EGEN

LIFE CYCLE ASSESSMENT REPORT

LIFE CYCLE ASSESSMENT OF IRON FUEL

April 21, 2025

CREATED FOR

RIFT

Confidential

This report is not intended for public disclosure before external verification has taken place.

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Executive Summary

This Life Cycle Assessment (LCA) study evaluates the environmental performance of RIFT's Iron Fuel Technology™ as a novel alternative for industrial saturated steam provision, in comparison with a natural gas-fired boiler system. Iron Fuel is an innovative circular energy carrier, where iron powder is oxidised (burned) to generate heat, and the resulting iron oxide can be regenerated back into Iron Fuel. The assessment is conducted in accordance with ISO 14040/14044 standards and applies the Environmental Footprint (EF) 3.1 method to analyse the 16 PEF midpoint impact categories. The study adopts a cradle-to-gate system boundary, including Iron Fuel production, combustion, and regeneration, as well as key upstream processes such as low-carbon hydrogen production and the associated carbon capture and storage (CCS) value chain. The functional unit is defined as one MWh (thermal) of saturated steam at 210 °C and 16 bar with a stack temperature of 120 °C.

The Iron Fuel system avoids direct CO_2 emissions during combustion and decreases fossil fuel dependence, leading to lower impacts in climate change, non-renewable energy resource depletion, and ozone depletion, categories closely linked to carbon-based energy. This performance is largely attributed to the zero CO_2 emissions during combustion of the Iron Fuel, the recyclability of iron oxide, and the use of low-carbon hydrogen in the regeneration process. Moreover, a reduction of 95% is observed in terms of water depletion compared to the natural gas reference. The Iron Fuel product further outperforms its competitor in the impact categories terrestrial and marine eutrophication, carcinogenic human toxicity and photochemical oxidant formation.

Environmental trade-offs are observed in the impact categories freshwater ecotoxicity and eutrophication, acidification, non-carcinogenic human toxicity, ionising radiation, land use, mineral and metal resource use and particulate matter formation. The impact categories where the Iron Fuel system reflects a higher environmental impact than the natural gas alternative can primarily be linked to the system's electricity consumption. The only impact category where the natural gas system performs better, which is not directly or indirectly caused by the relatively higher electricity usage of the Iron Fuel system, is particulate matter formation.

In this LCA study, economic allocation is applied based on the relative market value of the output products. This approach is preferred over physical allocation when the physical properties of the co-products do not correspond proportionally to their environmental or economic relevance, which is the case in the context of this study. Nonetheless, a sensitivity analysis using physical instead of economic allocation was conducted to test the robustness of the results. While five impact categories shifted in favour of natural gas under this scenario, the Iron Fuel system remained the better performer in case of climate change, ozone depletion, and water use, confirming the robustness of its environmental advantages in these categories. The study notes that a detailed contribution analysis on the categories that shifted could help RIFT further optimise the environmental performance of their Iron Fuel product but endorses the disproportionate allocation of impact to Iron Fuel in relation to iron oxide in case of physical allocation.

RIFT has a primary focus on the climate change impact of Iron Fuel, as their technology originates from the intention of decarbonising the energy industry. Therefore, a contribution analysis was carried out in this study focusing on the climate change impact category. In terms of climate change impact, the Iron Fuel Technology™ displays an impact on CO_2-eq reduction of almost 80% compared to the natural gas alternative. Additional reduction in its climate change impact can be realised by further decreasing the systems electricity requirements, from the boiler as well as the Iron Fuel production process. In addition, RIFT is advised to further investigate the potential of using green instead of low-carbon hydrogen for their regeneration process, to even further decrease the indirect dependence on fossil fuels.

The study acknowledges several limitations. Conservative assumptions were applied in multiple areas in the Iron Fuel product system, including boiler electricity use, particulate emissions, and the upstream LCI data of hydrogen and CCS systems. These insights suggest that the current results may overestimate Iron Fuel's environmental impacts in certain categories. RIFT has indicated that a follow-up LCA is planned for 2026, which will incorporate updated engineering data and supplier-specific values, which is expected to further enhance the precision and representativeness of the assessment.

Contents

1. INTRODUCTION

1 Introduction

RIFT Development BV, hereafter referred to as RIFT, requested EGEN (part of the PNO Group) to conduct a Life Cycle Assessment (LCA) of their Renewable Iron Fuel Technology™, as part of their sustainability ambitions and strategy.

This report is based on inputs received from RIFT as well as data from EGEN's or online databases. A corresponding Excel document with background data is attached to this LCA report.

1.1 BACKGROUND OF THE PROJECT

RIFT is a company envisioning to revolutionize industrial heat provision by means of Iron Fuel Technology™. Iron Fuel is an innovative circular energy carrier, where iron powder is oxidised (burned) to generate heat, and the resulting iron oxide (rust) can be regenerated back into Iron Fuel. The company's mission is to decarbonize heavy industry by providing this clean and innovative energy solution, and thus enabling a more sustainable future. This LCA is performed to assess the environmental impact of the Iron Fuel Technology™, in comparison with a relevant reference product. The LCA evaluates the environmental impacts associated with heat provision using Iron Fuel, considering its production, use, and disposal or regeneration cycle.

1.2 ENVIRONMENTAL LIFE CYCLE ASSESSMENT

In its Communication on Integrated Product Policy[1], the European Commission concluded that LCA provides the best framework for assessing the potential environmental impacts of products currently available. LCA is a method to quantify the raw material use and emissions of a product or service system over its life cycle in a systematic manner, eventually resulting in an assessment of their environmental impact. Subsequently, LCA can assist in:

- identifying opportunities to improve the environmental performance of products and services at various points in their life cycle;
- informing decision-makers in industry, government, or non-government organizations on the implications of certain actions or policies for the environment;
- the selection of relevant indicators of environmental performance, including measurement techniques, and;
- marketing purposes highlighting the environmental performance of a product or service.

ISO 14040 describes the principles and framework of LCA. The guidelines and requirements for LCA studies are provided by ISO 14044. The LCA methodology is explained on the basis of the different phases in the framework: goal and scope definition, inventory analysis, impact assessment, interpretation. Figure 2 shows the relationship among these four phases.

The aims of the different phases in the framework are briefly introduced beneath:

- Goal and scope definition: during the first phase, the goal and scope of the LCA study are defined. Through defining the goal of the study, the following questions are clarified: why perform an LCA? Who are the target audiences? What is the product under LCA study?
- Inventory analysis: life cycle inventory (LCI) analysis involves data collection and calculation to quantify inputs and outputs of materials and energy for each unit process associated with the product system under study.
- Impact assessment: during the life cycle impact assessment (LCIA), the focus is on understanding and evaluating the magnitude and significance of the potential environmental impacts of the product system(s) under study.
- Interpretation: life cycle interpretation occurs throughout the full LCA process in an iterative manner. The interpretation involves analysing and synthesizing results obtained in the different phases with an iterative character, meaning that it involves multiple cycles of analysis and refinement. During the final interpretation phase of the LCA method, the results of the LCI and/or the LCIA are summarized and discussed as a basis for conclusions, recommendations, and decision-making in accordance with the goal and scope definition.

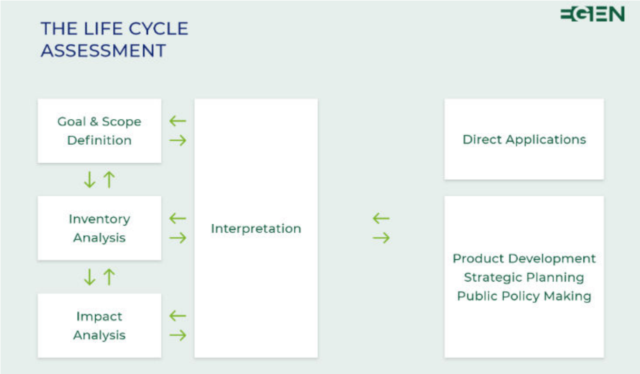

Figure 1. Phases of an LCA (Based on ISO 14040).

1.3 OUTLINE OF THE REPORT

The report consists of the following chapters:

Chapter 1 - introduces the contents of the report.

Chapter 2 – Goal and scope definition

Chapter 3 – Life Cycle Inventory (LCI)

Chapter 4 – Life Cycle Impact Analysis (LCIA)

Chapter 5 – Interpretation and conclusions

[1] *European Commission. (2003). Communication from the Commission to the Council and the European Parliament Thinking. Retrieved March 18, 2025, from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=celex:52003DC0302*

2. GOAL AND SCOPE DEFINITION

2 Goal and scope definition

This chapter defines the goal and scope of the LCA study. The goal and scope phase is a critical step in an LCA, as it establishes the foundation for the study by defining its purpose, intended application, and key methodological choices.

2.1 GOAL DEFINITION

The goal of the study outlines the intended use of the results of the analysis, the target audience, and any specific decision-making processes it aims to support.

The goal of this LCA study for RIFT is to assess and gain insights on the environmental impact of their Iron Fuel product and to identify climate impact hotspots. RIFT aims to use the insights gained from the LCA to further progress in future product development with the goal of increasing the carbon impact of their product.

In order to properly assess the environmental impact of the Iron Fuel product, the LCA provides a preliminary assessment of the environmental impact compared to a relevant reference product: steam provision by a natural gas boiler. RIFT will use this LCA to gather broader knowledge on the environmental profile of their product, in comparison to a representative alternative.

The LCA focuses on analysing and presenting the broad environmental profile of the Iron Fuel product in saturated steam provision for large industrial parties in the energy intensive industry.

Table 1. LCA study goal and intended use

Intended application(s):	• Evaluation of the potential environmental impacts of the Iron Fuel product • Preliminary comparative assessment of Iron Fuel's function compared to representative reference
Reasons for carrying out the study and decision context:	• Environmental performance documentation • Identification of climate hotspots • Substantiation of innovative and sustainable character of the Iron Fuel product and the company
Target audience:	• Internal stakeholders • MOOI422002 project participators
Commissioner of the study:	• RIFT • MOOI422002 project participators
Practitioner	• EGEN
Verifier:	• Critical review by internal expert • No external verification and validation are performed

2.2 SCOPE DEFINITION

The scope of the study determines the focus of the study and the system boundaries of the LCA. This is defined by the product system under study, the temporal, geographical and technological coverage, the coverage of processes and the coverage of impact categories.

2.2.1 PRODUCT SYSTEM, FUNCTION AND FUNCTIONAL UNIT

ISO defines product system as a collection of materially and energetically connected unit processes, which perform one or more defined functions. The product system under study is constituted by its end product and function: saturated steam provided to the energy intensive industry. The series of connected processes that define the product system are further described and presented in the next chapter.

The functional unit subsequently represents the quantitative description of the function provided by the system. In this LCA the functional unit is as follows:

The provision of 1 MWh of saturated steam at 210 °C and 16 bar (stack temperature of 120 °C) for the supply to an energy-intensive industry.

The functional unit provides a basis for comparing different systems. These different systems are reflected by the reference flows, which describe a physical flow in reality required to meet the functional unit. The reference flows in this LCA study are:

- *The provision of 1 MWh of saturated steam at 210 °C and 16 bar (stack temperature of 120 °C) through Iron Fuel combustion for the supply to the energy-intensive industry.*
- *The provision of 1 MWh of saturated steam at 210 °C and 16 bar (stack temperature of 120 °C) through natural gas combustion for the supply to the energy-intensive industry.*

2.2.2 TEMPORAL, GEOGRAPHICAL, AND TECHNOLOGICAL COVERAGE

This LCA is conducted in context of the Alpha One project which is based in Belgium and supplies to Dutch entities in the energy intensive industries. Nevertheless, this LCA should be representative for production and use of Iron Fuel throughout Europe. This is needed to provide insights into the impact of further roll-out of Iron Fuel projects throughout Europe. As such, the life cycle of all alternatives should be representative mostly to European circumstances and background processes from the Ecoinvent 3.11 database are as much as possible selected to reflect this. If no process from this region is available, a global or national background process is selected (in the order mentioned).

Besides the geographical coverage, the temporal and technological coverage are of importance in LCA. For this LCA study, the data used should be representative of the current state of technology. Considering the temporal scope, results should be representative for the present time. In terms of data age, a maximum of 1 year applies to primary data. For secondary data, a threshold up to up to 20 years applies.

2.2.3 COVERAGE OF ECONOMIC PROCESSES

The system boundary follows a cradle-to-cradle approach, considering that the iron oxide produced from Iron Fuel combustion is primarily regenerated into Iron Fuel for reuse in boiler systems. A small fraction of the iron oxides - valued for its high-quality characteristics. - is separated into fine and medium iron oxides and sold by RIFT to primarily the pigment industry, This portion is replenished with newly sourced iron powder to ensure a consistent supply to Iron Fuel off-takers.

The system includes, for both product systems under study, the following life cycle stages:

- Raw material extraction & processing
- Fuel production
- Fuel production system construction
- Transportation & distribution
- Boiler construction
- Combustion process

End-of-life is not considered in this LCA. There is no disposal of iron oxide or Iron Fuel. The iron oxide is regenerated into

Iron Fuel and partly off-taken as valuable material to other markets (either as feedstock or as specialty material).

The system boundary considers foreground and background processes. The foreground processes of both the Iron Fuel and natural gas product systems are modelled based on primary data from RIFT, supplemented with secondary data from RIFT's suppliers and off-takers and data from literature. The process data on the Iron Fuel system is validated in technical due diligence by Royal Haskoning DHV. For background processes, Ecoinvent v 3.11 is used. Table 2 elaborates on the life cycle stages within the system boundary.

2.3 COVERAGE OF IMPACT CATEGORIES

The life cycle impact assessment is conducted using the Environmental Footprint (EF) reference package version 3.1, focusing on the 16 Product Environmental Footprint (PEF) impact categories. This version was selected as it was the most up-to-date EF reference package available when the LCA was performed.

In addition, RIFT requests a deep dive on the impact category *climate change*. RIFT has a primary focus on the climate change impact of Iron Fuel, as their technology originates from the intention of decarbonising the energy industry. RIFT's technology avoids Greenhouse Gas (GHG) emissions during the combustion of the fuel compared to other energy carriers (scope 1). The further exploration of the life cycle climate change impact by means of a contribution analysis, enables RIFT to also gain insights into the potential upstream and downstream climate change effects in their product's value chain. This enables RIFT to keep innovating on relevant hotspots and increasing the life cycle carbon intensity of their product. The contribution analysis in this study on the climate change impact category is assessed using the EF 3.1 method.

2.4 STUDY SCOPE AND VERIFICATION PLAN

This Life Cycle Assessment (LCA) study has been conducted for research purposes, with the primary aim of assessing the environmental impacts of Iron Fuel throughout its life cycle. The study follows the principles and methodology outlined in ISO 14040 and ISO 14044, ensuring a consistent and structured approach to assessing environmental impacts.

Besides the primary aim of the LCA, the study includes a preliminary assessment of a comparison between Iron Fuel and a relevant alternative based on available reference data. When making comparative assertions intended for public disclosure, external verification is required under ISO 14044.

At this stage, the study serves as an internal analysis to support early-stage evaluation and decision-making. While the results offer valuable insights, they are not intended for public disclosure or comparative assertions that require third-party verification under ISO 14044 at this point.

To ensure methodological rigor, an internal critical review has been conducted by an LCA expert within EGEN's organization who are not involved in the study itself. This review aims to validate the study's consistency, completeness, data quality, and alignment with best practices in life cycle assessment.

To facilitate further external communication of the results RIFT has planned a full external verification process to take place in 2026, in accordance with ISO 14044 requirements. This process will include a critical review by an independent external expert, ensuring compliance with international standards for comparative LCA studies.

Table 2. Life cycle stages within the system boundary of this LCA study

PROCESS STAGES INCLUDED	IRON FUEL PRODUCT SYSTEM		NATURAL GAS PRODUCT SYSTEM	
	Process	***Included in***	***Process***	***Included in***
Raw material extraction & processing	Iron ore mining	*Background system*	Natural gas exploration and extraction	*Background system*
Fuel production	Iron Fuel production	*Foreground system*	Natural gas processing	*Background system*
Fuel production system construction	Iron Fuel production system construction	*Foreground system*	Gas turbine construction	*Background system*
Transportation and distribution	Transportation: distribution of Iron Fuel and collection of iron oxide	*Foreground system*	Transportation: distribution of natural gas via pipelines	*Background system*
Boiler construction	Iron Fuel boiler construction	*Foreground system*	Natural gas boiler construction	*Foreground system*
Combustion	Iron Fuel combustion and steam distribution to end user, and iron oxide production for reuse in Iron Fuel production	*Foreground system*	Natural gas combustion and heat distribution to end user	*Foreground system*

3. LIFE CYCLE INVENTORY

3 Life Cycle Inventory

The life cycle inventory phase focuses on defining the product system and the quantification of inputs and outputs of the Iron Fuel product system, and natural gas reference, throughout their life cycle.

3.1 CUT-OFF CRITERIA

Cut-off criteria establish thresholds for including or excluding specific inputs, processes, or outputs within the system boundary. When performing the analyses in the LCA software, no cut-off criteria were applied, meaning all available flows were included in the product system.

Nevertheless, some more general cut-offs were consistently applied throughout this study. These cut-offs and their reasoning are presented in the table below.

Table 3. Overview of general cut-offs.

CUT-OFF	REASON
On-site construction emissions and equipment or machinery required for construction purposes	On-site construction emissions are often excluded in LCA studies focusing on energy systems[2][3][4]. For consistency and comparability with other energy systems, construction emissions and equipment is not included in this LCA.
Cooling materials, chemicals and demineralized water required in boilers	In both 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 both boilers in this study, this has been cut-off.
The end-of-life stage of the Iron Fuel boiler and natural gas boiler	As Ecoinvent is inconsistent in including disposal sets or end-of-life stages of boilers and equipment in processes currently in the dataset. Therefore, this stage has not been included for the boilers in this study to allow for a fairer comparison.

3.2 FLOWCHART(S)

Figure 2 displays the flowcharts of the product systems under study. The system boundary is depicted by the dashed square, defining which parts of the life cycle and which processes belong to the analysed system, i.e. are required for providing its function as defined by its functional unit. The system boundary is the boundary between the modelled process and the rest of the Technosphere, i.e. all product and waste flows that enter or leave the product system cross the boundary and hence appear in its inventory. The flowcharts display the product and waste flows entering and leaving processes and the system boundary. The reference flow is also leaving the system boundary and is indicated in green.

Al flow rates are to be scaled for the provision of these reference flows representing the functional unit.

3.3 DATA COLLECTION AND RELATING DATA TO UNIT PROCESS

Appendix A presents the full inventory data for both product systems including sources, calculations and assumptions for all unit processes involved in the product systems. The appendix includes all economic and environmental inflows and outflows of the foreground processes, their amounts, units, product name, Ecoinvent data and additional assumptions/information.

The data that is necessary for constructing the LCI originate from several sources, differentiating per product system. Crucial data sources and assumptions are given in Table 4.

3.3.1 IRON FUEL PRODUCTION SYSTEM

The primary foreground system of the Iron Fuel product consist of Iron Fuel production, Iron Fuel production system construction, transport (distribution and collection), Iron Fuel boiler construction and product use (combustion). These processes are fully modelled in collaboration with RIFT, based on primary data from RIFT's internal engineering – as validated by Royal Haskoning in technical due diligence - and experience from previous demonstration and pilot projects.

In addition, a low carbon hydrogen system is separately modelled. RIFT uses a low carbon hydrogen feedstock, which is an important element in their production chain. The low carbon nature of the hydrogen is crucial for RIFT's production, because of its low carbon intensity compared to grey hydrogen. As there is no Ecoinvent process available for low carbon hydrogen, this process is separately modelled. As a basis, an Ecoinvent process for grey hydrogen is used[5], which is adapted to reflect a capture of the associated CO_2 emissions of 95% for permanent storage. Additionally, a Carbon Capture and Storage (CCS) chain[6] is modelled to handle the captured CO_2, based LCI data from an LCA study on CCS chains in Europe[7]. The CCS chain is slightly adopted to reflect RIFT's feedstock of low carbon hydrogen a little more based on supplier data[8]. The foreground system is further supplemented with background data from Ecoinvent database v. 3.11.

3.3.2 NATURAL GAS PRODUCT SYSTEM

The reference concerns the product system in which the saturated steam is produced from a natural gas boiler. For this, an Ecoinvent process for heat production of a condensing modulating natural gas boiler was used as a basis[9]. This process is subsequently adjusted to meet the functional unit of analysis. The foreground system is further supplemented with background data from Ecoinvent database v. 3.11.

[2] *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), 014012. https://doi.org/10.1088/1748-9326/11/1/014012*

[3] *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*

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

[5] *Ecoinvent v 3.11, cut-off system model. Hydrogen production, steam methane reforming - Europe (RER)*

[6] *CCS chain is not fully displayed in the flowchart. Unit process data. Further assumptions are presented in Annex A – attached Excel document*

[7] *Burger, J., Nöhl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., Reyes-Lúa, A., Riboldi, L., Sansavini, G., & Bardow, A. (2024). Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward. International Journal of Greenhouse Gas Control, 132, 104039. https://doi.org/10.1016/j.ijggc.2023.104039*

[8] *Adopted in terms of CO_2 transportation*

[9] *Ecoinvent v 3.11, cut-off system model. Heat production, natural gas, at boiler condensing modulating >100kW- Europe (RER)*

3.4 MULTIFUNCTIONALITY AND ALLOCATION

A multifunctional process is a process with more than one function. Functions could entail the producing of a product/good or the processing of waste. Figure 2 displays economic flows as solid arrows, whereas waste flows are displayed as dashed arrows. In the foreground systems of this LCA, only one multifunctional process is identified: Iron Fuel production. The Iron Fuel production process produces Iron Fuel to be used for heat provision, and includes iron oxide and scrap iron outputs for other off-take markets. To resolve the multifunctionality problem for multifunctional processes, economic allocation is applied. This entails that the environmental in- and/or outflows of a certain unit process are proportionally assigned to the different functional flows, based on their market price.

Economic allocation is generally preferred over physical allocation in situations where co-products have very different market values, and where their economic function better reflects their role in the system. This is particularly relevant when the physical properties (e.g., mass or energy content) of the co-products do not correspond proportionally to their environmental or economic relevance[10]. In such cases, physical allocation can lead to distorted results, assigning a disproportionately low share of environmental burdens to low-volume, high-value products. Economic allocation in this case aligns more closely with how these co-products are valued and used in the real economy, making it more suitable for market-based decision-making and in policy contexts.

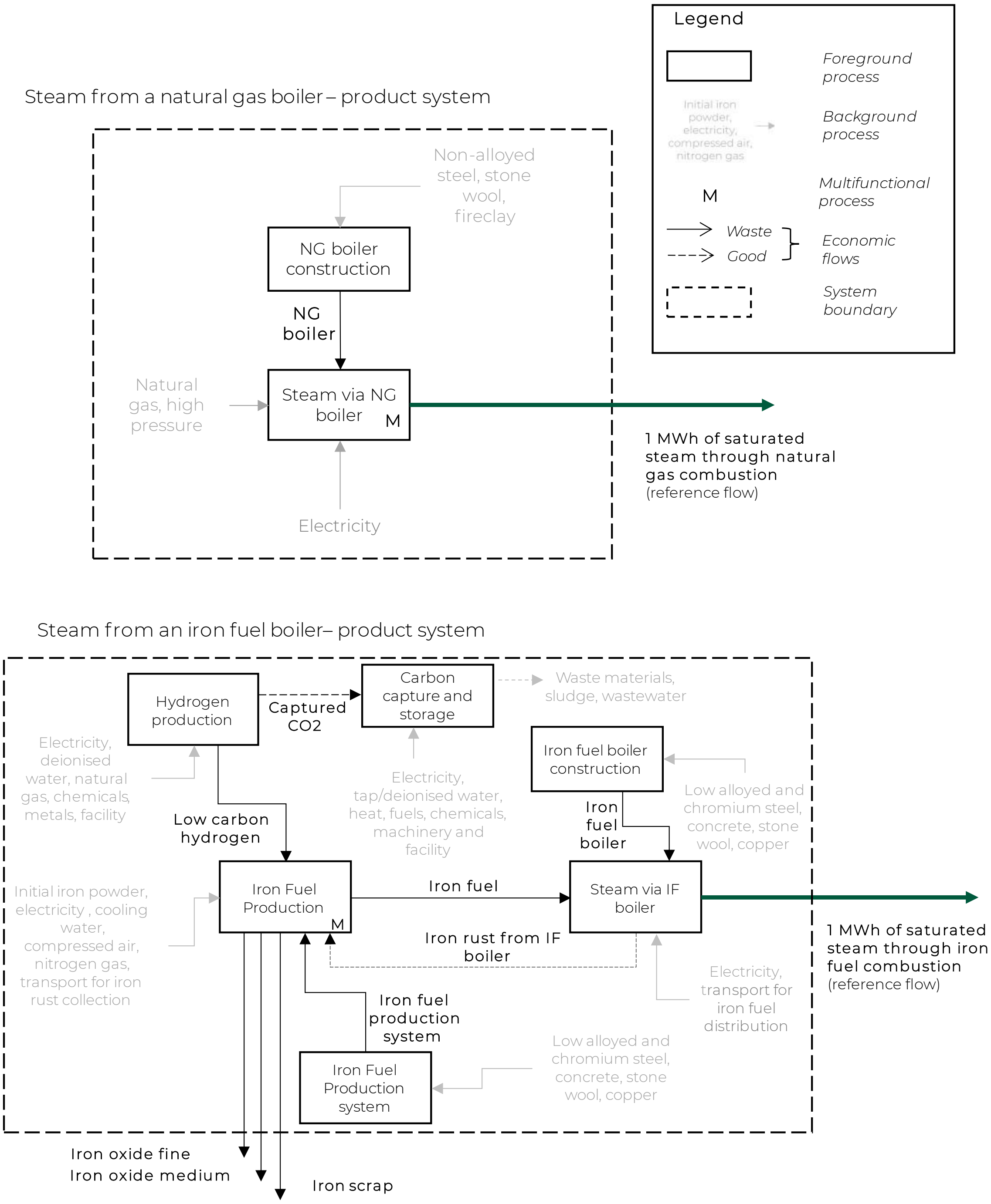

Figure 2. Flowcharts of the product system flow charts under study: the natural gas product system (above) and the Iron Fuel product system (below).

[10] *ISO 14044:2006, Section 4.3.4.2, Allocation procedure*

Table 4. Main data origins and assumptions overviewed for each product system

IRON FUEL PRODUCT SYSTEM	
Data Origin	**Key Assumptions**
• Primary data source for the Iron Fuel system is RIFT's internal engineering - in line with their energy-mass balances - and experience from previous Iron Fuel demonstration and pilot projects	- Iron ore concentrate produced via iron ore beneficiation[11] is assumed to be a suiting proxy to produce initial Iron Fuel from iron ore. - Iron oxide produced from Iron Fuel combustion can be reused for the production of Iron Fuel. A small fraction is sold to the iron oxide market, due to its high value characteristics, after which is it topped up with newly sourced iron powder. - Iron Fuel production system runs 6000 FLH - IF boiler runs 6000 FLH
• The low carbon hydrogen production process is primarily based on the Ecoinvent process for hydrogen production in Europe[12], supplemented by processes representing the CCS chain from Burger et al. [13] and Wildbolz[14].	- The hydrogen production process from Ecoinvent is adapted in terms of carbon dioxide emissions, to represent a 95% CO_2 capture rate based on CO_2 capture and storage agreements with RIFT's low carbon hydrogen supplier[15]. - An additional waste flow is added reflecting the 95% of captured CO_2, which is subsequently connected to the CCS chain processes. - The CCS LCI data of the HM Hannover chain in Germany and permanent storage in NL (Northern lights) are taken as a basis and slightly adapted to better fit RIFT's case and by use of a newer database (Ecoinvent v. 3.11 instead of v. 3.8). - For pipeline transport, LCI data pipeline transport of supercritical CO_2 is deemed representative. LCI data is given for pipeline transport with and without recompression. In the case of RIFT's supplier, CO_2 is transported on shore for 35 kilometres at 35 bars via pipeline, and offshore for 22 kilometres offshore at 130 bars. Based on these different pressure levels, the LCI for transport operation with recompression is selected as best fitting to this case.
NATURAL GAS PRODUCT SYSTEM	
Data Origin	**Key Assumptions**
• Process data for steam provision by natural gas is based on the Ecoinvent (v. 3.11) process: heat production by a condensing modulating natural gas boiler[16]. • Data on NG boiler production is based on aggregated VKK Standardkessel boiler data from one of RIFT's off-takers.	- The selected Ecoinvent process is chosen because it performs environmentally better than an only modulating boiler. - The selected Ecoinvent process has a quantitative reference set at one MJ of heat. A new flow is added to the system representing 1 MWh of saturated steam at 210 ℃, 16 bar, with a stack temperature of 120 ℃. - The consumption of natural gas at high pressure is increased to 122 m3, based on the requirements for achieving the right level of saturated steam, with the defined specs in the functional unit. This is not exactly the same as scaling the natural gas consumption up from the conversion of MJ to MWh for the functional unit, as the quantitative reference output of the Ecoinvent process (1 MJ heat) was not yet functionally equal to the functional unit of this study. Especially the stack temperature of 120 ℃ requires a relatively higher natural gas consumption compared to the Ecoinvent process standard. The consumption rate of 122 m3 per MWh is based on actual natural gas consumption at RIFT's off-takers for attaining the saturated steam at 210 ℃, 16 bar, with a stack temperature of 120 ℃ via a natural gas boiler. This is reflected in RIFT's supply contracts with off-takers, where the Iron Fuel pricing is actually based on this standard consumption rate of natural gas for the same quantity and quality of steam at the off-takers. - The methane content of 122 m3 natural gas is 123 kg. - The electricity consumption and environmental outflows from the Ecoinvent process are scaled to the new consumption rate of natural gas to be handled. - The industrial furnace inflow is altered to the newly modelled natural gas boiler, which is based on off-taker data. Inflow to the steam production process is based on natural gas boiler lifetime, capacity and yearly operation hours. - Environmental in- and outflows (oxygen and nitrogen) are added for the required reaction with methane in the natural gas flow. - Environmental outflow carbon dioxide and nitrogen oxides are separately calculated based on the methane content in natural gas inflow. Environmental outflow of heat is added. Heat outflow is considered 185,853 KJ/MWh(th) at stack temperature of 120 ℃ given the air fuel ratio of 1.2. - Environmental outflow of water to air is added, based on required reaction with methane in natural gas inflow.

[11] *Ecoinvent v 3.11, cut-off system model. iron ore beneficiation - Rest Of World (ROW)*

[12] *Ecoinvent v 3.11, cut-off system model. Hydrogen production, steam methane reforming - Europe (RER)*

[13] [13] *Burger, J., Nöhl, J., Seiler, J., Gabrielli, P., Oeuvray, P., Becattini, V., Reyes-Lúa, A., Riboldi, L., Sansavini, G., & Bardow, A. (2024). Environmental impacts of carbon capture, transport, and storage supply chains: Status and the way forward. International Journal of Greenhouse Gas Control, 132, 104039. https://doi.org/10.1016/j.ijggc.2023.104039*

[14] *Wildbolz, C. (2007). Life cycle assessment of selected technologies for CO_2 transport and sequestration. https://doka.ch/CCSDiplomaWildbolz07.pdf*

[15] *Carbon capture and storage agreement of 7.94 kg CO_2 stored per kg H2 supplied to RIFT. As the hydrogen production Ecoinvent process has direct emissions of 8.35 kg CO_2 per kg hydrogen, which results in a capture rate of approximately 95%*

[16] *Ecoinvent v 3.11, cut-off system model. Heat production, natural gas, at boiler condensing modulating >100kW- Europe (RER)*

RIFT's Iron Fuel production process has several valuable streams as output: Iron Fuel, iron oxide (medium and fine), and iron scrap sold to recyclers. Although the output streams of iron oxide are very small in weight compared to the Iron Fuel output, its economic value is substantial. This would cause physical allocation to allocate a disproportionate amount of the environmental impact of the product system to Iron Fuel, which is not in proportion to the economic reality, value and function of the products. In addition, Iron Fuel as output of the Iron Fuel production process is represented in mass units (kg), but its functional value is much more associated with its energy content. For this reason too, allocation based on these physical characteristics does not do justice to the practical value and reality of the product system and the various output products.

The usable iron oxide from Iron Fuel combustion is collected from the off-takers of RIFT, largely for reuse in Iron Fuel production (coarse iron oxide), but also partly for direct sale of the iron oxide in other off-take markets, such as the pigment industry (medium and fine iron oxide). RIFT's off-takers pay an initial service price for the Iron Fuel, which includes the re-collection of the produced iron oxide from the boilers.

The combustion process is modelled as a multi-output process producing steam (the functional output) and iron oxide, which includes both reusable iron oxide for Iron Fuel production and a portion of iron oxides for external off-take. In accordance with ISO 14044, Section 4.3.4.2, allocation of environmental burdens is only required when multiple products with market value are generated from a unit process. Although the iron oxide may possess potential downstream value at the point of combustion, it is neither marketable nor functionally useful to the off-taker. Under the commercial agreement, the material is contractually returned to RIFT and has no independent economic role within the off-taker's system boundaries. Therefore, it is treated as a waste output at this stage.

RIFT subsequently separates the iron oxides for external markets and iron oxides usable for Iron Fuel production. Since the economic value of the iron oxides is only realized after return to RIFT, allocation of environmental burdens is applied only once, at the Iron Fuel production stage, where marketable products (Iron Fuel and iron oxides) are first generated.

This approach is methodologically consistent with the ISO 14044 principle that allocation should be avoided where possible and only applied where necessary and justified. By modelling the iron oxide as a non-functional, non-marketed output at the combustion stage, and by concentrating allocation at the point of first economic differentiation, this method avoids double-counting of environmental impacts, ensures transparent and consistent burden distribution across life cycle stages, and reflects both the material flow and contractual reality of the system. This treatment aligns with common LCA practice in circular systems where the ownership and reuse of a material remain within the originating system boundary until market value is realised. For background processes, market price data is assigned by default by the Ecoinvent 3.11 database.

3.5 SOFTWARE

OpenLCA software has been used in this LCA study for modelling and analysing the LCA model.

3.6 RESULTS OF INVENTORY ANALYSIS

ISO 14044 defines the LCI result as the "outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment". The main life cycle inventory (LCI) results are displayed in Appendix B – S1.

4. LIFE CYCLE IMPACT ANALYSIS

4 Life Cycle Impact Analysis

This section presents the life cycle impact assessment results for the two steam generation systems under study: (1) an Iron-Fuelled boiler (combusting iron powder), and (2) a natural gas boiler (combusting natural gas). The EF 3.1 impact assessment method is applied to quantify potential environmental impacts for each scenario, and the results are compared side-by-side. All analyses are performed in accordance with ISO 14040/14044 standards to ensure a fair comparison and robust interpretation of results.

4.1 LCIA METHODOLOGY AND APPROACH

The LCIA was conducted using the Environmental Footprint (EF) 3.1 method, which is the EU-recommended characterization method for product environmental footprints. This method covers the 16 PEF midpoint impact categories, providing a comprehensive picture of environmental burdens. Emissions and resource flows from the life cycle inventory (LCI) of each boiler system were assigned to the appropriate impact categories (classification) and converted into indicator results using EF 3.1 characterization factors, following ISO 14044 guidelines. All assumptions and methodological choices (functional unit, system boundaries, impact categories, etc.) are consistent with the Goal and Scope definition to maintain ISO-compliant consistency and relevance of the results.

4.2 CHARACTERIZATION RESULTS

The characterized LCIA results of the Iron Fuel boiler and the natural gas boiler for the 16 PEF categories are summarized in Table 5. In Appendix B (B.1 of this report) the characterisation results of the full EF 3.1 analysis is presented. for all impact categories. Overall, the Iron Fuel combustion scenario shows a distinctly different impact profile from the natural gas scenario, with notably lower results in several key categories.

The normalised characterisation results are presented in Figure 3, which more clearly displays the product system with the higher environmental impact per impact category. For producing these results, the product system with the highest environmental impact for an impact category is set at 100%, and the impact score of the other product system is then presented in relative terms against this. As can be seen from Figure 3, the Iron Fuel boiler performs better in case of energy resources (non-renewable), terrestrial and marine eutrophication, carcinogenic human toxicity, ozone depletion, photochemical oxidant formation (human health), water use and climate change. The Iron Fuel system scores significantly better in terms of water use, climate change, ozone depletion and non-renewable energy resources, with a relative impact between 5% and 50% compared to the natural gas system.

The Iron Fuel system avoids direct CO_2 emissions during combustion and eliminates fossil fuel dependence, leading to significantly lower impacts in climate change, non-renewable energy resources and ozone depletion—categories.

The higher impact on human toxicity (carcinogenic effects) in the natural gas system is primarily driven by emissions of dioxins—specifically 2,3,7,8-tetrachlorodibenzo-p-dioxin—originating from the production of sodium hypochlorite. Sodium hypochlorite is used as a disinfectant and biocide in water treatment processes, particularly for preventing biofouling and microbial growth in gas processing and cooling systems. Although used in small quantities, its upstream production involves chlorinated compounds that result in trace dioxin emissions, which carry a high characterization factor for human toxicity, thereby contributing significantly to the impact score.

The relatively higher impacts of the natural gas system in terms of terrestrial and marine eutrophication, are explained by the nitrogen oxide emissions occurring during upstream sea transportation, and natural gas production and combustion for steam production. Photochemical oxidant formation in the natural gas system is caused by the same nitrogen oxide emissions, as well as from non-methane volatile organic compounds (NMVOC) emissions from natural gas venting.

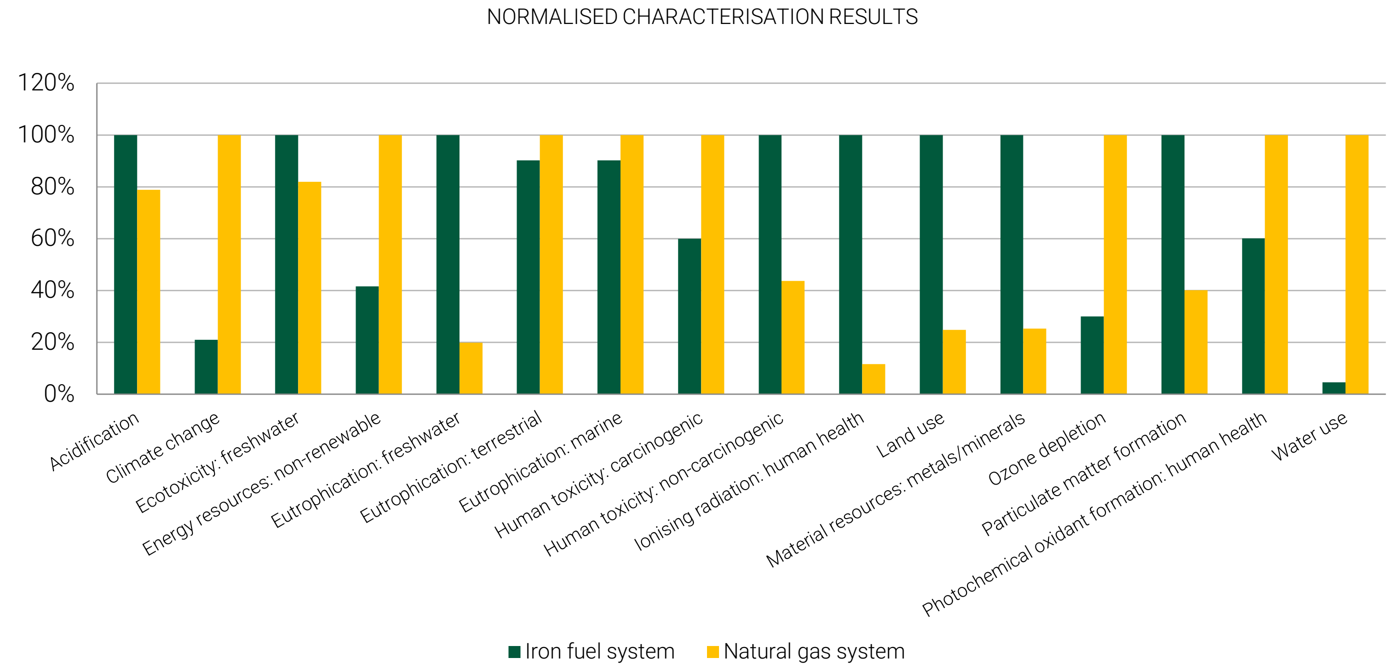

Figure 3. Normalised characterisation results comparing the environmental impact of Iron Fuel and natural gas-based steam production

Table 5. Characterisation results of 1 MWh(th) steam produced by 1) an Iron Fuel boiler and 2) a natural gas boiler

		IRON FUEL SYSTEM	NATURAL GAS SYSTEM
Impact category	**Unit**	**Impact results**	**Impact results**
Acidification	mol H+-Eq	0.32	0.25
Climate change	kg CO_2-Eq	65.97	315.01
Ecotoxicity: freshwater	CTUe	185.89	152.28
Energy resources: non-renewable	MJ, net calorific value	2,133	5,120
Eutrophication: freshwater	kg P-Eq	0.03	0.01
Eutrophication: terrestrial	mol N-Eq	0.80	0.89
Human toxicity: carcinogenic	CTUh	2.42E-08	4.03E-08
Human toxicity: non-carcinogenic	CTUh	7.59E-07	3.32E-07
Ionising radiation: human health	kBq U235-Eq	20.78	2.40
Land use	dimensionless	298.71	74.05
Material resources: metals/minerals	kg Sb-Eq	5.99E-04	1.52E-04
Ozone depletion	kg CFC-11-Eq	4.27E-06	1.43E-05
Particulate matter formation	disease incidence	3.09E-06	1.24E-06
Photochemical oxidant formation: human health	kg NMVOC-Eq	0.30	0.51
Water use	m3 world Eq deprived	552	11,896

The significantly lower impact on water use of the Iron Fuel system compared to the natural gas system primarily stems from the significant water emissions to the air of the natural gas boiler. In a natural gas boiler operating at 120 °C stack temperature, water vapor is formed during combustion as hydrogen in the methane fuel reacts with oxygen. The resulting steam remains in gaseous form and is emitted through the flue gas stream as part of the exhaust into the atmosphere. When water is emitted to the atmosphere in the form of vapor, whether through evaporation or combustion, it is temporarily or spatially unavailable for local reuse, thereby contribution to water depletion.

The Iron Fuel system has a higher environmental impact compared to the natural gas system when looking at acidification, freshwater ecotoxicity, freshwater eutrophication, non-carcinogenic human toxicity, ionising radiation (human health), land use, metal/mineral resources and particulate matter formation. The natural gas system scores significantly better in terms of ionising radiation, freshwater eutrophication, non-carcinogenic human toxicity, land use, and metal/mineral resource use, with relative impact scores compared to the Iron Fuel system between 10% and 50%.

The higher environmental impact of the Iron Fuel system compared to the natural gas system on most of these impact categories stem from a higher dependence on electricity usage. In this regard, it is good to mention that in order to meet the goal and scope of the LCA study, the European electricity mix was used for European representation. This also resulted in a weighted electricity consumption of various European countries being included, each of which is accompanied by its own upstream environmental impacts.

The impact of the Iron Fuel system on freshwater eutrophication primarily stems from its electricity consumption, specifically the German share in the European electricity mix. This is linked to phosphate emissions to water from the treatment of spoil from lignite mining in surface landfills. These emissions contribute significantly to eutrophication due to high characterization factors for phosphate, which is a key nutrient driving algal blooms. Carbon-14 and Radon-222 emissions represent the higher impact on ionising radiation, which stems primarily from nuclear energy generation as part of the electricity mix

For acidification, this is caused primarily by sulphur dioxide emissions from heat and power co-generation and electricity production from fossil sources upstream. Hydrogen sulphide emissions, primarily associated with sulfidic tailings treatment in upstream processes, contribute significantly to freshwater ecotoxicity due to their toxic effects on aquatic organisms. These emissions are indirectly linked to electricity production, as certain electricity sources (e.g., from metal mining or fossil fuels) involve tailings management practices that release sulphides into water bodies.

The relatively higher impact on non-carcinogenic human toxicity is mainly driven by emissions of lead (II) and mercury (II) compounds. Lead (II) emissions are predominantly linked to the production of ferronickel and copper, which are used in the manufacturing of components for electricity distribution networks, such as wiring and transformers. Mercury (II) emissions are primarily released during electricity generation, particularly from coal-based or poorly controlled fossil fuel sources, where trace metals in fuels or combustion residues enter the environment through air or water emissions.

Land use, on the other hand, stems from occupation and transformation of land. In the Iron Fuel system, this is primarily cause by the increased need of transportation compared to the natural gas system, resulting in more traffic area occupation for road networks. Related to the increased electricity consumption, land use impact is linked to bio electricity production and associated forest occupation.

Relatively higher impacts on metal/material resource use is not related to the virgin iron usage, as RIFT's system is primarily circular and only a small amount of virgin iron powder is needed. The higher impact on material and mineral resource use in the Iron Fuel system is primarily driven by the demand for tellurium and copper, which have high scarcity weights in the EF 3.1 method. This impact is largely a result of the system's higher electricity consumption, as tellurium and copper are critical for components in renewable energy technologies and electricity infrastructure. Additionally, the use of compressed air in Iron Fuel production and the associated requirements for facility equipment and construction materials contribute further to the demand for these scarce metals, reinforcing the overall impact in this category.

Particulate matter represent the only impact category where the Iron Fuel system perform worse compared to the natural gas system, which is not largely caused by electricity consumption. This impact is primarily represented by the relatively high PM < 2.5 um emissions from the combustion of Iron Fuel.

4.3 CONTRIBUTION ANALYSIS: CLIMATE CHANGE

The contribution analysis in this study focuses on the climate change impact category, in alignment with the goal and scope of the study, assessed using the EF 3.1 method.

The climate change impact of the Iron Fuel system for producing 1 MWh of saturated steam at 210 °C and 16 bar (stack temperature of 120 °C) through Iron Fuel combustion is 66 kg CO_2-eq. This is almost 80% lower than the climate change impact of the natural gas system for producing the same functional unit (315 kg CO_2-eq). This already displays the significant reduction the Iron Fuel Technology™ can provide in terms of global warming potential, but a deep dive into this impact category can display further reduction opportunities.

Figure 4 below displays the direct contribution results for producing 1 MWh of saturated steam by an Iron Fuel boiler. As can be seen in the graph, a significant part of the climate change impact stems from Iron Fuel transportation (10%) and direct electricity consumption (22%). Only 1% of the climate change impact can be linked back to the construction of the Iron Fuel boiler. The highest contribution, however, is related to the production of the Iron Fuel (67%), which calls for further investigation into this process.

The Iron Fuel production process has an impact of 44 kg CO_2-eq related to the eventual production of 1 MWh(th) of saturated steam via an Iron Fuel boiler. Figure 5 displays the contribution results of the Iron Fuel production process. The graph in Figure 5 displays how the contribution of cooling water consumption, wastewater treatment requirements and the construction of the Iron Fuel production system to the climate change impact of Iron Fuel production is negligible. The consumption of virgin iron powder and nitrogen gas both only represent 1% of the contribution of the Iron Fuel production process. The contribution of compressed air consumption (3%) and transport from the boiler to the Iron Fuel production system (5%) are also relatively small compared to the two biggest contributors: electricity consumption (30%) and low-carbon hydrogen consumption (59%). Since the impact of the latter of these, is significant (26 kg CO3-eq), we delve a little deeper into this.

Figure 6 displays the climate change contribution results of the low carbon hydrogen production process, related to the eventual production of 1 MWh(th) of saturated steam. Emissions with an impact lower than 1% to the overall impact of the low-carbon hydrogen production process are not included in the graph, but can be found in Appendix B, attached to this report.

Low carbon hydrogen production represents a general hydrogen production process - in this case steam methane reforming (SMR) – where CO_2 emissions are captured, conditioned and stored permanently to reduce the climate change intensity of the hydrogen product. As can be seen in the graph, the direct emissions of the hydrogen production process still represent approximately 10% of its climate impact. This represent the emissions that are not captured by the carbon capture unit. The CCS activities downstream, constituting of carbon capture, conditioning, temporary storage, pipeline transport, permanent storage and auxiliary services, represent 29% of the climate change impact of this process. a significant part of the climate change impact of the low carbon hydrogen production process, stems from its use of natural gas. Even though the CCS chain provides a significant reduction of the carbon emission intensity of the hydrogen production process, the additional emissions of the CCS activities should still be taken into account. For this reason, this chain has been modelled in detail as part of this LCA. The vast majority of these CCS emissions come from capture and conditioning activities, associated to the energy requirements of these processes.

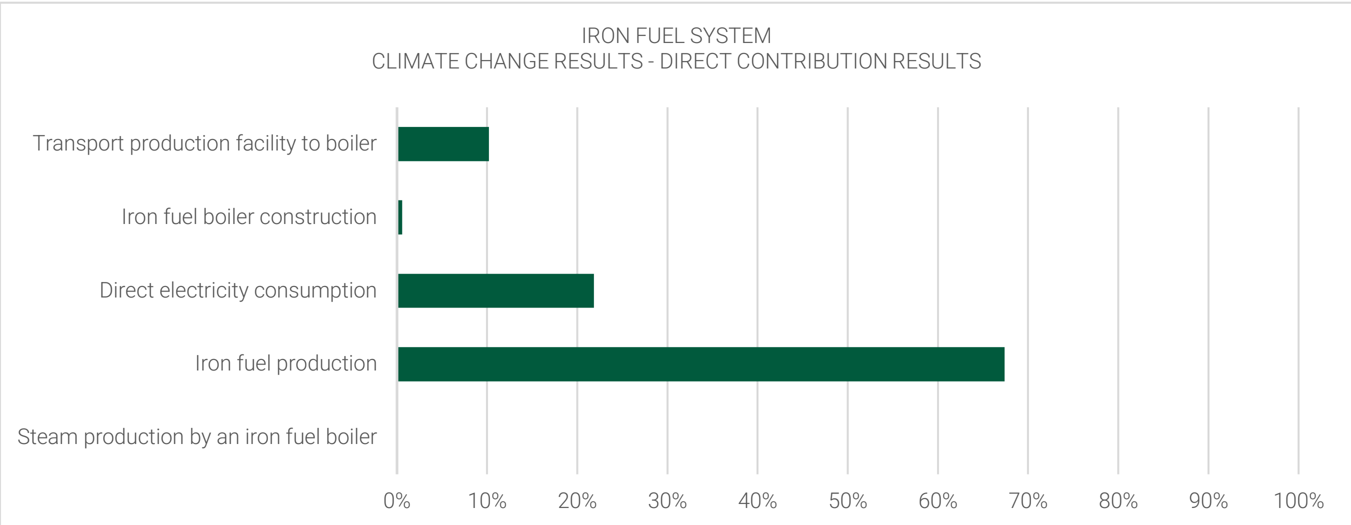

Figure 4. Direct climate change contribution results related to 1 MWh steam production by an Iron Fuel boiler

The highest contributor to the low carbon hydrogen process is natural gas consumption and the associated upstream emissions. In line with the goal and scope of the study, the Iron Fuel system is modelled to represent European average conditions. The natural gas consumption in this process is based on the market group for European natural gas, which gathers a mix of different quantities of high-pressure natural gas from various European countries. Natural gas from Italy and Germany contribute most to this impact. For the Alpha One project, RIFT's low carbon hydrogen supplier will make use of local natural gas, sourced from the Waddenzee, which is presented to have a lower upstream impact. The contribution of natural gas consumption as part of the low carbon hydrogen production process for the Alpha One project of RIFT is, thus, expected to be lower than presented in this study. Nevertheless, the results do represent the expected impact under average, European conditions.

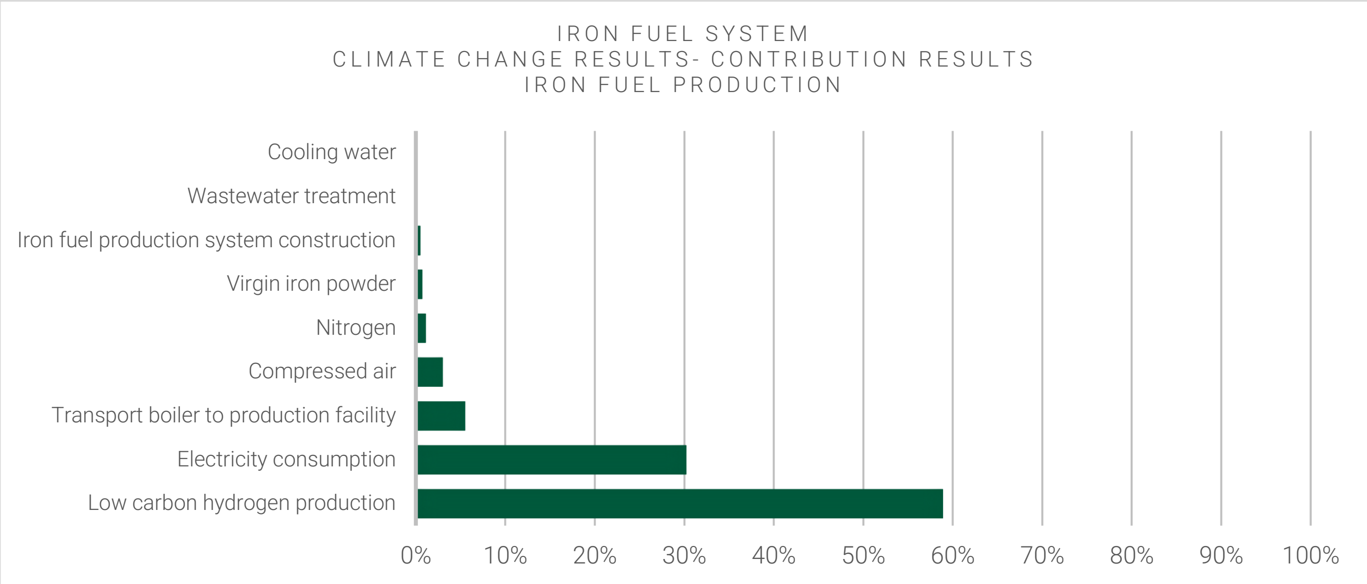

Figure 6. Climate change contribution results of the Iron Fuel production process, related to 1 MWh steam production by an Iron Fuel boiler

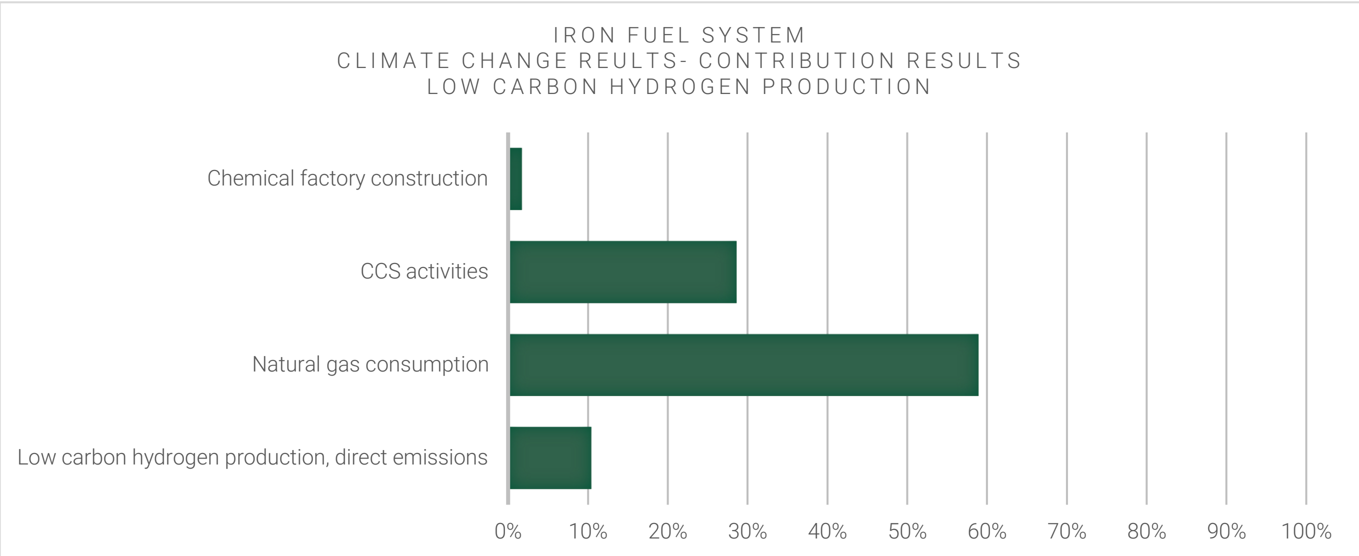

Figure 5. Climate change contribution results of the low carbon hydrogen production process, related to 1 MWh steam production by an Iron Fuel boiler

5. INTERPRETATION AND CONCLUSIONS

5 Interpretation

Interpretation is the fourth and final phase of the LCA framework. In this phase, the findings impact assessment are analysed in order to define conclusions and recommendations in context of the goal and scope of the study.

5.1 CONCLUSIONS AND RECOMMENDATIONS

The observed differences in environmental performance between the Iron Fuel and natural gas system stem from the fundamentally different nature of their energy carriers and life cycle processes. The Iron Fuel system avoids direct CO_2 emissions during combustion and decreases fossil fuel dependence, leading to lower impacts in climate change, non-renewable energy resources, and ozone depletion—categories, closely linked to carbon-based energy. The Iron Fuel system displays higher impacts in categories such as freshwater toxicity and mineral and metal resource usage, and certain toxicity indicators, which are primarily driven by the higher dependency on electricity usage.

RIFT has been conservative in their estimation of the electricity consumption of the Iron Fuel boiler in the LCI data for the Iron Fuel system. The latest insights from their engineers display an electricity consumption that is three times lower than the consumption rate shared for the performance of this LCA study. Moreover, the European Commission is increasingly committed to electrification of the European energy network and the transformation renewable electricity grids in Europe is in full swing[17]. Therefore, it is estimated that the impact of the Iron Fuel system will in reality even further decrease over time. In the Alpha one project, RIFT intends to ensure the sustainability by purchasing Guarantees of Origin (GOs) to match 100% of its electricity use (as part of the Iron Fuel production process) with renewable energy sources. The type of electricity used in the use phase (combustion of Iron Fuel in boilers), however, is outside RIFT's direct control. Therefore, RIFT is advised to further investigate and potentially reduce the dependence on electricity usage of the Iron Fuel boilers with continuous innovation.

The only impact category where the natural gas system performs better, which was not directly or indirectly caused by the relatively higher electricity usage of the Iron Fuel system, is *particulate matter formation*. This is primarily due to the PM < 2.5 emissions during combustion of the Iron Fuel. RIFT indicates that also the PM< 2.5 emissions considered in the LCA study are conservative, as the most recent boiler demonstration displays lower results. Therefore, RIFT is advised to include this updated boiler performance data in the follow-up LCA study planned in 2026. Moreover, as the impact of Iron Fuel on particulate matter formation according to the data in this study is 60% higher than the natural gas alternative, RIFT is advised to continue innovating to further decrease those particulate matter emissions from the Iron Fuel combustion in the boiler.

The Iron Fuel system displays a strong performance in impact areas related to climate mitigation and fossil resource reduction. In terms of climate change impact, the Iron Fuel Technology™ displays an impact on CO_2-eq reduction of almost 80% compared to the natural gas alternative. Additional reduction in its climate change impact can be realised by further decreasing the systems electricity requirements, from the boiler as well as the Iron Fuel production process. Moreover, by making use of low carbon hydrogen, produced by an SMR process making use of natural gas, RIFT still remains indirectly dependent on fossil fuel. Although the direct combustion emissions are largely captured by adding the CCS activities, the upstream emissions of natural gas are not avoided. There is also an additional impact due to the material and energy needs of the CCS chain. For the low carbon hydrogen production process and CCS chain, conservative estimations and assumptions have been used, in the absence of more specific supplier data. RIFT's low carbon hydrogen supplier indicates that the LCI data used in this LCA study are rather conservative compared to their processes on both hydrogen production plant efficiency and CCS data. In the follow-up LCA, planned in 2026, RIFT is advised to further align these processes with their own value chain, in collaboration with their supplier, given the large impact of this part of the value chain.

Although low carbon hydrogen currently offers a sound and sustainable alternative to grey hydrogen, the transition to green hydrogen may be interesting in the long term. Nevertheless, the impact of green hydrogen is also closely related to electricity consumption and large-scale adaption and implementation of it requires significant development in renewable energy infrastructure. By using green hydrogen, the Iron Fuel system would therefore become even more indirectly dependent on electricity usage. Using green hydrogen has not been economically and technically feasible by RIFT at this stage, but this should be further looked into when its production in Europe is available on a larger scale and, as a consequence, its use therefore becomes more economically feasible. In general, RIFT therefore benefits from innovation and implementation of renewable electricity production within Europe, thus aligning with European ambitions in further progressing this.

5.2 CONSISTENCY AND COMPLETENESS CHECK

A consistency check is performed to determine whether the assumptions, methods and data are consistent with the goal and scope of the study. Appendix B (Appendix B.2 in this document) presents the checks that are done. No inconsistency with the defined goal and scope was found.

A completeness check is performed to ensure that all relevant information and data required for the interpretation of the study are complete and available. A completeness check can be done by expert judgement of the study. In order to meet this requirement, an internal critical review has been conducted by LCA experts within our organization who were not involved in the study itself. This review aims to validate the study's consistency, data quality, and alignment with best practices in life cycle assessment.

5.3 SENSITIVITY ANALYSIS

As stated in section 3.4 of this report, applying physical allocation in the context of this LCA does not do justice to the practical value and reality of the product system and the various output products under study. As the value of iron oxide in mass produced from the Iron Fuel production process is relatively low, whereas the economic value associated to it is fairly high, a disproportionate share of the environmental impact would be allocated to Iron Fuel when applying physical allocation. This is not in proportion to the economic reality, value and function of the products. In addition, Iron Fuel as output of the Iron Fuel production process is represented in mass units (kg), but its functional

[17] *In focus: EU investing in energy infrastructure. (2024, October 15). Energy. https://energy.ec.europa.eu/news/focus-eu-investing-energy-infrastructure-2024-10-15_en*

value is much more associated with its energy content. For this reason too, allocation based on physical characteristics in this context does not do justice to the practical value and reality of the product system and the various output products. Nonetheless, to assess the robustness of the results, a sensitivity analysis is conducted by applying physical (mass-based) allocation instead of economic allocation in performing the LCIA analysis. The results are presented in Appendix B (appendix B.3 in this document).

The sensitivity results display that when applying mass allocation, the Iron Fuel system performs worse than the natural gas system in most impact categories. While Iron Fuel with economic allocation performed better in eight out of the 16 impact categories, it now outperforms the natural gas alternative in only three. The impact results have shifted in favour of the natural gas system in the case of non-renewable energy resources, terrestrial eutrophication, marine eutrophication, carcinogenic human toxicity and photochemical oxidant formation. Although it was to be expected from the above arguments that the impact results would shift disproportionately towards the Iron Fuel product when applying physical allocation, it is nevertheless interesting to zoom to particularly zoom in on those impact categories that are now favourable towards the alternative energy source. It is therefore recommended that RIFT places particular emphasis on these five shifted impact categories in the LCA scheduled for 2026.

Moreover, even under physical allocation, the Iron Fuel system still scores better on the impact categories *climate change, water* use and *ozone depletion*, thereby displaying the reduced impact of the Iron Fuel product compared to natural gas in these areas seems to be robust. For climate change, a 50% lower impact results from the sensitivity analysis compared to the natural gas scenario. Water use impact of the Iron Fuel system persist to be minimal (around 5%) relative to the natural gas alternative. A reduction in ozone depletion of 7% compared to natural gas remains.

5.4 LIMITATIONS

This LCA study has provided valuable insight into the environmental performance of the Iron Fuel system. However, several limitations and areas for improvement remain. Firstly, the contribution analysis of this LCA focused only on the climate change impact category. Although this is in line with the goal and scope of the study, the results suggest other impact categories that may be interesting for deeper analysis, such as the five impact categories for which the impact results shifted in favour of natural gas in the sensitivity analysis (based on physical allocation) A deeper investigation into these impact shifts would offer valuable guidance for RIFT in identifying environmental hotspots and directing future innovations beyond the carbon-related impacts.

Secondly, the study relies on several conservative data assumptions. Notably, the electricity consumption of the Iron Fuel boiler and PM<2.5 emissions during combustion were estimated conservatively, as recent engineering updates and demonstration data suggest significantly lower values. Additionally, the datasets used for hydrogen production and the CCS value chain are also based on conservative assumptions, with RIFT's low-carbon hydrogen supplier indicating that the actual upstream emissions are lower than modelled in this study. Although most of the CCS-related LCI data stems from recent literature (2024), the LCI data for CO_2 pipeline transport originates from 2007 sources. While this still falls within the predefined temporal scope for secondary data, the inclusion of more recent and technology-specific data would enhance the contemporary relevance and representativeness of the results.

RIFT has indicated to conduct a follow-up LCA in 2026, incorporating updated process data, refined emissions estimates. Moreover, this updated LCA study is planned to include more process-specific data on the hydrogen production process and CCS chain from RIFT's low carbon hydrogen supplier. In this way, the follow-up LCA can address the indicated limitations of this study. Improving on those aspects would strengthen the robustness and precision of the study's conclusions.

APPENDICES

Appendices

APPENDIX A

All unit process foreground and LCI data is noted within Appendix_A.xlsx, attached to this report. The Excel document includes separate tabs for the primary foreground processes in both product systems under study and includes two separate tabs for additional processes modelled within the Iron Fuel boiler system. These are the low carbon hydrogen production process and the associated CCS chain. The tabs present all economic and environmental inflows and outflows of the foreground (and in exceptions background processes) processes for which data is gathered.

APPENDIX B

All results are in LCA_Appendix B.xlsx, attached to this report. The multiple sheets included show LCI, LCIA, contribution and sensitivity results for both product systems under study.

B.2 LCIA RESULTS – EF 3.1

Below, the normalised characterisation results for the full EF 3.1 impact method are presented. Beyond the 16 PEF categories, this includes some additional categories: three separate climate change categories (biogenic, fossil and land use and land use change), freshwater ecotoxicity broken down into organic and inorganic and human toxicity (carcinogenic and non-carcinogenic) broken down into organics and inorganics.

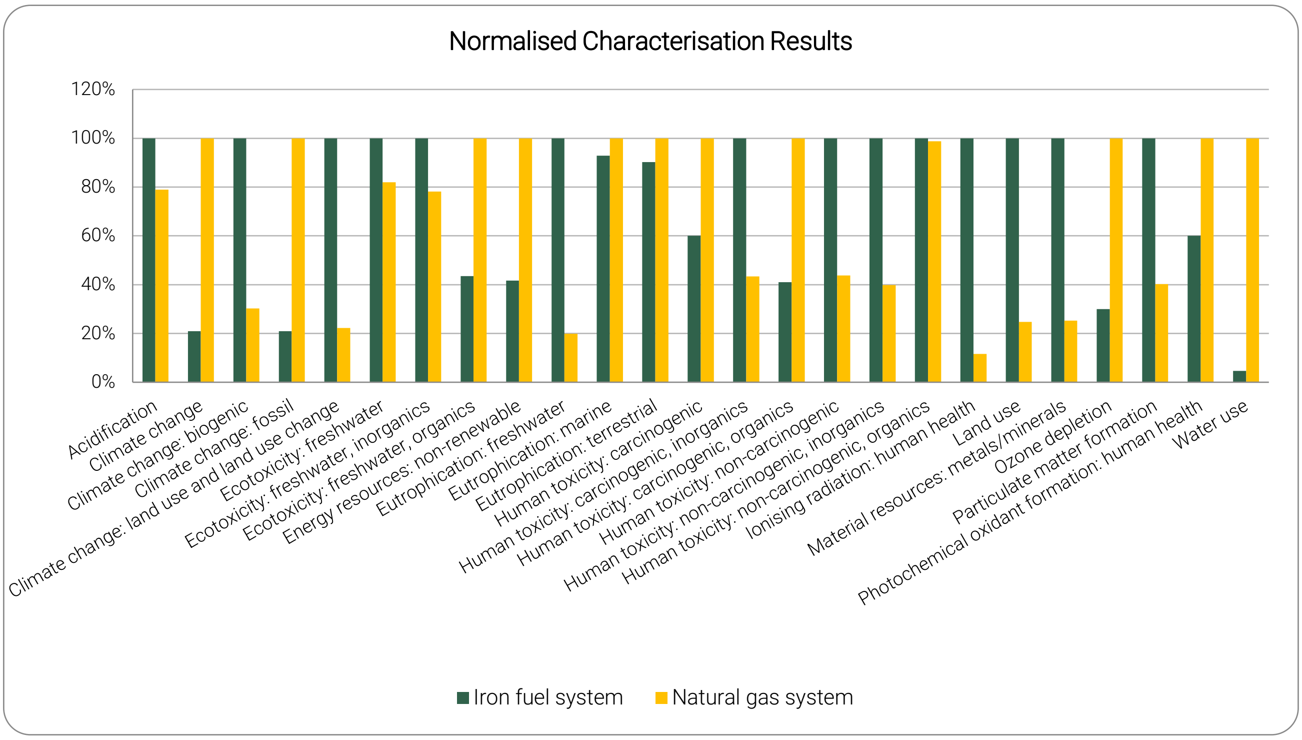

Figure 7. Normalised characterisation results comparing the environmental impact of Iron Fuel and natural gas-based steam production. Full EF 3.1 impact results, including all separate impact categories.

B.2 CONSISTENCY CHECK

Below, the consistency check table is presented. This provides the steps on several checks to make sure the study is performed in line with the set goal and scope definition. No inconsistencies were found.

Table 6. Consistency check table

Check	Iron Fuel system	Natural gas system	Consistence with goal & scope	Action
Data source	✓	✓	Consistent	No action
Data accuracy	✓	✓	Consistent	No action
Data age	✓	✓	Consistent	No action
Technology coverage	✓	✓	Consistent	No action
Time-related coverage	✓	✓	Consistent	No action
Geographical scope	✓	✓	Consistent	No action
Allocation rules	✓	✓	Consistent	No action
Impact Assessment	✓	✓	Consistent	No action

B.2 SENSITIVITY ANALYSIS – PHYSICAL ALLOCATION

By means of altering the allocation method from economic to physical, a sensitivity analysis is performed. Below, the normalised characterisation results for the PEF impact categories are displayed.

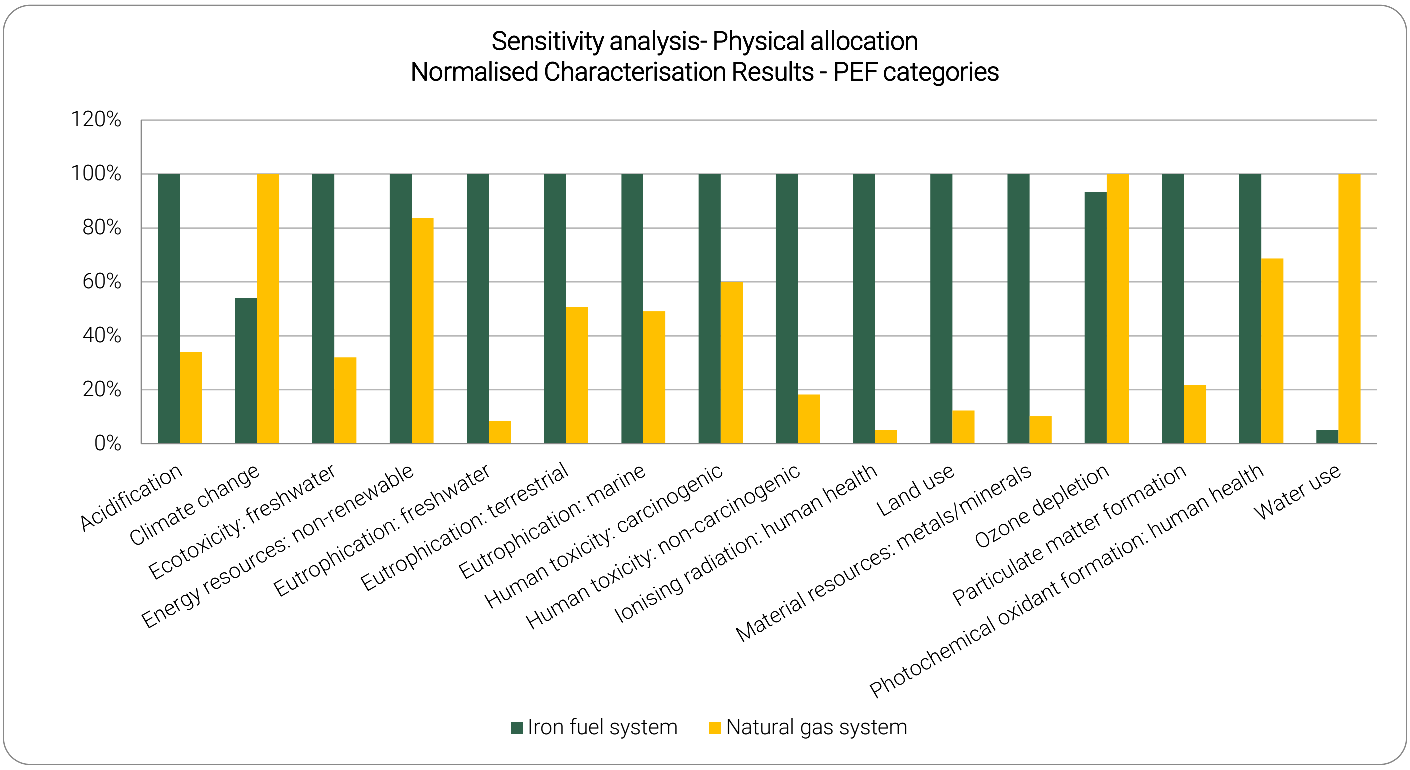

Figure 8. Sensitivity analysis – physical allocation. Normalised characterisation results comparing the environmental impact of Iron Fuel and natural gas-based steam production. EF 3.1 PEF category results are presented.

EGEN.GREEN

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April 2025