Iron Fuel Technology™

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RIFT DEVELOPMENT B.V.

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Introduction

One of the critical aspects to consider in the context of the energy transition is the significance of the energy-intensive industries, known for their substantial energy consumption. These sectors include, among others, iron and steel, mineral and metal processing, refineries, pulp and paper production, food and beverage, and chemical production. It also extends to fields like district heating and electricity production (de Bruyn et al., 2020; EIA, 2016; Rehfeldt et al., 2017). Notably, these sectors are collectively responsible for 47% of global CO_2 emissions (IPCC, 2014, p.7).

Currently, these industries emit large quantities of CO_2 due to reliance on fossil fuels for heat generation. These fuels are burned to produce industrial heat, a crucial component in manufacturing and energy production. Alarmingly, industrial heat accounts for a substantial 51% of the global heat consumption (IEA, 2022), with a consequent responsibility for 20% of all global CO_2 emissions (IEA, 2022b). Given that heat is critical for these industries, CO_2 emissions increase is inevitable unless sustainable fuel alternatives are adopted.

In response to the crucial need to decarbonize, 164 countries have enacted climate change legislation and policies aimed at reducing greenhouse gas emissions (UNFCCC, n.d.). These laws and policies translate into mechanisms that both reward and penalize companies to incentivize emissions reduction.

Such mechanisms include carbon pricing, the issuance or revocation of permits for industrial operations, and increased investments in emission reduction (European Council, n.d.). Additionally, there's a growing influence of a product's environmental footprint on consumer purchasing behavior, directly impacting the demand for greener supply chains (McKinsey, 2023).

As a result of these pressures, many companies have already addressed the low-hanging fruits, such as improving energy efficiency. With these measures already implemented to a significant extent, further decarbonization efforts must focus on more substantial challenges, particularly with industrial heat.

The pace at which companies need to transition to carbon-free industrial heat varies based on their unique circumstances. Currently, 8% of European companies claim that failure to achieve the 62% CO_2 reduction target by 2030 will render them non-competitive and force them to shut down their production facilities (RIFT, internal data). In other cases, companies may be compelled to reduce production capacities to comply with regulations, resulting in revenue losses. In some scenarios, companies face expansion limitations, leading to missed revenue opportunities.

In all cases, these situations translate to additional costs and harm the competitiveness of these companies. Consequently, businesses are actively seeking alternative solutions that can be implemented starting from 2025 onwards.

The current options for achieving zero-carbon industrial heat are primarily electrification and hydrogen. Despite the availability of these options, they are often not viable for many companies. Only 1-4% of industrial heat companies are connected to grids capable of supplying the required electricity and/or hydrogen at this moment (RIFT, internal data). It is expected that a mere 20% will have access to relevant grids by 2030, and only 40% in 2050 (Euroheat, 2019). This leaves a substantial portion of the market without a viable decarbonization solution, representing 12% of global CO_2 emissions. Furthermore, even with access to a hydrogen or electricity grid, additional barriers may arise, including supply uncertainty, price volatility and permit-related issues, such as exceeding nitrogen oxide emissions (RIFT, Internal data). Companies struggling with these challenges are also facing potential closure, increasing carbon costs, failing decarbonization certifications, and potential revenue losses.

The absence of a viable decarbonization solution for these companies also implies that 12% of global CO_2 emissions may remain unaddressed, posing a threat to climate targets. That is why RIFT introduces a novel clean technology to decarbonize industrial heat: Iron Fuel Technology™. This technology enables companies to decarbonize and denitrify their utilities while maintaining or increasing their production capacity.

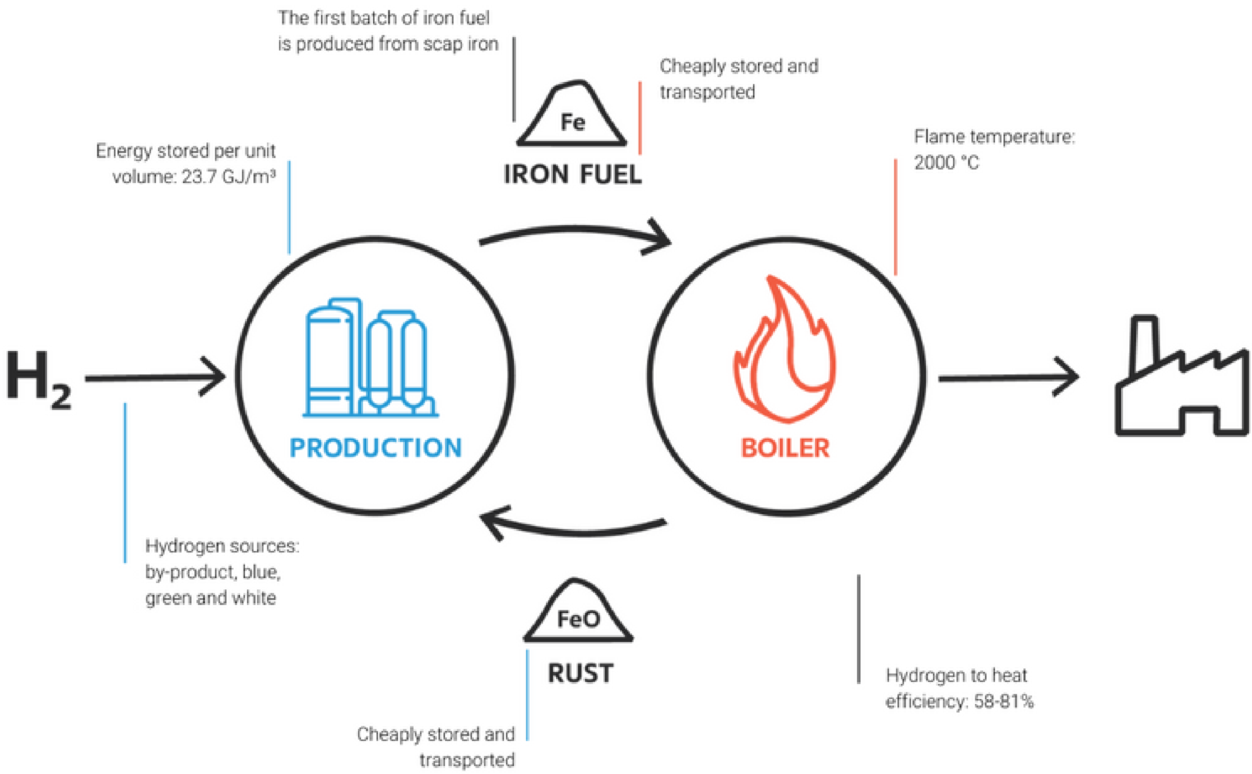
Iron Fuel Technology™

Iron Fuel Technology™ is a clean energy technology for producing industrial heat for industrial processes, district heating, and electricity plants. The circular and CO_2-free energy carrier can be easily stored and transported using existing network infrastructures leading to the ability to trade clean energy. RIFT develops the Iron Fuel Technology™ boiler and production systems toward commercialization and is currently the market leader.

Working Principle

The working principle of Iron Fuel Technology™, which uses iron in powder form, is quite straightforward. It can be compared to a rechargeable battery: the iron fuel (the powder) represents the charged battery, while the rust (or iron oxide) represents the empty battery. In its simplest description, we are rusting and unrusting iron to discharge the iron fuel's energy and recharge the iron fuel.

Before we start rusting and unrusting the iron, we need an initial batch of iron fuel. This initial batch, produced sustainably, can be readily obtained from the existing iron powder market. With the initial batch in hand, we can proceed to the iron fuel combustion and iron fuel production process.



In the boiler, iron fuel is combusted, releasing significant energy that can be converted into hot water (up to 180 °C), steam (up to 650 °C) or hot air (up to 1000 °C). This versatility allows us to cater to a wide range of small- and large-scale applications. Our iron fuel boilers can produce heat consistently (baseload), flexibly (peak-load), or quickly for a brief period (back-up). Importantly, the combustion of iron fuel has no direct carbon dioxide (CO_2) emissions and ultra-low emissions of nitrogen oxide (NOx)(<15 mg/MJ). The only by-product of the combustion process is rust (or iron oxide), which we capture, store, and transport to the production process location using trucks, trains or ships.

In the production process, the rust is converted back into iron fuel using a hydrogen source. Multiple hydrogen sources are applicable, such as by-product hydrogen, geological (white) hydrogen, blue hydrogen, and green hydrogen. As a result, Iron Fuel Technology™ enhances the business potential of hydrogen sources around the world.

Iron Fuel Boiler

Energy can be converted into

- Hot water up to 180 °C
- Steam up to 650 °C
- Hot air up to 1000 °C

Providing heat for different scenarios

- Baseload (consistent)
- Peak-load (flexibly)
- Back-up (quick, for brief period)

Key Characteristics

- No CO_2 emissions
- Ultralow NOx emissions
- Circular
- Competitive

Iron Fuel Production

Applicable hydrogen sources

- By-product Hydrogen
- Green Hydrogen
- White Hydrogen
- Blue Hydrogen

Cyclicity of the Iron Fuel

The process of rusting and unrusting (combustion and production process) can be done repeatedly and is therefore circular. If the iron fuel cannot be reused anymore for the purpose of Iron Fuel Technology™, it can be used as a feedstock in other industries, such as the steel and pigment industry. For economic viability, iron fuel should undergo a minimum of 15 cycles (combustion and production). Initial results indicate that it can exceed this number.

Long Duration Energy Storage & Transport

Iron fuel production and boiler systems do not have to be co-located. Furthermore, the iron fuel produced can be stored for later use. This makes Iron Fuel Technology™ an energy carrier, ensuring its availability for consumption at different locations and times.

Iron fuel and iron oxide can be transported affordably over both short and long distances (up to 10,000 kilometers) using existing transport infrastructure for trucks, trains and ships. Additionally, iron fuel can be stored for varying durations, including seasonal storage, using readily available bulk storage systems. As a result, Iron Fuel Technology™ does not require substantial infrastructural investments.

In practical terms, this means that clean energy, in the form of iron fuel, can be stored and transported from one location to another, meeting energy demands on a regional, continental, or intercontinental scale. This opens up new possibilities for clean energy trading using iron fuel. Geographical regions with limited clean energy can address their shortages by importing iron fuel, while areas with excess clean energy capacity can generate additional revenue by exporting it.

Energy Transport

- Regional <100 km
- Continental 100-3,000 km
- Intercontintental >3,000 km

Energy Storage

- Short <10 days
- Medium 10-180 days
- Seasonal >180 days

Energy Trade

Iron fuel enables global energy trade, addressing shortages and generating revenue.

History

While metal fuels had been explored for rocket applications, the spark for a groundbreaking idea came from a researcher involved in a European Space Agency project who pondered, "Why not use iron to decarbonize our energy-intensive industries?". In 2017, this question led to the collaboration of three students from Eindhoven University of Technology and their professor. After months of researching, experimenting and having to try again, they achieved a small, candlelight-like flame that would soon gain global recognition.

The little flame swiftly captured the hearts of many students, all wanting to contribute to this promising clean technology. What began with three voluntary students soon expanded to five, ten, twenty, and thirty students, eventually forming the student team SOLID. In 2018, this team presented a proof of principle for an iron flame within the laboratory of Eindhoven University of Technology. A milestone that generated increased interest from academia and businesses alike.

Subsequently, Eindhoven University of Technology, SOLID and various SME's joined forces in the Metal Power Consortium. Together they succeeded in creating the world's first proof of principle on an industrial scale (100 kW), demonstrating that iron fuel could be burned in an industrial setting. The system was tested and demonstrated at Swinkels Bavaria Brewery for three days, garnering international media attention.

After this, academia started testing and optimizing the system. Simultaneously, tests were executed for the production of iron fuel in the laboratory of Eindhoven University of Technology. To scale up iron fuel production, the initiative was taken to form the Metal Energy Carrier (MEC) Consortium, which included Eindhoven University of Technology, SOLID, SME's and multinational companies. Together, they explored three different methods for producing iron fuel from rust at proof of principle scale, ultimately concluding that iron fuel production was indeed feasible.

In October 2020, three former managers from student team SOLID founded the company RIFT. RIFT is dedicated to the development of the technology with a focus on commercialization.

Current Status

Since RIFT's foundation in 2020, the team has substantially grown and now comprises 49 employees (37 FTE), covering various areas of expertise, including finance, marketing, business development, and multiple engineering disciplines. RIFT's team has the highest concentration of knowledge and experience related to the Iron Fuel Technology™ globally.

Notable achievements by RIFT include the successful validation of Iron Fuel Technology™, the development of simulation models, and the installation of the first ever operational 1 MW boiler system that supplied hot water to 500 households in the city of Helmond, The Netherlands. With the successful completion of world's first industrial prototype (1 MW boiler and 20 kW production system), RIFT is currently working on world's first Iron Fuel Technology™ industrial pilot, featuring a 1 MW boiler and a 50-100 kW production system. RIFT protects its technological advancements through an ever-expanding portfolio of patents.

Furthermore, RIFT has signed Letters of Intent totaling 235 MW of installed capacity to date, reflecting substantial market interest in Iron Fuel Technology™ as a viable solution for companies in the energy-intensive industry. Feasibility studies have confirmed that Iron Fuel Technology™ can meet the necessary technical, operational, economic and environmental requirements as specified by these companies.

1 MW

The installation of the first ever operational 1 MW boiler system that supplied hot water to 500 households in the city of Helmond, The Netherlands.

37 FTE

The team now comprises 49 employees (37 FTE), covering various areas of expertise, including finance, marketing, business development, and multiple engineering disciplines.

235 MW

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Future

The first commercial system projects are slated to commence in 2024. It is anticipated that this technology will be fully prepared for large-scale deployment by 2027.

Note: The current status reflects the status quo in november 2023.

Applications

Iron Fuel Technology™ opens up opportunities for energy-intensive industries to decarbonize and denitrify their industrial heat. There are three distinct scenarios where Iron Fuel Technology™ can make a significant impact: (i) off-grid located companies, (ii) on-grid located companies facing operational challenges, and (iii) for on-grid located companies. In each scenario, the user incentives and the number of potential solutions vary. In some cases, Iron Fuel Technology™ is the only viable option, ensuring its adoption and a positive sustainable impact. In other scenarios, Iron Fuel Technology™ must compete with other alternatives based on customer requirements for adoption to occur. The following sections outline each use case and the competitiveness of Iron Fuel Technology™ in comparison to other applicable solutions.

Off-Grid Located Companies

Off-grid located companies are companies which do not have an electricity or hydrogen grid connection which poses challenges in their efforts to decarbonize. While clean alternatives may be available, their options are often limited, impacting their (economic) competitiveness and, in some cases, potentially leading to closure before 2030. Iron Fuel Technology™ can be applied off-grid and therefore provides a solution to decarbonize these production processes.

In the European Union, the market size of off-grid companies is significant. Currently, only 1-4% of energy-intensive companies are connected to a hydrogen or electricity grid with the necessary operating capacity to decarbonize industrial heat (Euroheat, 2019). With anticipated investments in grid extensions and upgrades by governments and companies, it is expected that this figure will increase to 20-30% in 2030 and 40-50% in 2050 (Euroheat, 2019). Nevertheless, this still leaves 70-80% and 50-60% of all companies off-grid in 2030 and 2050, respectively. In 2030, this market consists of over 2000 installations with an accumulated capacity of 281 gigawatts (Euroheat, 2019). Iron Fuel Technology™ can play a pivotal role in helping these companies achieve decarbonization.

Off-grid companies in the EU, in 2030

80% off-grid = **over 2,000** companies = **281 GW** capacity

In this scenario, the incentive for transformation is highest when:

- Replacement of boiler systems is required before 2030, as investments must be made promptly. According to research, 60% of all boiler systems need replacement before 2030 (Euroheat, 2019).
- Decarbonization is a crucial necessity for a business to maintain competitiveness, leaving fossil fuel alternatives as unviable options. According to research, this applies to 8% of the total market before 2030 (RIFT, Internal data).

Given that only limited commercially available zero-carbon solutions exist for off-grid locations, governments are increasingly investing in electricity networks and hydrogen pipeline networks (Sterling, 2022; Infrasite, 2023). With Iron Fuel Technology™, off-grid locations now have a potential solution that does not require major infrastructural investments. Consequently, governments can allocate these substantial financial resources to other areas.

On-Grid Located Companies with Operational Challenges

Companies that have a (current or planned) electricity or hydrogen grid connection sufficient for their energy capacity demands can still face operational problems when using these alternatives. Known issues (RIFT, Internal data) encountered by industrial heat-dependent companies when adopting electrification and hydrogen, are as follows:

Issues with hydrogen

- The price is highly volatile and uncertain in the future.
- Not sustainable when exceeding the renewable electricity input full load hours
- Difficulty guaranteeing supply certainty now and in the future.
- The increased NOx emissions exceed permitted level, and no extra permits are or will be given.

Issues with electrification

- The renewable electricity price is highly volatile and uncertain in the future.
- Not sustainable when exceeding the renewable electricity input Full Load Hours.
- Temperatures above 400 °C cannot be reached economically.

RIFT's market research indicates that 80% of all on-grid companies face one or multiple of these problems. As a result, these companies are unable to effectively use their grid connection, rendering decarbonization still not possible. Although they are theoretically connected to the grid, in practice, they are still off-grid. Iron Fuel Technology™ provides an alternative means to decarbonize and denitrify their production processes. In these cases, all (governmental) investments in new infrastructure go to waste since decarbonization remains unattainable.

On-Grid Located Companies

Companies with sufficient electricity or hydrogen grid connections, have the option to choose electrification or hydrogen as clean energy sources. Iron Fuel Technology™ presents a viable third alternative in such scenarios. While the on-grid market is currently the smallest (1-4% of the total market), it is poised for growth in the future. To gain adoption in this market, Iron Fuel Technology™ must outperform in energy price (€/MWh), price stability and supply certainty compared to electrification and hydrogen. Depending on the specific business case, Iron Fuel Technology™ can be competitive across all three aspects.

Electrification

On-grid electrification competes effectively with Iron Fuel Technology™ in scenarios where systems operate with limited Full Load Hours (FLH) annually and low electricity prices. The cost-effectiveness of heat generation in electrification depends largely on electricity prices. However, as FLH increases, the cost of electrification tends to rise beyond the point of competitiveness, especially when incorporating additional storage, such as batteries. This can deviate from the desired production process curve. Additionally, sustainability concerns arise as renewable electricity generation is limited by weather patterns, necessitating fossil fuel-fired electricity plants to meet the demand. As a result, base load electrification is not the most cost-efficient option, and on-grid electrification is primarily used alongside hydrogen or Iron Fuel Technology™ boilers.

Hydrogen

On-grid hydrogen is a competitive alternative to Iron Fuel Technology™ under specific conditions, including:

- When operating on green hydrogen
- When connected to dedicated electrolyzers with a supply contract
- When there is no requirement for on-site storage buffer
- When staying within the user's NOx permit operating window

If any of these requirements are not met, hydrogen becomes less competitive for heat-demanding companies as the sustainability, supply reliability, and/or the price stability cannot be guaranteed.

In all other cases, Iron Fuel Technology™ surpasses electrification and hydrogen as the more competitive solution. Therefore, Iron Fuel Technology™ can be used where other alternatives face infrastructural of operational challenges, or when it proves to be the most cost-effective option even when other relevant alternatives are feasible. For these reasons, Iron Fuel Technology™ has the potential to play a vital role in the energy transition, offering a promising alternative with significant market potential.

Industries

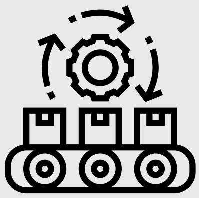
Within each of the three scenarios, Iron Fuel Technology™ is applicable across multiple industries that require indirect energy in the form of hot water (up to 180 °C), steam (up to 650 °C) or hot air (up to 1000 °C).

Examples of the potential use cases for Iron Fuel Technology™ span a range of industries, including district heating, pulp and paper, food and beverage, chemicals, ceramics and electricity generation. Although Iron Fuel Technology™ is not suitable for situations that require direct flame contact in the production process, the total size of the market in which Iron Fuel Technology™ is a possible solution remains a substantial 7680 GW.

Applications for Iron Fuel Technology™

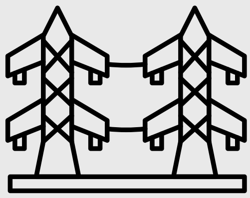
District heating

The centralized production of heat, typically for residential and commercial areas. District heating can be both on-grid and off-grid, .



Production processes

Can include various industrial processes across different industries, some of which may be on-grid, while others may operate in off-grid or semi-off-grid environments.



Electricity plants

The production of electrical power, which can include on-grid power plants and off-grid power generation solutions.

Virgin Iron Fuel

Virgin iron fuel is sourced from the global existing iron powder market. The current market can facilitate scaling to 14.7 GW (88 TWh/yr) installed capacity. The current excess production capacity is even sufficient for the upscaling to at least 2.6 GW or 16 TWh/yr (RIFT, 2020, internal document) installed capacity. Exceeding this threshold will necessitate acquiring market share from existing iron powder users or expanding production facilities. Any (resulting) price increase or fluctuation will not limit the upscaling of Iron Fuel Technology™ nor will the feedstock markets (scrap metal and iron ore) as these are sufficiently large. Moreover, the environmental impact of the supplied virgin iron fuel is minimal and does not compromise the life cycle feasibility of Iron Fuel Technology™. As the production of iron powder produces significantly lower CO_2 emissions than it indirectly prevents, the iron powder market has the potential to become a global enabler of decarbonization.

Virgin Iron Powder Requirements

Before the circular usage of iron fuel can begin, an initial batch of virgin iron fuel is needed. Iron fuel is a derivative of iron powder which is currently produced in a global existing iron powder market. Currently, none of the numerous iron powder producers (e.g. Rio Tinto, Hoganas, Kobelco) specifically produce iron fuel (QYResearch, 2018), but the technical and quality characteristics are similar to iron powders currently on the market. The product specifications of virgin iron fuel are actually lower compared to the most current iron powder standards ensuring that many iron powder producing parties can meet the quality requirements of iron fuel.

Iron Powder Market

The iron powders currently produced find primary usage in the automotive industry (additive manufacturing, powder metallurgy) as well as in the chemical (magnetic paints, recycling of industrial chemicals), general industrial (welding, soft magnets), and food industries (supplements and nutritional fortification) (Fortune Business Insights, 2020; QYResearch, 2018).

Production capacity
1,797,000 t/year

Current market
1,472,000 t/year

Excess capacity
325,000 t/year

The current production capacity is 1,797,000 tonnes per year, with the current market size reported at 1,472,000 tonnes (QYResearch, 2018). This leaves an excess capacity of 18%, representing an extra production capacity of 325,000 tonnes annually (QYResearch, 2018). This excess capacity is expanding as the iron powder market shrinks, mainly due to the growing market for electric cars (RIFT, Internal data).

Production Methods of Iron Powder

There are two main routes for producing iron powder. The first follows a blast furnace route while the second makes use of an electric arc furnace (EAF) using (green) electricity (Lu, Pan, & Zhu, 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, Pan, & Zhu. 2015; Editors of Encyclopaedia, 2023). This process produces pig iron (molten iron) as a result. The EAF route typically involved the use of scrap iron, where an electric arc melts the scrap to produce liquid iron (ArcelorMittal, 2023b; Wente et al., 2023). Both routes produce slag as a by-product (ArcelorMittal, 2023b). Subsequent processes (e.g., atomization) are then required to transform the molten iron into iron fuel, iron in powder form (Sista & Dwarapudi, 2018).

Whereas the blast furnace route and the EAF route are dedicated processes to produce iron, iron can also be produced as a by-product from the titanium dioxide production process. The smelting of natural titanium feedstocks (e.g., ilmenite) produces titania slag (the desired product) and liquid iron (Filippou & Hudon, 2009). 70% of this liquid iron is further processed into iron powders (Filippou & Hudon, 2009). Iron fuel can therefore also be retrieved as a by-product.

Environmental Impact

From an environmental perspective, the EAF route is more sustainable than the blast furnace route with the subsequent CO_2 emissions estimated at 0.67 t CO_2/t virgin iron fuel (IF) in comparison to 2.32 t CO_2/t virgin IF respectively (World Steel Association, 2022). The CO_2 emission associated with iron fuel derived as by-product from titania slag production is 1.6 t CO_2/t virgin IF (Sovereign Metals Limited, 2021).

2.32
t CO_2/t iF

BLAST FURNACE

The blast furnace route is considered less sustainable from an environmental perspective due to higher CO_2 emissions.

0.67
t CO_2/t iF

EAF ROUTE

The EAF route involves using scrap iron as a feedstock. An electric arc is used to melt the scrap, resulting in the production of liquid iron. It is considered more sustainable due to reduced CO_2 emissions.

1.6
t CO_2/t iF

BY-PRODUCT

While CO_2 emissions are generated in this process, life cycle assessments show that using iron powder for Iron Fuel Technology™ has a positive impact, preventing more CO_2 emissions than it emits.

Although, CO_2 emissions are emitted in this process, life cycle assessments show that a significant positive impact can be made with Iron Fuel Technology™ as using iron powder for the purpose of Iron Fuel Technology™ ensures that more CO_2 is prevented than emitted. From the perspective of an iron powder producer, one tonne of iron powder can directly prevent 13-32 tonnes of CO_2 (RIFT, 2020, internal document). The iron and steel industry can become an enabler of decarbonization with indirect positive CO_2 footprints.

Cost of Virgin Iron Fuel

The price of virgin iron fuel in 2017 was on average €996 per ton (QYResearch, 2018). Internal studies and supplier conversations indicate that a price of €600-€800 per ton is possible (Filippou & Hudon, 2009). The lower prices are the result of the low product specification for the virgin iron fuel. Next to this, virgin iron fuel can be ordered in larger quantities and process optimization can be implemented.

If there is a cost price increase, Iron Fuel Technology™ is less sensitive to price fluctuations than current uses of iron powder. This ensures the possibility of scaling beyond the excess capacity and generating more interest from suppliers compared to their current customer base.

Quantity of Iron Fuel in the Cycle

There are two purchases of virgin iron fuel required in the Iron Fuel Technology™ cycle. The first is part of the capital investment, while the second is needed to renew to iron fuel, depending on the number of cycles the iron fuel can be used within. The one-time initial purchase of virgin iron fuel depends on the cycle length, including the time between iron fuel production, storage, and combustion. For a cycle length of 6 days, the acquisition is 0.01 t virgin IF/MWh which can increase to 0.56 t of virgin IF per MWh for a 365-day cycle (RIFT, 2020, Internal document).

The amount of virgin iron fuel that needs to be renewed depends on the cyclicity of the iron fuel and the mass recovery rate. For commercial installations this is expected to be 0.02 t/MWh*year (for 30 cycles; mass recovery 99.4%) This results in indirect emissions of 3.8 kg CO_2/GJ or 0.014 t CO_2/MWh (RIFT, 2020, Internal document).

Iron Fuel Acquisition
Example

• Boiler capacity
10 MW

• Annual operation
6,000 FLH

• Initial Iron Fuel
580 tons

• Annual Renewal Range*
497-1,222 tons

***This is depending on the number of cycles and the mass recovery rate (RIFT, 2020, Internal document).**

Scaling Up

The current market has an excess capacity of 18% which is sufficient for the upscaling of Iron Fuel Technology™ to 16 TWh/year or 2.7 GW of installed capacity (QYResearch, 2018; RIFT, 2020, Internal document). If the annual installed capacity exceeds this, extra capacity can be acquired through gaining market share of existing users. The current iron powder market supports 14.7 GW (88 TWh/year) of installed capacity (RIFT, 2020, Internal document).

Extra capacity can also be achieved through expansion of production facilities or adding an iron powder production unit to existing steel making processes. Although both options may increase virgin iron fuel prices, multiple business cases show this is not a threat to hinder the scale up of Iron Fuel Technology™.

As mentioned earlier, virgin iron fuel can be produced through various routes. Considering the scrap market as the feedstock for the EAF route as well as the production market capacities of the mining of iron ore as the feedstock for the blast furnace route, both feedstock markets are large enough not to impose any limitations to the upscaling of Iron Fuel Technology™. Analysis shows that for the mentioned installed capacities, Iron Fuel Technology™ would hold a market share of 30,000 TWh/year (4,900 GW) and 125,000 TWh/year (20,800 GW) in the scrap and iron ore market, respectively (RIFT, 2020, Internal document).

The Use of Iron Fuel after Iron Fuel Technology™

If the iron fuel is not usable anymore for the purpose of Iron Fuel Technology™, the iron oxide or iron can be sold for use in other markets and production processes. For example, it can be used as scrap feedstock for the steel industry. The minimum residue price after Iron Fuel Technology™ is expected to be 150-250€/t (RIFT, 2020, Internal document). This could potentially be higher as the iron quality improves after multiple cycles.

Iron Fuel Boiler

The iron fuel boiler system has the objective of producing industrial heat in the form of hot water, steam or hot air which can be used to produce products and utilities. Iron fuel boiler systems can be used in indirect heat transfer applications operating in base, variable, peak and back-up load within both on- and off-grid markets. In comparison to other alternatives, iron fuel boiler systems are competitive (and often outperform alternatives) in terms of cost of heat, price stability, CO_2 emissions, NOx emissions, required space for storage, and supply reliability. Implementing an iron fuel boiler system is therefore a worthwhile consideration for every company using industrial heat.

The Boiler Plant

Newly produced iron fuel from the production location is supplied to the iron fuel boiler location by truck, train or ship. These multiple transportation options make iron fuel boilers accessible to a variety of locations, independent of a grid connection, such as hydrogen, electricity, or natural gas. Upon arrival, bulk-solid unloading systems handle the unloading process, transferring the iron fuel to a silo for storage. When there's a demand for industrial heat, the iron fuel is conveyed to the boiler's feeder using standard on-site transport equipment. The feeder system then introduces the iron fuel into the boiler, where it combines with ambient air in the right conditions. With an initial spark, the iron reacts with oxygen from the air, creating a self-sustaining flame and resulting in the formation of rust (iron oxide), as indicated by the following reaction:

4Fe + 3O2 -> 2Fe2O3 + energy

Direct CO_2 emissions
0 kg

Direct NOx emissions
<15 m/MJ

Energy density
(100% Fe)
25.8 GJ/m3
7.4 GJ/t

Energy density
(corrected by combustion)
25.5 GJ/m3
7.3 GJ/t

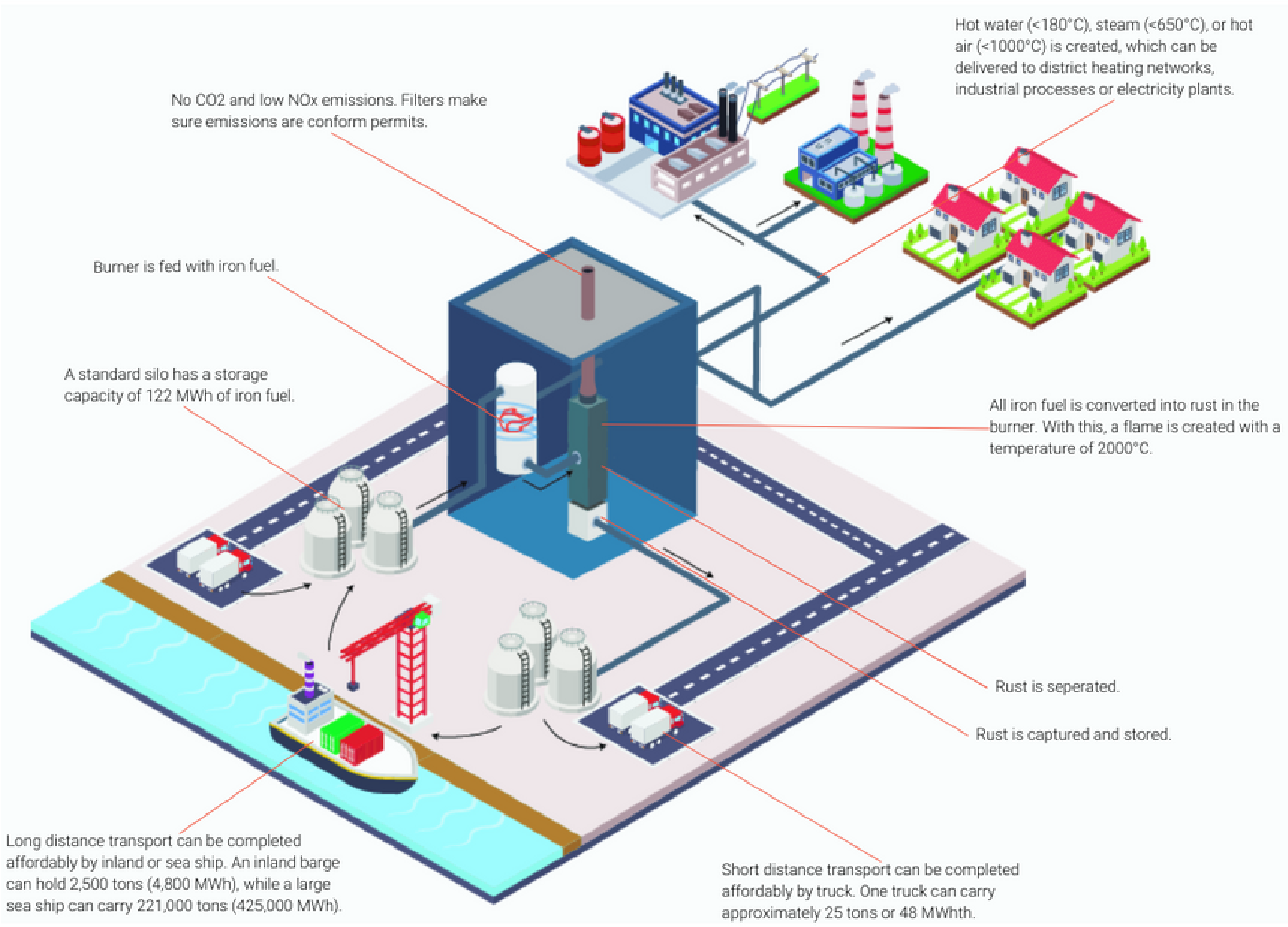
Energy efficiency
85-95%

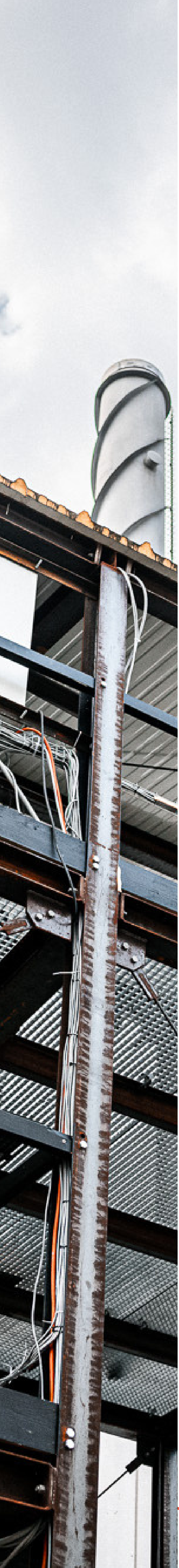
Fuel needed for 1MWhth*
0.15m3
520kg

*Assumed stack temperature of 135℃ (dependent on the case specific stack temperature and boiler design)

The combustion process releases a substantial amount of energy in the form of heat, equivalent to 25.5 GJ/m3 or 7.3 GJ/t, which can generate temperatures of up to 2000°C. Importantly, there are no CO_2 and only limited NOx emissions (<15 mg/MJ). After combustion, the energy resides in the iron oxide-air mixture and is transferred to a heating medium, typically water, within the boiler. Subsequently, the iron oxide particles are separated, and the resulting flue gas is cleaned before clean air is released into the atmosphere via a chimney.

The outcome of this process includes clean air, captured rust, and energy available in the form of hot water (up to 180°C), steam (up to 650°C), or hot air (up to 1000°C). This versatility makes iron fuel boiler systems suitable for a wide range of applications, such as for district heating, industrial processes, and electricity production. Captured rust is stored in a silo and can be transported back to an iron fuel production location, closing the loop.





Applications & Operations

Iron fuel boiler systems can accommodate indirect heating applications using hot air, hot water or steam as a medium of transferring the generated heat. They are not suitable for direct heating because the iron oxide produced during combustion is a valuable product that can be reclaimed. As previously described, these systems offer an industrial heat profile that includes hot air up to 1000 °C, hot water at 180 °C, and steam at 650 °C. This versatility makes iron fuel boiler systems well-suited for a wide range of industries, including district heating, pulp and paper production, food and beverage production, chemicals production, ceramics manufacturing, and electricity generation.

One of the primary advantages of iron fuel boilers is that, unlike alternatives such as hydrogen, electrification and natural gas, they do not require a grid connection for the feedstock to produce industrial heat. As a result, Iron Fuel Technology™ caters to a broader set of industries and applications, both on- and off the grid. Furthermore, the design of the iron fuel boiler system aligns with the capacity requirements of these industries, which can range from 2-500 MW, and these systems are engineered to operate reliably for a minimum of 15-30 years.

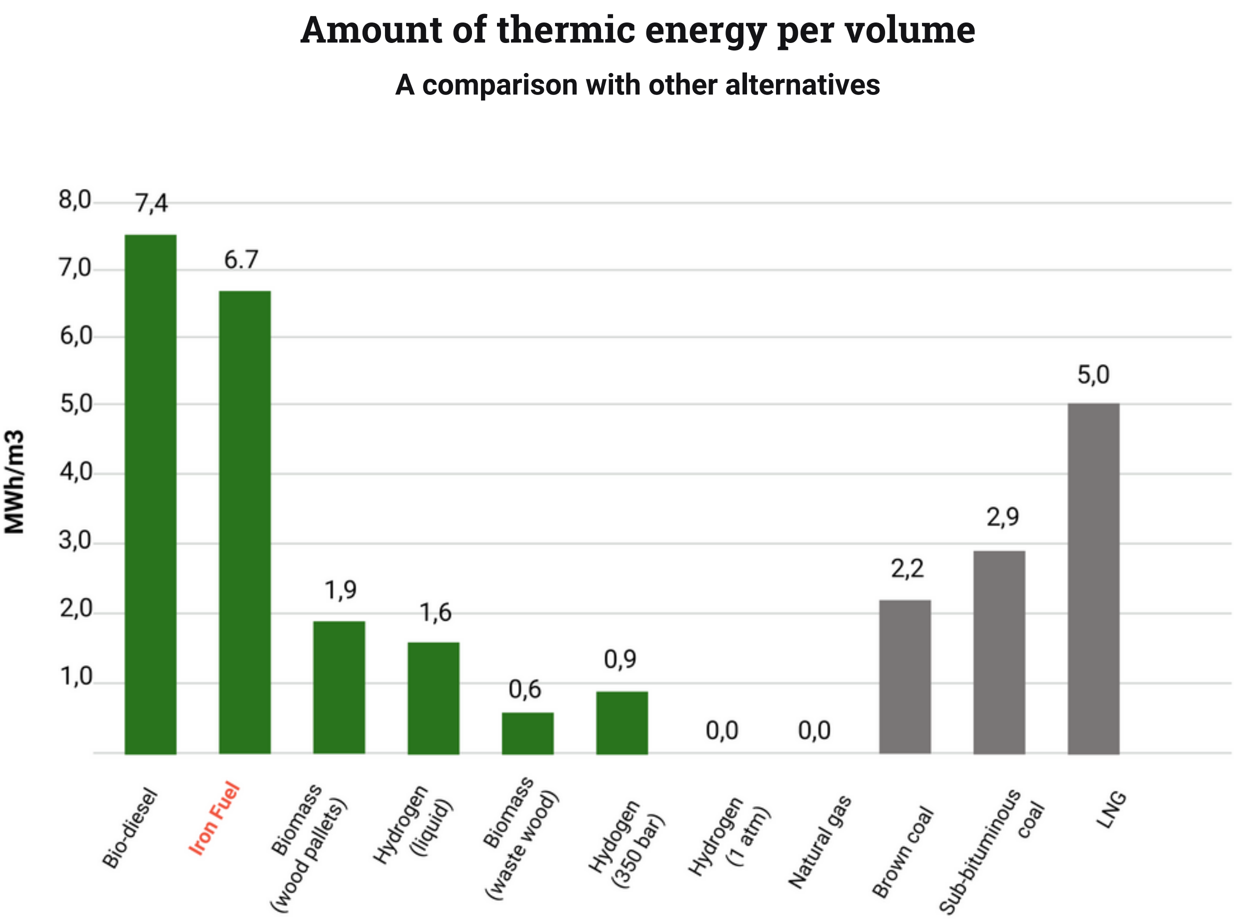
Iron fuel boiler systems can run stably at 16-25% of the maximum capacity of a system (i.e., turn down ratio 1:4 to 1:6), allowing for adjustable capacity over a broad operating profile. For example, a 1 MW system can consistently operate from 0.16/0.25 MW to 1 MW. This flexibility enables iron fuel boilers to effectively respond to fluctuating heat demand curves. Additionally, these systems feature a relatively high ramp-up/down ratio, ranging from 10-40% per minute. This means they can quickly adapt to sudden increases or decreases in industrial heat demand. Moreover, the start-up time for the iron fuel boiler system is relatively short, ensuring a swift transition from shutdown to heat production. The combination of the ramp-up, ramp-down, start-up time and turn down ratio is desirable as it enables the boiler systems to be applicable in multiple load bearing situations. These include variable loads (capacity of the boiler varies hour to hour), peak loads (the capacity of the boiler must increase and decrease quickly to match large or small demands), and even back-up situations (the capacity of the boiler must be quickly increased when heat demand is excessive or when another boiler fails).

In summary, the characteristics of the iron fuel boiler systems set them apart from other solid fuel boiler systems, such as coal and biomass boiler systems, as they offer unparalleled flexibility and applicability in diverse load-bearing situations (Babcock & Wilcox, 2015; Miller & Tillman, 2008).

Space Requirements

An iron fuel boiler system less than 10 MW will be approximately 12 meters high, 10 meters long, and 6 meters wide. Moreover, the on-site storage space required for these systems is quite limited. To put it into perspective, a 1 MW system can operate continuously for 24 hours using just 3.6 m³ of iron fuel (RIFT, 2023, Internal data). This storage space footprint stands in significant contrast to other clean energy alternatives, such as a 1 MW system requiring 27 m³ of space for 350-bar hydrogen storage, 13-39 m³ for biomass storage, or 24 m³ for electric storage (RIFT, 2023, Internal data).

A standard storage silo, designed with a 3.6-meter diameter and a height of 14 meters, when filled with iron fuel, can store as much as 122 MWh. What makes iron fuel storage even more convenient is that it can be completed in regular, readily available silos with minimal losses under atmospheric conditions and without any additional energy input. This ease of on-site storage makes Iron Fuel Technology™ a practical choice for companies with limited available space or those requiring substantial strategic storage reserves on-site (see: Chapter 8 for further information).



Supply Reliability

One or multiple dedicated iron fuel production plants will supply iron fuel to an iron fuel boiler plant through supply contracts. This coupling of plants enhances supply reliability by ensuring that feedstocks are consistently transported between the boiler and production locations. Furthermore, due to the compact storage requirements of iron fuel and iron oxide, both the iron fuel boiler and production plant can maintain strategic storage reserves. This helps overcome operational irregularities in production processes or logistics, ensuring the continuity of operations. This construction is in part possible due to the cost-competitive transport and storage costs of iron fuel and iron oxide (see: Chapter 8 and 9 for further information). This supply reliability is unique to Iron Fuel Technology™ compared to the less certain supply of renewable electricity and hydrogen, which are dependent on variable renewable energy sources and grid supply and demand.

Implementation & Scalability

Iron fuel boiler systems can be implemented reliably as long as a supply contract exists between an iron fuel production and iron fuel boiler operator, and a permit is obtained. The importance of the supply contract has been mentioned previously, and with regards to the permit, there should be no hindrance since the emissions from the iron fuel boiler system already adhere to the emission standards specified in current industry permits.

Additionally, implementing iron fuel boiler systems is not externally reliant on uncontrollable governmental actions regarding infrastructure investments. This is because iron fuel boiler systems do not require a grid connection, unlike alternatives like electricity or hydrogen. This reduces the potential sunk costs for companies investing in infrastructure. Furthermore, there is limited reliance on subsidies to kick-start the implementation of Iron Fuel Technology™ since the existing business cases are already attractive.

To physically implement an iron fuel boiler system, silos, on-site logistical systems and the boiler itself need to be installed at the boiler system's location. It's important to note that, apart from the boiler system itself, all the storage and bulk-solid handling equipment required for transporting and storing iron fuel or iron oxide are mature technologies available from multiple suppliers.

Furthermore, the design of the iron fuel boiler does not necessitate new or rare materials. This is because the combustion temperature of iron fuel aligns with that of fossil fuel combustion. As a result, all current boiler manufacturers have the capability to produce iron fuel boilers using existing production methods. The operation and maintenance (O&M) of the iron fuel boiler system can also be completed by existing O&M service providers with minimal additional training.

The flexibility of the iron fuel boiler system extends to the reuse of other present on-site equipment and infrastructure. For instance, the boiler system can be integrated into an already existing heating network at a site. Other reusable equipment includes boiler water treatment systems and industrial heat distribution networks.

The ability to reuse equipment and infrastructure, the utilization of commercially available components, the absence of new or rare materials, and the involvement of existing companies in building and maintaining the systems collectively enable iron fuel boiler systems to be implemented quickly, with systems up to 20 MW taking approximately two weeks for installation. This feature facilitates easy scalability and minimal investments.

Current Status

2022

In September 2022, the iron fuel boiler technology was successfully demonstrated through the operation of an Industrial Prototype featuring a 1 MW boiler system. The prototype was installed at Ennatuurlijk's district heating plant in Helmond, and decarbonized 500 households.

2023

At the end of 2023 the initial Industrial Pilot for a 1 MW system will be completed.

2024

The First-Of-A-Kind commercial system projects are set to kickstart in 2024, marking the next phase of development.

2027

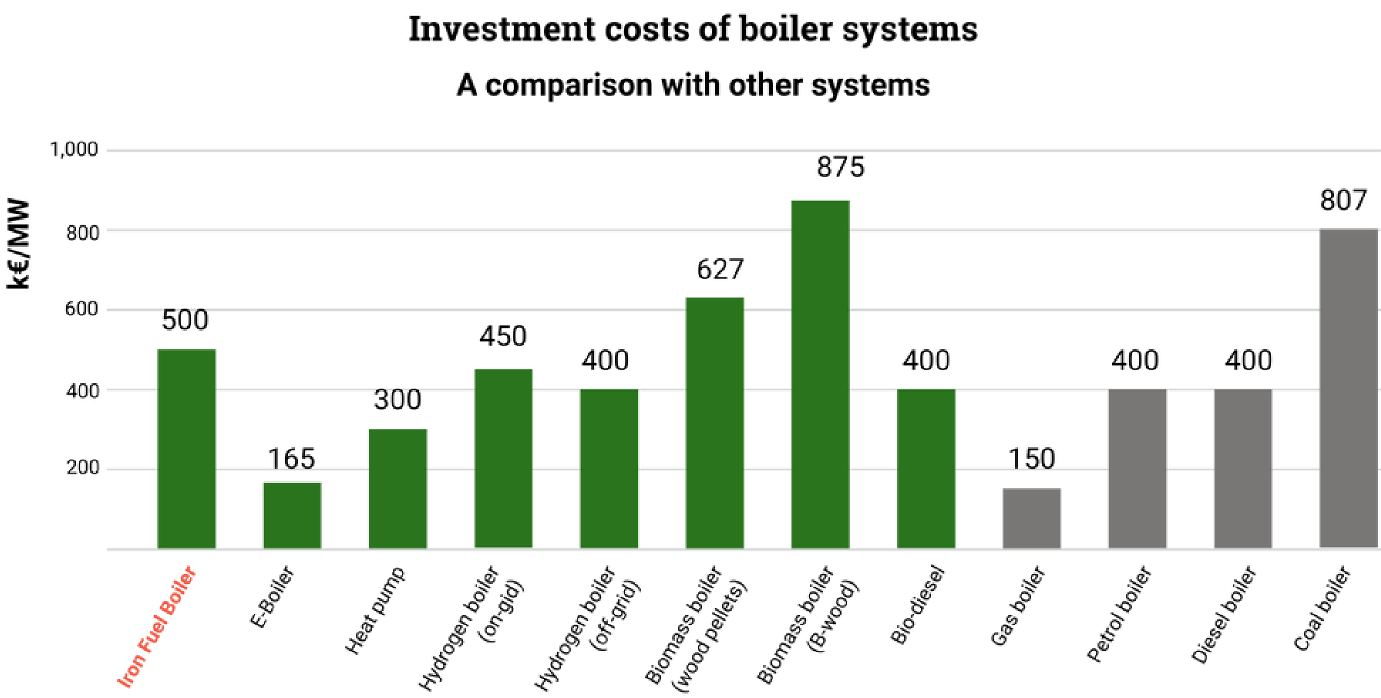
Anticipated for full-scale readiness in 2027, this technology holds promising prospects for large-scale deployment.

Investment

The cost of an iron fuel boiler plant is cost-effective. This is attributed to the fact that a significant portion of the equipment is standard and readily available from various suppliers. Moreover, the option to reuse existing plant structures and associated equipment, such as water purification systems and pumps, substantially reduces the overall investment costs. As a result, the expected investment outlay for an iron fuel boiler system typically ranges from €500K-€600K per MW installed. This estimate encompasses systems within the 5-25 MW capacity range and includes standard storage tanks and on-site transport equipment.

€500-€600K
per MW installed

To compare this with other technologies, (see: figure below) the investment costs for an iron fuel boiler system are higher than those of natural gas, in line with on-grid electrification and on-grid hydrogen boilers, and lower than biomass, off-grid hydrogen and off- grid electrification systems. Note that for iron fuel boiler systems there is no need for a grid connection, and thus, there are no network investment costs associated. This contrasts with natural gas, on-grid hydrogen and on-grid electrification. In the figure, however, it is important to note that the investment costs for a grid connection are excluded in the indicative cost estimates for alternatives that require this, as the network investment costs vary widely per geographical location.



Operational Costs

When it comes to operational costs (excluding the iron fuel itself), it is expected to be approximately 2-10€/MWh. These operational costs vary depending on the number of operational hours annually but generally align with on-grid electrification, on-grid hydrogen, and biomass boilers. They are higher than gas boilers and lower than off-grid hydrogen and off-grid electrification systems.

One key advantage of Iron Fuel Technology™ is its independence from grid connections, which translates into no associated costs for grid operation and maintenance (O&M). This distinguishes it from alternatives such as on-grid hydrogen, on-grid electrification, and natural gas, which may incur O&M grid connection costs. However, it's important to note that the inclusion of such costs in comparisons, as shown above, would be location-dependent. This inherent economic control and limited reliance on grid O&M contribute to the resilience and cost-effectiveness of Iron Fuel Technology™.

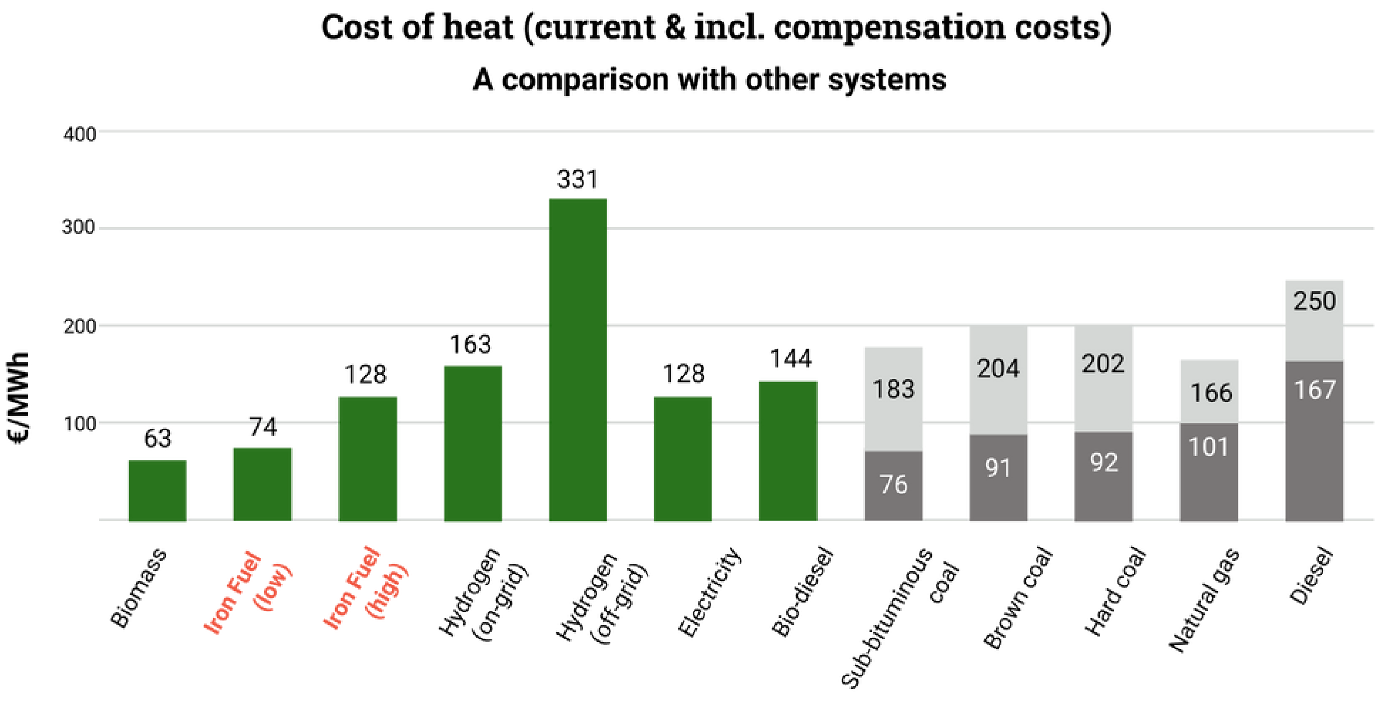
Note: The costs depicted in the figure are estimates. Maximum costs may vary and could be up to 1.5 times higher for all values shown.

Cost of Heat

The cost of heat is dependent on the number of operating hours. In terms of cost-efficiency among clean technologies, Iron Fuel Technology™ stands out. It offers a more cost-effective solution than hydrogen (both off-grid and on-grid), on-grid electrification (when operating more than 2,750 FLH), and off-grid electrification (when operating more than 3,500 FLH). However, it may have a higher cost compared to heat pumps and biomass.

It is important to consider the limitations and practicality of some alternatives. Biomass, while potentially providing lower-cost heat, faces social resistance as well as sustainability challenges due to the limited supply of sustainable biomass (Tonini & Astrup, 2012; Turconi et al., 2013). As a result, large-scale adoption of biomass may be unlikely.

At this moment, Iron Fuel Technology™ is not yet competitive with coal and natural gas, considering a carbon pricing of 90€/t CO_2, but it is competitive with diesel. When carbon prices exceed 150-200€/t, the green premium of Iron Fuel Technology™ will decrease to 0 or lower meaning that Iron Fuel Technology™ will at that point be cheaper than the current fossil fuels.



Comparing carbon-free alternatives to fossil alternatives on a level playing field, including carbon compensation (indicated by the light grey surplus in the graph above), Iron Fuel Technology™ currently offers a negative green premium and a return of investment (ROI) of less than 3 years. This means that Iron Fuel Technology™ is economically more attractive than fossil alternatives. Simultaneously, it remains highly competitive with other sustainable alternatives, making it an economically compelling choice.

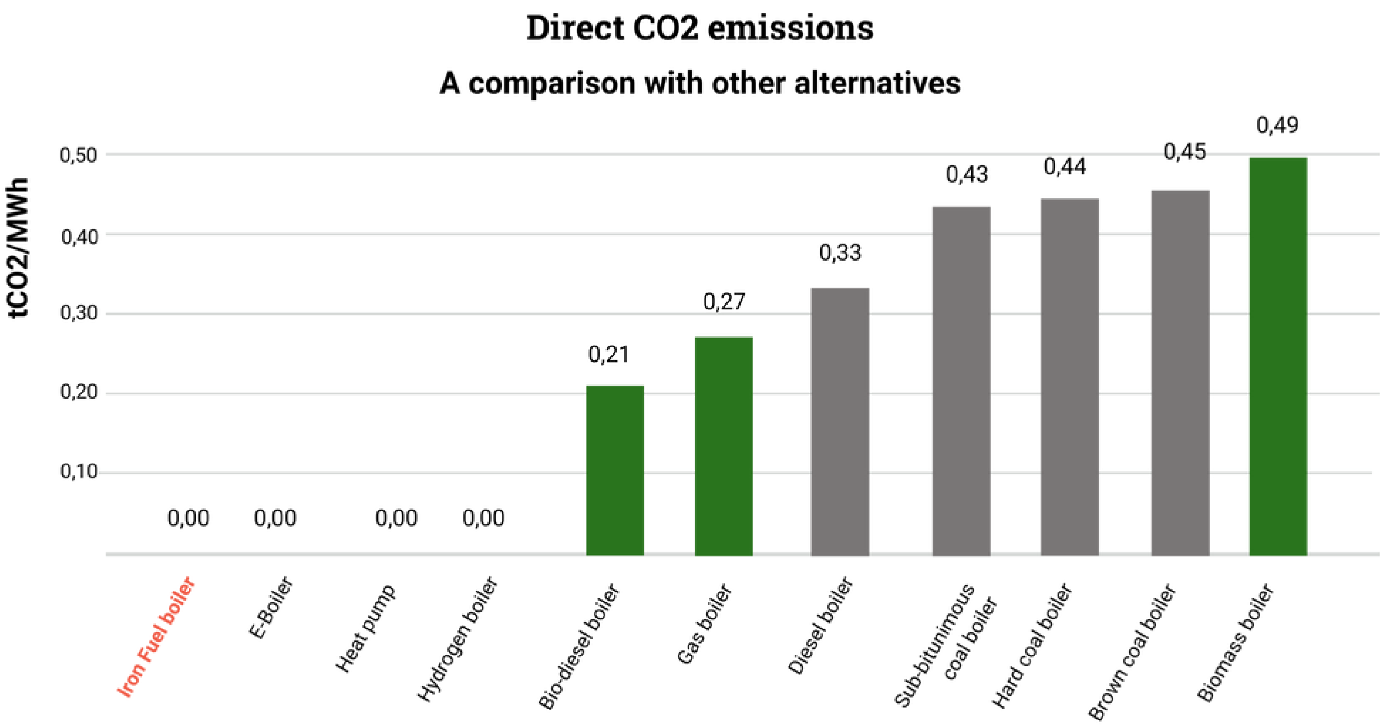
Note: All prices shown are stationary prices, indicating comparable feedstock prices for each alternative. In practice, trade between geographical locations will occur over time and distance, potentially resulting in price differences.

Price Sensitivities

Iron Fuel Technology™ has the potential to become even more economically appealing when economic and financial KPI's are further improved. The competitiveness of iron fuel can also increase when feedstock prices (electricity and hydrogen) become volatile. This negatively affects other clean energy technologies but benefits Iron Fuel Technology™ due to the ease of iron fuel/iron oxide storage and transport, which allows for more stable prices. Especially in the early years of the commercial implementation of Iron Fuel Technology™, prices will remain stable, as limited iron fuel production plants will have supply contracts with multiple boiler plants.

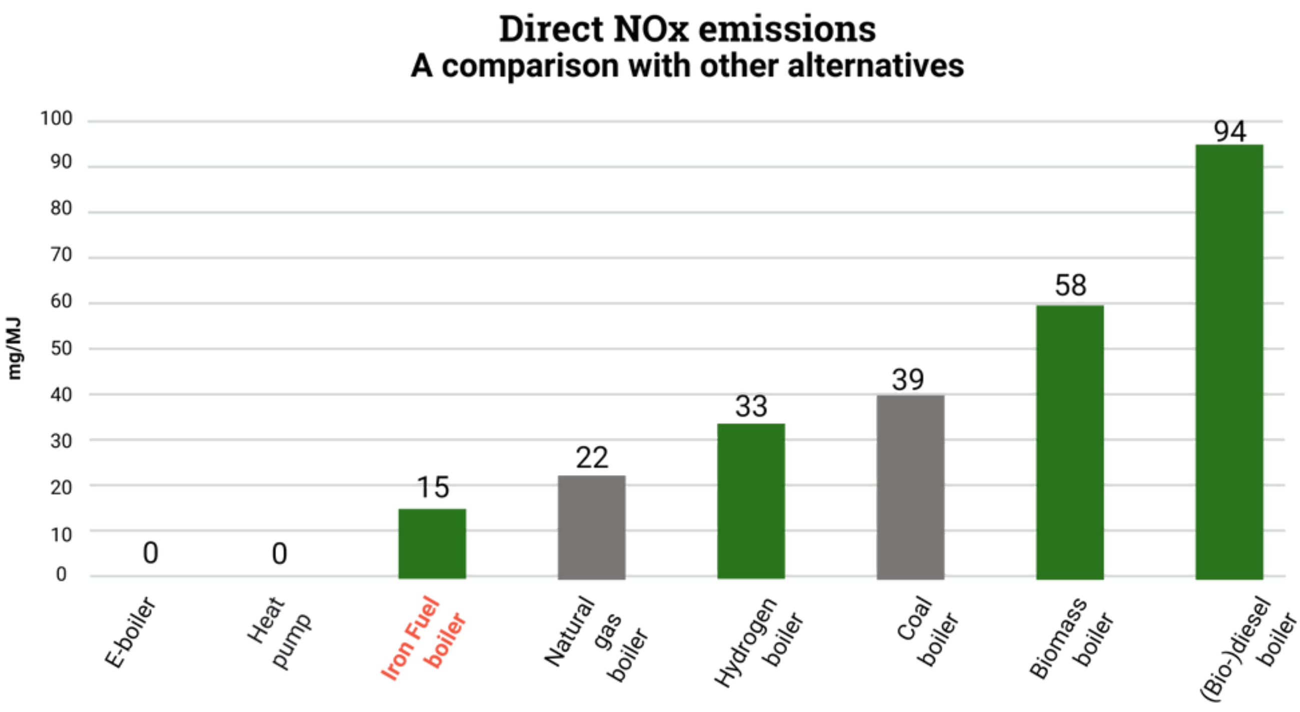
Direct Emissions

No direct CO_2 is emitted during the combustion of iron fuel due to the absence of carbon atoms in the iron fuel. This also holds true for hydrogen and electrification. Adjusting the emission factors to account for thermal boiler efficiency, replacing natural gas boilers with iron fuel boilers would prevent 0.27 ton CO_2/MWhth in comparison to natural gas, 0.33 ton CO_2/MWhth in comparison to diesel, 0.44-0.45 ton CO_2/MWhth in comparison to coal and 0.49 ton CO_2/MWhth in comparison to biomass. Due to the lack of CO_2 emissions in Iron Fuel Technology™, industrial heat companies can either sell their carbon rights or reduce the costs associated with carbon rights compared to fossil fuels.



Iron fuel combustion has the lowest NOx emissions of any combustible fuel with ambient air, with levels below 15 mg/MJ. In comparison, natural gas emits 22 mg/MJ, hydrogen releases over 33 mg/MJ, coal produces 39 mg/MJ NOx, biomass emits 58 mg/MJ, and (bio)diesel contributes 94 mg/MJ (Activiteitenbesluit Milieu, 2023). Iron fuel boiler systems can play a role in reducing NOx emissions, preventing approximately 0.03, 0.07, 0.09, 0.16, and 0.29 kg of NOx per MWh (RIFT, Internal data) compared to natural gas, hydrogen, coal, biomass, and (bio)diesel, respectively. Given the potential variation of NOx emissions across the operating range, it's important to consider emissions throughout the entire operational curve. Iron fuel boilers exhibit the most consistent NOx emissions across this range, surpassing other alternatives, which further enhances their NOx reduction capabilities (RIFT, Internal data).

The lower NOx emissions of Iron Fuel Technology™ are partly explainable by the absence of hydrogen atoms in the fuel. In carbon-hydrogen based fuels and hydrogen-based fuels, the hydrogen atoms form radicals during combustion. These hydrogen radicals act as a catalyst between nitrogen and oxygen at high temperatures (as is the case at combustion temperatures) which accelerate the creation of NOx emissions. NOx emissions are detrimental for the environment as they are a key emission contributor to climate change as well as other environmental impacts including acidification, and terrestrial and marine eutrophication among others (Botter, 2023). The low NOx emissions of Iron Fuel Technology™ therefore provide an environmental advantage over other alternatives. It also ensures that Iron Fuel Technology™ is likely to fit even the strictest permit standards which other alternatives have more difficulty meeting. For companies that have limited NOx permit allowances, Iron Fuel Technology™ can therefore be a great choice. The implementation of Iron Fuel Technology™ might even create additional operating space allowing these companies to expand production processes (conform the permit) creating extra revenue for them.

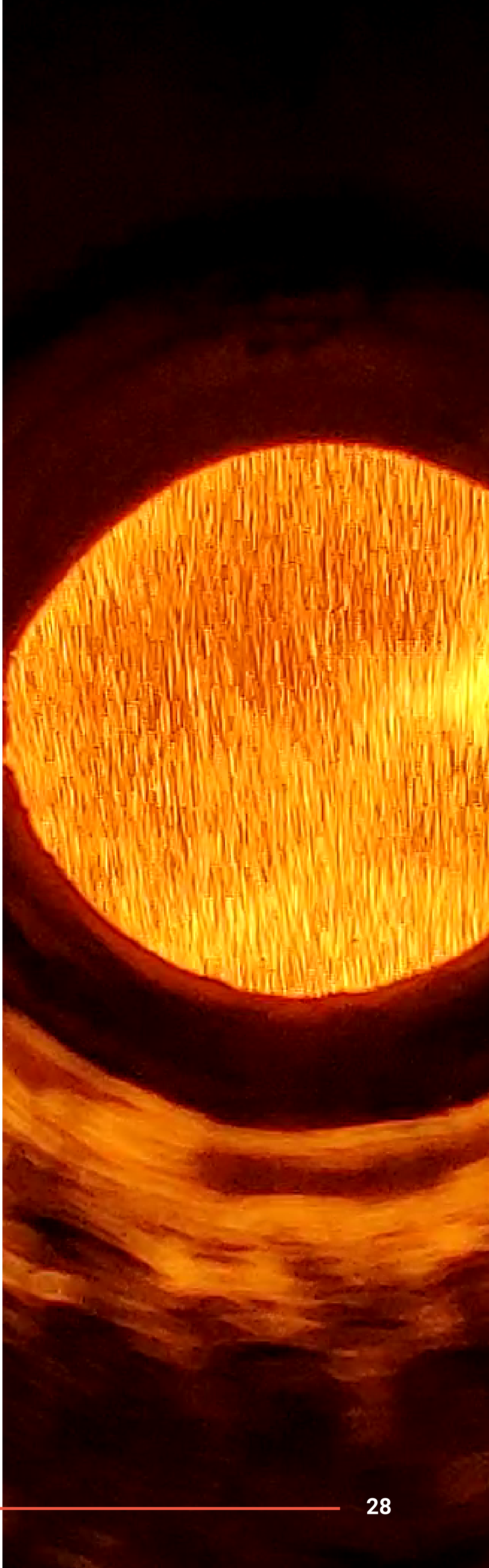


As iron oxide particles are created during combustion, Iron Fuel Technology™ produces particulate matter (PM) emissions. Excessive PM emissions can pose risks to human health and the environment (EPA, 2023; Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, n.d.). Therefore, it is imperative that PM emissions remain within permissibable limits, in accordance with established regulations designed to mitigate exposure to harmful levels of particulate matter (Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat, n.d.).

The PM emissions associated with Iron Fuel Technology™ fall below the required permit thresholds, ensuring compliance with regulatory standards. For those seeking even further reduction of PM emissions beyond the prescribed standards, additional filtration technologies are available, although their implementation may entail added costs.

Safety

Iron fuel is non-corrosive, non-toxic, non-carcinogenic, environmentally benign, non-irritating, and non-mutagenic, ensuring safe operations at the boiler plant. As a result, the on-site storage, logistics, and boiler systems have limited safety risks. The high safety profile of iron fuel boiler plants allows for their proximity to residual areas, distinguishing Iron Fuel Technology™ from other energy carriers like hydrogen, which may present more significant safety concerns.



Iron Fuel Production

The iron fuel production process converts rust (iron oxide) into iron fuel by using a hydrogen source. The production plant will, therefore, be located close to the hydrogen source. This hydrogen can be by-product, geological (white), blue, green or any other types of low emission hydrogen. The iron fuel production system can produce capacities of 1 to 1,000 ton iron fuel per hour and can operate up to 8,600 FLH per year. While the iron fuel production process is a novel process, it makes use of existing available components and complies with the current legal standards, ensuring reliability, scalability and faster product development.

The Production Plant

Rust from the iron fuel boiler plant is transported to the iron fuel production plant via truck, train or ship. Upon arrival, the rust is unloaded by bulk-solid unloading systems and then transferred to a bulk silo for storage. On-site bulk-solid transport equipment is employed to transport it to a feeder. The feeder system continuously supplies the rust into the reactor. Within the reactor, the rust undergoes a conversion process into iron fuel by using a hydrogen source, which is heated by either an electric heater or another type of heater. This transformation is represented by the following endothermic reaction:

$Fe2O3 + 3H_2 \rightarrow 2Fe + 3H_2O$

Production capacity
1-1000 t/h

Energy efficiency
up to **85%**

Hydrogen required
(for one ton IF)
53.6 kgH_2/tIF

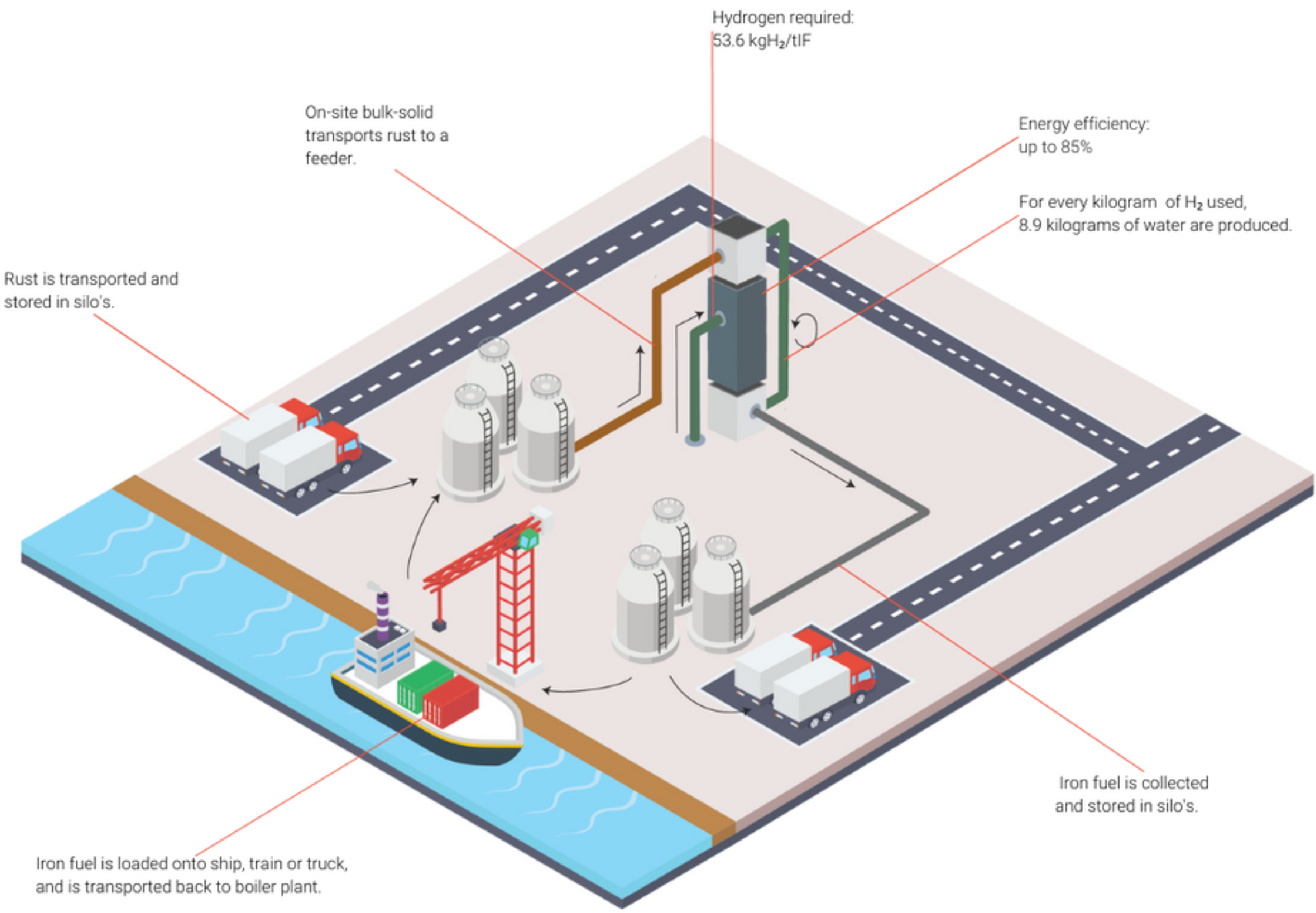
Hydrogen required
(for one MWhth)
27.75 $kgH_2/MWhth$

Amount of electricity
305-620 kWh/tIF

Water produced
0.456 tH_2O/tIF
8.9 $kgH_2O/kg\ H_2$ used

The hydrogen source can be geological (white), by-product hydrogen, blue hydrogen, green hydrogen or any other low emission type of hydrogen, as detailed further in Chapter 7. After the reaction has taken place, the iron fuel is collected and transported towards a bulk storage silo of iron fuel. Subsequently, it is loaded into a truck, train or ship and transported towards the iron fuel boiler plant, where it can be combusted once again.

Iron fuel production plants will be strategically located at or near a hydrogen source as this is economically most appealing. The iron fuel boiler system, on the other hand, will be positioned at the location where the industrial heat is required, meaning that the iron fuel production location will likely be at a different location than the iron fuel boiler system.



Operations

The iron fuel production system is capable of producing iron fuel within a range of 1 to 1000 ton per hour, with an energy efficiency of up to 85%. For each ton of iron fuel produced, 53.6 kg of hydrogen is required. This translates to an input of 27.75 kg H_2 for each thermic MWh of heat produced at the boiler. Each production system is designed to last at least 15-30 years and can be operated 8,600 FLH per year, requiring only 160 hours of annual maintenance. The iron fuel production system operates optimally and cost-effectively as a baseload system, although it can also be adjusted to variable capacities if needed. This flexibility is made possible due to the modular nature of the systems.

System lifespan
15-30 years

Operation hours
8,600 hours annually

Maintenance requirement
160 hrs annually

Additionally, the production system must maintain a specific temperature to efficiently produce iron fuel, which can be achieved using either an electric or natural gas heater. While an electric heater powered by green electricity is a more environmentally sustainable option, both alternatives are feasible from both cost and environmental perspectives.

Space Requirements

A system with a production capacity of 10 ton per hour is expected to fit within a 15x15x15-meter construction. When compared to other industrial processes, this is relatively small. This compactness is further enhanced by the fact that both rust and iron fuel are inherently space-efficient, requiring minimal storage space.

For instance, a standard storage silo with a diameter of 3.6 meters and a height of 12 meters can store a substantial amount of iron fuel, holding up to 122 MWhth. The same silo filled with iron oxide can hold up to 77 MWhth equivalent. Given the small amount of space required for the storage of both iron fuel and iron oxide and considering the cost-effectiveness of storage (as discussed in Chapter 8), an iron fuel production plant may opt for a continuous base load production approach, even when the demand for iron fuel from boiler locations experiences fluctuations.

Supply Reliability

The iron fuel production plant has established delivery contracts with the iron fuel boiler systems to secure its iron oxide supply over extended periods. In the event of any shortage, the plant also has the option to purchase iron oxide from existing markets at a rate of €400 per ton for large quantities, based on quotations from various suppliers. These flexible acquisition methods enable iron fuel production plants to maintain consistent production, ensuring optimal operations and competitive pricing of iron fuel.

Implementation

To physically implement an iron fuel production system, the silos, on-site logistical systems and production unit operations need to be installed at the production system's location. Except for the production system itself, all storage and bulk-solid handling equipment to transport and store iron fuel and iron oxide on-site are mature, available technologies which can be supplied by multiple suppliers. Although the process design of the iron fuel production plant and reactor design is novel, all unit operations, components and other equipment are also available, mature technologies which can be built, supplied and maintained by many parties over the world. Hence, no new or rare materials are used in all the required equipment. The use of standard mature technologies ensures the use of components and equipment that is certified and operates within legal standards. It also ensures reliability, scalability and faster product development as well asperformance guarantees by suppliers.

Current Status

In September 2022, the iron fuel production technology was proven by RIFT through an industrial prototype of a 10 kWth production system located at Energy Demo Field in Arnhem, the Netherlands. In December 2023 RIFT will finish the first industrial pilot of 50-100 kWth. The first commercial production system projects will start in 2024. It is expected that this technology is fully ready in 2027 for roll-out at large scale.

Investment

The investment of the iron fuel production plant is estimated to be €2.4-€2.7 million per ton iron fuel capacity. This is equivalent to an investment of €1.2-€1.4 million per MWth including all unit operations, on- site logistics and storage.

€2.4-€2.7 million
per ton
Iron Fuel capacity

€1.2-€1.4 million
per MWth

Cost of Produced Iron Fuel

The cost of the produced iron fuel is highly location and case dependent. The local hydrogen price, electricity price, O&M costs, transport distance and other key financial metrics make up the production cost of the iron fuel. Analysis shows that multiple cases spanning various geographical locations can be made economically appealing.

Direct Emissions

The production process of iron fuel results in limited direct emissions, mainly consisting of water and a nitrogen-containing medium (when electric heating is employed). The produced water can be recycled on-site, such as in a hydrogen electrolyzer, offering a solution to the water drainage challenges associated with electrolyzers – a beneficial side effect.

However, the iron fuel production process requires specific temperatures, necessitating heating using either an electric or natural gas heater. When a natural gas heater is used, direct carbon dioxide emissions associated with the use of natural gas occur, totaling 55kg CO_2/GJ of natural gas. In contrast, using electricity to heat the reactor (300-450 kWh/t IF) results in significantly lower indirect emissions (9-13 kgCO_2/GJ for the industrial heat at the iron fuel boiler). From an environmental perspective, the use of an electric heater is more environmentally favorable than a natural gas heater.

Safety

The iron fuel production system meets the standards for operability within normal industrial areas. Within the reactor of an iron fuel production system, hydrogen reacts with iron oxide to produce iron fuel at higher temperature and pressure conditions than the surrounding ambient conditions. As a result, the production system is designed to meet the highest safety standards and personnel is trained to guarantee safety of the environment and the individuals involved.

Hydrogen Sourcing

To produce iron fuel in a circular manner, hydrogen is a crucial component. Given the relatively low requirements from technical, economic, and environmental perspectives, various types of hydrogen, such as geological (also known as white), by-product, blue, and green hydrogen, can be used. The current hydrogen capacity is substantial, supporting the scalability of Iron Fuel Technology™ to numerous gigawatts of installed capacity and terawatt-hours of heat production. The scaling potential is further strengthened by the ongoing increase in hydrogen production and the decrease in prices. Importantly, as iron fuel not only utilizes hydrogen but also liberates its production from grid boundary constraints, it emerges as an accelerator for the hydrogen economy.

Hydrogen Requirements

To produce iron fuel from iron oxide, the oxygen must be removed through the chemical process of reduction (deoxidation/derusting). Hydrogen serves as the reducing agent in this process to create the products iron and water. To align with the requirements of Iron Fuel Technology™, the first criterion is that the hydrogen must have a purity of >60%. This allows for the consideration of contaminated hydrogen, such as by-product or geological (white) hydrogen. Syngasses and off-gasses may also be feasible. Additionally, the hydrogen needs to have pressure higher than 1 bar. Finally, to ensure positive life cycle impact of Iron Fuel Technology™, the indirect emissions should be lower than <7 kg CO_2/kgH_2. These criteria are relatively low compared to the current industrial standard. The minimal hydrogen requirements make various types of hydrogen feasible and open up the possibility of achieving lower hydrogen priceds, thereby strengthening the competitive edge of Iron Fuel Technology™.

H_2 purity
>60%

Pressure
>1 barg

Life cycle requirement
<7 kg CO_2/kgH_2

The Quantity Required

To produce 1 MWhth in an iron fuel boiler 27.75 kg of hydrogen is required, equivalent to 53.57 kg H_2/t iron fuel produced. For example, a 10 MW boiler system running 6,000 FLH annually (60,000 MWh) requires 1,665 tons of hydrogen per year. To ensure sufficient hydrogen supply at the start of commercialization, RIFT focusses on 10-15 -year supply contracts representing 17-250 kT of hydrogen, a contract value of €17-€625M.

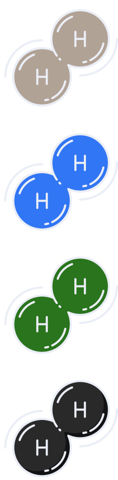
Location of Hydrogen Production

As mentioned before, the (economic) attractiveness of iron fuel production significantly increases when it is situated in proximity to the hydrogen source. This strategic placement optimizes the process, as iron oxide is transported to the hydrogen source, and the resulting iron fuel is conveyed to locations where heat is in demand. In this sense, iron fuel can be seen as a long-duration energy carrier for hydrogen. Iron Fuel Technology™ expands opportunities for hydrogen projects that were previously hindered by logistical constraints, thereby accelerating the growth of the hydrogen economy. This included unlocking geological hydrogen at well locations where no pipeline network exists, as well as in areas with hydrogen overcapacity but limited pipeline networks.

Furthermore, hydrogen production in combination with Iron Fuel Technology™ opens doors to locations that were previously unsuitable due to water drainage limitations. One of the by-products of the iron fuel production process is water, which can be redirected to supply an electrolyzer for hydrogen production. The quantity of water produced as by-product from the iron fuel production process is sufficient to cut the water usage of electrolyzers by 70-95% (Ramirez et.al., 2023). This increases the potential locations for hydrogen production on a global scale.

Types of Usable Hydrogen

Given the relatively low hydrogen requirements, many hydrogen types are suitable for the iron fuel production process. These include geological (white), blue, green hydrogen, as well as other forms like by-product hydrogen. As lower percentages of purified hydrogen can be used, contaminated hydrogen like geological and by-product hydrogen do not pose any issue. Additionally, green syngas, which may contain impurities, can also be used without any adverse effects.



From a technical perspective, all hydrogen streams are feasible for use. Environmentally, geological and by-product hydrogen stand as the most preferable options. Nevertheless, the ultimate choice for the ideal hydrogen stream hinges on a combination of factors, including adherences to technical requirements, cost-effectiveness, price stability, and supply reliability.

By-Product Hydrogen

Globally, there are multiple outlets for by-product hydrogen, which is generated as a by-product in various chemical processes. This market has an approximate size of 14.8 Mton H_2/year (International Energy Agency, n.d.). Presently, a significant portion of this by-product hydrogen, ranging from 20-50%, is flared as there are limited practical applications for this by-product stream (Lee & Elgowainy, 2018). By-product hydrogen is usually contaminated, which does not allow it to be used as a feedstock for producing ammonia or methanol, the two largest hydrogen consumers currently, as the contaminations will have a significant impact on the quality of the ammonia. Additionally, the removal of these contaminants is not a cost-effective process (RIFT, Internal data). Furthermore, direct use of this hydrogen as a fuel is not feasible due to several reasons: (i) there is often no energy demand for its use as fuel, (ii) burning it as a fuel would exceed the nitrogen oxide permit allowances, and (iii) transportation via pipeline networks, trucks or ships is too costly and not economically competitive for the end user (RIFT, Internal data). This market is anticipated to remain stable as long as the production processes that generate by-product hydrogen continue to operate without alternative applications. This stability provides an excellent opportunity for utilizing this stream for Iron Fuel Technology™.

The size of this market is sufficient for a production of 282 Mt IF/year, 533 TWhth or 89 GW installed capacity of iron fuel systems and therefore preventing 144 Mt CO_2/year (RIFT, Internal data). Moreover, the elimination of hydrogen flaring, which is practiced in some instances, can also mitigate nitrogen oxide emissions. These emissions, totaling 34 kilotons of NOx per year (Activiteitenbesluit Milieu, 2023), can be significantly reduced when the by-product hydrogen is utilized for Iron Fuel Technology™. Because of the limited uses of by-product hydrogen, it also stimulates synergies and contributes to the transition towards a circular economy.

Market size	Iron Fuel production capacity	Installed capacity	CO_2 prevention
14.8 Mton/year	**533 TWhth/year**	**89 GW**	**144 Mt CO_2/year**

Geological (White) Hydrogen

Geological, also known as white or sometimes referred to as gold hydrogen, is a term associated with hydrogen derived from underground geological structures, where it is naturally produced (Day, 2023). This renewable source of hydrogen can be extracted from the earth, with estimates suggesting an annual extraction potential of up to 100 million tonnes of hydrogen (Vujasin, 2023). Several startups, including Koloma, NH_2E and Hydroma, are in the race to explore, extract and produce geological hydrogen (Day, 2023). While numerous geographical locations with exploitable white hydrogen deposits have been identified, no company has yet initiated hydrogen extraction from these sources. Unleashing the full potential ensures a market size of 3600 TWh/year, enough to install 604 GW of installations.

It is expected that geological hydrogen production will cost €0.5-€0.75 per kilogram (Hogenkamp, 2023), rendering it an economical option, even in comparison to current grey hydrogen prices (1-2€/kg)(European Commission, 2020; PwC, n.d.). As an inexpensive hydrogen stream, geological hydrogen can be a great stream for the purpose of Iron Fuel Technology™. However, these deposits are frequently located in challenging or remote areas, such as mountainous or isolated regions. In such scenarios, ensuring the safe and cost-effective storage and transportation of usable hydrogen becomes a critical aspect for unlocking its full potential. Moreover, as geological hydrogen is inherently contaminated, it aligns better with the requirements of iron fuel technology compared to alternative uses. This compatibility presents the potential for multiple synergies, a topic explored in more detail in Chapters 8 and 9

Expected market size	Exp. Iron Fuel production capacity	Exp. installed capacity	Expected price
>100 Mton/year	3600 TWh/year	604 GW	€0.50-€0.75 p/kg

Blue Hydrogen

Blue hydrogen is another viable feedstock for the iron fuel production process. In theory, every currently operating grey hydrogen plant can be modified into a blue hydrogen production location. Projections for the blue hydrogen market indicate that it could reach 7-10 million tons by 2030 if all current projects in development are realized (IEA, 2021). Looking ahead to 2050, global blue hydrogen production is expected to grow to 37.5 million tons of H_2 (IEA, 2021). Our calculations suggest that this would be sufficient for 360 TWh in 2030, and 1350 TWh in 2050 (60GW and 225 GW installed capacity of iron fuel systems in 2030 and 2050 respectively).

Blue hydrogen prices are expected to decrease from approximately 2€/kg today to 1.5€/kg by 2030 (Heid, Sator, Waardenburg & Wilthaner, 2022; European Commission, 2020), which according to our calculations translates into an Iron Fuel Technology™ price difference of 13-15 €/MWh. Blue hydrogen has a CO_2 footprint of 1.7-8.5 kg CO_2-eq / kg H_2 (Moberg & Bartlett, 2022). Although some blue hydrogen production is expected to exceed the 7 kg CO_2-eq / kg H_2 requirement, most of it will be under this limited ensuring the potential use of it.

	Expected market size	Expexted Iron Fuel production capacity	Expected installed capacity	Expected price
2030	**7-10 Mton/year**	**360 TWh/year**	**60 GW**	**€1.50/kg**
2050	**37.5 Mton/year**	**1350 TWh/year**	**225 GW**	

Green Hydrogen

Currently, dedicated green hydrogen is still limited to demonstration projects (IRENA, n.d.). However, expectations are high for green hydrogen production to surge, with anticipated volumes of 8-25 million tons by 2030 (IEA, 2022; IEA, 2021; Hydrogen Council & McKinsey 2023) and 128 million tons by 2050 (IEA, 2021). Our calculations indicate that this increase could translate into a sufficient supply for scaling up to 900 TWh (150 GW installed capacity of iron fuel systems) by 2030 and 4600 TWh (767GW installed capacity of iron fuel systems) in 2050.

Depending on specific geographical locations, green hydrogen prices are projected to decrease from €2.5 to €5/kg today to €1 to €2/kg in 2050 (PWC, n.d.; (Heid, Sator, Waardenburg & Wilthaner, 2022; European Commission, 2020). Notably, green hydrogen has a limited environmental impact, with emissions of less than 1 kg CO_2-equivalent per kg H_2 (GH_2, 2022; Van Dorsten & De la Cruz, n.d.). The utilization of green hydrogen in the context of Iron Fuel Technology™ has the potential to significantly enhance the CO_2 reduction capabilities of industries that rely on heat. Furthermore, with no grid location restrictions and the potential for water reuse, it may accelerate the initiation or expansion of green hydrogen projects.

	Expected market size	Expexted Iron Fuel production capacity	Expected installed capacity	Expected price
2030	**8-25 Mton/year**	**900 TWh/year**	**150 GW**	
2050	**128 Mton/year**	**4600 TWh/year**	**767 GW**	**€1-€2/kg**

Upscaling

With the projected market sizes, prices, and environmental footprints for each examined hydrogen stream, it is anticipated that the availability of hydrogen will not pose a barrier to the upscaling potentital of Iron Fuel Technology™. Given the versatility of Iron Fuel Technology™, which allows for the use of various hydrogen types and the creation of unique synergies, it exibits a distinctive scaling potential with adaptable routes.

Alternatives to Using Hydrogen for Production of Iron Fuel

As previously mentioned, the production of iron fuel from iron oxide requires the removal of oxygen through a chemical reduction process, with hydrogen serving as the primary reducing agent. However, there is an alternative approach involving electrochemical methods, where iron oxide is reduced of its oxygen using (renewable) electricity directly. While this process has been investigated over the years, it has not been implemented due to various techno-economic constraints (Hempenius, 2021). Therefore, at present, hydrogen remains the most viable and efficient reducing agent for the iron fuel production process.

Iron Fuel Technology vs. Direct Combustion of Hydrogen

Many people naturally question the choice of using hydrogen and not opting for its direct utilization. There are three key reasons why the conversion of hydrogen energy into iron fuel presents a superior approach compared to its direct combustion, such as burning hydrogen.

1

Firstly, opting for direct use of hydrogen requires a direct connection between the source and the end-user, a connection that is currently realized only in a fraction of cases. Even with committed infrastructure investments, an estimated 60% of locations will remain unconnected. Iron Fuel Technology™, however, overcomes this limitation by unlocking these locations for decarbonization. Moreover, it facilitates the connection of hydrogen production sites to end-users by transforming hydrogen into iron fuel, capitalizing on distinct advantages in terms of transport and storage.

2

Secondly, the direct combustion of hydrogen leads to elevated NOx emissions that surpass existing permit limits, thereby delaying or restricting its potential implementation for industrial heat applications.

3

Thirdly, the quantity of hydrogen required for direct combustion (34.26 kg H_2/MWhth) exceeds the amount needed for iron fuel production (27.75 kg H_2/MWth). This discrepancy stems from the highly efficient transfer of all hydrogen-contained energy to the iron fuel during the production process, coupled with the high energy efficiency of the iron fuel boiler. In contrast, direct combustion results in larger energy losses. This unlocks an energy potential that would otherwise be emitted. From an energy-to-hydrogen efficiency standpoint, direct hydrogen utilization proves less efficient than the application of Iron Fuel Technology™. By consuming less hydrogen, Iron Fuel Technology™ ensures more than a 23% increase in resource efficiency, thereby maximizing decarbonization potential, positively influencing prices, and indirectly impacting the environment.

Iron Fuel Technology™ Storage

Iron Fuel Technology™ excels in storage due to its inherent safety, compactness, and compatibility with existing methods. This cost-competitive solution requires no extra energy for storage or discharge. Iron Fuel Technology™ boasts minimal energy losses, making it ideal for seasonal storage, while its compactness outperforms other clean energy technologies. The safety of iron fuel and oxide allows for storage near residential areas with standard equipment, resulting in low costs and straightforward permitting. Independent studies consistently confirm its economic competitiveness, and compliance with operational standards simplifies implementation.

High Energy Efficiency

During the storage of iron fuel, no extra energy input is required to store or discharge the iron fuel or iron oxide. Other alternatives, like hydrogen, require energy to be stored effectively (Monterey Gardiner, 2009). Moreover, there are almost no energy losses of the iron fuel during storage (the so-called boil-off losses). Tests demonstrated an energy efficiency of >99.9%, meaning a maximum loss of 0.01% per 60 days. Comparing this to hydrogen storage, where approximately 10% or 30% of the energy is lost to store it at 350 bar and liquid form respectively (Monterey Gardiner, 2009), Iron Fuel Technology™ is much better suited for energy storage. This makes Iron Fuel Technology™ especially suitable for seasonal storage, while also ensuring low operational costs due to the lack of energy input required.

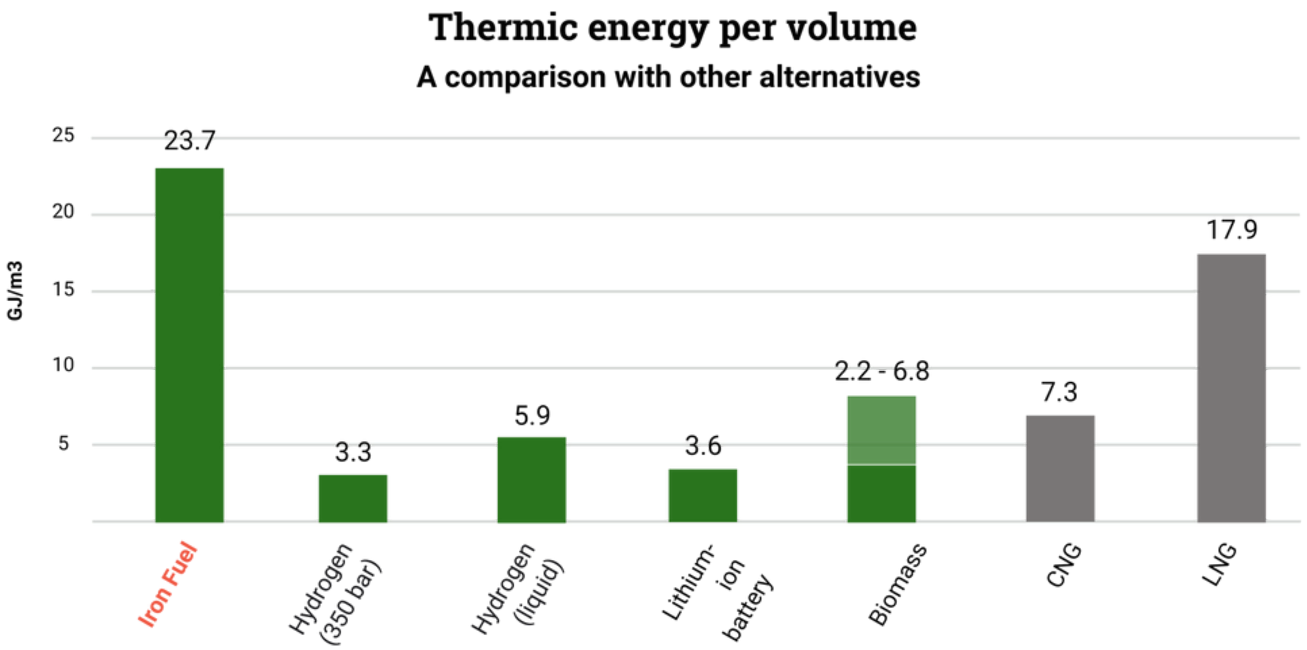
Energy efficiency
>99.9%

Compactness advantage
23.7 GJ/m3

Storage space efficiency
0.14 m3/MWh

Thermic Storage Space

Iron fuel is compact, meaning it has a lot of thermic energy per volume (23.7 GJ/m3, 6.6 MWh/m3). It is the most compact clean energy technology in comparison to compressed hydrogen 350 bar (3.3 GJ/m3, 0.9 MWh/m3), liquid hydrogen (5.9 GJ/m3, 1.6 MWh/m3), lithium-ion battery (3.6 GJ/m3, 1 MWh/m3), biomass (2.2-6.8 GJ/m3, 0.6-1.9 MWh/m3), CNG (7.3 GJ/m3, 2 MWh/m3), and LNG (17.9 GJ/m3, 5 MWh/m3). As a result, Iron Fuel Technology™ requires the smallest space footprint for storing energy (0.14 m3/MWh) (Fuels – Higher and Lower Calorific Values, n.d.). According to calculations, 6.6 MWh can be stored in a 1 m3 iron fuel storage tank. For the same amount of energy, a battery, biomass or hydrogen storage requires approximately 6.6, 3.5-10.5 and 4-7.5 times more space respectively. As a result of the compactness of Iron Fuel Technology™, less space is required on plant locations and smaller storage tanks can be used. This can decrease the storage costs significantly. Moreover, it allows Iron Fuel Technology™ to be applied in situations where limited space is available, such as in dense urban areas.



Safety

Iron fuel and iron oxide are completely safe when stored in a silo at atmospheric conditions. It is not harmful for the environment nor for human health. As a result, in contrast to other energy carriers, limited safety measures are required and the permit efforts are low. Standard storage equipment can therefore also be used, hence decreasing costs. The high safety of Iron Fuel Technology™ also allows for storage close to residential areas.

Use of Existing Storage Technologies

The characteristics of iron fuel and iron oxide allow for storage in a standard steel silo with loading and discharging through standard pneumatic or mechanical equipment. For extra safety and improved energy efficiency over time, companies can choose to add a standard dry-air installation. All equipment used for the storage is mature and can be supplied by many parties around the world. As the equipment is standard, suppliers are comfortable with performance guarantees.

This is beneficial for the adoption of Iron Fuel Technology™ as other developing technologies may carry more risks and problems with storage. The usage of standard equipment results in low costs of storage. Furthermore, the available storage equipment can be scaled easily allowing for faster implementation of Iron Fuel Technology™ in comparison to other technologies.

Storage Costs

Several independent studies have been conducted to assess the feasibility of storing energy and hydrogen using iron fuel. These studies include comparisons with alternative storage methods, such as hydrogen storage, electricity storage, and other hydrogen carriers like ammonia, methanol, and LOHC. The results of these studies consistently demonstrate the economic competitiveness of iron fuel as a storage solution.

For more detailed information or access to these studies, please feel free to contact us.

Legal Standards & Permits

All components necessary for storing iron fuel and iron oxide comply with legal operational standards. Additionally, there are no anticipated issues with obtaining permits, as iron fuel and rust are derivatives of existing markets that already adhere to established legal and permitting procedures.

Iron Fuel Technology™ Transport

Iron Fuel Technology™ is a cost-effective energy carrier for transportation. Its compactness, safety, and high energy efficiency make it a practical choice for various transport methods, including road, rail, and waterways. This negates the need for significant infrastructure investments, making it an attractive option. For both short and long distances, the environmental impacts are relatively limited and present no obstruction to the development of Iron Fuel Technology™. Furthermore, the safe nature of iron fuel and iron oxide and the existing available transport means no regulation must be defined and no legal hurdles must be overcome.

Use of Existing Methods of Transport

Iron fuel and iron oxide can make use of mature transport methods already present on a large scale and used in similar markets. Transport services are offered by many providers that are familiar with similar types of transport.

No product development is needed for transporting iron fuel and iron oxide, but further optimization is possible for the purpose of Iron Fuel Technology™.

To supply iron fuel and iron oxide to the location where it is needed, transportation can be done by road, rail, or waterway. As it is a solid material, pipeline transport is only an option for on-site transport. All equipment needed to transport, load and unload the iron fuel and iron oxide is mature technology which can be delivered by many suppliers.

Safety

Iron fuel and iron oxide are non-corrosive, non-toxic, and pose no environmental or health hazards, making them safe for transport by truck, train, and ship. Also, their low flammability and non-explosive nature add to the safety of transportation. As a result, the transportation costs are relatively low, especially when compared to less-safe alternatives. Some of those alternatives cannot even be transported via truck, train or ship due to safety concerns or are strictly limited in their transport quantities as a result.

Transport Infrastructure Investment

Iron fuel transportation can utilize existing road, rail, and waterway networks. This eliminates the need for major infrastructure investments, unlike technologies like hydrogen and electricity, potentially saving government funding for other purposes.

Regulation

Iron fuel is a derivate of the iron powder market. As a result, there are global legal standards to transport iron fuel by truck, train or ship. In contrast to many novel energy technologies, like hydrogen, no regulation must be defined and no legal hurdles have to be overcome allowing for faster upscaling.

Transport by Road

Transport of solids, like iron fuel and iron oxide, can be done in bulk solid trucks, a mature technology employed worldwide.There are multiple types of trucks on the market that can transport solid bulk and many providers are able to do so. The road transport providers foresee no difficulty in transporting iron fuel and iron oxide. They also claim that iron fuel and iron oxide can be transported in the same truck or with use of standard cargo containers. Logistic optimization is then possible and the number of empty trucks can be decreased to a minimum.

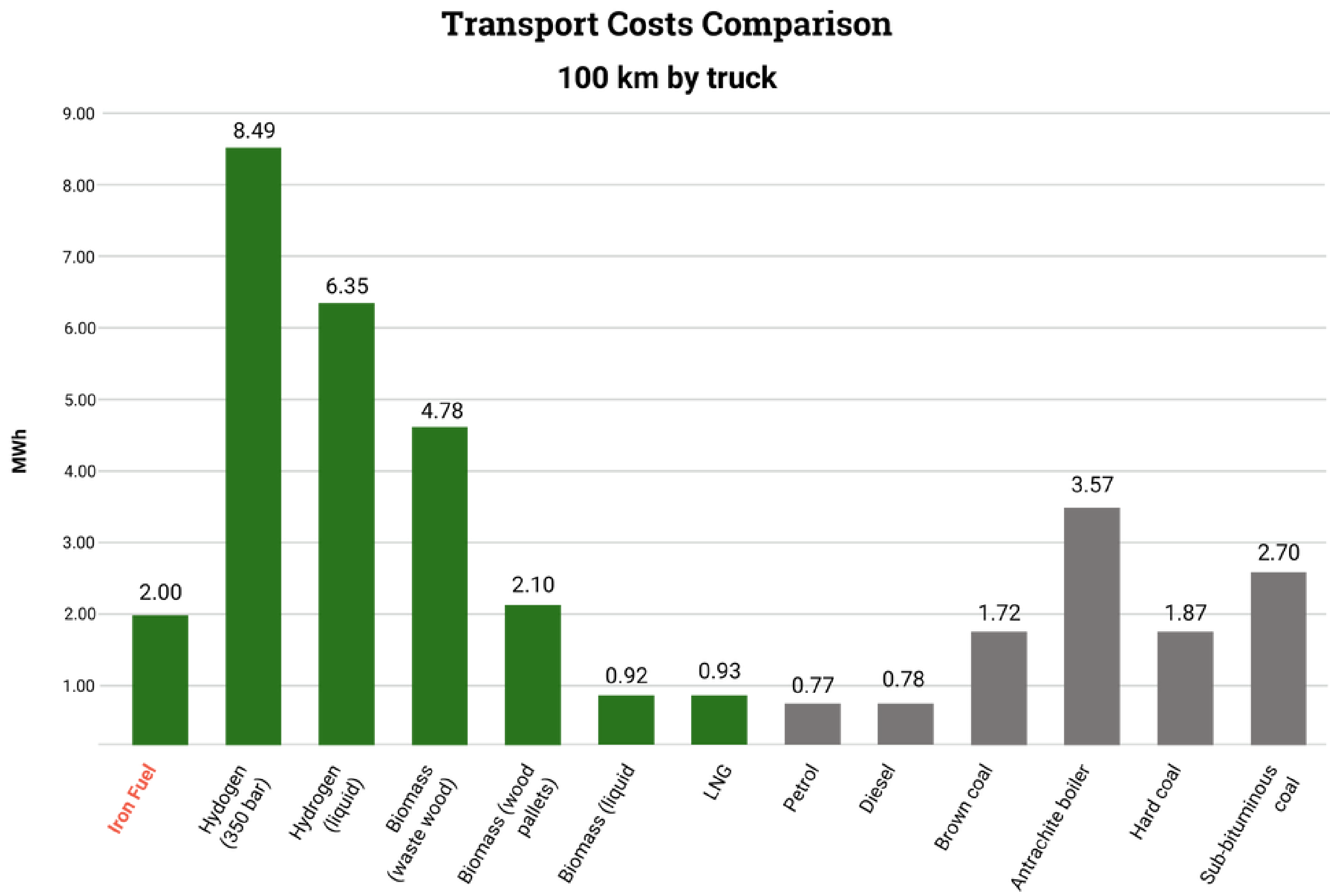
The amount of iron fuel a truck can carry is limited by the maximum weight of road transport. In the European Union (Directive 96/53/EC), this is 40 tons (Žnidarič, 2015). As a result, the load limit is approximately 25 tons (48 MWhth) (Žnidarič, 2015). A 1 MWth system can operate 69 hours or 137 hours on one truck load when operated at 6,000 or 3,000 FLH per year respectively (RIFT, Internal data). Larger iron fuel boiler plants will require a more frequent supply. According to internal calculations, a 15 MWth plant will need 0.5-7.5 trucks a day (depending on the number of operating hours per day). Whether road transport is operationally feasible depends largely on the number of trucks permitted to drive to the plant. Potential customers claim that the number of transport movements are within the given permits (10 times a day) for capacities until 20 MWth running at 8,000 FLH per year (RIFT, Internal data). If higher capacity systems are installed, these systems must operate at fewer hours or find alternative transport methods.

Operation duration
1 load equals
1 MWth for 137 hrs
(based on 3,000 FLH)

Cost of transport
€0.02-€0.08
MWhth/km

Load limit
25 tons
48 MWhth

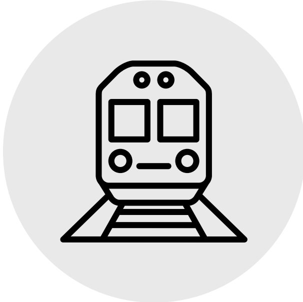
The costs of road transport vary between 0.02-0.08 €/MWhth per km depending on the distance and provider (Van der Meulen et.al., 2023). A distance of 150 km (+3-12.5 €/MWhth on cost price) is therefore economically feasible, but distances could also be higher or lower depending on the specific user case. In comparison with other sustainable alternatives, the transport costs of Iron Fuel Technology™ are economically more appealing. To exemplify, a truck carrying hydrogen at 200bar will be 3-4 times more expensive (0.07-0.30 €/MWhth). Current fossil-based transport is slightly cheaper than iron fuel with a price range of 0.01-0.05 €/MWhth. In short, road transport is economically feasible and competitive with alternatives.



Road transport by diesel trucks has indirect CO_2 emissions which accumulate to approximately 0.04-0.08 kg CO_2/MWh*km (0.01-0.02 kgCO_2/GJ*km; dependent on the type of truck) (Lijst Emissiefactoren, 2023). A trip of 300 km will therefore cause indirect CO_2 emission of approximately 3.5-7 kgCO_2/GJ. To put this into perspective, the direct emissions of natural gas are 55 kg CO_2/GJ. Therefore, iron fuel transport by truck is also environmentally relevant.

Transport by Rail

Bulk solid transport by railway is also mature technology. In case of rail transport, the amount of iron fuel and iron oxide is limited by the maximum weight of railway transport. The maximum weight is dependent on the route and country. Costs are therefore also highly dependent on the route. Train transporters expect the price for transporting iron fuel and iron oxide to be between 0.01 and 0.04 €/MWh per km (Van der Meulen et.al., 2023). A transport distance of 500 km will thus cost 5-20 €/MWh. Therefore, train transport might be economically feasible. The indirect CO_2 emissions depend on the type of train and therefore need to be considered for each route. However, these are expected to be lower than transport by truck and thus relevant from an environmental perspective.



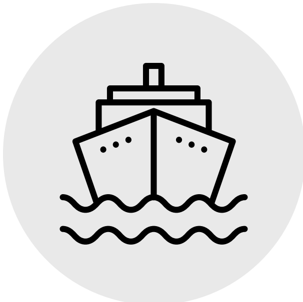
Cost of transport
€0.01 - €0.04 MWhth/km

Weight limit
Varies depending route & country

Transport by Waterways

According to our research, over 55% of energy-intensive industries are conveniently located near waterways, with larger companies (90%) having easy access to them. Transport by ship is often the cheapest, cleanest and largest supply method, making it appealing for transporting iron fuel and iron oxide. Next to this, ship transport would also be required for capacities >40 MW as the number of trucks needed would exceed most permits standards.

Inland and overseas bulk solid transport by ship is well-established and supported by numerous service providers (RIFT, Internal data). All providers claim that iron fuel and



Cost of transport
€0.001 - €0.02 MWhth/km

Cargo capacity
2,500 tons (small)
221,000 tons (large)

iron oxide can be transported in the same ship, enabling logistic optimization and minimizing empty ship transport to a minimum. One ship is also able to supply multiple locations as measurement equipment is present on the ship allowing loaded and discharged amounts to be weighed. On-site loading and unloading equipment is readily available from various suppliers and is compatible with Iron Fuel Technology™ (RIFT, Internal data).

The amount of iron fuel a ship can carry is limited by the ship's maximum weight (RIFT, Internal data) This depends on the type of ship and the (current) depth of the waterway (Kerkhoven & Terwel, 2019). Although the weight is limited, like in the case of road and railway transport, weight is of less influence on the water than on land. A small inland ship is already able to carry 2,500 tons (4,800 MWh) while a large sea ship can carry 221,000 tons (425,000 MWh) (Kerkhoven & Terwel, 2019). Both can supply many smaller or larger iron fuel boiler plants.

The cost of water transport depends heavily on the demand at that moment in time (Kerkhoven & Terwel, 2019). In general, it is the cheapest method of transportation. The price lies between 0.001-0.02 €/MWh*km for inland water transport and 0.001-0.004 €/MWh*km for sea freight (Van der Meulen et.al., 2023). The cost of heat increases by 1-20 €/MWh with a one-way inland ship (1000 km) while long distance sea transport (5,500 km) will increase the cost of heat by 5.5-22 €/MWh. Business cases will not be negatively influenced based on these transportation costs thus ship transport is economically feasible. In contrast, the low long distance transport costs give further potential for iron fuel to be used for trading as iron fuel production costs may differ per location (see Chapter 10).

If ships run on fossil fuels, CO_2 emissions occur during the transportation of iron fuel and iron oxide. Emissions range from 0.001 to 0.002 kg CO_2/GJ for sea ships and 0.006 to 0.009 kg CO_2/GJ for inland ships per kilometer traveled (Thunder Said Energy, n.d.; Statista, 2023; International Chamber of Shipping, n.d.; CE Delft, 2021). Hence, a 1,000 km inland trip and 5,500 km on sea will include CO_2 emissions of 6-9 kg CO_2/GJ and 5.5-11 kg CO_2/GJ respectively. Comparing this to the direct CO_2 emissions of the cleanest fossil fuel (natural gas at 56 kg CO_2/GJ), iron fuel and/or iron oxide transport by ship does not pose a significant environmental concern. It only becomes a consideration if ship transport exceeds 28,000 km, at which point the CO_2 impact could see an adverse increase. However, it's worth noting that the maritime industry is actively working on decarbonization, and CO_2 transport emissions are expected to decrease eventually (European Council, n.d.). Therefore, ship transport is not anticipated to impede the progress of Iron Fuel Technology™

In comparison with other technologies, Iron Fuel Technology™ transport emerges as one of the most cost-effective methods for transporting clean energy. It surpasses the costs associated with electricity transport via high voltage direct current (HVDC) cables and hydrogen transport by ship or pipelines. Moreover, it offers cost advantages over other potential hydrogen carriers, such as ammonia, formic acid, and methanol.

Iron Fuel Technology™ Trade

Iron Fuel is an ideal energy carrier for trading. Both the storage and transport of iron fuel (and especially the combination of these) will give rise to new business cases while improving the cost competitiveness of Iron Fuel Technology™. It will enable energy demands to be met regionally, nationally, and internationally ensuring clean energy price stability, equality and supply certainty.

Energy trade is crucial for maintaining a reliable and affordable energy supply. Currently, most interregional energy trade relies on interconnected grids (both electrical and gas) and the shipping of carbon-based energy carriers (such as LNG, coal, and biomass).These carbon-based energy carriers enable us to transport energy over distances as well as over time. In the case of oil, gas and coal, ground reserves are functioning as our storage over time. From a clean energy perspective, iron fuel is the ideal energy carrier for trading as it:

- is one of the most affordable clean energy carriers to store and transport;
- can be applied in cases where other clean energy technologies cannot be used (off-grid);
- is cost competitive with other clean energy technologies.

Consequently, new business cases for trading clean energy emerge, opening opportunities previously unattainable with cleaner energy sources. Iron fuel can be traded across time and distance to mitigate seasonal price fluctuations, restore energy availability, and enhance competitiveness. This will allow for a reliable and affordable clean energy supply in the future. As a result, Iron Fuel Technology™ supports economic continuity, equality and stability while preventing energy poverty.

Cost competitive
One of the most cost-effective clean energy carriers for both storage and transport

Accessible
Adaptable to various applications and regions

Clean energy supply
Facilitates clean energy trading, ensuring a reliable and affordable supply

Iron Fuel Trading over Time

Iron Fuel Technology is a perfect energy carrier to trade over time, mainly because iron fuel:

- has one of the lowest storage costs
- is cost competitive with alternatives
- can be applied in both base- and peak-load installations enabling it to balance our energy system

As a result, Iron Fuel Technology™ enables the storage of clean energy, so that it can be used at times when demand and price are higher. Many different business cases thus present itself. Two use cases for illustration:

1 **Store iron fuel to provide supplementary energy when an additional amount is required in an energy network, whether it's for electricity or heat**

As iron fuel boilers can be operated at peak-load, additional systems can be turned on when there is high demand for energy. The price competitiveness combined with the low storage costs of iron fuel ensure that it becomes a highly competitive energy source in cases where there is a sudden need for additional energy. Iron Fuel Technology™ can be especially helpful in meeting energy demands in high demand periods like winter.

2 **Store iron fuel to mitigate energy feedstock price fluctuations and/or supply risks**

Stored iron fuel can be used at a later moment when prices of feedstocks are higher or when there is limited supply available. As a result, a company can still maintain price stability and supply certainty, improving their competitive position.

In both scenarios, it is crucial that the storage cost remains lower than the price fluctuations and the expenses associated with ensuring a reliable supply. Further information on the cost competitiveness of trading can be provided upon request.

Iron Fuel Trading over Distance

Iron Fuel Technology is a perfect energy carrier to trade over distance because iron fuel:

- has low transport costs;
- is cost competitive with alternatives;
- can be applied at locations (off-grid) where other alternatives cannot be applied.

As a result, Iron Fuel Technology™ allows for the production of iron fuel in cost competitive geographical areas with an abundance of renewable energy and for its use at locations where energy is needed. Hence, it can be used to transport clean energy. Two example use cases for illustration:

1 **Iron fuel trade over distance can be used to outperform other alternatives or regionally produced iron fuel in price and/or sustainability**

Certain regions may produce iron fuel for lower prices due to lower feedstock prices, investment costs, land prices and/or labor prices. As transport costs are relatively low, the cost of producing iron fuel regionally may be higher than producing it somewhere else and importing it. Our analysis shows that a decrease of 0.5 €/kg H_2 could reduce iron fuel prices to under the prices of producing it regionally (dependent on the region). This ensures that energy stays affordable while allowing for regional, national, and international competitiveness.

2 **Iron fuel trade over distance can be used to overcome regional or national energy shortages**

The production and boiler systems of Iron Fuel Technology™ do not have to be placed at the same location, it could be a different region, nation or even continent. The low transport costs of iron fuel allow for the importing of energy in iron fuel to ensure energy reliability so regional or national energy shortages do not occur.

The Combination of Transport and Storage

The combination of cheap storage and transport allows the full potential of energy trading to be unlocked. Many combinations and use cases can be made giving rise to new business cases. It will all contribute to a clean energy supply that is reliable, affordable and equal, helping us combat clean energy scarcity and poverty now and in the future.

Impact of Iron Fuel Technology™

Iron Fuel Technology™ has both a positive environmental and social impact. By decarbonizing and denitrifying the energy-intensive industries, Iron Fuel Technology™ significantly reduces direct CO_2 and NOx emissions. Replacing traditional energy sources with iron fuel boilers would prevent 0.27 ton CO_2/MWhth and 0.03 kg NOx/MWhth of direct emissions in comparison to natural gas, 0.30 ton CO_2/MWhth and 0.29 kg NOx/MWhth to diesel, 0.42-0.45 ton CO_2/MWhth and 0.09 kg NOx/MWhth in comparison to coal, and 0.49 ton CO_2/MWhth and 0.16 kg NOx/MWhth in comparison to biomass (RIFT, Internal data). Even when considering the worst-case scenario for indirect carbon dioxide emissions, Iron Fuel Technology™ still has a significant positive impact. Its circular nature aligns with the requirements of a sustainable economy, and the limited safety risks to human and animal health, along with zero reliance on scarce materials, further contribute to a sustainable world.

Effectivity & Energy Efficiency

The combustion system has an energy efficiency of 85-95% depending on the chosen configuration. Additionally, iron fuel storage has an energy efficiency of 99.99%, the production system an efficiency of up to 85% (which is also dependent on the configuration), and the hydrogen to heat efficiency is 58-81%. This is comparable to other technologies, with the Iron Fuel Technology™ energy efficiencies being similar or higher.

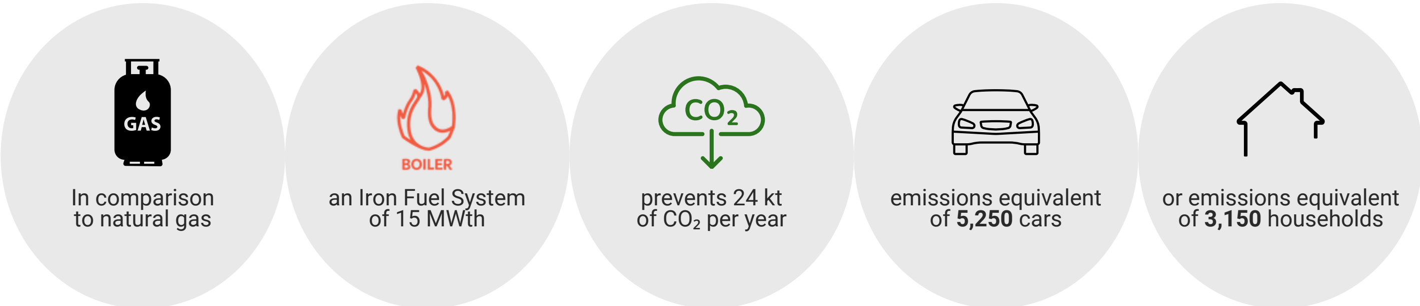
While energy efficiency is important, we must also consider usability. Iron Fuel Technology™ enables (long-term) storage and (long-distance) transport of energy, allowing companies to become sustainable when they otherwise might not. As a result, Iron Fuel Technology™ can enhance the efficiency of the global energy system.

Energy efficiencies

Iron Fuel Boiler System	85-95%
Iron Fuel Storage	99.9%
Iron Fuel Production System	up to 85%
Hydrogen to heat	58-81%

Direct CO_2 Emissions

When iron fuel is combusted, no CO_2 is directly emitted. In comparison to natural gas , it prevents 0.27 ton CO_2 per MWh, and in comparison to coal, it prevents 0.42-0.45 ton CO_2 per MWh (RIFT, Internal data) (as shown in the figure on page 26). For a 1 MWth installed capacity of Iron Fuel Technology™ this translates to preventing approximately 1.6 kilotons of CO_2 per year in comparison to natural gas. This reduction is the equivalent to the emissions from about 350 cars or the carbon footprint of 210 households. With an average system size of 15 MWth, the installation of one system corresponds to preventing the equivalent of the emissions of 5,250 cars or 3,150 households. When Iron Fuel Technology™ is implemented at large scale, many megatons of CO_2 may be prevented from entering the atmosphere each year.



Indirect CO_2-Equivalent Emissions

Indirect CO_2-equivalent emissions can be emitted at four main points in the value chain: the virgin iron fuel production, hydrogen production, the iron fuel production plant, and/or the transport of the iron fuel and iron oxide. The level of indirect CO_2 emissions can vary between 2-28 kg CO_2/GJ, depending on the value chain's configuration (e.g. transport distance and the source of the initial iron fuel). It's important to note that as all parts of the economy move towards sustainable practices, the indirect CO_2 emissions of Iron Fuel Technology™ will gradually decrease.

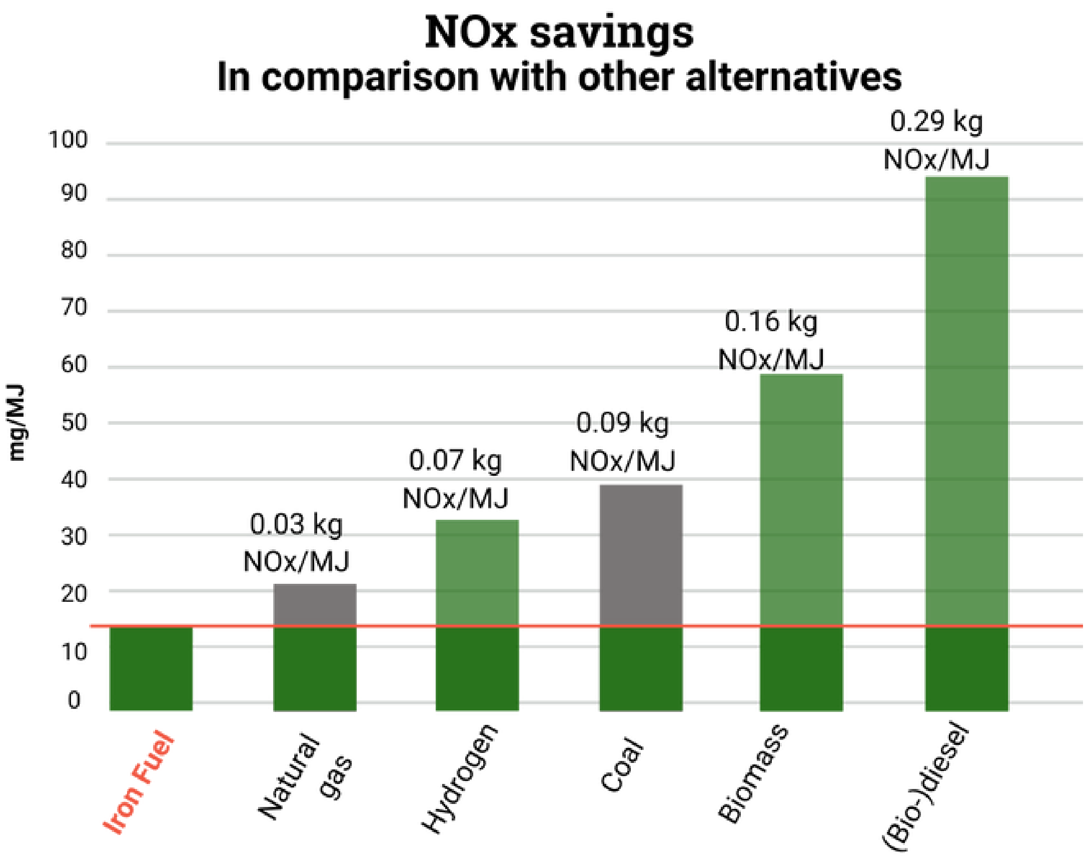
For comparison, consider that natural gas, which is often considered the most environmentally friendly fossil fuel, already generates 56 kg CO_2/GJ in direct emissions (Joshi & Bolech, 2022; H. H. Cho & Strezov, 2020; Mac Kinnon et al., 2018; Mohammad et al., 2021; Turconi et al., 2013). This means that the iron fuel value chain has a significantly lower environmental impact than the direct CO_2 emissions of natural gas alone, thus preventing a significant proportion of CO_2 emissions in any configuration.

NOx Emissions

In all combustion processes, nitrogen oxide (NOx) emissions are generated. While these emissions can be limited, they cannot be entirely prevented. The specific NOx emissions vary between the kind of fuel as it largely depends on the fuel characteristics and boiler design (National Energy Technology Laboratory, 2022).

Direct NOx emissions from iron fuel (<15 mg NOx/MJ) are significantly lower than those from fossil fuels (>22 mg NOx/MJ), hydrogen (>33 mg NOx/MJ), coal (39 mg NOx/MJ), biomass (58 mg NOx/MJ), and (bio)-diesel (94 mg NOx/MJ). According to internal calculations, iron fuel boiler systems therefore prevent 0.03, 0.07, 0.09, 0.16, and 0.29 kg NOx/MWh in comparison to natural gas, hydrogen, coal, biomass, and (bio)diesel respectively. Thus, iron fuel can be a viable solution for regions or companies with restrictions on NOx emissions, as seen in the Netherlands.

The installation of 1 GW can already lead to a reduction of 180-1,750 tons of NOx emissions annually, which is equivalent to 0.06-0.6% of the total Dutch NOx emissions (CBS, n.d.). Lowering NOx emissions has a positive impact on the environment, as NOx is known to contribute to climate change and other environmental issues, including acidification, terrestrial and marine eutrophication, among others (Botter, 2023).



The numbers shown represent the amount of NOx emissions prevented per MWh, when using iron fuel instead of the alternative mentioned below the bar.

Moreover, using waste hydrogen has an additional NOx emission benefit because the waste hydrogen is otherwise flared, resulting in nitrogen oxide emissions of 100 mg/MJ (Activiteitenbesluit milieubeheer, 2023). Using this waste hydrogen for the purpose of making iron fuel may prevent more than 240 tons of NOx emissions per year in the Netherlands only (RIFT, Internal data). Using this hydrogen source will decrease the NOx emissions significantly and might help governments combat NOx problems.

Particle Emissions

Iron Fuel Technology™ meets the regulatory standards of particle emissions. Therefore, it has no detrimental effects on the environment in comparison to other energy technologies.

Circularity

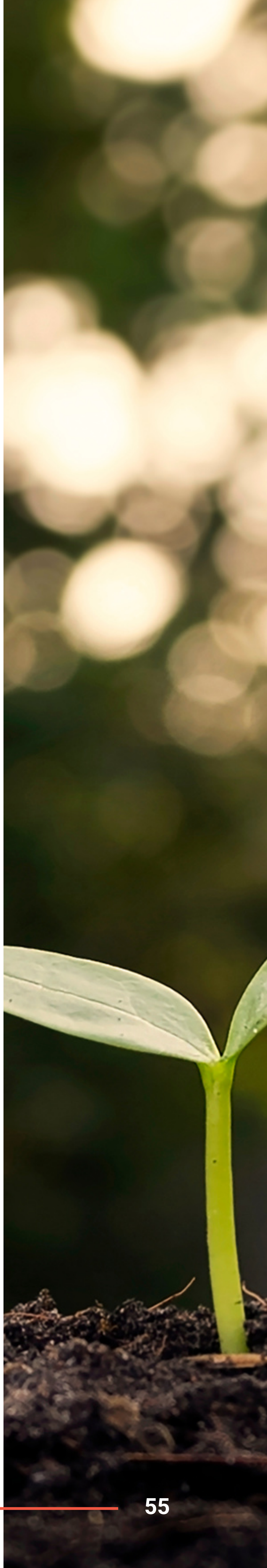
The Iron Fuel Technology™ value chain is completely circular. The virgin iron fuel can be produced from scrap iron, a waste product. Subsequently, the iron fuel is used cyclically many times throughout its lifetime as used in Iron Fuel Technology™. When the iron fuel and iron oxide cannot be used for the purpose of Iron Fuel Technology™ anymore, the iron can be used as a feedstock for various industries (e.g. the steel industry), thus fully closing the loop.

Scarce Materials

Iron Fuel Technology™ makes no use of scarce raw materials. In contrast to other technologies, it minimizes the use of critical raw materials in its required system components. This not only reduced costs but also mitigates dependency on external factors.

Health

The iron fuel market is a derivate market of the iron powder market. Numerous studies have scrutinized the potential health impacts of iron powder, and none have revealed any short-term or long-term adverse health effects. To the best of our knowledge, Iron Fuel Technology™ is not anticipated to present any health hazards.



Governmental Expenditures

Iron Fuel Technology™ stands out by not necessitating infrastructure investments, thanks to its off-grid capabilities. This sets it apart from other technologies that typically require significant infrastructure investments. Consequently, the funds earmarked for infrastructure can be redirected towards other critical areas, including efforts to combat climate change and enhance social security.

Jobs

The implementation of Iron Fuel Technology™ facilitates job creation across various sectors within the value chain. It is anticipated that the number of jobs directly linked to Iron Fuel Technology™ could reach approximately 2,500 full-time equivalents (FTE) by 2030, 187,000 FTE by 2040, and a substantial 14 million by 2050. These jobs encompass various roles such as operators, component manufacturers, hydrogen producers, iron powder producers, financial consultants, technology developers, and engineering, procurement, and construction (EPC) professionals. This increase in employment opportunities has a positive impact on the final energy price, given that a significant portion of it comprises direct employee wages, thus stimulating the gross domestic product.

Expected increase in directly linked jobs

2030	2040	2050
2,5K FTE	187K FTE	14M FTE

Sources

• Activiteitenbesluit milieubeheer. (2023, July 1). Retrieved from https://wetten.overheid.nl/jci1.3:c:BWBR0022762&z=2023-07-01&g=2023-07-01

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

• ArcelorMittal. (2023b). Electric arc furnace. Retrieved from https://corporate.arcelormittal.com/about/making-steel/making-iron-steel-electric-arc-furnace#:~:text=These%20furnaces%20are%20typically%20charged4

• Babcock & Wilcox. (2015). STEAM / its generation and use. Babcock & Wilcox.

• Botter, C. (2023). Examining the Future Environmental Impacts of Clean Fuels for Generating Heat [Master Thesis, Delft University of Technology]. http://resolver.tudelft.nl/uuid:51785a1a-59cc-49ac-93f1-158959034aa3

• Carbon footprint of cargo ship in the United Kingdom 2023, by type. (2023). Statista. https://www.statista.com/statistics/1233482/carbon-footprint-of-cargo-ships-by-type-uk/

• CE Delft. (2021). STREAM Freight Transport 2020 [PDF]. https://cedelft.eu/wp-content/uploads/sites/2/2021/03/CE_Delft_190325_STREAM_Freight_Transport_2020_FINAL.pdf

• 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).

• CBS. (n.d.). Stikstofemissies naar lucht. https://www.cbs.nl/nl-nl/dossier/dossier-stikstof/stikstofemissies-naar-lucht#:~:text=De%20stikstofuitstoot%20naar%20de%20lucht,vooral%20uit%20verkeer%20en%20industrie

• Day, P. (2023, September 7). Startups race to strike hydrogen gold. Reuters. https://www.reuters.com/business/energy/startups-race-strike-hydrogen-gold-2023-09-07/

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

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

• European Commission. (2020). A hydrogen strategy for a climate-neutral Europe (COM(2020) 301 final). Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52020DC0301

• European Council. (n.d.). Fit for 55: The EU plan for a green transition. https://www.consilium.europa.eu/en/policies/green-deal/fit-for-55-the-eu-plan-for-a-green-transition/

• Filippou, D., & Hudon, G. (2009). Iron removal and recovery in the titanium dioxide feedstock and pigment industries. JOM, 61(10), 36-42. (Publication available to members of The Minerals, Metals & Materials Society).

• Fortune Business Insights. (2020). Iron Powder Market Size, Share & COVID-19 Impact Analysis (Report ID: FBI105050). Retrieved from https://www.fortunebusinessinsights.com/iron-powder-market-105050

• Fuels - Higher and Lower Calorific Values. (n.d.). Engineering Toolbox. https://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html

• GH2. (2022). The GH2 Green Hydrogen Standard. The Green Hydrogen Organisation (GH2). https://gh2.org/our-initiatives/gh2-green-hydrogen-standard

• Heid, B., Sator, A., Waardenburg, M., & Wilthaner, M. (2022, October 25). Five charts on hydrogen's role in a net-zero future. McKinsey Sustainability. https://www.mckinsey.com/capabilities/sustainability/our-insights/five-charts-on-hydrogens-role-in-a-net-zero-future

• Hempenius, A. (2021). Techno-economic comparison between the reduction of iron-oxide using hydrogen or electrowinning, powered by sustainable energy from the grid . Eindhoven University of Technology. https://pure.tue.nl/ws/portalfiles/portal/206958813/BEP_Ate_Hempenius_1257331.pdf

• Hogenkamp, R. (2023, May 5). Dit heeft de potentie om alle fossiele energiebronnen te vervangen. Financieel Dagblad. Retrieved from: https://fd.nl/bedrijfsleven/1475103/dit-heeft-de-potentie-om-alle-fossiele-energiebronnen-te-vervangen

• Infrasite. (2023, March 14). TenneT investeert recordbedrag in uitbreiding elektriciteitsnet. https://www.infrasite.nl/energie/2023/03/14/tennet-investeert-recordbedrag-in-uitbreiding-elektriciteitsnet/?gdpr=accept&gdpr=accept

• International Energy Agency (IEA). (2021). Global Hydrogen Review 2021. Revised November 2021. [PDF]. https://iea.blob.core.windows.net/assets/5bd46d7b-906a-4429-abda-e9c507a62341/GlobalHydrogenReview2021.pdf

• International Energy Agency. (n.d.). Low Emission Fuels: Hydrogen. IEA. https://www.iea.org/energy-system/low-emission-fuels/hydrogen

• IPCC. (2014). Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (O. Edenhofer, R. Pichs-Madruga, Y. Sokona, E.
Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S
Joshi, J. U., & Bolech, M. (2022). Decarbonisation Options for the Dutch Onshore Gas and Oil Industry [Report]. © PBL Netherlands Environmental Assessment Agency; © TNO. https://www.pbl.nl/sites/default/files/downloads/pbl-2022-decarbonisation-options-for-the-dutch-onshore-gas-and-oil-industry-4958.pdf

•Kerkhoven, J., & Terwel, R. (2019). HyChain 2: Cost implications of importing renewable electricity, hydrogen, and hydrogen carriers in the Netherlands. ISPT. https://ispt.eu/publications/si-20-06-final-report-hychain-2/

• Lee, D.-Y., & Elgowainy, A. (2018). By-product hydrogen from steam cracking of natural gas liquids (NGLs): Potential for large-scale hydrogen fuel production, life-cycle air emissions reduction, and economic benefit. International Journal of Hydrogen Energy, 43(43), 20143-20160. https://doi.org/10.1016/j.ijhydene.2018.09.039 (Version of Record)

• Lijst emissiefactoren. (2023). CO2emissiefactoren.nl. https://www.co2emissiefactoren.nl/lijst-emissiefactoren/

• Lu, L., Pan, J., & Zhu, D. (2015). Quality requirements of iron ore for iron production. In L. Lu (Ed.), Iron Ore, 475-504. Woodhead Publishing. https://doi.org/10.1016/B978-1-78242-156-6.00016-2

• 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.

• McKinsey & Company. (2023, February 6). Consumers care about sustainability and back it up with their wallets. https://www.mckinsey.com/industries/consumer-packaged-goods/our-insights/consumers-care-about-sustainability-and-back-it-up-with-their-wallets

• Moberg, J., & Bartlett, S. (2022, January 28). The mirage of blue hydrogen is fading. Blog Name. https://gh2.org/blog/mirage-blue-hydrogen-fading

• 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

• PricewaterhouseCoopers (PwC). (n.d.). The green hydrogen economy: Predicting the decarbonisation agenda of tomorrow. Retrieved from https://www.pwc.com/gx/en/industries/energy-utilities-resources/future-energy/green-hydrogen-cost.html

• QYResearch. (2018). Global Iron Powder Market Research Report 2018. QYR Chemical & Material Research Center.

• Ramirez, K., Weiss, T., Kirk, T., & Gamage, C. (2023, August 2). Hydrogen Reality Check: Distilling Green Hydrogen's Water Consumption. RMI. https://rmi.org/hydrogen-reality-check-distilling-green-hydrogens-water-consumption/#:~:text=Per%20chemistry%20fundamentals%2C%209%20liters,20%20L%2Fkg%20is%20needed.

• RIFT. (2020). Initial Iron Fuel Production. Cost, quality and supply scenario analysis for production of initial iron fuel. [Internal report]

• Rijkswaterstaat Ministerie van Infrastructuur en Waterstaat. (n.d.). Fijnstof. Kenniscentrum InfoMil. https://www.infomil.nl/onderwerpen/landbouw/stof/handreiking-fijn-1/sitemap/fijn-stof/

• Sista, K. S., & Dwarapudi, S. (2018). Iron Powders from Steel Industry by-products. ISIJ International, 58(6), 999-1006. https://doi.org/10.2355/isijinternational.ISIJINT-2017-722

• Sovereigen Metals Limited. (2021, April 20). Studies confirm Sovereign's natural rutile coude significantly reduce global titanium industry CO2 emissions. Retrieved from: http://www.investi.com.au/api/announcements/svm/13976139-5ce.pdf

• Sterling, T. (2022, June 29). Dutch government to invest 750 mln euros to develop hydrogen network. Reuters. https://www.reuters.com/markets/europe/dutch-government-invest-750-mln-euros-develop-hydrogen-network-2022-06-29/

• The Editors of Encyclopaedia Brittanica (2023). Blast Furnace. Britannica. https://www.britannica.com/technology/blast-furnace

• 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

• 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

• United Nations Framework Convention on Climate Change [UNFCCC]. (n.d.). The Paris Agreement. https://unfccc.int/process-and-meetings/the-paris-agreement

• United States Environmental Protection Agency. (2023). Health and Environmental Effects of Particulate Matter (PM). Last updated on August 23, 2023.https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

• United States Environmental Protection Agency. (2023). Particulate Matter (PM) Basics. Last updated on August 23, 2023. https://www.epa.gov/pm-pollution/health-and-environmental-effects-particulate-matter-pm

• van Dorsten, B., & De la Cruz, F. L. (n.d.). Decoding the hydrogen rainbow. Wood Mackenzie.https://www.woodmac.com/news/opinion/decoding-the-hydrogen-rainbow

•Vujasin, M. (2023, October 2). White Hydrogen: Sustainable Energy from Depths of Earth. Balkan Green Energy News. https://balkangreenenergynews.com/white-hydrogen-sustainable-energy-from-depths-of-earth/

• World Steel Association. (2022). Sustainability indicators 2022 Report.https://worldsteel.org/wp-content/uploads/Sustainability-Indicators-2022-report.pdf

• Žnidarič, A. (2015). Heavy-Duty Vehicle Weight Restrictions in the EU: Enforcement and Compliance Technologies (23rd ACEA). ZAG – Slovenian National Building and Civil Engineering Institute. https://www.acea.auto/files/SAG_23_Heavy-Duty_Vehicle_Weight_Restrictions_in_the_EU.pdf

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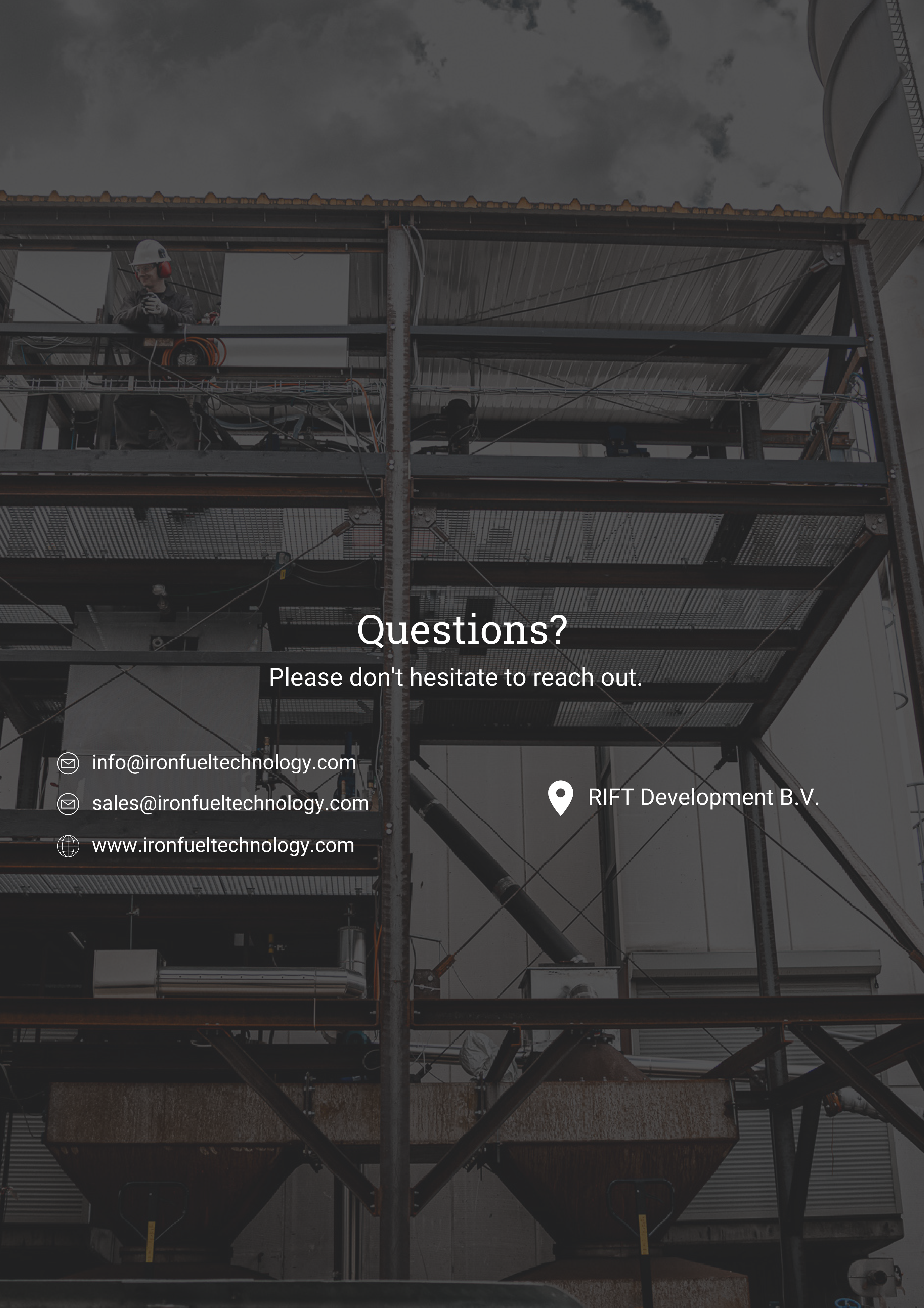

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