance, it is noteworthy to mention that with every increase in hydrogen leakage the electricity required to produce one MWh of superheated steam at 240°C at 20 bar via a hydrogen boiler also goes up. The first 5% increase in hydrogen leakage results in an increase of ~300 MJ of electricity required to produce the hydrogen lost from the baseline of 5648.5 MJ. This number increases by an extra ~330 MJ if the leakage increases from 5 to 10% and increases even further by another ~370 MJ should the leakage reach up to 15%.[14] The difference between a 0% hydrogen leakage and a 15% hydrogen leakage is a significant ~1000 MJ of extra electricity required to produce sufficient hydrogen for every MWh of steam. To put this in perspective, the electricity

[14] The reason why this does not scale linearly has to do with the modelling and parametrization and is explained further in Appendix H.

consumption with 0% leakage is 5648 MJ per MWh steam and with a 15% leakage at the transportation phase the electricity required at the production stage would total 6645 MJ.

14.3 Results of the Variation in the Hydrogen Quantity Required for Combustion – Hydrogen PA only

As seen in Table E4, the need for extra hydrogen results in a higher environmental impact in all categories. The larger amount of hydrogen required at the end of the life cycle chain also translates into a greater need for producing hydrogen. The electricity supply required to the hydrogen production via electrolysis per MWh of steam in the base case is 5648 MJ whereas it totals 6581 MJ if the amount of hydrogen required for combustion would increase by approximately 2 kg. Increasing the amount of hydrogen required for combustion raises the amount of electricity required upstream the life cycle chain to about the same level as a 15% hydrogen loss due to leakage would give.

Table E4: Sensitivity analysis results of a change in required hydrogen for combustion, only C1 tested.

Impact Category	Unit	H-boiler 2030, incl. network construction [C1]	
		Base Case	~33kg/MWh
Acidification	mol H+-Eq	1.23E+00	1.44E+00
Climate change	kg CO2-Eq	1.95E+02	2.27E+02
Ecotoxicity, freshwater	CTUe	1.67E+03	1.95E+03
Resource use, fossils	MJ, net calorific value	3.51E+03	4.09E+03
Eutrophication, freshwater	kg P-Eq	1.24E-01	1.45E-01
Eutrophication, marine	kg N-Eq	1.64E-01	1.91E-01
Eutrophication, terrestrial	mol N-Eq	1.82E+00	2.12E+00
Human toxicity, cancer	CTUh	2.89E-07	3.36E-07
Human toxicity, non-cancer	CTUh	1.15E-05	1.34E-05
Ionising radiation	kBq U235-Eq	4.60E+01	5.35E+01
Land use	dimensionless	1.73E+03	2.02E+03
Resource use, minerals and metals	kg Sb-Eq	1.09E-02	1.27E-02
Ozone depletion	kg CFC-11-Eq	1.02E-05	1.19E-05
Particulate matter	disease incidence	7.94E-06	9.24E-06
Photochemical oxidant formation	kg NMVOC-Eq	5.86E-01	6.82E-01
Water use	m3 world eq. deprived	1.21E+04	1.22E+04

14.4 Results of the Variation in the Electricity Consumption of an IF Production System –IF PAs only

From Table E5, it becomes clear that the lowest electricity consumption has the best environmental impact followed by the base case (~476 kWh) and lastly the highest electricity consumption. This is in line with the notion that the higher the overall electricity consumption, the worse a process alternative performs environmentally. Generally, the increase in electricity consumption here has limited impact in changing the order of favorability of each process alternative, except for one case. Notice that with the highest possible electricity consumption of the IF production system, process alternative C1 starts to perform better than E1 in the impact categories of fossil resource use and land use. Should the electricity consumption thus significantly increase in the IFT PAs, C1 will perform better environmentally in these two impact categories.

Table E5: Sensitivity analysis results of a variation in the electricity consumption of the IF production system (IFT process alternatives tested only). A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

Impact Category [Unit]	**E1**			**F1**			**G1**			**H1**			**A1**	**C1**
	Base Case	388 kWh/t IF	604 kWh/t IF	Base Case	388 kWh/t IF	604 kWh/t IF	Base Case	388 kWh/t IF	604 kWh/t IF	Base Case	388 kWh/t IF	604 kWh/t IF	Base Case	Base Case
Acidification [mol H+-Eq]	1.15E+00	1.13E+00	1.19E+00	3.29E-01	3.04E-01	3.65E-01	1.06E+00	1.04E+00	1.10E+00	2.34E-01	2.09E-01	2.71E-01	7.37E-01	1.23E+00
Climate change [kg CO2-Eq]	2.07E+02	2.03E+02	2.13E+02	7.65E+01	7.24E+01	8.25E+01	1.80E+02	1.76E+02	1.86E+02	4.97E+01	4.56E+01	5.58E+01	1.22E+02	1.95E+02
Ecotoxicity, freshwater [CTUe]	1.55E+03	1.51E+03	1.60E+03	4.30E+02	3.95E+02	4.80E+02	1.57E+03	1.53E+03	1.62E+03	4.47E+02	4.12E+02	4.98E+02	1.02E+03	1.67E+03
Resource use, fossils [MJ, net calorific value]	3.42E+03	3.35E+03	3.53E+03	1.07E+03	9.96E+02	1.18E+03	3.14E+03	3.07E+03	3.25E+03	7.93E+02	7.18E+02	9.02E+02	2.20E+03	3.51E+03
Eutrophication, freshwater [kg P-Eq]	1.15E-01	1.13E-01	1.19E-01	3.21E-02	2.95E-02	3.60E-02	1.05E-01	1.02E-01	1.08E-01	2.14E-02	1.87E-02	2.52E-02	7.81E-02	1.24E-01
Eutrophication, marine [kg N-Eq]	1.75E-01	1.71E-01	1.80E-01	6.48E-02	6.13E-02	6.99E-02	1.51E-01	1.47E-01	1.56E-01	4.10E-02	3.75E-02	4.60E-02	1.02E-01	1.64E-01
Eutrophication, terrestrial [mol N-Eq]	1.91E+00	1.88E+00	1.97E+00	6.94E-01	6.55E-01	7.50E-01	1.66E+00	1.63E+00	1.72E+00	4.45E-01	4.06E-01	5.01E-01	1.14E+00	1.82E+00
Human toxicity, cancer [CTUh]	4.34E-07	4.28E-07	4.43E-07	2.42E-07	2.36E-07	2.51E-07	8.23E-07	8.17E-07	8.32E-07	6.31E-07	6.25E-07	6.40E-07	1.79E-07	2.89E-07
Human toxicity, non-cancer [CTUh]	9.55E-06	9.30E-06	9.90E-06	1.87E-06	1.62E-06	2.23E-06	9.72E-06	9.48E-06	1.01E-05	2.04E-06	1.80E-06	2.40E-06	7.24E-06	1.15E-05
Ionising radiation [kBq U235-Eq]	3.77E+01	3.67E+01	3.91E+01	6.91E+00	5.93E+00	8.35E+00	3.79E+01	3.70E+01	3.94E+01	7.19E+00	6.21E+00	8.63E+00	2.90E+01	4.60E+01
Land use [dimensionless]	1.69E+03	1.66E+03	1.75E+03	5.34E+02	4.97E+02	5.89E+02	1.67E+03	1.64E+03	1.73E+03	5.15E+02	4.78E+02	5.69E+02	1.09E+03	1.73E+03
Resource use, minerals and metals [kg Sb-Eq]	8.84E-03	8.61E-03	9.18E-03	1.52E-03	1.29E-03	1.86E-03	8.96E-03	8.73E-03	9.30E-03	1.64E-03	1.41E-03	1.98E-03	6.87E-03	1.09E-02
Ozone depletion [kg CFC-11-Eq]	9.32E-06	9.12E-06	9.62E-06	2.49E-06	2.28E-06	2.79E-06	8.62E-06	8.42E-06	8.92E-06	1.79E-06	1.58E-06	2.09E-06	6.10E-06	1.02E-05
Particulate matter [disease incidence]	1.14E-05	1.12E-05	1.16E-05	6.09E-06	5.92E-06	6.33E-06	1.01E-05	9.89E-06	1.03E-05	4.76E-06	4.60E-06	5.00E-06	4.89E-06	7.94E-06
Photochemical oxidant formation [kg NMVOC-Eq]	7.21E-01	7.09E-01	7.38E-01	3.29E-01	3.17E-01	3.47E-01	5.60E-01	5.48E-01	5.78E-01	1.69E-01	1.57E-01	1.87E-01	3.61E-01	5.86E-01
Water use [m3 world eq. deprived]	7.64E+01	7.46E+01	7.91E+01	1.56E+01	1.37E+01	1.83E+01	7.86E+01	7.67E+01	8.13E+01	1.78E+01	1.59E+01	2.05E+01	5.57E+01	1.21E+04

14.5 Results of the Variation in FLH of Boilers

Table E6 shows the largest percentage difference between any two sensitivity results when changing the number of FLH a boiler system runs for. As the percentage difference in any impact category is a maximum of 1%, varying the boiler's FLH shows limited changes in environmental impact. As the FLH are directly linked to the impacts related to the construction of the boiler, they can be considered negligible. This is briefly further explained in Box E2.

Table E6: Sensitivity analysis results on varying the FLH of the boilers. A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

Impact Category	**Maximum Percentage Difference between base case, 1000 FLH and 3000 FLH**					
	A1	C1	E1	F1	G1	H1
Acidification	0%	0%	0%	1%	0%	1%
Climate change	0%	0%	0%	1%	0%	1%
Ecotoxicity, freshwater	0%	0%	0%	1%	0%	1%
Resource use, fossils	0%	0%	0%	0%	0%	1%
Eutrophication, freshwater	0%	0%	0%	1%	0%	1%
Eutrophication, marine	0%	0%	0%	1%	0%	1%
Eutrophication, terrestrial	0%	0%	0%	1%	0%	1%
Human toxicity, cancer	0%	1%	1%	1%	0%	1%
Human toxicity, non-camcer	0%	0%	0%	1%	0%	0%
Ionising radiation	0%	0%	0%	0%	0%	0%
Land use	0%	0%	0%	0%	0%	0%
Resource use, minerals and metals	0%	0%	0%	0%	0%	0%
Ozone depletion	0%	0%	0%	0%	0%	0%
Particulate matter	0%	0%	0%	1%	0%	1%
Photochemical oxidant formation	0%	0%	0%	1%	0%	1%
Water use	0%	0%	0%	1%	0%	1%

Box E2: FLH explained

Full load hours refer to the number of hours that a system (e.g. machinery, boilers) runs annually. The maximum number of FLH a system can run annually is 8760 hours. FLH have an influence as it is a key determinant in the "amount" of system required for the production process for which the system is designed. The following equation describes this:

$$\text{the amount of system required for a process} = \frac{(\text{the amount of product produced by the system})}{(\text{FLH})(\text{lifetime of the system})(\text{capacity of the system})}$$

To exemplify with two problems, a boiler produces 1 MWh of heat and can run either 6000 FLH or 1000 FLH annually. It has a lifetime of 20 years and a capacity of 2 MWh of heat.

$$\text{the amount of system required for a process with 6000 FLH} = \frac{(1)}{(6000)(20)(2)} = 4.2x10^{-6}$$

$$\text{the amount of system required for a process with 1000 FLH} = \frac{(1)}{(1000)(20)(2)} = 2.5x10^{-5}$$

As becomes clear from these two examples is that less FLH will translate to an underutilization of the system. This results in the system depreciating over less hours run and the environmental impacts associated with the system will be higher for each hour the system runs.

14.6 Results of the Variation in FLH of the Iron Fuel Production System – IFT PAs only

A similar conclusion as to the boilers can be made about the iron fuel production system. As seen in Table E7, a change in the number of FLH an iron fuel production system runs makes very little difference to any of the environmental impact categories. The emissions related to the construction of the iron fuel production system can be considered negligible.

Table E7: Sensitivity analysis results on varying FLH of iron fuel production system. E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

Impact Category	**Maximum Percentage Difference between base case, 3000 FLH and 4500 FLH**			
	E1	F1	G1	H1
Acidification	0%	0%	0%	1%
Climate change	0%	0%	0%	0%
Ecotoxicity, freshwater	0%	0%	0%	0%
Resource use, fossils	0%	0%	0%	0%
Eutrophication, freshwater	0%	0%	0%	0%
Eutrophication, marine	0%	0%	0%	1%
Eutrophication, terrestrial	0%	0%	0%	1%
Human toxicity, cancer	0%	1%	0%	0%
Human toxicity, non-cancer	0%	0%	0%	0%
Ionising radiation	0%	0%	0%	0%
Land use	0%	0%	0%	0%
Resource use, minerals and metals	0%	0%	0%	0%
Ozone depletion	0%	0%	0%	0%
Particulate matter	0%	0%	0%	0%
Photochemical oxidant formation	0%	0%	0%	1%
Water use	0%	0%	0%	0%

14.7 Results of the Variation in FLH of the Electrolyzer – Hydrogen and IFT with electrolyzer PAs only

The number of FLH made annually by a boiler system or by an iron fuel production system made little difference to any of the impact categories. However the number of FLH made by an electrolyzer create a much larger difference in comparison, as seen in Table E8. The more FLH made (base case being 8300 FLH) the lower the exertion on the environment per MWh of steam generated. This is especially the case for the impact categories of acidification and ozone depletion where an 8%, 6% and 6% difference is seen between operating at 3000 FLH and 8300 FLH in h-boiler, 2030, incl. network construction (C1), IF boiler, 2030, pig iron + electrolyzer (E1) and IF boiler, 2030, scrap iron + electrolyzer (G1) respectively. This can be explained by two reasons. The first is that the environmental impacts related to the construction of the hydrogen electrolyzer are responsible for a larger contribution to certain impact categories of the process alternatives. Secondly, the electrolyzer consists of a multitude of materials that are not present in boilers including nickel, polytetrafluoroethylene and multiple acids among other materials. These materials and their related upstream (production) processes can have a larger environmental impact in addition to being large contributors to the total electrolyzers environmental impact. To exemplify, for the impact category acidification the upstream impacts of nickel account for 94% of the total impacts of an electrolyzer in C1 whereas polytetrafluoroethylene accounts for 93% of the total upstream impacts of an electrolyzer for ozone depletion. A similar trend is applicable for E1 and G1. However, as the required amount of hydrogen in the Iron Fuel Technology™ process is smaller in comparison to the hydrogen process alternative, the environmental impact is smaller. Hence, the maximum difference as seen in E1 and G1 is also smaller in Table E8.

Table E8: Sensitivity analysis results of varying FLH of hydrogen electrolyzer

Impact Category + Unit	**H-boiler 2030, incl. network construction [C1]**			**IF boiler 2030, pig + H electrolyzer [E1]**			**IF boiler 2030, scrap + H electrolyzer [G1]**			**Maximum Difference - C1**		**Maximum Difference - E1**		**Maximum Difference - G1**	
	Base Case	3000 FLH	4500 FLH	Base Case	3000 FLH	4500 FLH	Base Case	3000 FLH	4500 FLH	absolute	%	absolute	%	absolute	%
Acidification [mol H+-Eq]	1.23E+00	1.35E+00	1.29E+00	1.15E+00	1.23E+00	1.19E+00	1.06E+00	1.14E+00	1.10E+00	1.14E-01	8%	7.78E-02	6%	7.78E-02	7%
Climate change [kg CO2-Eq]	1.95E+02	1.97E+02	1.96E+02	2.07E+02	2.08E+02	2.08E+02	1.80E+02	1.82E+02	1.81E+02	2.23E+00	1%	1.53E+00	1%	1.53E+00	1%
Ecotoxicity, freshwater [CTUe]	1.67E+03	1.70E+03	1.69E+03	1.55E+03	1.57E+03	1.56E+03	1.57E+03	1.59E+03	1.58E+03	2.91E+01	2%	1.99E+01	1%	1.99E+01	1%
Resource use, fossils [MJ, net calorific value]	3.51E+03	3.54E+03	3.53E+03	3.42E+03	3.44E+03	3.43E+03	3.14E+03	3.16E+03	3.15E+03	2.76E+01	1%	1.89E+01	1%	1.89E+01	1%
Eutrophication, freshwater [kg P-Eq]	1.24E-01	1.26E-01	1.25E-01	1.15E-01	1.16E-01	1.16E-01	1.05E-01	1.06E-01	1.05E-01	1.48E-03	1%	1.01E-03	1%	1.01E-03	1%
Eutrophication, marine [kg N-Eq]	1.64E-01	1.68E-01	1.66E-01	1.75E-01	1.77E-01	1.76E-01	1.51E-01	1.53E-01	1.52E-01	3.07E-03	2%	2.10E-03	1%	2.10E-03	1%
Eutrophication, terrestrial [mol N-Eq]	1.82E+00	1.86E+00	1.84E+00	1.91E+00	1.94E+00	1.92E+00	1.66E+00	1.69E+00	1.68E+00	3.33E-02	2%	2.28E-02	1%	2.28E-02	1%
Human toxicity, cancer [CTUh]	2.89E-07	2.98E-07	2.93E-07	4.34E-07	4.41E-07	4.37E-07	8.23E-07	8.30E-07	8.26E-07	9.24E-09	3%	6.32E-09	1%	6.32E-09	1%
Human toxicity, non-cancer [CTUh]	1.15E-05	1.15E-05	1.15E-05	9.55E-06	9.58E-06	9.56E-06	9.72E-06	9.75E-06	9.74E-06	4.92E-08	0%	3.37E-08	0%	3.37E-08	0%
Ionising radiation [kBq U235-Eq]	4.60E+01	4.62E+01	4.61E+01	3.77E+01	3.78E+01	3.77E+01	3.79E+01	3.81E+01	3.80E+01	2.42E-01	1%	1.66E-01	0%	1.66E-01	0%
Land use [dimensionless]	1.73E+03	1.74E+03	1.74E+03	1.69E+03	1.70E+03	1.70E+03	1.67E+03	1.68E+03	1.68E+03	1.12E+01	1%	7.63E+00	0%	7.63E+00	0%
Resource use, minerals and metals [kg Sb-Eq]	1.09E-02	1.11E-02	1.10E-02	8.84E-03	8.94E-03	8.89E-03	8.96E-03	9.06E-03	9.01E-03	1.46E-04	1%	1.00E-04	1%	1.00E-04	1%
Ozone depletion [kg CFC-11-Eq]	1.02E-05	1.10E-05	1.06E-05	9.32E-06	9.89E-06	9.60E-06	8.62E-06	9.19E-06	8.89E-06	8.29E-07	8%	5.67E-07	6%	5.67E-07	6%
Particulate matter [disease incidence]	7.94E-06	8.21E-06	8.07E-06	1.14E-05	1.16E-05	1.15E-05	1.01E-05	1.02E-05	1.01E-05	2.65E-07	3%	1.82E-07	2%	1.82E-07	2%
Photochemical oxidant formation [kg NMVOC-Eq]	5.86E-01	6.05E-01	5.95E-01	7.21E-01	7.34E-01	7.27E-01	5.60E-01	5.73E-01	5.66E-01	1.92E-02	3%	1.32E-02	2%	1.32E-02	2%
Water use [m3 world eq. deprived]	1.21E+04	1.21E+04	1.21E+04	7.64E+01	7.95E+01	7.79E+01	7.86E+01	8.17E+01	8.01E+01	4.50E+00	0%	3.06E+00	4%	3.06E+00	4%

14.8 Results of the Variation in Transport Distance

From Table E9 and E10, it can be derived that any change in transport distance for process alternatives A1 and C1 makes little difference whereas for the process alternatives E1, F1, G1 and H1, the potential environmental impact can drastically increase when the distance changes. To understand why this is the case see Box E3.

Table E9: Sensitivity analysis results of varying transport distance, percentage difference. A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen

Impact Category	**Maximum Percentage Difference between base case, 500 km, 1000 km and 5000 km**					
	A1	C1	E1	F1	G1	H1
Acidification	0%	0%	50%	78%	52%	83%
Climate change (total)	0%	0%	70%	86%	72%	91%
Ecotoxicity: freshwater	0%	0%	69%	89%	69%	89%
Resource use, fossils	0%	0%	68%	87%	70%	90%
Eutrophication: freshwater	0%	0%	23%	52%	25%	62%
Eutrophication: marine	0%	0%	65%	83%	68%	89%
Eutrophication: terrestrial	0%	0%	63%	83%	66%	88%
Human toxicity, cancer	0%	0%	33%	47%	20%	25%
Human toxicity, non-cancer	0%	0%	35%	74%	35%	72%
Ionising radiation	0%	0%	19%	57%	19%	56%
Land use	0%	0%	81%	93%	81%	93%
Resource use, minerals and metals	0%	0%	13%	47%	13%	45%
Ozone depletion	0%	0%	53%	81%	55%	86%
Particulate matter	0%	0%	80%	89%	82%	91%
Photochemical oxidant formation	0%	0%	73%	85%	77%	92%
Water use	0%	0%	33%	71%	32%	68%

Box E3: Transport Changes Explained

The required "amount" of transport infrastructure is derived by the following equation:

$$\frac{(distance\ required\ to\ travel)}{(quantity\ transportable\ by\ the\ transportation\ method)(lifetime)} \tag{1}$$

As a result, if a specific transport method (e.g. electricity network or hydrogen pipeline) can transport large quantities the transport footprint and the associated emissions will be relatively small even over long distances. When a mode of transport has limited transport capacity, several of the same transport modes will need to be used in parallel to fulfill the quantity demanded (e.g. multiple trucks).

By increasing the distance from 150 km (base case) to 5000 km some impact categories of the IFT process alternatives can almost double the impacts. As just explained in Box E3, the quantity transportable by the transportation method plays a role in determining the transportation footprint and the associated emissions. As each truck is only able to carry a specific quantity of material in addition to it having operational emissions (i.e. the combustion of diesel in this case) as well as a trace amount of truck construction impacts, truck maintenance impacts etc. all the associated emissions with transporting a specific quantity over a specified distance will start to add up.

It is also interesting to see that when transport distance changes, the best performing process alternative can also switch. Notice how C1, E1 and G1 perform better or worse in multiple impact categories depending on which cases you compare together. To exemplify, for the impact category acidification, comparing all base cases of the three PAs together, G1 performs best with E1 coming in second and C1 performing worst as seen in Table E10. Then when comparing the 500 km scenarios together G1 still outperforms C1 and E1, yet C1 just slightly performs better than E1. However, when comparing the 1000 km distance scenarios, G1 and E1 both exert more environmental impact than C1. The transportation distance chosen is thus quite a sensitive parameter with the ability to alter which PA is the most environmentally beneficial.

14.9 Results of the Variation in Transport Method – IFT PAs only

As seen in Table E11, ship transport would be recommended over truck transport from an environmental perspective whenever both options are possible as ship transport reduces environmental impacts across all impact categories. The difference between short (150 km) and long (5000 km) distance transport by ship can also be considered negligible for all process alternatives. This is the result of the large quantities a ship can transport, the same principle as described earlier in Box E3.

Comparing across process alternatives, F1 and H1 generally still perform the best environmentally – H1 apart from the impact category human toxicity, cancer. In contrast, C1 and E1 generally perform the worst. Interesting to see is that with the switch to ship transport E1 performs better in comparison to C1 in the impact categories of climate change, terrestrial eutrophication and land use. Hence, a change in transportation method can also be a sensitive parameter.

Table E10: Sensitivity analysis results of varying transport distance. Abbreviations: IC: Impact Category; AC: Acidification [mol H+-Eq]; CC: Climate change [kg CO2-Eq]; EC: Ecotoxicity, freshwater [CTUe]; FR: Resource use, fossils [MJ, net calorific value]; EF: Eutrophication: freshwater [kg P-Eq]; EM: Eutrophication, marine [kg N-Eq]; ET: Eutrophication, terrestrial [mol N-Eq]; TC: Human toxicity, cancer [CTUh]; TNC: Human toxicity, non-cancer [CTUh]; IR: Ionising radiation [kBq U235-Eq]; LU: Land use [dimensionless]; MR: Resource use, minerals and metals [kg Sb-Eq]; OD: Ozone depletion [kg CFC-11-Eq]; PM: Particulate matter [disease incidence]; PO: Photochemical oxidant formation [kg NMVOC-Eq]; WU: Water use [m3 world eq. deprived].

IC	E-boiler 2030, incl. network construction [A1]				H-boiler 2030, incl. network construction [C1]				IF boiler 2030, pig + H electrolyzer [E1]				IF boiler 2030, pig + waste H [F1]				IF boiler 2030, scrap + H electrolyzer [G1]				IF boiler 2030, scrap + waste H [H1]			
	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km	Base Case	500 km	1000 km	5000 km
AC	7.37E-01	7.37E-01	7.37E-01	7.38E-01	1.23E+00	1.23E+00	1.23E+00	1.24E+00	1.15E+00	1.24E+00	1.36E+00	2.32E+00	3.29E-01	4.13E-01	5.35E-01	1.50E+00	1.06E+00	1.14E+00	1.26E+00	2.23E+00	2.34E-01	3.19E-01	4.40E-01	1.41E+00
CC	1.22E+02	1.22E+02	1.22E+02	1.22E+02	1.95E+02	1.95E+02	1.95E+02	1.96E+02	2.07E+02	2.41E+02	2.89E+02	6.78E+02	7.65E+01	1.11E+02	1.60E+02	5.52E+02	1.80E+02	2.14E+02	2.63E+02	6.51E+02	4.97E+01	8.40E+01	1.33E+02	5.25E+02
EC	1.02E+03	1.02E+03	1.02E+03	1.02E+03	1.67E+03	1.67E+03	1.67E+03	1.68E+03	1.55E+03	1.80E+03	2.15E+03	4.99E+03	4.30E+02	6.80E+02	1.04E+03	3.89E+03	1.57E+03	1.81E+03	2.17E+03	5.00E+03	4.47E+02	6.97E+02	1.05E+03	3.91E+03
FR	2.20E+03	2.20E+03	2.20E+03	2.20E+03	3.51E+03	3.51E+03	3.51E+03	3.52E+03	3.42E+03	3.94E+03	4.68E+03	1.06E+04	1.07E+03	1.59E+03	2.34E+03	8.33E+03	3.14E+03	3.66E+03	4.40E+03	1.03E+04	7.93E+02	1.32E+03	2.06E+03	8.05E+03
EF	7.81E-02	7.81E-02	7.81E-02	7.82E-02	1.24E-01	1.25E-01	1.25E-01	1.25E-01	1.15E-01	1.18E-01	1.21E-01	1.50E-01	3.21E-02	3.47E-02	3.83E-02	6.72E-02	1.05E-01	1.07E-01	1.11E-01	1.39E-01	2.14E-02	2.39E-02	2.75E-02	5.64E-02
EM	1.02E-01	1.03E-01	1.03E-01	1.03E-01	1.64E-01	1.65E-01	1.65E-01	1.65E-01	1.75E-01	1.98E-01	2.30E-01	4.92E-01	6.48E-02	8.79E-02	1.21E-01	3.85E-01	1.51E-01	1.74E-01	2.07E-01	4.68E-01	4.10E-02	6.41E-02	9.71E-02	3.61E-01
ET	1.14E+00	1.14E+00	1.14E+00	1.14E+00	1.82E+00	1.82E+00	1.83E+00	1.83E+00	1.91E+00	2.15E+00	2.48E+00	5.17E+00	6.94E-01	9.31E-01	1.27E+00	3.98E+00	1.66E+00	1.90E+00	2.24E+00	4.93E+00	4.45E-01	6.82E-01	1.02E+00	3.73E+00
TC	1.79E-07	1.79E-07	1.79E-07	1.79E-07	2.89E-07	2.89E-07	2.89E-07	2.90E-07	4.34E-07	4.50E-07	4.71E-07	6.45E-07	2.42E-07	2.57E-07	2.79E-07	4.54E-07	8.23E-07	8.39E-07	8.60E-07	1.03E-06	6.31E-07	6.46E-07	6.68E-07	8.43E-07
TNC	7.24E-06	7.24E-06	7.25E-06	7.25E-06	1.15E-05	1.15E-05	1.15E-05	1.15E-05	9.55E-06	9.92E-06	1.04E-05	1.47E-05	1.87E-06	2.24E-06	2.78E-06	7.06E-06	9.72E-06	1.01E-05	1.06E-05	1.49E-05	2.04E-06	2.42E-06	2.95E-06	7.23E-06
IR	2.90E+01	2.90E+01	2.90E+01	2.90E+01	4.60E+01	4.60E+01	4.60E+01	4.61E+01	3.77E+01	3.83E+01	3.92E+01	4.67E+01	6.91E+00	7.57E+00	8.50E+00	1.60E+01	3.79E+01	3.86E+01	3.95E+01	4.69E+01	7.19E+00	7.84E+00	8.78E+00	1.63E+01
LU	1.09E+03	1.09E+03	1.09E+03	1.09E+03	1.73E+03	1.73E+03	1.73E+03	1.74E+03	1.69E+03	2.22E+03	2.96E+03	8.95E+03	5.34E+02	1.06E+03	1.82E+03	7.85E+03	1.67E+03	2.20E+03	2.94E+03	8.93E+03	5.15E+02	1.04E+03	1.80E+03	7.83E+03
MR	6.87E-03	6.87E-03	6.87E-03	6.87E-03	1.09E-02	1.09E-02	1.09E-02	1.10E-02	8.84E-03	8.94E-03	9.08E-03	1.02E-02	1.52E-03	1.62E-03	1.76E-03	2.88E-03	8.96E-03	9.06E-03	9.20E-03	1.03E-02	1.64E-03	1.74E-03	1.88E-03	3.00E-03
OD	6.10E-06	6.10E-06	6.10E-06	6.10E-06	1.02E-05	1.02E-05	1.02E-05	1.02E-05	9.32E-06	1.01E-05	1.12E-05	2.00E-05	2.49E-06	3.27E-06	4.38E-06	1.33E-05	8.62E-06	9.39E-06	1.05E-05	1.93E-05	1.79E-06	2.56E-06	3.68E-06	1.26E-05
PM	4.89E-06	4.90E-06	4.90E-06	4.91E-06	7.94E-06	7.94E-06	7.94E-06	7.97E-06	1.14E-05	1.47E-05	1.96E-05	5.80E-05	6.09E-06	9.48E-06	1.43E-05	5.31E-05	1.01E-05	1.34E-05	1.82E-05	5.67E-05	4.76E-06	8.15E-06	1.30E-05	5.18E-05
PO	3.61E-01	3.62E-01	3.62E-01	3.62E-01	5.86E-01	5.86E-01	5.86E-01	5.88E-01	7.21E-01	8.58E-01	1.05E+00	2.62E+00	3.29E-01	4.68E-01	6.66E-01	2.25E+00	5.60E-01	6.98E-01	8.94E-01	2.46E+00	1.69E-01	3.07E-01	5.05E-01	2.09E+00
WU	5.57E+01	5.57E+01	5.57E+01	5.57E+01	1.21E+04	1.21E+04	1.21E+04	1.21E+04	7.64E+01	7.91E+01	8.29E+01	1.13E+02	1.56E+01	1.83E+01	2.21E+01	5.29E+01	7.86E+01	8.13E+01	8.51E+01	1.16E+02	1.78E+01	2.04E+01	2.43E+01	5.50E+01

Table E11: Sensitivity analysis results of varying the transport method (IFT process alternatives tested only). Abbrevations: A1: Steam production through e-boiler, 2030, with infrastructural construction; C1: Steam production through h-boiler, 2030, with infrastructural construction; E1: Steam production through IF boiler, 2030, pig iron + hydrogen electrolyzer; F1: Steam production through IF boiler, 2030, pig iron + waste hydrogen; G1: Steam production through IF boiler, 2030, iron scrap + hydrogen electrolyzer; H1: Steam production through IF boiler, 2030, iron scrap + waste hydrogen; AC: Acidification [mol H+-Eq]; CC: Climate change [kg CO2-Eq]; EC: Ecotoxicity, freshwater [CTUe]; FR: Resource use, fossils [MJ, net calorific value]; EF: Eutrophication: freshwater [kg P-Eq]; EM: Eutrophication, marine [kg N-Eq]; ET: Eutrophication, terrestrial [mol N-Eq]; TC: Human toxicity, cancer [CTUh]; TNC: Human toxicity, non-cancer [CTUh]; IR: Ionising radiation [kBq U235-Eq]; LU: Land use [dimensionless]; MR: Resource use, minerals and metals [kg Sb-Eq]; OD: Ozone depletion [kg CFC-11-Eq]; PM: Particulate matter [disease incidence]; PO: Photochemical oxidant formation [kg NMVOC-Eq]; WU: Water use [m3 world eq. deprived].

IC	**E1**			**F1**			**G1**			**H1**			**A1**	**C1**
	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	ship 150km	ship 5000 km	Base Case	Base Case
AC	1.15E+00	1.12E+00	1.12E+00	3.29E-01	2.92E-01	2.92E-01	1.06E+00	1.02E+00	1.02E+00	2.34E-01	1.98E-01	1.98E-01	7.37E-01	1.23E+00
CC	2.07E+02	1.92E+02	1.92E+02	7.65E+01	6.18E+01	6.18E+01	1.80E+02	1.65E+02	1.65E+02	4.97E+01	3.50E+01	3.50E+01	1.22E+02	1.95E+02
EC	1.55E+03	1.44E+03	1.44E+03	4.30E+02	3.22E+02	3.22E+02	1.57E+03	1.46E+03	1.46E+03	4.47E+02	3.40E+02	3.40E+02	1.02E+03	1.67E+03
FR	3.42E+03	3.20E+03	3.20E+03	1.07E+03	8.47E+02	8.47E+02	3.14E+03	2.92E+03	2.92E+03	7.93E+02	5.68E+02	5.68E+02	2.20E+03	3.51E+03
EF	1.15E-01	1.14E-01	1.14E-01	3.21E-02	3.10E-02	3.10E-02	1.05E-01	1.04E-01	1.04E-01	2.14E-02	2.03E-02	2.03E-02	7.81E-02	1.24E-01
EM	1.75E-01	1.65E-01	1.65E-01	6.48E-02	5.49E-02	5.49E-02	1.51E-01	1.41E-01	1.41E-01	4.10E-02	3.11E-02	3.11E-02	1.02E-01	1.64E-01
ET	1.91E+00	1.81E+00	1.81E+00	6.94E-01	5.92E-01	5.92E-01	1.66E+00	1.56E+00	1.56E+00	4.45E-01	3.43E-01	3.43E-01	1.14E+00	1.82E+00
TC	4.34E-07	4.28E-07	4.28E-07	2.42E-07	2.35E-07	2.35E-07	8.23E-07	8.17E-07	8.17E-07	6.31E-07	6.24E-07	6.24E-07	1.79E-07	2.89E-07
TNC	9.55E-06	9.39E-06	9.39E-06	1.87E-06	1.71E-06	1.71E-06	9.72E-06	9.56E-06	9.56E-06	2.04E-06	1.88E-06	1.88E-06	7.24E-06	1.15E-05
IR	3.77E+01	3.74E+01	3.74E+01	6.91E+00	6.63E+00	6.63E+00	3.79E+01	3.77E+01	3.77E+01	7.19E+00	6.91E+00	6.91E+00	2.90E+01	4.60E+01
LU	1.69E+03	1.47E+03	1.47E+03	5.34E+02	3.08E+02	3.08E+02	1.67E+03	1.45E+03	1.45E+03	5.15E+02	2.89E+02	2.89E+02	1.09E+03	1.73E+03
MR	8.84E-03	8.80E-03	8.80E-03	1.52E-03	1.48E-03	1.48E-03	8.96E-03	8.92E-03	8.92E-03	1.64E-03	1.60E-03	1.60E-03	6.87E-03	1.09E-02
OD	9.32E-06	8.99E-06	8.99E-06	2.49E-06	2.16E-06	2.16E-06	8.62E-06	8.29E-06	8.29E-06	1.79E-06	1.45E-06	1.45E-06	6.10E-06	1.02E-05
PM	1.14E-05	9.94E-06	9.94E-06	6.09E-06	4.63E-06	4.63E-06	1.01E-05	8.62E-06	8.62E-06	4.76E-06	3.31E-06	3.31E-06	4.89E-06	7.94E-06
PO	7.21E-01	6.62E-01	6.62E-01	3.29E-01	2.70E-01	2.70E-01	5.60E-01	5.01E-01	5.01E-01	1.69E-01	1.10E-01	1.10E-01	3.61E-01	5.86E-01
WU	7.64E+01	7.53E+01	7.53E+01	1.56E+01	1.44E+01	1.44E+01	7.86E+01	7.74E+01	7.74E+01	1.78E+01	1.66E+01	1.66E+01	5.57E+01	1.21E+04

15. Appendix F

The following recommendations are made for ecoinvent:

1. Recycling and waste treatment of capital goods is currently inconsistently included within ecoinvent with some processes including all parts and other processes not including all parts. An example of this is that a biomass heat production process included within the ecoinvent database includes the end-of-life stage including the steel used for constructing the boiler/furnace. A similar process, namely a gas heat production process included within the ecoinvent database, includes some waste streams but not for any of the steel used. As steel is one of the largest materials that makes up a boiler, this is odd and more consistent modelling should be considered.
2. The road construction toward freight transport of EURO 6 lorry is relatively high (0.00109 ma). Typically these processes are more on the order of e-11/e-12 rather than so high. Perhaps this is an error in inputting data?
3. A quick double check calculation into the natural gas values of ecoinvent showed that a very high energy content of methane was assumed (55 MJ/kg). This is the very high end of the range and most natural gas that is combusted in industries has this high of an energy content. This can result in lower environmental impacts in the LCA than are made practically.
4. It is also difficult to compare the processes of ecoinvent as important parameters like stack temperature and efficiencies are not well documented for combustion processes. Hence, if using ecoinvent processes to compare two different fuels it is not known whether the comparison is fair in that you are comparing similar cases.
5. Generally, data of ecoinvent is quite dated. This limits any analysis completed with the ecoinvent database. More frequent updating of data or more transparently communicating exactly how the data was produced and the values behind it may allow for easier updating as a researcher.

16. Appendix G

10 billion cubic meters of hydrogen of which 20% is by-product leading to 2 billion cubic meters waste hydrogen (Milieu Centraal, n.d.-b). Assuming a density of hydrogen of 0.08375 kg/m3 there is 167,500,000 kg of waste hydrogen. 25 kg hydrogen is required for 1 MWh which results in 6,700,000 MWh able to be installed. Assuming 6000 FLH per year results in 1.1 GW of installed capacity in the Netherlands if all waste hydrogen in the Netherlands is used.

Worldwide there is 14.8 MT of by-product hydrogen (2022) (Bermudez et al., 2023). Again 25 kg hydrogen is required for 1 MWh which results in the ability to install 592,000,000 MWh capacity. Assuming 6000 FLH per year 99 GW installed capacity if all worldwide by-product hydrogen is used.

The demand of hydrogen in 2030 has been estimated to be approximately 125-213 PJ solely for industrial applications on the coast of the Netherlands with an additional 25-40 PJ demand estimated for the industrial cluster Chemelot (Limburg, consisting mostly of chemical applications) (Ministerie van Economische Zaken en Klimaat, 2019d). This totals to a 150-253 PJ expected demand in 2030. Converting this to MWh, results in 41666667-70277777 MWh of hydrogen demanded. Assuming 6000 FLH annually it results in 6944-11713 MW or 6.9-11.7 GW of installed capacity required.

The Dutch government has goals to install 8 GW electrolysis capacity by 2032 (Ministerie van Algemene Zaken, n.d.-e; Ministerie van Economische Zaken en Klimaat, 2019d). Assuming that they mean by this an electricity supply of 8 GW for electrolysis this results in 8000 MWe. Taking that the electrolyzer uses 50 kWh for each kg hydrogen produced (standard and used consistently throughout this research) it results in 960000000 kg of hydrogen / year.
For hydrogen: assume 31 kg hydrogen / MWh resulting in 30967742 MWh. Assuming 6000 FLH this leads to 5161 MW or 5.1 GW of installed capacity.
For IFT: assume 27 kg hydrogen /MWh resulting in 35555556 MWh. Assuming 6000 FLH this leads to 5926 MW or 5.9 GW of installed capacity.

The market size of scrap in 2022 is 624.5 million metric tons (Jha, 2023). For every MWh 0.28 kg iron is required resulting in 2,230,357,142,857 MWh. Assuming 6000 FLH results in 371,726 GW installed capacity. Scrap is not a problem therefore and the projected market value of 2033 is only larger – 1050 million metric tons (Jha, 2023).

17. Appendix H

The reason why hydrogen leakage does not scale linearly is because the ‘product recipe’ changes as a result of the way it was modelled (a formula of 1-x was inputted). To explain, assume you use 1 apple and 1 banana, which together make 2 apple/banana smoothies. Now assume you still use 1 apple and 1 banana, but this only makes 1.5 apple/banana smoothies because 0.5 apple/banana smoothies fell on the floor and hence you cannot do anything with it. You still had the same input so the upstream impacts related to that 1 apple and 1 banana remain the same, but the output is different. If you, however, really need to have 2 apple/banana smoothies, you will need to use more apples and bananas to compensate for the loss. If this continues, then your upstream impacts will consistently become higher and higher, and they will not be linear. The hydrogen leakage doesn’t scale linearly because this is the way it is modelled for easier data parametrization.