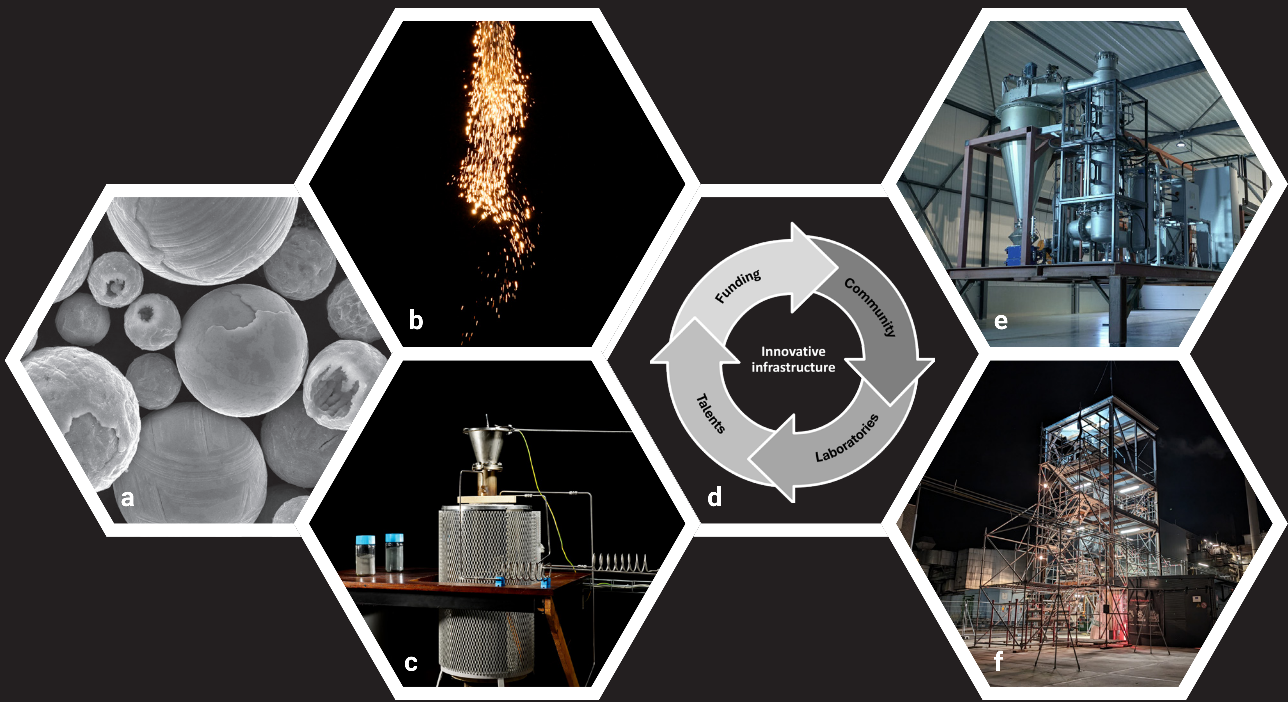
It's time for Circular Energy
It's time for **Iron Power**



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Cover images:

a Iron oxide particles (Photo: Conrad Hessels, Eindhoven University of Technology)
b Turbulent iron flame (Photo: Bart van Overbeeke, Eindhoven University of Technology)
c Fluidized bed reactor (Photo: Bart van Overbeeke, Eindhoven University of Technology)
d Metalots concept of innovative infrastructure (Metalot)
e Integrated 500kW iron combustor and boiler of the "Lighthouse Metal Power" consortium (Photo: Bart van Overbeeke, TU/e)
f Industrial scale regeneration plant (Photo: RIFT Development B.V.)

1. SUMMARY

Iron Power program			
Name of submitters	Eindhoven University of Technology (TU/e), TNO, Metalot, RIFT, Iron+		
Project duration	10 years (2025 through 2034)		
Area	Research, development & innovation		
Total investment (million euros)	**Requested contribution NGF (million euros)**	**Contributions from other parties (mln. euros)** Wv. Public	Wv. Private
395	156	33 (including earning model)	206

There is a global energy crisis and signs of climate change are becoming more visible every day. The world is setting sustainability goals to limit global warming and accelerate the energy transition in industries. Because energy-intensive industries are difficult or even impossible to electrify, alternative energy sources are needed. However, their supply - such as hydrogen - will be (by far) insufficient or locally available to meet energy demand. The **Iron Power program** has the ambition to prove and make **the Iron Power technology and value chain available** as a decarbonization solution for energy-intensive industries. The program accelerates the transition of energy-intensive industries, builds an ecosystem for Iron Power technology, strengthens the Dutch and European business climate and strategic independence, reduces harmful emissions and supports the development of talents and (new) business activity.

The Iron Power program consists of three mutually reinforcing pillars (see Figure 1):

- **R&D** in which research and development projects are conducted along the value chain themes to improve existing technologies and develop new technologies
- **Pilots & demos** in which technologies already proven (in research) are tested in pilot and demo projects until they are commercially proven
- An **Innovation infrastructure** that provides services to build an Iron Power ecosystem (Community), support parties/projects in technology development (Laboratories), educate talents in Iron Power (Talents) and connect innovators with financiers (Funding).

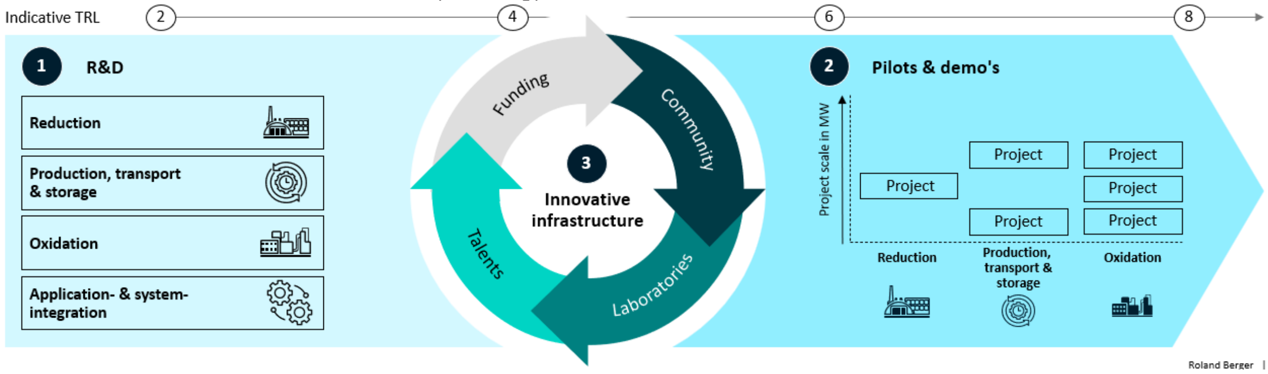
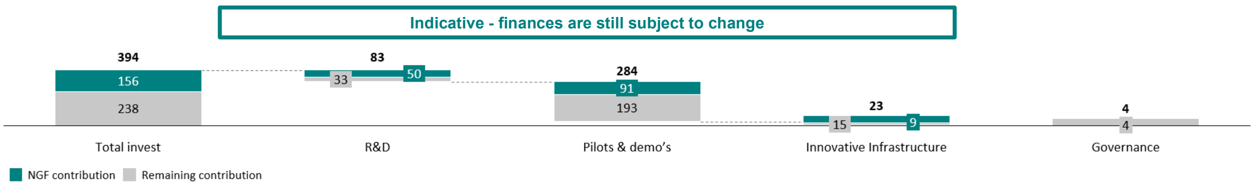


Figure 1: Strategy - Iron Power Program

The investment required over 10 years is EUR 395 mln, of which EUR 156 mln is requested from the NGF.



The Netherlands can become a world leader in Iron Power technology and thereby realize great economic, strategic and sustainability impact. The development and availability of Iron Power systems by Iron Power *champions* and by supplying Iron Power energy to companies (including so-called Cluster 6 companies in the Netherlands) leads to structural economic growth. In addition, the program creates greater strategic import independence from traditionally energy-supplying countries and an improved living environment through lower emissions.

The Iron Power program is realized by a strong core consortium of leading parties – Eindhoven University of Technology, TNO, Metalot, RIFT and Iron+ – in cooperation with many public and private partners such as Veolia, Ennatuurlijk, AsfaltNu and Kingspan.

2. STRATEGIC RATIONALE

2.1 PROBLEM DEFINITION

The world needs energy carriers for long-distance transportation and decentralized storage to accelerate the energy transition and complement the future energy mix.

Abstract - *Iron powder is a clean, safe and cost-effective energy carrier for long-distance transportation and storage. It can play a crucial role in the energy transition by accelerating it and providing hard-to-decarbonize industries with a green option. In addition, it can serve as strategic (seasonal) energy storage.*

Since demand for renewable energy in northwestern Europe will exceed local green energy production, countries such as the Netherlands are investing in importing green molecules and developing a hydrogen network to connect industrial clusters. However, green molecules and the development of a hydrogen network will be (far from) sufficient or locally available to meet the demand. Moreover, not all industrial clusters, such as Cluster 6 in the Netherlands, will be in close proximity to the hydrogen network. Therefore, it is essential and strategic for the Netherlands to complement the hydrogen strategy with alternative decarbonization solutions: sustainable energy carriers that can power key industries (use), transport energy over long distances (import), transport energy regionally (local distribution) and strategically enable large-scale and local energy storage (storage).

Iron powder is an extremely promising, clean and efficient alternative energy carrier. It offers a cost-effective solution for long-distance transportation, decentralized storage and applications requiring high process heat. By decarbonizing industries in the Netherlands and other countries, iron powder can be an essential addition to the future sustainable energy mix.

The Iron Power program focuses first on implementation in the Cluster 6 industrial cluster. This cluster consists of industries looking for a way to decarbonize their high-value heat processes without direct access to the hydrogen grid and with minimal alterations to their existing, well-established industrial methods. By working with companies in this cluster, the Iron Power program will build the market and logistics chain that can then be scaled up to become a strategic part of our energy supply. With iron powder as a promising energy carrier and the Iron Power program as a driving force, we can help both the Netherlands and Europe accelerate towards a sustainable future, strengthen strategic independence and promote the business climate.

By 2050 and even beyond, green energy production in northwestern Europe will be insufficient to meet demand or decarbonize energy-intensive industries.

As the signs of climate change become increasingly visible in everyday life, the demand for sustainable, carbon-free energy solutions increases. Decarbonization targets at every level of government - such as the Paris Climate Agreement, the EU's Fit for 55 initiative, and the national Climate Agreement in the Netherlands[1] - have been set to combat global warming. Geopolitical turmoil, such as the war in Ukraine, has reinforced efforts to achieve these goals with national-level energy solutions and imports from various markets. Renewable energy production in Northwest Europe will mainly consist of wind farms in the North and Baltic Seas. Even if all Dutch plans and ambitions become reality, renewable electricity production in 2050 (>150 GW[2]) will not be able to meet total electricity consumption. While solar energy (centralized and decentralized) could potentially fill the shortfall, it will only be seasonal and energy consumption will still exceed production in the fall and winter months. The urgency is further compounded by end-use applications that cannot be electrified. Applications such as glass and brick production require high-temperature heat, making electrification complex and in most cases nearly impossible. Green molecules, such as hydrogen, will need to play a key role in bringing renewable energy to these industries (see Figure 2), and the global pipeline network for large-scale green molecules with export potential is expanding rapidly. With non-electrification and energy-intensive industries forming a large part of the Dutch economy (through companies such as TATA Steel and Shell), the Netherlands occupies a strong position within the global hydrogen economy by rolling out onshore and offshore hydrogen production projects. For example, the National Growth Fund (NGF) has granted support to "Groenvermogen" to realize a green hydrogen hub and hydrogen network. However, even if all plans and ambitions regarding clean hydrogen in the Netherlands materialise, projected consumption by 2050 will exceed production by as much as 6-7 Mtonnes consumption[3].

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[1] Dutch Government – Climate Agreement (2019, https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord)
[2] Tennet – Adequacy Outlook (2023, https://tennet-drupal.s3.eu-central-1.amazonaws.com/default/2023-05/TenneT_Adequacy%20Outlook_2023_publ.v1.2.pdf)
[3] Royal Haskoning DHV, Roland Berger - MAKING THE HYDROGEN MARKET (2022)

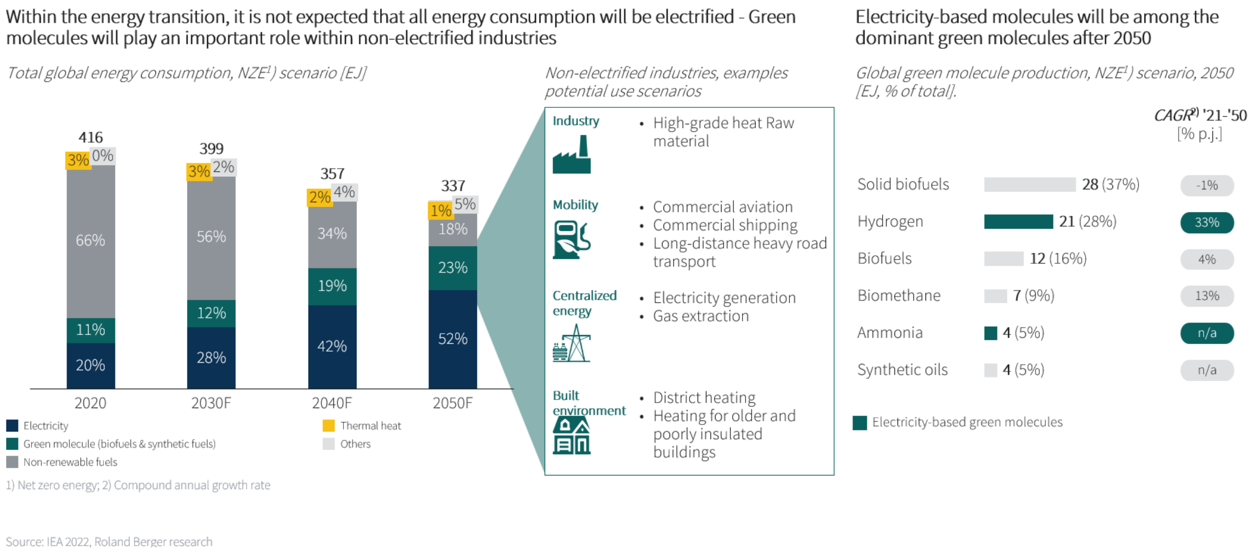

Figure 2: Global energy consumption and need for green molecules for non-electrification solutions[4]

If the Netherlands wants to decarbonize large industries, imports of large amounts of green energy will be needed and we must be able to store and transport this energy locally to the needed locations.

Imports of green molecules will come from regions with low hydrogen production costs (LCoH). Many of these countries are in the Middle East (see Figure 3), geographically far from the Netherlands, and thus long-distance transportation is required. Although the Netherlands and Europe are investing heavily in a hydrogen network to connect industrial clusters, not every industrial company will be connected to it. In the Netherlands, for example, Cluster 6 is a large group of production sites spread across the country that includes several energy-intensive industries. Because of the geographical distribution of the companies in the cluster, these plants cannot be connected to the proposed hydrogen network (see Box 1). As sustainability policies intensify, companies in Cluster 6 will have to consider alternative operations, relocation or even closure.

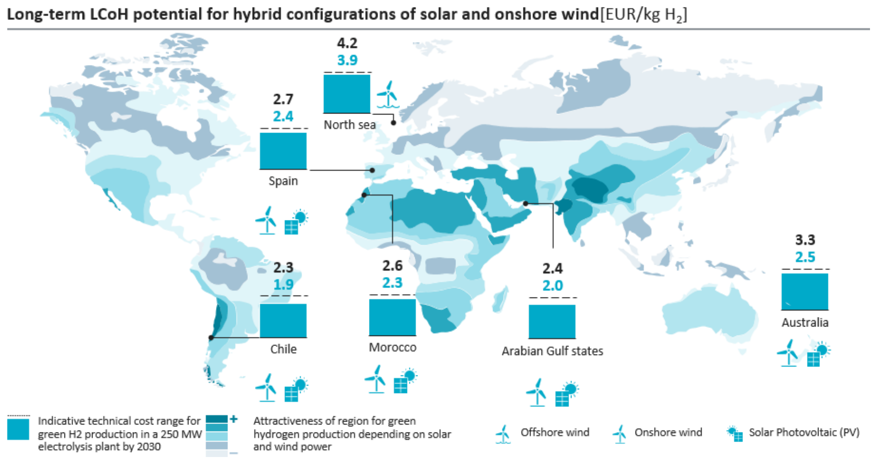

Figure 3: Estimated production cost for green hydrogen, 2030[5,6]

Reliance on green molecule imports means not only bringing hydrogen and its derivatives into the Netherlands, but also brings the challenge of getting it to industrial facilities at the right times. Long-distance and regional transportation must be complemented by local decentralized storage solutions or strategic large-scale storage that can be deployed strategically with the changing transportation and consumption patterns. Given the challenging properties of hydrogen (e.g., low volumetric energy density compared to natural gas), long-distance transportation, storage and regional transportation without pipelines may become inefficient and/or costly as well as being unproven at any significant scale. Therefore, industry and academics are looking for renewable energy carriers to power industries that are not connected to the hydrogen grid - renewable energy carriers that can be cost-effectively used for long-distance transportation, regional transportation and storage.

[4] IEA – Global Hydrogen Review (2022)
[5] Roland Berger – Study (2023)
[6] IEA – Global Hydrogen Review (2022)

Box 1: Cluster 6 and the challenge of decarbonization

Cluster 6 is a group of Dutch factories operating in energy-intensive industries such as food, chemicals, agriculture, metal, stone, glass, ceramics, waste treatment and technology. These factories fall outside the five geographically concentrated industrial clusters in Zeeland, Noord Holland, Rotterdam-Moerdijk, Chemelot and the North Sea Canal area. Cluster 6 has an annual turnover of about €125 billion and employs more than 210,000 people (source: Water Energy Solutions - CES Cluster 6). Interestingly, Cluster 6 is responsible for about 30% of the total CO2 emissions in the Netherlands (CES Cluster 6 - 'Cluster Energy Strategy').

These non-electrification, energy-intensive industries are actively looking for ways to decarbonize their production. This can be achieved through solutions such as carbon capture and storage (CCS) or the transition to hydrogen as an energy source. However, the transition to hydrogen carries risks, as these plants are scattered across the country and cannot be connected to the planned hydrogen network. They must provide their own continuous supply of hydrogen. Because of their dispersion, it is also costly and difficult to implement CCS solutions. Therefore, the decarbonization pathway for Cluster 6 is challenging and not yet clear.

The energy carriers currently being researched and developed all have complications regarding long-distance transportation, storage and/or regional transportation, such as safety, efficiency or cost as well as short and long term geo-political uncertainties.

Much research is being done on the possibilities of converting hydrogen into other renewable energy carriers that can be transported by ship and stored overseas before being transported (converted) and used to end uses. Ideally, an energy carrier meets the following criteria:

- High volumetric energy density [MWh/m^3]: To continue using existing infrastructure and transportation solutions (such as natural gas), an energy carrier must contain as much energy as possible in as small a volume as possible.
- Safe: In its natural form, an energy carrier must be non-toxic, non-explosive and non-flammable to ensure safe transportation, storage and handling. An energy carrier must also not produce emissions that are harmful to the environment.
- Low CAPEX and OPEX (simple infrastructure): An energy carrier should not require additional and complex facilities or equipment for transportation, storage or use in end applications to keep capital and operational costs low.
- High cycle efficiency [% remaining energy for use compared to initial energy]: An energy carrier should retain as much of its initial energy as possible during transportation, storage and use.
- Energy cost [EUR/MWh]: The cost of an energy carrier must be competitive. Energy costs include the entire process from energy production to the use of the carrier in an end application.

No energy carrier meets all the criteria needed for a clean, safe and cost-effective solution for energy-intensive industries (see Figure 4). An overview of current renewable energy carriers with a high Technology Readiness Level (TRL) (the commercial readiness of the technology) includes gaseous hydrogen, liquid hydrogen, ammonia, methanol and LOHC (liquid organic hydrogen carrier). The future energy mix will depend to some extent on all of these carriers because each has properties that make them ideal for specific use cases. However, for energy-intensive and difficult-to-electrify industries, the current carriers offer few advantages. In this context, the main disadvantages of each are listed below.

- Gaseous hydrogen has a low volumetric energy density, requiring large capacity to transport and store significant amounts of hydrogen energy. This makes it unsuitable for long-distance ship transportation and decentralized storage. In addition, gaseous hydrogen is also highly explosive and toxic, requiring strict safety measures for equipment and procedures.
- Liquid hydrogen has a slightly higher volumetric energy density than gaseous hydrogen, but is very expensive to transport because of its extremely low temperature (-253 °C vs. -162 °C for LNG), the high pressure required to maintain its liquid form and the still high hydrogen losses during the process.
- Ammonia also has a relatively low volumetric energy density at low temperatures (although higher than liquid hydrogen), making it not only less attractive economically but also technically challenging for long-distance transportation. In addition, ammonia is also highly toxic and can cause environmental and health problems. The oxidation process of ammonia also requires higher temperatures and results in harmful NOx emissions. It is unlikely that ammonia will be used for direct combustion in Europe.
- Methanol requires scarce carbon atoms at the conversion site, but more importantly, the conversion of hydrogen to methanol is relatively inefficient. Its combustion also results in CO2 emissions.
- LOHC must be converted to hydrogen to burn it, and thus be useful for energy-intensive industries. There are also concerns about toxicity, environmental and health problems associated with it.

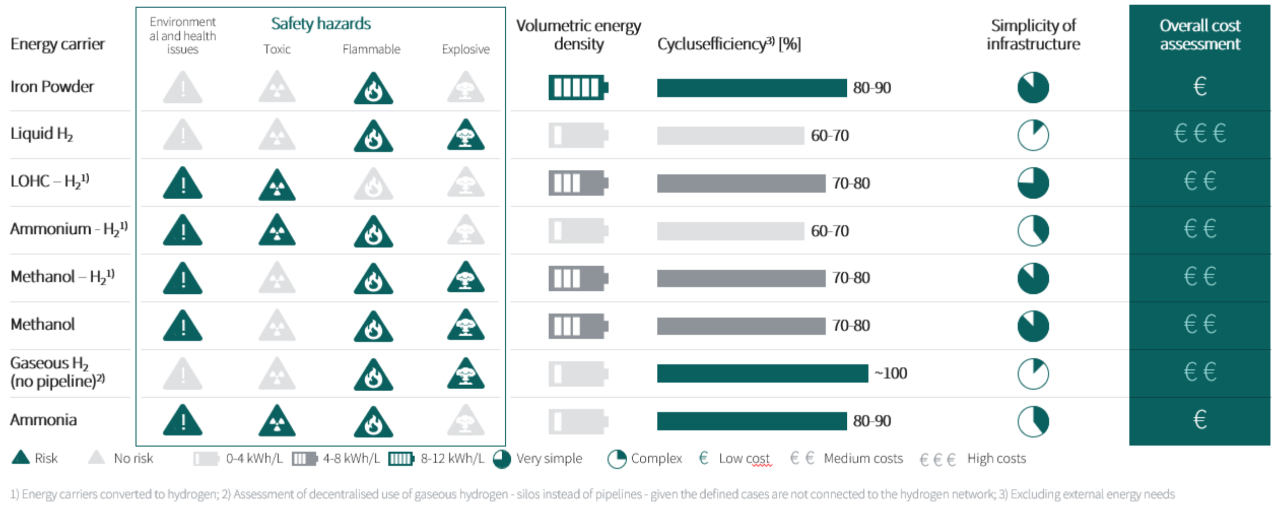

Figure 4: Comparison of renewable energy carriers in long-distance transmission and storage versus hydrogen[7]

Iron powder is a clean, relatively safe and cost-effective energy carrier that can enable the energy transition for industries that are difficult to decarbonize.

Reacting hydrogen with iron oxide creates a metallic fuel known as iron powder (see Box 2). Iron powder is ideal as an energy carrier for long-distance transportation, decentralized storage and direct combustion in an end application (see Box 2).

Box 2: Metal fuels and iron powder

Iron powder is a type of metal fuel that can be burned with oxygen from the air or can react with water to release chemical energy in the form of high-temperature heat (a process called oxidation). After oxidation, metal fuels can be converted back to their original form by reduction. The advantages of metal fuels are that the oxidation and reduction processes can be decoupled, combustion results in low direct emissions, and existing infrastructure (high-temperature applications) can be adapted to use the metal fuel. Although there are several types of metal fuels, such as magnesium and aluminium, iron powder is the most promising. Iron powder can be produced sustainably by reduction of iron oxide with hydrogen, iron oxide is relatively easy to obtain, and combustion produces temperatures similar to hydrocarbons.

The advantages of iron powder as an energy carrier include:

- That iron powder is chemically stable at room temperature in a low oxygen environment, making it relatively safe and generally suitable for the use of **existing infrastructure for transportation and storage**.
- In addition, iron powder has **a high volumetric energy density** (8-12 kWh/L) compared to other renewable energy carriers, making it attractive for long-distance transportation and decentralized storage.
- Iron powder can be **directly oxidized**, resulting in high-quality heat (>1500 °C) that is ideal for applications in energy-intensive industries. In addition, it can also be converted to hydrogen in a cycle called wet-cycle oxidation.
- The conversion (reduction) and oxidation processes result in **no direct emissions of CO_2, SO_x and low NO_x emissions.**
- Iron powder oxidation setups (high-temperature release) can be **realized off-grid** (without a high-voltage connection), making it deployable in locations where grid congestion makes electrification difficult.
- The iron used in oxidation can be **captured and reused** (cyclability/circularity of materials) in a new cycle (Iron Power cycle). Moreover, iron (oxide) is a relatively common resource in the Earth's crust.
- In the context of high-value heat applications in buildings or factories not connected to the hydrogen grid, the Iron Power value chain (hydrogen conversion, long-distance transportation, decentralized storage, oxidation at end application) is expected to be **cost-effective**.
- Initial studies also indicate that **iron powder can be produced directly** by electrolysis of iron oxide, **without the use of hydrogen**. This technology is called *Direct Electrochemical Reduction* (DER). Although the TRL of this technology is currently low, it could significantly further reduce the cost of the energy carrier because it would eliminate the need for expensive and locally scarce green hydrogen.

This direct electrical reduction route is receiving attention in both the steel industry and academia, among others such as ArcelorMittal, Fortescue and TU/e.

[7] Source: IRENA

Box 3: The Iron Power technology

Iron powder is a metallic fuel that can be used as an energy carrier for energy storage and transportation. Iron powder technology creates a circular system of energy storage, transport, use and reuse that can help industries in the energy transition.

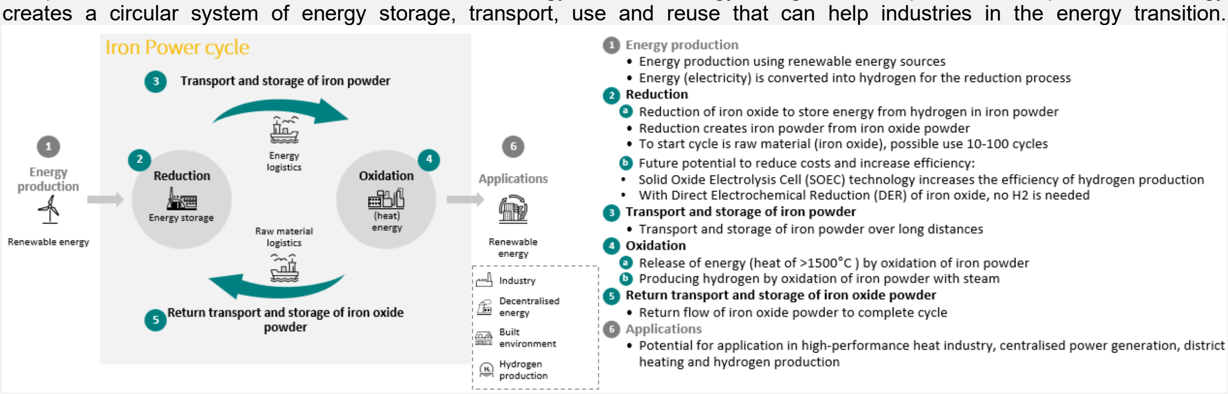

Figure 5: Schematic overview of the Iron Power cycle

The Iron Power value chain consists of five steps:

- Step 1: Energy Production - The value chain begins with the production of hydrogen by electrolysis with renewable energy. The hydrogen is briefly stored before being used in reduction. In the future, there is potential to use renewable energy directly by performing direct electrolysis to the iron oxide to create iron powder, replacing the need for green hydrogen.
- Step 2: Reduction - In the reduction step, the hydrogen (thermochemical reduction) reacts with iron oxide to create iron powder and water. The energy in the hydrogen is transferred to iron powder in a carbon-neutral process. As mentioned earlier, there is potential in the future to avoid the use of green hydrogen.
- Step 3: Transportation and storage - After reduction, the iron powder is transported, stored in bulk storage tanks and distributed locally for oxidation in a final application.
- Step 4: Oxidation in final application - The iron powder reacts with oxygen, releasing energy in the form of high temperatures (>1500 °C) that can be used in certain applications (Step 6). Alternatively, iron powder can be oxidized with steam to produce hydrogen and heat.
- Step 5: Return of iron oxide - The iron oxide resulting from the oxidation of iron powder is collected and returned to the point of reduction to re-create iron powder. Initial estimates put reuse at 10-100 times (cyclability), after which it can be used as a raw material for the steel industry.
- Step 6: The released high temperatures can be used both directly (heat) and indirectly (to generate energy) in applications such as plants in Cluster 6, stand heating, building heating and converted coal-fired power plants.

2.2 Opportunities

Iron Power technology is a promising way for the Netherlands to make energy-intensive industries more sustainable, reduce the shortage of renewable energy supplies and gain access to global markets - a technology that is a good fit for the Netherlands.

The Netherlands has the potential to become a world leader in Iron Power technology and thereby realize great economic and social impact. Political momentum and socioeconomic opportunities make this the ideal time to invest in Iron Power.

Politics: The Iron Power program will not only help the Netherlands achieve its climate goals, but it will do so faster and with more certainty.

Meeting global climate goals is high on the Dutch government's agenda, as evidenced by the National Climate Agreement signed in 2019, and more recently by the Coalition Agreement 2021-2025. In the new program to accelerate industrial energy transition[8], the Dutch government is taking a stronger position to achieve climate targets. At the European level, the REPowerEU program is drawing up plans to promote the diversification of energy imports and the reduction of gas consumption. The European Commission recently published the report "Scaling up innovative technologies for climate neutrality"[9] which calls for a greater role of government in supporting and investing in sustainable innovations for energy-intensive industries. The consensus is that the future renewable energy mix will not only include hydrogen, but will require more renewable alternatives to make climate goals achievable. The Iron Power program ensures robustness in the energy system.

[8] Dutch Government - Kabinet wil verduurzaming industrie versnellen als tegenwicht hoge energieprijzen (2022, https://www.rijksoverheid.nl/actueel/nieuws/2022/12/16/kabinet-wil-verduurzaming-industrie-versnellen-als-tegenwicht-hoge-energieprijzen)

[9] European Commission – Innovative clean technologies can make energy-intensive industries climate neutral (2023, https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/innovative-clean-technologies-can-make-energy-intensive-industries-climate-neutral-2023-06-22_en)

Compared to Europe, the Netherlands has a relatively large energy-intensive industry and energy sector. Energy-intensive industries produce many products for export, such as steel, oil, gas and chemicals, as well as products for everyday life, such as zinc (for high-tech products), glass (for infrastructure) and cement (for infrastructure). In Europe, these industries accounted for about 15% of EU emissions in 2019[9], and in the Netherlands, these industries accounted for about 30% of Dutch CO_2 emissions in 2022[10]. Structurally rising energy prices threaten the ability of companies to explore sustainable alternatives, and thus the Netherlands as a location for energy-intensive industries. The challenge for the Dutch government is therefore to reduce emissions while ensuring that the industry remains competitive, and to position itself to exploit the huge potential of the global market for low-emission technologies and services.

Socio-economic: Iron Power is a solution for companies that are not connected to the hydrogen network to decarbonize their processes to ensure their continuity.

It is expected that the hydrogen network in the Netherlands and elsewhere will not be able to supply energy to all companies. This will jeopardize the continuity of companies not connected to the hydrogen network if they cannot find another way to achieve the energy transition. If companies have to relocate or cease operations, unemployment will rise in these sizeable sectors, negatively impacting Dutch GDP. Iron Powder, on the other hand, can store and transport energy to locations that will not be connected to the hydrogen grid, giving these companies the opportunity to switch to renewable energy and keep their license to operate.

Economic: The Iron Power program will open new global markets.

Once Iron Power's technology is proven and commercialized, it can be sold around the world. If the Netherlands takes a leading position in the development of this technology, it will not only decarbonize its own industry, but also open up new global markets. Moreover, the expertise, facilities and value chain partners present in the Netherlands will attract innovative companies, talent and capital, strengthening the country's economy and international competitiveness.

As technology is currently building on hydrogen innovation, the size and growth of the market will be partially driven by the hydrogen market. The global hydrogen market was estimated to exceed 150 billion in 2021 and is expected to grow at more than 9% per year until 2030[11]. The iron powder market will grow and possibly even surpass the global hydrogen market as penetration rates increase.

The market for iron powder as an energy carrier includes the sale of energy to companies not connected to the hydrogen grid, such as Cluster 6, district heating, building heating and converted power plants. Currently, the market size for "polluting" energy in these sectors in the Netherlands exceeds €1 billion (2023) (see Figure 6). Iron powder can fulfill heat demand within Cluster 6. The high-quality heat demand within the companies in the cluster is currently 4.5-5.5 TWh, and is expected to grow by 1% per year. Since the Netherlands will have one of the most developed hydrogen networks in the world, the global market potential for iron powder is even greater. Countries that are expected to have underdeveloped hydrogen networks, such as Poland, France and many others outside Europe, will become major buyers of Dutch-produced iron powder.

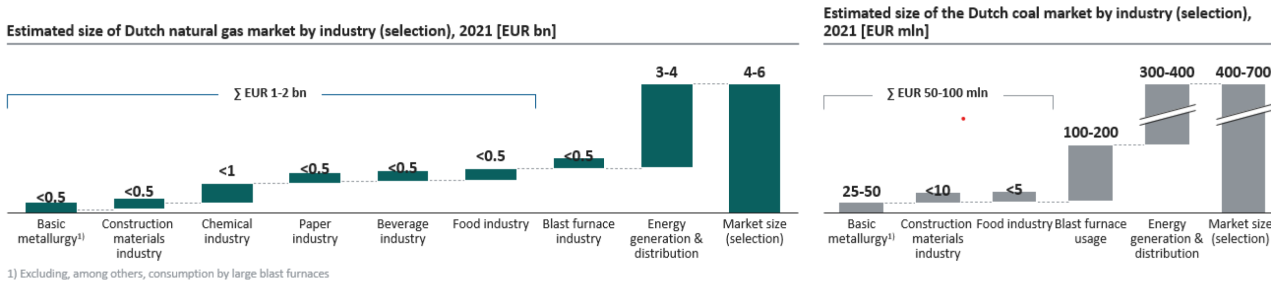

Figure 6: Estimated market size of natural gas and coal in selected industries in the Netherlands[12,13]

In addition, another important market is the supply of equipment/systems required for iron powder production in Europe and the rest of the world. This market includes technologies required along the iron powder value chain, from reduction and oxidation processes, transportation equipment and storage facilities to iron oxide treatment and reconversion. The Iron Power program will therefore also provide new opportunities for the development and sale of such technologies.

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[10] Water Energy Solutions - CES Cluster 6 – Cluster Energie Strategie (2022, https://www.nldigital.nl/wp-content/uploads/2022/03/Cluster-Energie-Strategie-Cluster-6.pdf)
[11] Grand View Research - Hydrogen Generation Market Size, Share & Trends Analysis Report By System (2021, https://www.grandviewresearch.com/industry-analysis/hydrogen-generation-market)
[12] CBS - Energiebalans; aanbod en verbruik, sector (2021, https://opendata.cbs.nl/statline/#/CBS/nl/dataset/83989NED/table?ts=1691579782984)
[13] CBS – Aardgas en elektriciteit, gemiddelde prijzen van eindverbruikers (2021, https://www.cbs.nl/nl-nl/cijfers/detail/81309NED#shortTableDescription)

Given its pioneering role in the hydrogen economy and preparations for an iron powder value chain, the Netherlands is well positioned to take a leading role in this new technology.

To create a robust iron powder value chain, reduce costs and increase investment, technologies need to be applied at an increasingly large scale. This requires an ecosystem that connects R&D and pilots with large-scale commercial applications. The Netherlands already has such an ecosystem. The Netherlands is one of the largest producers and processors of hydrogen in Europe, and is taking this a step further by leading the hydrogen economy - and thus the energy transition - globally by providing support and investment in green hydrogen projects (e.g., Green Power) to lower prices and promote green hydrogen development. The Netherlands aims to roll out an electrolysis capacity of 3-4 GW by 2030. In addition, the Netherlands is also investing heavily in hydrogen infrastructure development through Gasunie's planned hydrogen network projects and is developing knowledge and expertise in this field (e.g. Hydrohub MW Test Center, HyLabNL Multi-Purpose Hydrogen Test Center). The Iron Power program will make the Dutch hydrogen strategy more robust by providing a sustainable way to store and transport energy, respond to peaks in demand and production surpluses, and supply industries not connected to the hydrogen network. At the same time, the Netherlands is taking a leading role in accelerating the transition to a green steel industry by supporting projects such as "Growing with Green Steel." In addition, the Iron Power program can potentially strengthen this green steel strategy by providing a method to produce green steel (i.e., *Direct Reduced Iron*).

The Dutch industry is extremely well positioned to capture a significant part of the iron powder value chain and become a global market leader (see Figure 8). Much of the iron powder value chain can be obtained in the Netherlands or exported by Dutch industry, especially in the areas of storage and equipment production - these sectors are known for their high efficiency. Besides the internationally leading VDL in the field of equipment production, the Netherlands already has two Iron Power *champions* (RIFT and Iron+) leading in technology development, and the number of Iron Power start-ups is growing rapidly. World leaders such as ArcelorMittal and Tata Steel will be able to develop and implement iron powder raw materials and technologies once proven, companies such as Port of Rotterdam can adapt/implement import, storage and transshipment methods, and multinationals such as Shell and Uniper can accelerate global exports.

Finally, the Netherlands hosts leading academic and research institutions in renewable energy and the new Iron Power technology, including TNO, TU/e and Metalot (see Box 4). These organizations will foster innovation and R&D to ensure that the ecosystem continues to develop.

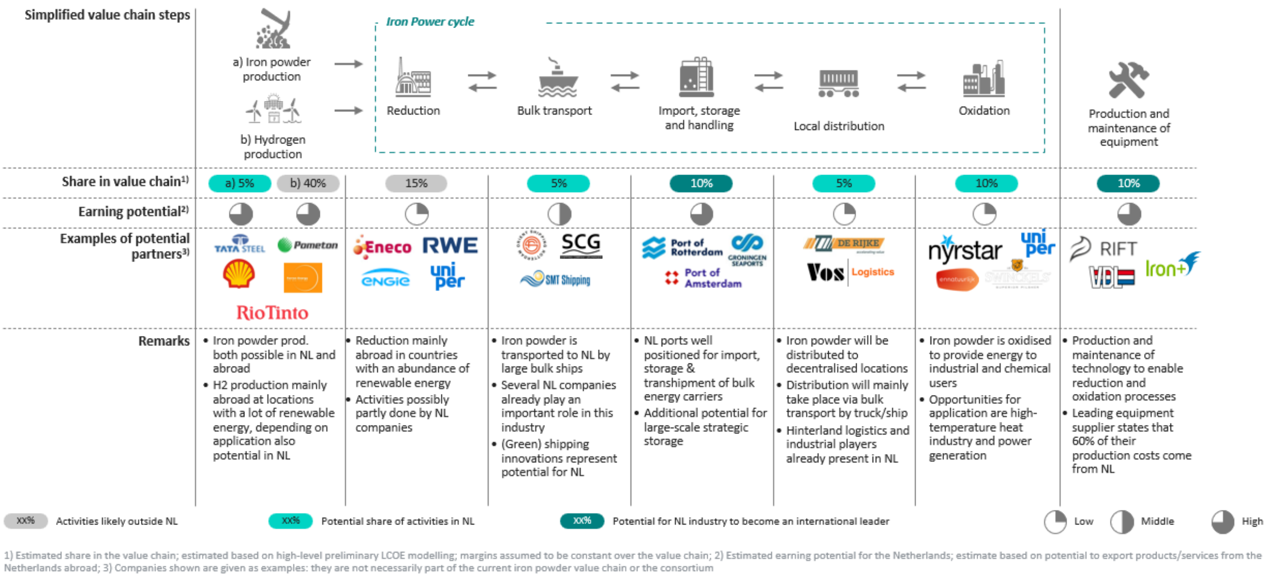

Figure 7: Presence of the Dutch industry in the iron powder value chain

Box 4: The strength of the Dutch Iron Power consortium

In 2015, far ahead of others, TU/e and Metalot founded the Iron Power consortium. In addition to an extensive portfolio of academic research, they have organized valorization/ecosystem activities around Iron Power technology - leading to the establishment of 7 successful startups. The core consortium of the Iron Power program consists of five leading knowledge institutions and market leaders in iron powder technology: TU/e, TNO, Metalot, RIFT and Iron+ (a group awarded the "Best Team Science award" of the TU/e Science Awards). The core consortium pools its knowledge and expertise to close the Iron Power value chain and solidify a thriving Iron Power ecosystem:

- **TU/e** ranks among the absolute world's top technical universities and is considered a leader in Iron Power research. Among others, they have received the prestigious "ERC Advanced Grant" and "ERC PoC Grant". The university has high-quality equipment and is involved in the development of innovative SOEC and ICONIC technologies to improve the competitiveness of iron powder.
- **TNO** is the knowledge and research institute in the Netherlands. TNO is internationally respected and is active in practical research on metal fuels in the areas of transportation, storage and applications. TNO has already published several papers on the feasibility and competitiveness of metal fuels.
- **Metalot** is the first umbrella Iron Power organization that bridges the knowledge and expertise of scientists, entrepreneurs and the market. In the Metalot Future Energy Lab, large-scale iron powder technology can be tested and developed. In addition, Metalot facilitates the Ironfuel platform, the Metalot community and cooperation with students from team SOLID (see Box 10).
- **RIFT** is one of the leaders in Iron Power technology. They developed the first operational 1 MW Iron Power boiler plant for Ennatuurlijk's district heating network, providing ~500 homes with heat. RIFT's technology has now been rewarded with an EnergyBreakthrough investment from the Bill Gates Foundation and the Brainport Gerard and Anton Award.
- **Iron+** is one of the leaders in Iron Power technology. Iron+ developed one of the first 1 MW Iron Power boiler plants to supply sustainable process heat to the Bavaria brewery in Lieshout
.

In addition, Dutch Iron Power consortium has strengthened its position by seeking international collaborations with leading parties to jointly further launch Iron Power technology.

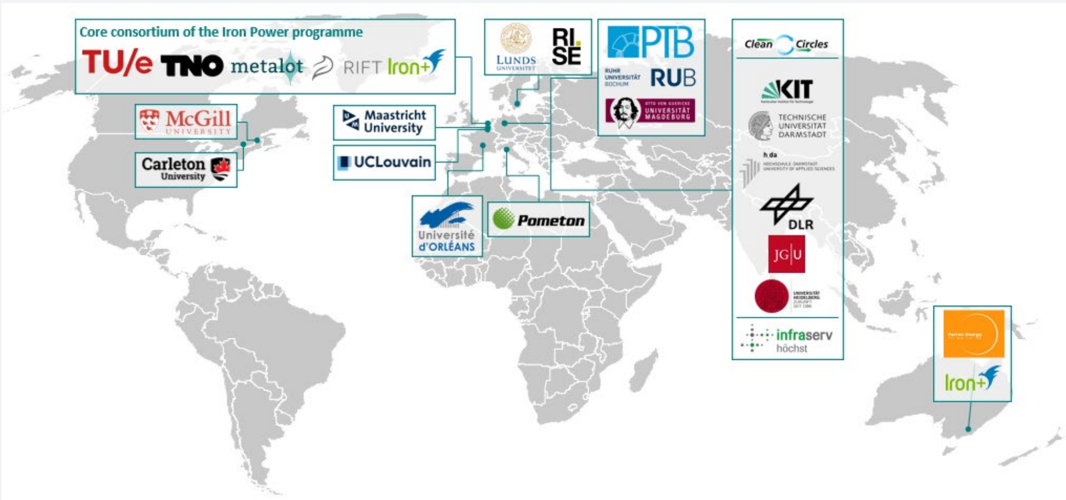

Figure 8: The Iron Power program core consortium and ecosystem

2.3 CHALLENGES

Iron Power technology, which uses iron powder as an energy carrier, has not yet been widely implemented commercially due to technical challenges, low market interest, lack of awareness and insufficient cooperation in the value chain.

Iron powder is gaining popularity among researchers and industry, but cannot get off the ground on its own. The new energy carrier faces four obstacles that prevent scale and wide market acceptance.

(1) Technical challenges - Scientists are convinced of the potential of iron powder, but cannot make the leap in development.

Many scientists are researching iron powder sub-technologies, and some sub-technologies have reached advanced stages. Nevertheless, several obstacles prevent research from making large TRL jumps. Related technology areas require significant research to realize the potential of iron powder and validate its advantages over alternatives. This maintains the market dominance of alternatives such as natural gas. For example, oxidation technology is still at a low TRL level (~6), making it still relatively inefficient (iron powder loss, powder breakage), harmful (fine particle contamination) and not yet sufficiently circular (low iron oxide recovery rate). Moreover, different solution paths for reduction and oxidation are being pursued by different parts of the market, which limits the diffusion of the knowledge and techniques (research results) being researched and developed. To make the technological and ultimately commercial leap, a push is needed to establish a comprehensive research program that explores all possibilities (sub-technologies and applications of iron powder) and reaches industry participants.

Comparatively, innovative start-ups, scale-ups and SMEs lack access to appropriate laboratories and experimental environments to test and prove their innovations on an increasingly large scale. Such testing facilities require structural investments too high for a single company, and as a result multiple innovations fail to get past the initial development stage.

(2) Little market interest - Iron powder is promising, but high costs and investment risks limit interest.

Although the prospects for iron powder are promising and the energy carrier is essential for the energy transition, market interest in the energy carrier is tempered. This is mainly because iron power is not yet cost-effective compared to fossil fuels and the business case still has risks.

Iron Power technology is not yet cost-effective compared to fossil fuel-based or even most hydrogen-based energy solutions. Despite the Carbon Credit system, fossil fuels are still cheaper than hydrogen. Innovations that build on the hydrogen value chain are therefore even more expensive. Until the price of hydrogen falls to market-competitive values, market interest in iron powder will remain low.

The broader business case for iron powder, beyond market prices, also challenges the current market potential. Although Iron Power technology is promising, it is not yet proven on a commercial scale, and the use of iron powder as an energy carrier is a new development. Public investment is needed to fund initial use scenarios and prove to future private investors that this technology is commercially feasible and viable.

(3) Lack of awareness and training - Generally, only known energy carriers get the attention of the public, government and training organizations.

Many people have little to no knowledge of the existence of Iron Power technology, nor of its potential. Well-known energy carriers such as hydrogen, ammonia and methanol, and decarbonization technologies such as CCS, have received more attention from the public and government over the past decade, for example, grants have become available to companies willing to implement such solutions. Without such awareness, which often comes in the form of R&D funding and regulatory considerations, iron powder development is delayed.

The energy transition requires talents who will carry and accomplish this energy transition into the future. Despite the enormous shortage[14] in the labour market that does not seem to be resolved in the medium term, large-scale training programs have been set up for people who will carry the energy transition at the WO, HBO and MBO levels. However, little attention has so far been paid within these courses to Iron Power technology and the impact it will have. Government support, complemented by increased educational efforts, will generate the awareness the technology needs to take the next steps in technical and commercial development and implementation.

(4) Insufficient unity and cooperation in the value chain - A divided innovation landscape and lack of leadership prevent the systemic change needed for iron powder.

Iron powder is not only a new technology to decarbonize industries, but it is also a complete value chain solution. To adapt the energy system to iron powder, many different parties must work together. Most research groups work on separate topics and in isolated structures, limiting joint research opportunities and knowledge sharing. Moreover, many parties have committed to hydrogen as the (only) solution for energy-intensive industries, overlooking the fact that the energy transition requires the deployment of multiple solutions (energy mix)

[14] Techniek Nederland - Labour Market Shortage Attack Plan Engineering, Construction and Energy. (2022, https://www.technieknederland.nl/stream/aanvalsplan-techniek-nov-2022)

simultaneously to decarbonize the economy. Even in the field of iron power itself, different approaches from different market areas are being explored (e.g. reduction by *fluidized bed*, plasma or *flash*) with hardly any cooperation nor knowledge sharing. A central Iron Power ecosystem could play a leading role and bring together the many industries, sectors and players in the value chain to integrally take Iron Power technology to the next level.

Box 5: Legitimacy of government intervention

The appropriate tool to accelerate the energy transition through the Iron Power program is government subsidy. The (currently) high cost of fuel makes it unattractive for the market to take the lead in technologies that build on the hydrogen chain. Combined with remaining bottlenecks in technology development, this leads to **market failure**: private parties have no (financial) incentive to invest in Iron Power technology.

In addition, there is also **system failure**. The "climate cost" of harmful emissions is not priced, so sustainable energy systems, currently more expensive than fossil alternatives, are not developed and tested on a large scale. Paying for and standardizing emissions as stipulated in 'Fit for 55' will only provide an incentive to invest extra in new sustainability solutions such as Iron Power after 2030. This leaves necessary development behind, fails to achieve the scale needed to reduce costs, and prevents market demand for Iron Power from taking off. This failure delays the transition to sustainable energy carriers in the energy-intensive industry, and inhibits the Dutch manufacturing industry that is willing to develop these innovations.

Although stricter laws and regulations can create a level playing field between fossil and renewable, this does not solve the market and system failure. One factor hindering the adoption of Iron Powder technology in the market is the currently high cost of green hydrogen. **This requires government intervention through structural policy measures from governments**. Among other things, this sends a clear signal about the need for greater diversity of energy carriers to enable the energy transition for the entire industry, makes the necessary technological leaps, addresses and resolves ecosystem bottlenecks, and mobilizes the private sector. The impetus also enables the Netherlands to obtain a leading role and benefit economically and socially from this.

2.4 PURPOSE

The Iron Power program aims to build an ecosystem using iron powder as a clean, safe and cost-effective energy carrier for import, export and storage to decarbonize energy-intensive industries.

The Iron Power program's ambition is to accelerate the development of Iron Power technology as a promising and essential energy solution. This is done by demonstrating that it is possible, helping researchers and companies scale up, and implement the solution, with the goal of decarbonizing energy-intensive industries.

The ambition of the Iron Power program is threefold: economic, strategic and sustainability impact. The economic goals are:

(1) Achieve strength in Iron Power technology and market: The Iron Power program will advance the TRL of the technology, which industry and the private sector can then further develop into commercial products and make scalable for wider use, including export. Iron Power technology will provide struggling industries without anticipated access to the hydrogen grid a way to decarbonize their operations, renew their license and become more internationally competitive.

(2) Building an established, international value chain around Iron Power: The Iron Power program will work with international parties to create solutions across the value chain to make the technology cost-effective and thus part of the global renewable energy mix.

The strategic goals are:

(3) Strengthen strategic independence: The Iron Power program will open up an additional value chain, whose raw materials are not controlled by only a few countries - this increases the Netherlands' independence from traditional energy exporting countries such as Russia.

(4) Improvement of the Dutch investment climate: The availability of Iron Power in the Netherlands as a green solution, for industries without direct access to renewable energy sources, will create an attractive climate for companies to invest and locate.

The sustainability goals of the Iron Power program are:

(5) Improve the direct environment of energy-intensive businesses: By significantly reducing CO_2, NO_x and SO_x emissions, Iron Power will improve the direct environment of industrial operations and reduce overall national emissions.

(6) Improving access to clean energy and knowledge: The Iron Power program will build an ecosystem around Iron Power technology to improve general awareness, share knowledge about Iron Power technology and make Iron Power energy accessible to industry.

In line with these ambitions, the Iron Power program formulates **concrete objectives** for the investment period of the National Growth Fund until 2035 (see Table 1).

Table 1: Ambitions and concrete objectives of the Iron Power program

Ambitions	Concrete target (in 2035, unless otherwise stated)
Economic **(1) Strong position in Iron Power technology and market** **(2) Established, international value chain**	• **More than 5 Iron Power technologies** have been successfully developed from TRL 2/3 to TRL 6 during the Iron Power program • **More than 5 Iron Power technologies** have reached TRL 8 during the Iron Power program and are commercially viable • **More than EUR 100mln annual sales** from companies supplying iron powder systems and equipment (Iron Power champions) • **More than EUR 30 mln additional** sales per year as a result of the retention and improved competitive position of energy-intensive companies in the Netherlands • **More than 5 successful product/service concepts** (spin-offs generating turnover) partly thanks to the support of the Innovation Infrastructure • More than **5 end-to-end Iron Power value chains** tested on a >1 MW scale • **10-30 parties per year** using the Services of the Innovation infrastructure
Strategic **(3) Strengthen strategic independence.** **(4) Improve the Dutch investment climate**	• **More than 60 TWh/year of industrial process** heat supplied by Iron Power technologies (by 2050) • **More than 30 (international) companies** affiliated with the Iron Power Community
Durability **(5) Reduced emissions (CO_2, NO_x and SO_x) from industries difficult to decarbonize** **(6) Improved access to clean energy and knowledge**	• **Over 180 mmt GHG-eq/TWh avoided emissions** per year through the use of Iron Power for industrial process heat (by 2050) • **More than 200 students and 50 professionals trained** in Iron Power technology through the materials produced by the Talents Service • **More than 40 additional papers published** in the field of Iron Power technology as a result of the Iron Power program

2.5 SUGGESTED SOLUTION

2.5.1 IRON POWER PROGRAM

The Iron Power program is based on three strengthening pillars: (1) R&D, (2) Pilots & demos demonstrations, (3) and Innovation infrastructure.

The core consortium partners - Metalot, TU/e, TNO, Iron+ and RIFT - all share the goal of accelerating the development of Iron Power as an energy solution and overcoming the obstacles holding back the technology. The Iron Power program therefore aims to create a world-leading ecosystem based in the Netherlands. At its core, the questions that the companies in the ecosystem are trying to answer will focus on the process of making iron powder a sustainable energy source/carrier for energy-intensive industries and district heating, for example. The program is based on three mutually reinforcing pillars (see Figure 9).

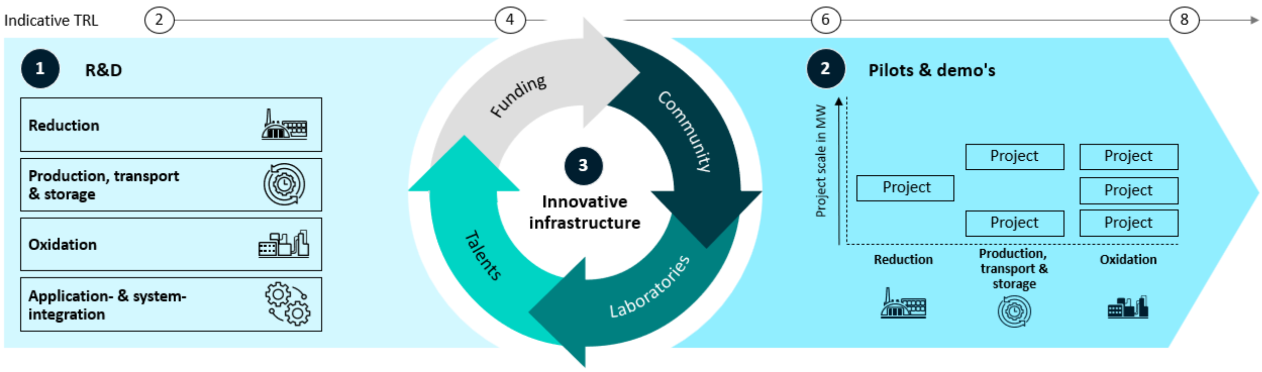

Figure 9: Iron Power Program

1. **R&D**: The Iron Power program will conduct research and development projects along the value chain in four themes: 1) Reduction, 2) Production, Transport & Storage, 3) Oxidation and 4) Application & Systems Integration. Each of the projects aims to answer existing fundamental questions about Iron Power technology, or research specific applications (new or improved) of Iron Power technology. These projects will take place in a public-private environment, with academics and industry working together. Lessons from the R&D projects can be applied to the pillars of Pilots and Demos and Innovation Infrastructure, strengthening the innovation ecosystem.

2. **Pilots & demos**: there are Iron Power technologies proven in basic/industrial research that will be tested in pilot and demo projects. The projects in the portfolio will differ in focus (value chain theme) and in TRL. The goal of these projects is to test technologies (to obtain Proof of Concept (PoC)) until they are commercially proven. These projects will take place in an industrial environment with established industrial partners. The lessons and technologies from the pilot and demo projects will also contribute to the Innovation Infrastructure Pillar.

3. **Innovation infrastructure**: the R&D and pilot and demo pillars result in expertise and resources (e.g., knowledge, expertise, facilities, experimental setups and partner networks) that will be used and transformed into services. These services will (1) provide access to Laboratories for experimental testing, (2) provide access to a Community of Iron Power experts to realize the value chain and set up experiments, share experiences and perform simultaneous engineering, (3) provide challenges and courses for Talents (professionals and students), (4) provide easier access to public Funding and private funds. The goal of Innovation Infrastructure services is to obtain TRL and ecosystem growth, related to Laboratories, Community, Talents and Funding. Infrastructure services for key partners will become financially self-sustaining through payment per use/membership from customers, combined with ongoing contributions from partners (education partners). After the momentum period, the Innovation Infrastructure will continue to encourage and enthuse spin-offs/start-ups and existing companies to join the Iron Power Community and start the next wave of R&D and pilot and demo projects.

Box 6: Effectiveness of the Iron Power program.
Each bottleneck (mentioned in Chapter 2.3) is addressed by one or more key components of the Iron Power program. In addition to addressing the listed bottlenecks, the Iron Power program also strengthens the transition in the steel market to Direct Reduced Iron (DRI). The infrastructure solution for availability of green hydrogen is partially outside of this NGF proposal. However, the Iron Power program does align with market participants who will develop this infrastructure.

	Bottlenecks	R&D	Pilots and demos	Innovative infrastructure
KP 1. Technical challenges	No proven Iron Power technology	Low TRL technologies are validated and optimised by R&D projects	High TRL technologies are proven by setting up pilot and demo projects at different scales, and applications	The Laboratory provides parties with access to test environments where technologies can take the necessary TRL development steps
KP 1. Technical challenges	Minimal knowledge sharing between disciplines	The integrated project approach (collaborative) ensures knowledge sharing across disciplines and provides a clear development path to higher TRL levels (R&D to commercialisation)		Innovation infrastructure introduces Iron Power standards for benchmarking in the Laboratory and shares knowledge in the Community and beyond
KP 1. Technical challenges	No 'one size fits all' Iron Power solution	The project portfolio, across different value chain links, set-ups, capacities, and end-markets, ensures widely deployable solutions		The Laboratory supports Iron Power's future feasibility studies within new domains/applications
KP 1. Technical challenges	No access to necessary infrastructure	N/A	N/A	Innovation infrastructure services give researchers/companies access to technology testing/innovation platforms, education and funding
KP 2. Low market interest	Bottleneck 1, 3, and 4 provide a non-cost-competitive solution	Efficiency studies will improve the performance of the technology and thus reduce costs	Realising pilots will stimulate demand for iron powder/hydrogen which will increase supply and reduce price	The Laboratory provides parties with access to more affordable testing environments that will reduce development costs
KP 2. Low market interest	Use cases and/or pilot set-ups missing	N/A	Realising pilots with industrial partners will increase market confidence and interest in Iron Power technology	The Laboratory gives researchers/companies access to sample set-ups on which experiments can be done
KP 3. Low awareness	Low awareness among universities, HBOs and MBOs	Projects are carried out in collaborations with various universities and industry partners	N/A	The Talent Service aims to train future talents by enriching existing education, and establishing new educational subjects with a focus on Iron Power technology, and also to improve awareness within schools, MBO, HBO, universities, companies, and governments (in the Community)
KP 3. Low awareness	Low awareness among businesses & governments	Projects are carried out in collaborations with various universities and industry partners		
KP 4. Value chain leadership	"'All eyes on hydrogen' to make energy transition	The projects and activities aim to prove Iron Power technologies - Iron Power technology is integral to the hydrogen value chain. Iron Power will further strengthen the hydrogen business case and thus the transition. In addition, Iron Power technology will be available to all parties, including those that will not have direct access to green hydrogen.		
KP 4. Value chain leadership	Lack of coordination across the value chain	The projects focus both on all link solutions (e.g. oxidation), and whole system solutions (entire value chain)		The programme takes initiative in this divided landscape by collaboratively strengthening and directing the ecosystem

Figure 10: Effectiveness of the Iron Power program

2.5.2 PILLAR I - R&D

R&D projects are established to research the technological challenges of the Iron Power cycle, to raise the TRL level of Iron Power technologies, and to prove the potential of Iron Power in various use cases.

The projects are aimed at investigating and addressing the key technological challenges facing Iron Power technology to remove one of the obstacles to further development and commercialization of Iron Power (as mentioned in Chapter 2). The research will focus both on fundamentally new Iron Power technologies and on improving already known sub-technologies in a broad collaborative framework. Knowledge and results from the R&D projects can be applied first in the Field lab (see Chapter 2.5.4) and then in small-scale pilot projects (see Chapter 2.5.3) to validate or improve results. The successes achieved in the R&D projects will be able to be implemented and tested in the pilot and demo environment, thereby directly contributing to raising the TRL level. Moreover, the knowledge and expertise gained during the projects (e.g., methodology, results) can be used to improve the services offered to potential customers (see section 2.5.5).

Each R&D project has been carefully chosen so that the R&D project portfolio addresses key challenges along the entire Iron Power value chain. Therefore, projects have been defined in the following four value chain themes (see Figure 11): (1) Reduction, (2) Production, Transportation and Storage, (3) Oxidation, (4) Application and System Integration. This value chain approach ensures improvement and scale-up of the entire Iron Power technology.

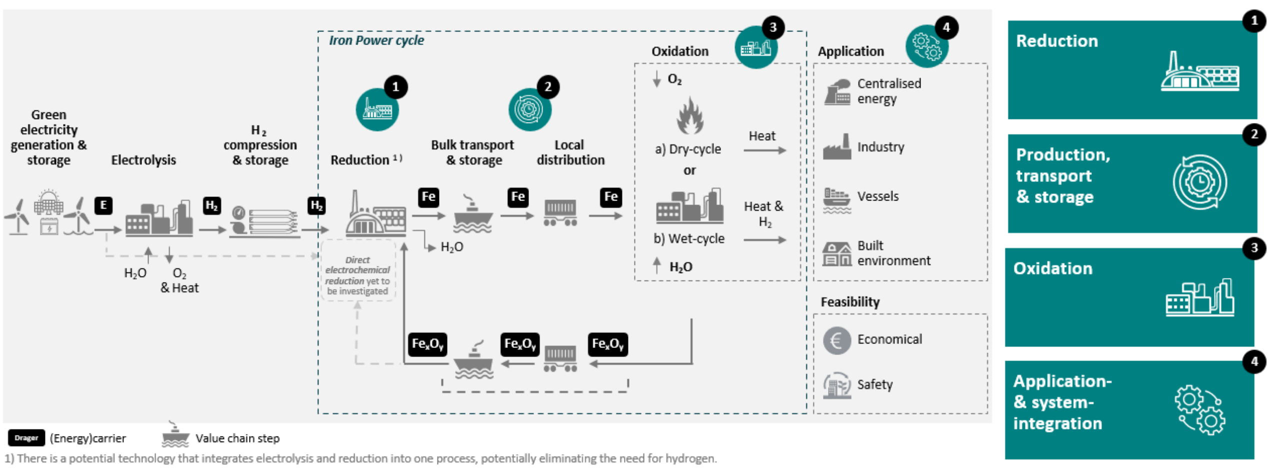

Figure 11: R&D value chain themes

Each of the four themes has its own goal:

- The goal of **reduction projects** is to increase conversion efficiency, improve circularity and increase reaction speed to eventually optimize existing reduction techniques at different temperatures and develop new reduction techniques.
- The goal of **production, transportation and storage projects** is to increase the efficiency of the full cycle by optimizing and standardizing the characteristics of iron powder, investigating various iron residue streams from industry for use within the Iron Power cycle, and improving existing (regular) powder storage methods to use them for iron powder storage.
- The goal of **oxidation projects** is to increase reconversion efficiency and reduce emissions by developing and improving various oxidation methods, resulting in increased stability, reduction of losses and optimized circularity of the overall process.
- The goal of **application and system integration projects** is to improve safe and economic use of iron powder by focusing on the high-temperature heating industry, exploring alternative applications such as wet-cycle oxidation (hydrogen production), analysing retrofit options, developing safety regulations, developing business models and improving integration with existing and new energy infrastructure.

The projects within each theme have been chosen so that the "challenge" in each research project is different, to ensure broad coverage of the solution area. Technology setbacks may occur during the program, given the relatively low TRL level of the technology and the complexity of optimization. GO/NO-GO milestones will be used along the way to intervene if necessary. In any case, the Iron Power technology and its market potential will have been proven and the optimization potential significantly explored due to the systematic approach of the R&D projects.

2.5.3 PILLAR II - PILOTS & DEMOS

Pilot and demo projects are used to prove the feasibility and potential of Iron Power technologies with a high TRL level in different industrial environments.

Several basic Iron Power technologies have demonstrated in research (basic/experimental) their potential for success. The pilot and demo projects will focus on these technologies by testing them in an experimental environment to prove the potential of the technologies in first-of-a-kind facilities. The experimental setups created in these projects will serve (in addition to the Innovation Infrastructure Laboratories) as testing environments for further development of the technologies, thereby raising the TRL level. Thus, like the Innovation infrastructure, the pilot projects are an experimental space for new sub-technologies of iron powder flowing from the R&D projects. The main research question will be similar for each pilot and demo project: *Is the Iron Power (sub-)technology a viable innovation that can be used in an industrial environment, or does it have potential to become so in the future?* The knowledge, equipment and experimental setups proven in the projects will be used by the Innovation infrastructure pillar to develop services for future users (e.g., providing test environments for future Iron Power sub-technologies).

The portfolio of pilot and demo projects is carefully selected so that it covers the different **(i) development phases/scales**, encompasses the entire **(ii) value chain position** and thus closes the chain, tests and demonstrates different **(iii) technology platforms**, encompasses different **(iv) end-use applications**, and **(v)** enables **operational learning** (e.g., maintenance cycles and long-term reliability).

- **Development phases / scales** - Pilot and demo projects are conducted at different scales (5 to 20 MW). This approach allows technologies with a relatively low TRL level to be tested on a smaller scale and technologies with a high TRL level to be tested on a larger scale.
- **Value chain** positions - Iron Power technology can only be commercially established if the entire value chain develops and becomes connected: reduction, transportation and storage, and oxidation. Without the reduction technology, there is no iron powder for oxidation, and without oxidation (including reconversion), there is no iron oxide to reuse in the reduction step. Ultimately, this should lead to the development of an international iron powder market that provides access to affordable green molecules, helping to reduce overall costs.
- **Technology platforms** - Iron Power technology depends on several technology developments, such as *fluidized bed*, *rotating drum* or *furnace/moving belt reduction* to regenerate iron powder. Each of these technology developments needs to be tested and demonstrated.
- **Application & System Integrations** - The end-use application is needed to explore the potential and challenges of Iron Power technology in different end-use settings (high temperature / low temperature). Iron Power oxidation technology as a heat source in district heating faces different challenges than Iron Power technology as direct heat in, for example, the process industry.
- **Operational Settings** - By creating several first-of-a-kind pilots at different sites/industrial environments (e.g., peak/medium load, hybrid/multi-fuel), experience is gained on equipment lifetime performance and insight into

opportunities for operational efficiencies. The goal is to reduce future operational expenses of Iron Power technology.

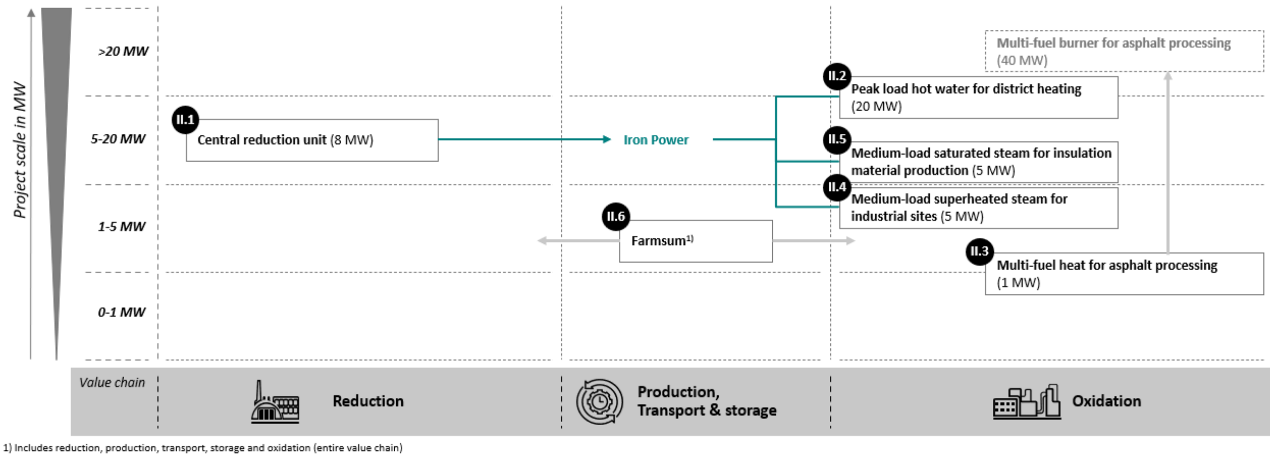

Figure 12: Projectportfolio Pilots and demo's

The pilot and demo projects of the Iron Power program are:

- **Project II.1 Central reduction unit -** This project is a pilot of an 8 MW reduction unit at a strategic location (including local storage and transportation), which produces iron powder as input for the oxidation projects.
- **Project II.2 Peak load hot water for district heating** - This pilot project is a 20 MW peak load boiler (low temperature) to produce hot water for district heating.
- **Project II.3 Multi fuel heat system for asphalt processing** - This pilot project is a 1 MW and (if successful) 40 MW multi fuel (hydrogen and iron powder) heat systems (high temperature) to be integrated with asphalt processing plants.
- **Project II.4 Medium load superheated steam for industrial sites** - This pilot project is a 5 MW medium load boiler to produce superheated steam for industrial sites.
- **Project II.5 Mid-load saturated steam for insulation material production -** This pilot project is a 5 MW mid-load steam production boiler capable of on/off switching (e.g. during weekends) for a special application in the chemical industry.
- **Project II.6 Farmsum** - This pilot project includes the Iron Power value chain with four companies to produce hydrogen, iron powder, oxidation to provide heat/energy and iron oxide reconversion.

2.5.4 PILLAR III - INNOVATION INFRASTRUCTURE

Knowledge, expertise, experimental setups and partner networks built can be leveraged to create services aimed at future users of Innovation infrastructure.

Within the pilots & demos pillar, the Iron Power program will develop expertise, facilities (equipment and experimental setups), a partner network and successful methods to set up/implement projects that can be leveraged to support and lead the transition to Iron Power as a sustainable energy carrier. Together with the expertise and knowledge gained from the R&D projects, **services** will be developed for institutions and companies interested in Iron Power technology. The central base will be the laboratory facilities (to be realized), where public and private (international) partners can jointly work on Iron Power technology challenges. The services offered by the Innovation Infrastructure are aimed at accelerating TRL gains, valorizing innovations and promoting ecosystem growth. Moreover, these services will be an integral part of the sustainable Iron Power business model.

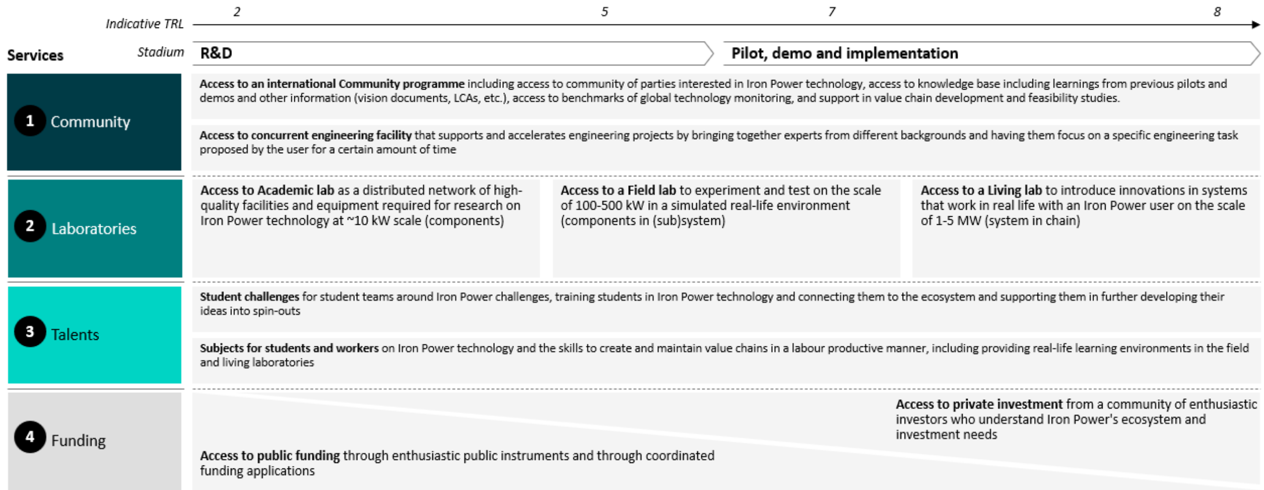

Figure 13: Innovative infrastructure services

The Innovation Infrastructure offers four types of services (see Figure 13):

- **Community**: Scaling up, implementing and widely applying Iron Power requires innovators and stakeholders to jointly establish value chains and value chain experiments. The Community Service provides innovators (Community members) access to an international Community program and a concurrent engineering facility and associated process support with experience in leading/designing concurrent engineering sprints.
- **Laboratories**: Overcoming technical challenges and scaling up Iron Power innovations requires testing on an increasingly large scale and in increasingly realistic environments. However, access to such environments is limited, limiting Iron Power's innovation capacity in the Netherlands. The Laboratories services bridge this innovation barrier by providing innovators (researchers and/or companies) access to three laboratories - and the associated knowledge to use them and design experiments - to test and scale their innovations across the (TRL) chain. The Service provides access to an Academic lab for small-scale research (TRL 1-3), a Field lab for practical studies (TRL 3-5) and a Living lab for studies on the entire chain in an operating environment.
- **Talents**: The success of the program requires trained talents with the skills to build and maintain Iron Power value chains. The Talents Service provides challenges for students by working with Iron Power experts on challenging and socially relevant issues and using the program's laboratories for their activities. In addition, given the tight labour market for technical personnel, the program offers courses to students (WO/HBO/MBO level) and professionals to prepare or retrain talents for a role in the value chain (maintenance, logistics, regulations, among others), as well as to innovate in a more labour-productive way.
- **Funding**: Iron Power innovators need significant investment to develop and scale their technologies and build value chains. The Funding Service provides enhanced access to funding, through public financing of public instruments and through coordinated assistance with funding applications, and access to a private investor community actively seeking opportunities in the ecosystem. The Funding Service also provides support to parties who want to use ecosystem services but cannot yet afford to do so. In that case, the Iron Power program offers deferred payment or equity payment options.

2.5.5 STRUCTURAL EMBEDDING

The R&D and Pilots and demos pillars are closely linked to and strengthen the Services of the Innovation infrastructure. The Pilots and demos provide scaled and developed technologies that can be used to develop Services that can be valorised for a broader ecosystem within the Netherlands and beyond. In addition, the knowledge and expertise gathered in the R&D projects will be used to broaden and/or deepen the Services of the Innovation infrastructure. The Iron Power program will be structurally embedded in the Dutch innovation ecosystem as the Iron Power innovation will prove itself and the Services become self-sustaining. The activities to be undertaken in the defined R&D and Pilot and demo projects within this program are time-bound. However, the Innovation infrastructure will remain beyond the investment horizon. The infrastructure built and proven by this program will be funded beyond the term of this initiative from fees from customers (pay-per-use and membership models) and dedicated long-term partners that will strengthen the innovation ecosystem in the long term. Enthusiastic national and international customers will be attracted to the Iron Power program - through the accelerated development and proof of Iron Power potential on an industrial scale, and the facilities - to research, develop or test Iron Power technologies. Furthermore, the (sub)services will create a new "economy" with companies (existing or spin-outs) developing technologies and/or services, which can be marketed internationally.

Box 7: Effectiveness of the Iron Power program.

The Iron Power program is designed to maximize the opportunities around setting up the value chain for Iron Power technology. The R&D, Pilot and Demo and Innovation infrastructure projects are designed to (i) demonstrate the potential of Iron Power in the energy transition; (ii) develop efficient methods and technologies along the entire value chain; and (iii) to develop an Iron Power ecosystem at the national and international level to promote cooperation and knowledge exchange. The entire portfolio of projects has been chosen so as to develop and optimize the various technologies needed along the value chain. Given that sound implementation is important to the success of the NGF program, executive activities under the Iron Power program will take place with different goals. It will be ensured that there is no overlap of activities and costs, the projects will accurately complement and reinforce each other. In addition, with the encouragement of spin-out activities, the outcomes of the projects will be maximally valorised and used to involve many companies and scientists in the Iron Power program.

The premise of the Iron Power program is to minimize implementation costs and use NGF resources efficiently and effectively. One way to reduce the investment is to implement fewer projects. However, a major drawback is that this creates a gap in the portfolio in the breadth of different technologies and methods needed to realize the Iron Power value chain. For example, all the Pilots and demos in the program are essential given that the projects explore different applications. Thus, while the basic "hardware" used for each project is similar, both the post-treatment (process and system integration) and parameterization are different for each application, resulting in different optimization processes for each system. The scrapping of projects is therefore at the expense of the impact this program can have on the energy transition.

A second option to reduce costs is to reduce the investment in the Innovation infrastructure. The downside to this is a less developed (inter)national ecosystem and talent service, both of which are crucial to the program given the international value chain that requires collaboration and knowledge sharing and the tight labour market.

In conclusion, for the Iron power program there is a careful consideration of scale and project portfolio that balances between limiting investment, scale developments needed, technology development and optimization, impact and ecosystem.

Table 2: General risks and dependencies for achieving objectives

Risk	Explanation	Mitigation measures
Further development outside the Netherlands	The possibility exists that large companies take over spin-offs and start-ups and locate operations outside the Netherlands, precipitating some of the effects abroad.	The Iron Power program forms a strong umbrella Community that spin-offs can be part of. This Community provides support, opportunities and knowledge to member companies, anchoring them in the ecosystem. This significantly reduces the likelihood of companies relocating abroad.
International competition	Other foreign universities, start-ups and developers could undermine the competitiveness of the Iron Power program and draw business away.	The Iron Power program will not compete with international parties, but rather seeks cooperation. The Community will be formed by both national and international parties pursuing a shared goal.
Availability of qualified staff	Due to the continuing tightness in the labour market, there is a risk that there will not be enough personnel available, with the right knowledge and abilities, to implement the plans in this program.	Through education and course programs for both students and professionals, as described in Section 2.5.4, covering all levels of training, the Iron Power Talents program aims to interest and train people in Iron Power technology.
Affordability of green hydrogen	Given that green hydrogen is the main cost driver in the Iron Power value chain, its affordability is a critical issue. There is a risk that costs will not fall enough to give iron power a competitive advantage as an energy carrier.	The Iron Power program includes projects investigating the optimization of iron powder production. One important research is the DER technology that eliminates the need for green hydrogen in iron powder production. The Iron Power program also undertakes projects in which relatively "low-cost" hydrogen is produced/imported (Farmsum and Central reduction unit projects, 3.1.2), and investigates cost reduction by integrating hydrogen production with reduction (SOEC reduction integration project, 2.5.2).
Regulatory constraints	The production, transport and storage of (hazardous) energy carriers is highly regulated at both European and national levels. This can limit the actual application of innovations in this domain.	The Iron Power program will establish an *Industry Advisory Board* with prominent opinion leaders who will represent the interests of the program. In addition, the program focuses on ongoing dialogue and coordination with regulators.
Social and scientific acceptance.	A lack of awareness and acceptance by both the general public and government may hinder the development of Iron Power technology.	The Iron Power program reaches a wide audience by establishing both a Community and a Talents program. The Community focuses on creating awareness through *out reach* presentations and events. The Talents program provides training and education to both students and professionals.

2.6 SUBSIDIARITY AND FLANKING POLICIES

The benefits of the Iron Power program accrue at the national level, an investment in the Iron Power program at the central government level is therefore appropriate, also the program is consistent with European policies.

Both energy-intensive industries and the built environment in the Netherlands will benefit from the Iron Power program. The program will not only facilitate but also accelerate the decarbonization of industries that may not be connected to the hydrogen grid. An investment by the national government from the Growth Fund is crucial to make the Iron Power program a reality. It is a strategic investment in the development of an ecosystem of great national importance and great international potential.

The central government is the appropriate level to provide support for the proposed project for the following reasons:

- The parties in the consortium at the national level should cooperate in the areas of R&D, Pilots & Demos and Innovation infrastructure.
- National cooperation makes it possible to pool expertise on a large scale, thus strengthening the international position of the program.
- The program fulfils both national goals and missions in the field of sustainability and decarbonization and sector-specific goals of the industry to achieve the climate objectives.
- The economic and social benefits (business activity, earning capacity, new knowledge and CO_2 reduction) largely precipitate at the national level and are of economic strategic importance by, among other things, reducing dependence on other countries.
- The program fits with the national mission-driven innovation policy developed from broad knowledge and innovation agendas for a future-proof Netherlands.

At the national level, the Iron Power program aligns with the "**Integral Knowledge and Innovation Agenda for Climate and Energy**" which highlights 16 multi-year mission-driven innovation programs for the period 2024-2027[15]. The program specifically aligns with the missions of Top Sector Energy, both "**Mission B - Built Environment**" and "**Mission C - Industry**". In addition, "**The Dutch Climate Agreement**" sets CO_2 reduction targets for industry. Finally, "**The Frontrunners Program The Sixth Cluster**" describes the plans that industries in the sixth cluster must undertake to meet the ambitious 2030 and 2050 climate goals[16]. Also, the Iron Power program aligns with mission-driven innovation policies of the Top Energy Sector[17] (on climate and energy, and circular economy themes), and the NWO National Science Agenda (Circular Economy, and Energy Transition).

The flanking policies of the central government form a strategic core in the dynamics of the innovation ecosystem. The long-standing policies of the Ministry of Economic Affairs and Climate and the Ministry of Education, Culture and Science describe, among other things, industry sustainability policies and the promotion of innovation[18]. The Iron Power program needs clear, reliable and calculable policies and timely licensing to enable investment. This requires both legislative and regulatory clarity at the national level and an incentive for new renewable initiatives, such as increasing carbon taxes. In addition, there is a risk of continued tightness in the labour market. Good training and working conditions within the sector remain priorities. Flanking policy focuses on a revaluation of vocational training at MBO and HBO level.

Box 8: International positioning of the Iron Power program

The realization of a new energy value chain requires both national and international cooperation, and Iron Power is no exception. All projects take place physically in the Netherlands, but international partners are needed for supply, co-development and/or off-take (raw materials, equipment, assets, network, iron powder/energy). Key (international) partners are involved early in project definition, others become subcontractors to the projects. Furthermore, key international parties have a seat on the social advisory board of the Iron Power program board (see Chapter 3) to ensure/monitor the international and industrial relevance and acceptance of the iron powder technologies and ecosystem. The members of the social advisory board represent parties that are not part of the program: they provide an *outside-in* view to reflect on the program's strategy.

In addition, the ambitions and activities of the Iron Power program strengthen policy at the European level. The program focuses on cooperation around relevant challenges and themes in the energy transition that are relevant for the entire EU. For example, the ambitions in the program align seamlessly with "**The European Green Deal**"[19] which sets out, among other things, the following goals: to achieve zero greenhouse gas emissions by 2050, economic growth without resource depletion, and no region left to fend for itself.

3. ACTIVITY PLAN AND COOPERATION

This chapter successively describes the (3.1) program activity plan, planning and phasing (3.2), monitoring and evaluation methodology (3.3), plan specific risks (3.4) and legal feasibility (3.5). Finally, this chapter describes the collaboration and governance structure (3.6). The activity plan and planning and phasing are outlined in this chapter.

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[15] Integrale Kennis- en Innovatie Agenda voor Klimaat en Energie (2023)
[16] VNCI – Klimaattransitie door de Nederlandse industrie (2020, Cluster 6 Klimaattransitie door de Nederlandse industrie.pdf (vnci.nl))
[17] Topsector Energie – Energietransitie en Duurzaamheid Missies (2024, https://topsectorenergie.nl/nl/maak-kennis-met-tse/missies/)
[18] Ministerie van Economische Zaken en Klimaat – (2022, - (overheid.nl))
[19] European Commission – The European Green Deal (2020, The European Green Deal - European Commission (europa.eu))

3.1 ACTIVITY PLAN

The Iron Power program is an integrated plan consisting of activities within the three pillars: R&D, Pilots & Demos, and Innovation Infrastructure (see Figure 9).

3.1.1 PILLAR I - R&D

The Iron Power program conducts research within the four main themes of the Iron Power value chain: (1) Reduction, (2) Production, Transport & Storage, (3) Oxidation and (4) Application & Systems Integration. A total of 21 R&D projects are being conducted to solve the biggest bottlenecks in the further development of Iron Power technology and realize economic earning potential in new application areas through technology spin-outs (new products and equipment). An overview of the projects within the different value chain themes is given for each theme.

Relevant results (technologies, knowledge and expertise) from the R&D projects will be used in affiliated R&D projects, tested in the first-of-a-kind pilot projects and/or tested in the Innovation Infrastructure. For example, results/expertise obtained in the project "Strengthening fundamental reduction knowledge" will benefit the other projects within the reduction theme such as the SOEC project, and vice versa. Go/no-go moments ensure that technology paths without commercial viability are stopped in time and no unnecessary costs are incurred (see Application & Systems Integration Theme).

Theme Reduction

Reduction technology is already possible today (as will be piloted in pilot project II.1 Central reduction unit), but second-generation systems require reduction technology that is even more energy- and material-efficient, and in which the reduction reaction is faster and more controllable. Most of the existing reduction research focuses on the reaction mechanism and kinetics between hydrogen and crude iron ore (iron oxide found in nature). However, in current applications, iron oxide powders differ in size, shape, composition, surface morphology and impurities, among others. Recent research by TU/e[20] showed that this leads to significantly different results (reaction kinetics, mass and heat transfer, and solid solution sintering/sticking of powder particles) and thus requires a different process design (reduction temperature, reducing agent, reactor design). Consequently, current knowledge of Iron Power reduction mechanisms is not yet sufficient in critical areas to overcome the technological challenges that stand in the way of scale-up and commercialization of current reduction techniques. The reaction is not yet energy efficient, fast stable enough, and the material loss too high.

In addition to improving existing technology, a huge opportunity exists to develop new abatement technologies. One promising research direction is toward an integration of SOEC (*Solid Oxide Electrolysis Cell*) with a reduction reactor, which has the potential to improve the combined efficiency of hydrogen-to-iron powder production to 80% (currently <70%). In addition, the Iron Power consortium will develop a reduction technology that no longer requires costly green hydrogen: Electrochemical Reduction. Electrochemical reduction produces iron powder by applying direct electrolysis to iron oxide in an aqueous alkaline solution, requiring only green energy (i.e., no expensive hydrogen). This technology is currently at an early stage, but has the potential to greatly improve the commercial viability of Iron Power (now the conversion of green energy to hydrogen is still a significant part of the iron powder price).

Driven by the above shortcomings, the goal of the Reduction theme is: *To improve the energy and material efficiency, responsiveness and stability of existing and develop new reduction technologies.*

The main questions that the Reduction theme aims to answer are:

- Is there a set of existing/new reduction reactions, iron oxide characteristics and/or setups in which iron powder production is energy efficient, continuous, material loss is minimal and the resulting iron powder is of the desired quality?
- Are these research results scalable and can they be used to improve existing reduction technologies?

This theme answers the main questions in five projects as shown in Figure 14.

[20] Hessels, C. J. M. (2023) – TU/e – Reduction of combusted iron using hydrogen.

Project	Activities (selection)	Partners: Research institutions	Partners: Industrial partners
I.1 Strengthen fundamental reduction knowledge	Analyse in lab-scale reactors and model the relationship kinetics, transport properties with reduction characteristics (e.g. dendrite formation) under different conditions (e.g. plasma).	TU/e, University of Twente, Maastricht University	metalot, Iron+, RIFT, DOOSAN
I.2 Improve existing abatement technology	Conduct reduction experiments for optimisation, validate by numerical simulations, analyse materials, analyse techno-economic feasibility..	TU/e, Maastricht University, Chalmers, TNO, RISE	metalot, Iron+, RIFT
I.3 Hydrogen plasma-reduction	Design proof-of-concept for a continuous iron powder production process, investigate plasma reduction by creating hydrogen plasma, investigate interaction plasma with powder, and process engineering.	TU/e, Maastricht University	metalot, Iron+, RIFT
I.4 SOEC-reduction integration	Investigate the technical and economic feasibility and design an integration of a *Solid Oxide Electrolysis Cell* (SOEC) for hydrogen production and a reduction system.	TU/e, DIFFER, TNO	metalot, Iron+, RIFT
I.5 Direct Electrochemical Reduction (DER)	Develop a small Iron Power chain around electrochemical reduction and investigate the requirements and effects of pre- and post-treatment of the iron (oxide) powder.		Iron+

Initiation & realisation · Research · Validation and anchoring

Figure 14: R&D Reduction – Activity plan

Box 9: Project I-5 Direct Electrochemical Reduction (DER).

This project investigates the feasibility of iron powder production using DER and of reusing in the DER process the iron oxide resulting from the oxidation of the iron powder produced by DER. To investigate this, a lab-scale chain of a DER and an oxidation unit will be set up in Australia by (partly) Dutch parties Iron+ and Ferron Energy.

During the study a number of cycles will be run of: (1) production of iron powder using DER, (2) oxidation of iron powder, (3) feed back to the DER process and (4) production of iron powder. During this whole cycle, the powder (iron and iron oxide) will be analyzed and characterized and oxidation performance (energy and material efficiency) will be evaluated, in order to investigate and/or develop the necessary pre- and post-treatment processes of the iron powder and iron oxide powder. Overall, the technical and economic viability of the DER technology in the Iron Power chain will be analyzed.

When the project is successfully completed, the acquired knowledge of technology and iron powder characterization will eventually also be tested in the Fieldlab and made available in the Living lab for the education of industrial parties as well as (future) talents.

Theme Production, Transportation & Storage

Successful implementation of an Iron Power ecosystem will require shipping iron powder (and subsequently iron oxide) (e.g., from the Middle East, Australia or African countries such as Namibia) in volumes many times greater than now for iron powders used in paint, pigment and automotive applications (about 2m tons per year). This will require a shift from transportation in *big-bags* to bulk transportation and possibly specialized equipment. The introduction of the Iron Power logistics value chain will also lead to a shift/redistribution of the Dutch, European and eventually global energy system and market. However, the necessary transport and storage equipment and handling standards are still lacking, and the safety aspects, the effect of long-distance transport on iron powders (e.g.H_2 formation through contact with water, corrosion, solidification, oxidation, contamination) and the change of the energy system (e.g. required storage infrastructure/network) have not yet been investigated in detail.

In addition, much research focuses on improving iron powder/oxide cyclability in only one of the two critical Iron Power production technologies, either reduction or oxidation. To achieve optimal cyclic performance (minimal iron (oxide) powder loss) for the entire system, more integrated research will need to be conducted on the powder characteristics/parameters for reduction as well as oxidation (in conjunction).

The goal of the Production, Transport & Storage theme is: *Develop necessary transport and storage infrastructure, safety standards and powder parameter settings for the optimal cyclic performance during transport and storage.*

The main questions answered are:

- What infrastructure and operations are needed for long-distance transport and storage of iron powder and iron oxide, and can these be standardized?
- How can transporting and handling iron powder/oxide be safely ensured (throughout the logistics process), what precautions are necessary?
- Under what set of powder parameter settings and reactor setups are iron powder cycle performance optimal?

This theme answers the main questions in five projects as shown in Figure 15.

Project	Activities (selection)	25	26	27	28	29	30	31	32	33	34	Research institutions	Industrial partners
I.6 Iron powder cyclability	Analysing oxidation-reduction performance of a number of times oxidised iron oxide powders and reduced iron powders in different test setups.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e, TNO	Pometon
I.7 Safety aspects	Analyse, test and model effect of powder characteristics on flammability during handling and transport and develop safety regulations (laws and regulations) - in collaboration with the pilot projects.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e	RIFT, Iron+, Pometon
I.8 Transport and logistics	Develop new transport and storage, equipment and operations between the value chain links (incl. standards), analyse safety during transport, storage and the operations in between through lab-scale experiments.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e	Spliethoff, Iron+
I.9 National energy system integration	Modelling national, European, and global energy flow system for the design of transport, storage, and production capacities.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e, TNO	metalot
I.10 International supply chain	Investigate the feasibility and design of a demonstration plant and required storage and transportation infrastructure for hydrogen production and iron powder reduction in Namibia.	Initiation & realisation	Research									TU/e, TNO	metalot

Initiation & realisation · Research · Validation and anchoring

Figure 15: R&D Production, transport & storage – Activity plan

Theme Oxidation

Scaling up to full-time (high *full load hours*) deployable oxidation systems on a large industrial scale requires systems that can run continuously with higher efficiency of energy, heat transfer and material. For example, pilots will need to prove that iron powder loss during oxidation is at most 0.2%, where a commercially viable process calls for a loss of 0.1%. To make the necessary technology steps, the reaction, ignition and emission mechanisms of iron powder oxidation in a wide range of conditions and with different oxidants will need to be investigated. For example, the impact of iron powder particle size and shape, flame turbulence, reaction temperature (iron powder phase) and oxidants have not yet been fully understood. Also, the cyclic performance of existing technologies is still insufficient - too much of the iron powder with valorisation potential is still lost. This worsens the cost per heat supplied and, consequently, the commercial viability. A promising research direction therefore focuses on the valorisation of these lost waste streams through low-temperature oxidation, in order to improve the material efficiency of the entire process and reduce the cost of delivered heat.

In addition, current oxidation systems are mostly based on systems used in coal and biomass combustion. These systems currently use propane to create a continuous process and suffer from significant particle deposition in the combustion chamber. The scale-up of oxidation technologies requires a new technology for these combustion and heat exchange systems that is better suited to the high-temperature oxidation process of iron powder as well as being able to operate continuously with minimal deposition in the reactor.

There is also a huge opportunity to convert the iron powder into hydrogen through an oxidation reaction of iron powder with water vapor: wet cycle oxidation. This technology is currently in its infancy, but plays a critical role in the value chain for using iron powder as a temporary hydrogen storage medium.

Driven by the above shortcomings and opportunities, the goal of the Oxidation Theme is: *Improve energy and material efficiency, continuity and heat transfer of existing and develop new oxidation technologies.*

The main questions that the Oxidation theme aims to answer are:

- In which set of existing/new oxidation reactions, iron powder characteristics, oxidation media and/or combustion setups is heat production energy efficient and continuous, and emissions and material losses minimal?
- Is it possible to use low-temperature oxidation to valorise the residual streams from the oxidation process?
- Is wet-cycle oxidation of iron powder to hydrogen technically and economically feasible?
- Are these research results scalable and can they be used to improve existing oxidation technologies?

This theme answers these main questions in three projects as shown in Figure 16.

Project	Activities (selection)	25	26	27	28	29	30	31	32	33	34	Research institutions	Industrial partners
I.11 Strengthening fundamental oxidation knowledge	Analysing and modelling link between iron powder properties (liquid/solid, powder size, etc.) in different ignition in/arrangements in air, water vapour and hydrocarbon fuels through experiments and thermogravimetric analysis.	Initiation & realisation	Research	Research	Research	Validation and anchoring						TU/e, TNO	metalot, ArcelorMittal, TATA STEEL, ENGIE, RIFT, Iron+
I.12 Improving existing oxidation technology	Construction and simulation of a 'fluidised-bed' reactor for iron powder oxidation, and a 'fixed-bed' reactor for iron pellet oxidation; Construction of two ~100kW reactors ('fluidised'/'fixed') for testing and validation of oxidation at larger scale.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e, TNO	metalot, Iron+, RIFT
I.13 Development of new oxidation technology	Development of a lab-scale turbulent flame burner, analysis of flame stabilisation, emission reduction and particle deposition mechanisms; Modelling (CFD) of mechanisms for simulating industrial-scale oxidation systems, among others.	Initiation & realisation	Research	Research	Research	Research	Validation and anchoring					TU/e, TNO	metalot, Iron+, RIFT

Initiation & realisation · Research · Validation and anchoring

Figure 16: R&D Oxidation – Activity plan

Theme Application & systems integration

In addition to the application and system integration of Iron Power in the pilot projects (oxidation), Iron Power technology can be used more broadly. However, identifying the *sweet* spot requires research into the technical and economic feasibility of Iron Power in various applications and the integration of Iron Power systems into existing processes. That research is relatively little done now, and it is also often unclear whether and how Iron Power technology can be integrated into existing operations, such as by retrofitting iron powder oxidation technology to a coal- or gas-fired power plant. For now, the uncertainty about applicability and integration possibilities is keeping the industry from further exploring, developing and embracing Iron Power technology.

The objective of the Application & Systems Integration theme is: *To identify industrial applications and develop systems integrations of Iron Power technology with high technical and economic feasibility*

The main questions of this theme are:

- Are there Iron Power system configurations within the various applications (industries) that are technologically and economically viable?
- Which industrial waste streams are technologically and economically feasible to be used as energy carriers within the Iron Power concept?

This theme answers this main question in eight projects as shown in Figure 17.

Project	Activities (selection)	Planning 25 26 27 28 29 30 31 32 33 34	Partners: Research institutions	Partners: Industrial partners
I.14 Calcination process (cement)	Development of new type of burner for maximum heat transfer and minimum interference of iron oxide in cement flour.		TU/e	metalot, HOLCIM
I.15 Alternative feedstocks	Analyse and characterise various dust streams (residual streams) from industrial partners for application within the Iron Power cycle.		TU/e	metalot, ArcelorMittal, KWR, nyrstar
I.16 Retrofit powerplants	Investigate technical and economic feasibility for retrofit of coal-fired power plant and gas-fired power plant.		TU/e	metalot, uniper, ArcelorMittal, ENGIE, EMGROUP
I.17 Hybrid systems	Develop oxidation-reduction integration for energy storage and transport or release, and a wet-cycle reactor proof of concept.		TU/e, TNO	metalot, DOOSAN, Pometon
I.18 Residual streams	Analysis, modelling and testing of industrial iron residue streams (i.e., in water treatment, metal processing) as input for Iron Power.		TU/e	nyrstar, metalot, ArcelorMittal, KWR
I.19 Electricity production	Design, modelling, integration and testing of an iron powder boiler in a Rankine Gas Turbine.		TU/e	HEAT POWER, Iron+, metalot
I.20 Iron Power holon	Defining a first-of-a-kind total Iron Power chain as a single source of energy (heat, electricity).			esa, metalot
I.21 Hybrid Heat production	Modelling hybrid heat systems (electr. and Iron Power) for high temp. heat (>400°C) and medium temp. steam (~200°C).		TU/e, TNO	metalot

Initiation & realisation | Research | Validation and anchoring

Figure 17: R&D Application- & system integration – Activity plan

The start of the Calculation Process and Direct Electrochemical Reduction projects (Projects II.14 and I.5) will depend on the results of the feasibility studies in the Transportation Logistics and National Energy System Integration projects (Projects I.8 and I.9). To avoid unnecessary costs, these projects will start only when the objectives of the feasibility studies are achieved and the predefined criteria are met.

3.1.2 PILLAR II - PILOTS & DEMOS

The Iron Power program realizes six first-of-a-kind pilot & demo projects to prove the validated Iron Power technology at larger scale and in industrial application. The overview of pilot & demo projects is given in Figure 18 and below the projects are explained one by one.

Each of the projects requires a totally different approach. An oxidation system (boiler) for high saturated steam requires a completely different system setup, powder/parameter settings and/or components than an oxidation system for producing high temperature steam. The projects were also carefully chosen to prove the different Iron Power technologies and potential at different scales, with different technology bases and in different applications.

Project	Activities (selection)	Planning 25 26 27 28 29 30 31 32 33 34	Partners: Research institutions	Partners: Industrial partners
II.1 Central reduction unit	Design and realisation of a first-of-a-kind reduction system for iron powder production.			RIFT
II.2 Peak load hot water for district heating	Design and realisation of a first-of-a-kind Iron Power peak load boiler for a district heating network.			ennatuurlijk, VEOLIA, RIFT
II.3 Multi-fuel heat system for asphalt processing	Design and realisation of a first-of-a-kind multi-fuel heat system for asphalt production.			ASFALTNU, Iron+
II.4 Medium-load superheated steam for industrial estates	Design and realisation of a first-of-a-kind mid-load boiler for superheated steam production.			VEOLIA, RIFT
II.5 Medium-load saturated steam for insulation material production	Design and realisation of a first-of-a-kind mid-load boiler for saturated steam production			Kingspan, RIFT
II.6 Farmsum	Design and realisation of a first-of-a-kind complete Iron Power value chain.			Xirqulate, Re-Forme, Iron+

Initiation & realisation | Research | Validation and anchoring

Figure 18: Pilots & demo's – Activity plan

As indicated earlier, the pilot and demo projects were carefully selected in terms of their interrelationship and complement each other perfectly in terms of the research questions and knowledge to be generated. As an example, each type of boiler has a substantially different design from the other types. These designs themselves have to be optimized with respect to the performance requirements of the intended application (pressure, temperature, energy efficiency, ramp-up/ramp-down ratio, down-time, durability/O&M), and all of this has to be validated (and further optimized) in practice. Thus, the wording of the research questions are reasonably similar for each project ("optimize design for specific application performance requirements"), but the answer to this (i.e. the resulting design) will be substantially different because the performance requirements differ for each application/type of system.

With the proposed projects, we cover the full load of these profiles with the least number of projects.

	Peakload/backup	**Midload**	**Baseload**
Hot water	ENN (II.2)		
Saturated steam		Kingspan (II.5)	
superheated steam			Veolia (II.4)

With hot water as in project II.2, there is a fire & flame pipe boiler, vs. a water pipe boiler for superheated steam. With this, there is a difference between the two types of boilers with respect to flame profile, process conditions, mechanical design, etc., which affects the integral performance (energy efficiency, ramp-up/ramp-down ratio) and thus the integration/optimization issue.

With superheated steam & saturated steam as in project II.5 and II.4, one has to deal with flue gas recirculation. There is also a deaerator (degasser) to be integrated with these two types of boilers. The integration of these two components affects the integral performance (energy efficiency, ramp-up/ramp-down ratio) and thus affects the integration/optimization issue. Standards regarding pressurized equipment place different requirements on the different designs given the different pressures (otherwise one will not get CE certification). This in turn affects the integral performance (energy efficiency, ramp-up/ramp-down ratio) and thus the integration/optimization issue.

The systems also involve different loads (peakload/midload/base-load), which also results in substantial differences in the designs, but mainly differences in the goals of the integration & optimization issues (read: the definitions of "optimal" differ for each load). These differences are further explained below. Each profile has different performance requirements (e.g. with respect to ramp-up/ramp-down ratios), which affect the optimization issue and thus the designs. E.g. the integration with the bulk solid heat exchanger and with the flue gas recirculation differs for each type as a result.

Pilot project II-1: Central reduction unit

In order to accelerate the energy transition through Iron Power technology, it is necessary for iron powder to be produced on a large scale and thus be widely available to industrial users at a competitive price However, the reduction technology to produce iron powder has now only been demonstrated in a small industrial demonstration setup (100kW, TRL-6), in which the economic competitiveness was not yet adequate The small-scale proof and the still limited availability of sustainably produced iron powder, deters the market from investing in the further development of affiliated Iron Power technologies and the large-scale adoption of Iron Power systems for decarbonizing the operation. Proving the abatement technology on a larger scale, as well as the economic viability of the abatement technology, is needed to provide the impetus the market needs

To accomplish this, RIFT is launching a project with the goal of: Developing *an iron powder reduction system suitable for producing iron powder, with zero direct CO_2 and NO_x emissions* This project focuses on iron powder production that will serve as input for the pilot projects "Peak load hot water for district heating," "Mid-load heat & power for industrial sites," and "Mid-load saturated steam for insulation material production.

The main questions the pilot project aims to answer are:

- What are the optimal specifications (designs of components, process conditions and operational processes) of a reduction system for the production of iron powder that is suitable/optimal for use in oxidation systems and can also be economically competitive?
- What is the achievable efficiency of the reduction process?
- How can the (already demonstrated) safety be optimized for this larger scale?
- How can the (already limited) indirect emissions be further reduced?

To answer the research questions, a pilot setup (at a location to be determined) will be realized with a reduction reactor (including regulation and control systems), and four storage facilities for iron powder, iron oxide powder, hydrogen and water (vapor) (see Figure 19).

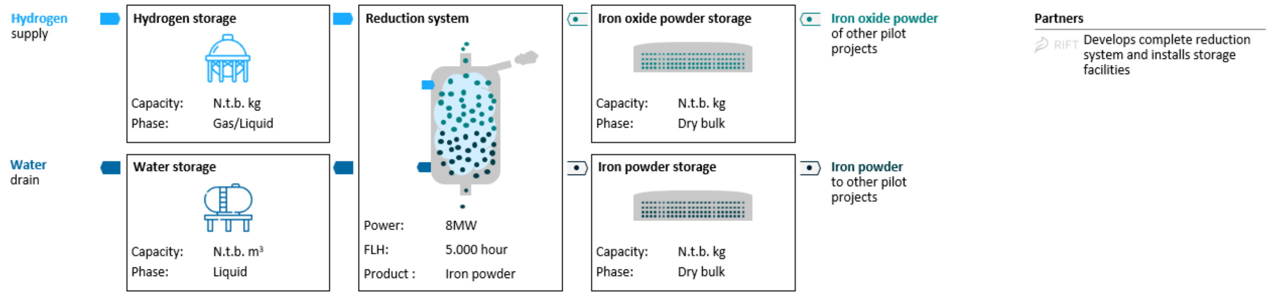

Figure 1: Schematic overview of pilot unit - Project: Central reduction unit, Location n.t.b..

The proposed reduction system has a capacity of 8 MW and can produce over 24,000 tons of iron powder in a maximum of 6,000 hours per year. This requires up to [X] tons of iron oxide and 1,300 tons of hydrogen per year. About 11,700 tons of clean water are produced annually in the process. To initiate the circular process, an initial batch of iron oxide will be purchased and stored once. From storage, the iron oxide is mechanically transported to the *feeder* of the reduction system (at the top), which ensures proper dosing towards the reduction reactor. In the reactor, the iron oxide is brought into contact with hydrogen under hot conditions, where unused hydrogen is captured for reuse and heat integration is applied to maximize energy efficiency. The iron oxide and hydrogen are converted to iron and water, with a target energy efficiency of >86%. The produced iron is collected and stored in an iron powder silo, from where it is transported by truck, train or ship to the pilot projects "Peak load hot water for district heating", "Medium load superheated steam for industrial sites", and "Medium load saturated steam for insulation material production". Upon arrival, the iron powder is unloaded, and the iron oxide (created from previous oxidation of iron powder) is loaded and transported back to and stored at the reduction site.

The 10-year project is divided into three phases. In the first two years, the infrastructure will be dimensioned, critical components simulated (in a CFD model) and optimized, and finally realized including required safety procedures. In the following five years, research is conducted by conducting reduction experiments. During this phase, component design, process conditions and operational processes are optimized to bring *availability, reliability*, maintenance hours/cost, recyclability (of the iron powder), energy efficiency, and *mass recovery* to commercially viable levels. The optimization research is looking not only at this pilot project, but also at the three affiliated oxidation pilot projects in which the iron powder will be used. Indeed, the most energy-efficient reduction reactor does not necessarily result in an iron powder that provides the best oxidation efficiency. This indicates the complexity of this optimization issue - an integral optimization study is being conducted. Also in this phase, the knowledge flowing from the R&D projects "Improve fundamental reduction knowledge" and "Improve existing reduction technology" (if successful) is integrated into this project. In the last three years, the business case of the pilot is evaluated - where the price for delivered iron powder is an important parameter - and suitable business models are investigated and designed.

Pilot project II-2: Peak load hot water for district heating.

Ennatuurlijk is a major supplier of heat in the Netherlands, supplying some 500,000 households and businesses with heat (a total of 4,400,000 GJ per year). Ennatuurlijk aims for CO_2-neutral supply of heat and cold by 2040, and to achieve that, Ennatuurlijk is looking for sustainable heat sources for its heat networks. By 2030, Ennatuurlijk wants to reduce CO_2 emissions by 70% compared to heating with a central heating boiler. To this end, they are making large-scale efforts to open up geothermal heat and residual heat from industry. However, that does not solve the entire problem. At peak load times - periods in the year when heat demand is at its highest - Ennatuurlijk still relies on additional heat sources using natural gas. Ennatuurlijk faces a complex sustainability challenge: Natural gas and residual heat cannot bear this kind of peak demand burden, but neither are there currently any relevant CO_2-neutral technologies available that can replace it in the long term.

In order to operate$_{CO_2}$ neutral by 2040, Ennatuurlijk, RIFT and Veolia are launching a project with the aim of: *Developing a boiler with iron powder combustion suitable for supplying heat during peak load moments to an existing heat network, with zero direct CO_2 and NO_x emissions.* This project focuses on the Midden- and West-Brabant heat grid, which in 2022 supplied approximately 51,000 homes and 355 businesses in Breda and Tilburg, among others, with heat from the residual heat of the RWE Amer power plant (91%), but also from natural gas boilers (7%)[21]. Given that the residual heat supply from the Amer power plant will stop within a few years, the ultimate goal is to (partially) compensate for this with iron powder technology. A similar 1 MW test boiler has already been realized and briefly tested on Ennatuurlijk's heat network in Helmond (500 houses), but not before has the technology been proven on this scale, nor tested for a long time.

The main questions the pilot project aims to answer are:

[21] Ennatuurlijk - Warmte voor Midden- en West-Brabant (2022, https://ennatuurlijk.nl/thuis/in-jouw-buurt/warmtenet-midden-en-west-brabant)

- What are the optimal specifications (designs of components, process conditions and operational processes) of an iron powder peak load boiler for connection to heat networks? What new infrastructure is required, and what facilities need to be modified?
- What is the achievable efficiency of the oxidation process in this industrial setting?
- How can the (already demonstrated) safety be optimized for this larger scale?
- How can the (already limited) indirect emissions be further reduced?

To answer the research questions, a pilot setup will be realized in Tilburg with **an iron powder peak load boiler** (incl. regulation and control systems) connected to the existing heat exchanger/heating system, and **two storage facilities** for iron powder and iron oxide powder (see Figure 20).

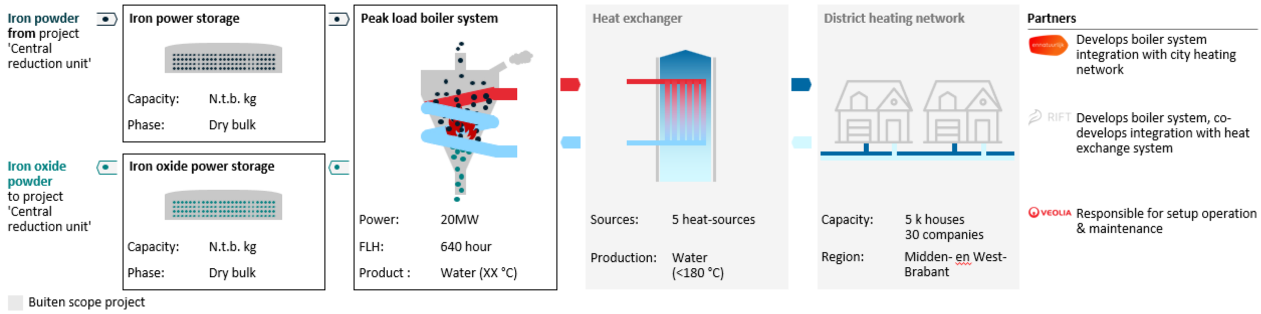

Figure 20: Schematic overview of pilot setup - Project: Peak load hot water for district heating, Tilburg

The proposed boiler has a capacity of 20 MW and can be used for up to 640 *full-load hours* per year, requiring over 7,500 tons of iron powder per year. The iron powder - supplied by the Central Reduction Unit project - will be mechanically transported from storage to the *feeder* of the boiler system (at the top), which ensures proper dosing towards the boiler. The iron powder is fed into the boiler, mixed in the correct ratio with ambient air. A pilot flame (on natural gas) is used to create the self-sustaining iron powder flame that produces heat (>1500°C; 25.5 GJ/m^3; 7.3 GJ/t) without any CO_2 emissions. The heat is then fed into the heat grid through a heat exchanger. In addition to heat (120°C), iron oxide (rust) is produced. This is captured and stored in a silo, to be returned to the reduction site when iron powder is delivered, where it can be reduced again for reuse.

The 10-year project is divided into three phases. In the first two years, the infrastructure is dimensioned, critical components are simulated (in a CFD model) and optimized, and is finally realized including required safety procedures. In the following five years, trials are conducted for providing heat during peak demand times. During this phase, component design, process conditions, and operational processes are optimized to bring *availability, reliability*, maintenance hours/cost, recyclability (of the iron powder), energy efficiency, and *mass recovery* to commercially-viable levels. Also in this phase (if successful), the knowledge flowing from R&D projects I.1 and I.6 through I.8 will be integrated into this project. In the last three years, the business case of the pilot is evaluated - where the price for supplied heat is an important parameter - and the integration with Ennatuurlijk's current processes is investigated and designed. These include operations, maintenance and procurement, as well as decision-making processes.

Pilot project II-3: Multi-fuel heat system for asphalt processing

AsfaltNu is one of the larger asphalt producers in the Netherlands, with a total of seven asphalt plants where they recycle asphalt and produce new asphalt. AsfaltNu's ambition is to proactively transform the asphalt industry into a 100% circular and sustainable industry: "Asphalt that is both fully climate- and energy-neutral and circular and sustainable."[22] To this end, AsfaltNu aims to replace the fossil natural gas that currently fuels asphalt plants with sustainable alternatives such as renewable hydrogen, electricity or innovations such as Iron Power within a decade.

In order to prove the potential of Iron Power technology in the asphalt production process, AsfaltNu and Iron+ are initiating a pilot project with the goal of: *Developing a multi-fuel heat system on hydrogen and iron powder that can be used for asphalt production/processing, with zero direct CO_2 and NO_x emissions.* This project focuses on potentially replacing a 1 MW biogas boiler, and (if successful) developing a new 40 MW multi-fuel heat system.

The main questions the pilot project aims to answer are:

- Technical design: What implications does the use of various renewable energy carriers have for the design of both the aforementioned power components in the asphalt process and for the design of drum and other parts of the process?

- Product quality: To what extent do iron and ash residues enter the asphalt during the production process and what implications does this have for the qualities of the asphalt, both in the short and long term?

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[22] AsfaltNu - 100% duurzaam asfalt en duurzame productie (https://www.asfaltnu.nl/over-ons/duurzaamheid)

- **Efficiency**: How efficient is the use of circular iron powder and/or renewable hydrogen compared to traditional energy sources for an asphalt plant?
- **Logistics:** What quantities of circular iron powder and/or renewable hydrogen are needed per day/week to structurally feed the asphalt plant with renewable energy carriers? What does this imply for minimum stocks and what buffers are needed to avoid having to fall back on backup supplies such as gas and electricity. How does this translate to the design of storage silos, conveyors and supply lines to the burners?
- **Environmental Impacts:** What are the environmental impacts of using the circular iron powder and/or renewable hydrogen in terms of carbon emissions and resource use?
- **Economic feasibility:** To what extent is the implementation of asphalt plant based on circular iron powder and/or renewable hydrogen economically feasible in the long term?

To answer the research questions, a project will be set up in two phases. In phase 1, a *dual-fuel heat unit* will be developed at the AsfaltNu site in Amsterdam, connected to a heat exchanger for asphalt production and two storage facilities for iron powder and iron oxide powder (see Figure 21). If successful, phase 2 at the AsfaltNu site in Deventer will validate the *dual-fuel* technology at field scale in a 40 MW multi-fuel heat system (four times 10 MW), based on renewable energy carriers (including iron powder)

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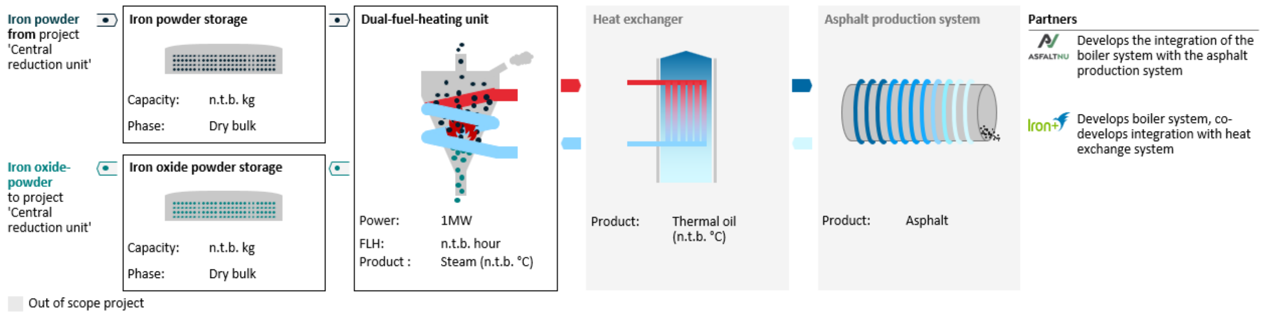

Figure 21: Schematic overview of pilot setup- Project: Multi-fuel heat system for asphalt processing, Amsterdam.

The proposed phase 1 *dual-fuel heater unit* has a capacity of 1 MW where it must supply heat of [n.t.b.]°C to a thermal oil heat exchanger. This requires over [n.t.b.] tons of iron powder per year. The iron powder is purchased from third parties and stored in bags. From storage, the iron powder is fed through a mechanical conveyor belt, which feeds the powder into the *heater unit*. This silo, together with the *feeder*, controls the *flow rate* of the iron powder to the combustion chamber. Together with the burner control, these determine the oxygen-iron powder ratio during the oxidation reaction. In the combustion chamber, the initial ignition is provided by a natural gas flame, after which the oxidation reaction will maintain itself (without significant natural gas consumption). The resulting iron oxide powder falls below from the reactor/boiler, and is collected and discharged to storage. The heated thermal oil is passed through the heat exchanger that is used for reuse in the asphalt production process.

The total pilot project (phases 1 and 2) is expected to be implemented in about six years. In phase 1, the design of the a *dual-fuel heat unit* will be finalized and then realized. After realization of the 1 MW *dual-fuel heater unit*, a two-year research and testing program will be initiated to gain knowledge and experience with the use of circular iron powder, renewable hydrogen and a combination of both these renewable energy carriers as an alternative to the use of gas for heating. Research is also needed on the qualities of the asphalt, both in the short and long term. The various studies thus also serve to validate the theoretical expectations that exist on topics such as efficiency, emissions, heat development and transfer and quality aspects. When phase 1 is successfully completed, after a go-no go decision, phase 2 will start with the development, realization and demonstration of multiple *dual-fuel* energy systems on a practical scale. In total, thanks to this new design of four *dual-fuel* energy systems within the project, approximately 40 MW of power should be generated through the use of renewable energy carriers as an alternative to the use of gas and electricity. After physical realization of these energy systems, the additional facilities required and the necessary modifications to the plant design, research will be conducted for two years on heating with renewable energy carriers, iron powder firing, plant efficiency and emissions, and possible improvements. In addition, research is needed on the qualities of the asphalt, both in the short and long term.

Pilot project II-4: Medium-load superheated steam for industrial sites

Veolia is a leading company in the field of environmental services and has been providing its customers with sustainable solutions related to energy, water and secondary raw materials for more than 50 years. Veolia faces a huge challenge, including making Industriepark de Kleefse Waard (IPKW) more sustainable, where Veolia owns the power plant. This power plant currently produces superheated steam using gas boilers and (non-sustainable) biomass. IPKW will not be connected to the national hydrogen network, nor will it be able to electrify in the reasonable future, which is why Veolia is diligently looking for alternatives.

In order to make IPKW more sustainable, Veolia and RIFT are starting a project with the goal of: *Developing a boiler with iron powder combustion that produces superheated steam for IPKW, with zero direct CO_2 and NO_x emissions.* This project focuses on replacing the current biomass plant (50400 MWh per year).

The main questions the pilot project aims to answer are:

- What are the optimal specifications (designs of components, process conditions and operational processes) of an iron powder medium load boiler for superheated steam production for industrial applications? What new infrastructure is required, and what facilities need to be modified?
- What is the achievable efficiency of the oxidation process in this industrial setting?
- How can the (already demonstrated) safety be optimized for this larger scale?
- How can the (already limited) indirect emissions be further reduced?

To answer the research questions, a pilot setup will be realized at the Industriepark de Kleefse Waard in Arnhem with **an iron powder mid-load boiler** (incl. regulation and control systems) installation for production of superheated steam, connected to a heat exchanger of the IPKW steam grid. In addition, **two storage facilities** will be realized for iron powder and iron oxide powder (see Figure 22).

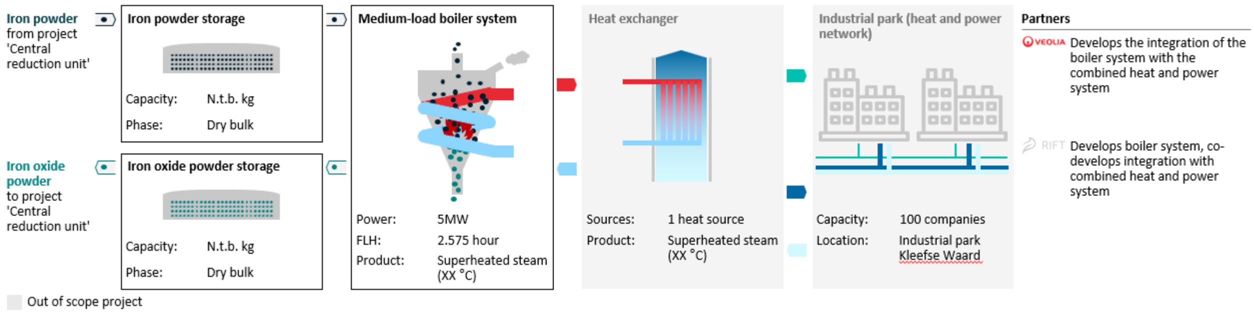

Figure 222: Schematic overview - Project: mid-load superheated steam for industrial estates, Arnhem

The proposed boiler has a capacity of 5 MW and is used to produce superheated steam (245 °C). This boiler should be able to be used for a maximum of 2,575 hours per year, which would require a maximum of 7,500 tons of iron powder per year. The iron powder is provided by the Central Reduction Unit project. In this pilot, superheated steam is produced instead of low-temperature steam as in the pilot project 'Peak load hot water for district heating'. This superheated steam is then delivered to end users in the industrial area. Despite the similarities with other pilots, a 5 MW superheated-steam boiler requires a completely different technical approach (than e.g. saturated steam/hot water) that has not been proven before.

The 10-year project is divided into three phases. In the first two years, the infrastructure is dimensioned, critical components are simulated (in a CFD model) and optimized, and the project is finally realized including required safety procedures. In the following five years, experiments are conducted on medium-load superheated steam delivery. During this phase, the design of components, process conditions and operational processes will be optimized to bring *availability, reliability*, maintenance hours/cost, recyclability (of the iron powder), energy efficiency, and *mass recovery* to commercially viable levels. Also in this phase (if successful), the knowledge flowing from R&D projects I.1 and I.6 through I.8 will be integrated into this project. In the last three years, the business case of the pilot is evaluated - where the price for delivered heat is an important parameter - and the integration with Veolia's current processes is investigated and designed. These include operations, maintenance and procurement, as well as decision-making processes.

Pilot project II-5: Mid-load saturated steam for insulation material production

Kingspan Unidek consumes significant amounts of energy, mainly in the form of saturated steam for the production of the insulation material EPS (in pre-foaming and block forming). This steam is now mostly generated with gas boilers (emissions of 6,188 Tons of CO_2 p. y.). However, Kingspan Unidek wants to become more sustainable and has set a goal for 2030 that the entire production of materials must be CO_2-free, and 60% of all energy required must be generated sustainably[23]. In part, Kingspan can electrify the steam it needs, but that does not include mid-load saturated steam - steam without water droplets. So far, Kingspan Unidek is searching in vain for alternative sustainability solutions, as they are part of Cluster 6 and are not given priority access to the hydrogen grid.

In order to produceCO_2 neutral by 2030, Kingspan Unidek, RIFT and Veolia are launching a project with the aim of: Developing *a boiler plant with iron powder combustion suitable for producing (mid-load) saturated steam used in*

[23] Kingspan Unidek - https://www.kingspan.com/content/dam/kingspan/unidek/other/kingspan-unidek-duurzaamheid-brochure-nl-nl.pdf

the production of EPS, with zero direct CO_2 and NO_x emissions. This project focuses on replacing the 5 MW gas boiler (28,100 MWh per year) currently used to generate saturated steam.

The main questions the pilot project aims to answer are:

- What are the optimal specifications (designs of components, process conditions and operational processes) of an iron powder boiler used to produce saturated steam? What new infrastructure is required and what facilities need to be modified?
- What is the achievable efficiency of the oxidation process in this industrial setting?
- How can the (already demonstrated) safety be optimized for this larger scale?
- How can the (already limited) indirect emissions be further reduced?

To answer the research questions, a pilot setup will be realized at the Kingspan Unidek plant in Gemert with an iron powder mid-load boiler (incl. regulation and control systems) for saturated steam production, connected to the existing production systems, and two storage facilities for iron powder and iron oxide powder (see Figure 23).

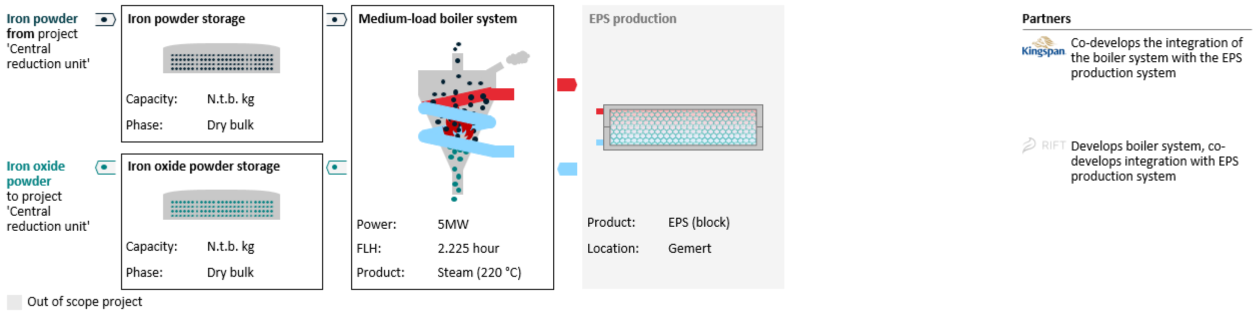

Figure 23: Schematic overview - Project: mid-load saturated steam for insulation material production, Gemert

The proposed boiler has a capacity of 5 MW and is used to produce saturated steam (220°C), with weekly startup and shutdown (due to a weekend shutdown). This boiler should be able to operate a maximum of 2,225 hours per year, requiring a maximum of 6,500 tons of iron powder per year. The iron powder is provided by the Central Reduction Unit project. In this pilot, saturated steam is produced. This steam is used to convert polystyrene 'Styrofoam balls' into EPS blocks - used as insulation material for walls and roofs, among other things. Despite the similarities with other pilots, a 5 MW saturated steam boiler, as well as the possibility for weekly start-up and shut-down, requires a completely different approach (than e.g. continuous operation and hot water/overheated steam applications) that has not been proven before.

The entire project (10 years) is divided into three phases. In the first two years, the infrastructure is dimensioned, critical components are simulated (in a CFD model) and optimized, and the project is finally realized including required safety procedures. In the following five years, experiments are carried out on providing medium-load saturated steam for EPS production. During this phase, the design of components, process conditions and operational processes will be optimized to bring *availability, reliability*, maintenance hours/cost, recyclability (of the iron powder), energy efficiency, and mass recovery to commercially viable levels (i.e. resulting in economic competitiveness of iron powder as an energy carrier). Also in this phase (if successful), the knowledge flowing from R&D projects I.1 and I.6 to I.8 will be integrated into this project. In the last 3 years, the business case of the pilot is evaluated - where the price for supplied heat is an important parameter - and the integration with Kingspan's current processes is investigated and designed. These include operations, maintenance and procurement, as well as decision-making processes.

Pilot project II-6: Farmsum

The Delfzijl/Eemshaven industrial area has the opportunity to become one of the sustainable energy hubs of the Netherlands. Both port areas of Groningen Seaports have about 160 companies, active in energy, offshore wind, chemistry, data, circular processes, and innovation. However, a significant mismatch exists in the area between sustainable energy supply and demand. It is therefore here in Farmsum-Delfzijl, with both good access to industry and maritime logistics, that the Iron Power program is realizing a *first-of-a-kind* complete Iron Power value chain. One of the core challenges of Iron Power technology is the cost of the raw materials required, particularly hydrogen. The Farmsum project and the DER and SOEC reduction integration projects focus on lowering the cost of feedstock per heat delivered to improve the business case for Iron Power.

To realize the full chain, Iron+, Xirqulate, Re-Forme are launching a project with the goal of: *Developing a full (Iron Power) value chain for sustainably producing (in sequence) ceramics, hydrogen, and iron powder and Iron Power heat with zero direct CO_2 and NO_x emissions.* This project focuses on realizing a *first-of-a-kind* pilot to supply approximately 10 factories (~134 GWh) currently using fossil fuel sources.

The main questions the pilot project aims to answer are:

- What are the optimal specifications (reduction and oxidation setup, parameter settings and operational process) of an Iron Power value chain used to produce heat? What new infrastructure is needed, and what facilities (end user) or processes need to be modified?
- What is the achievable efficiency of the reduction and oxidation process in this entire Iron Power value chain?
- Is it safe, and/or are safety measures needed?
- What emission reductions are feasible?
- Is this pilot technically and economically feasible and scalable? Is a larger size reduction system and/or boiler conceivable?

To answer the research questions, a pilot setup will be realized in Farmsum with a RDF (Dynamic Thermal Oxidizing) plant, a SMR (*Steam Methane Reforming*) setup, a reduction reactor (incl. regulation and control systems), an iron powder boiler and storage facilities for iron powder, iron oxide powder, hydrogen and water (see Figure 24).

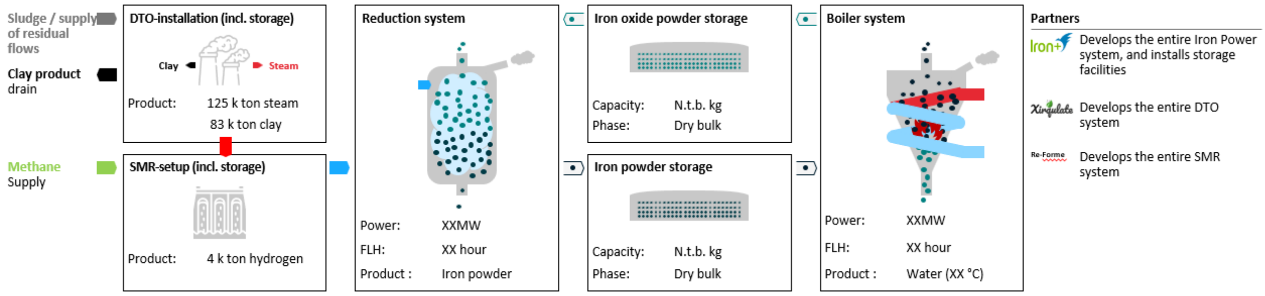

Figure 24: Schematic overview - Project: Farmsum

The proposed RDF plant can (co-)produce 125,000 tons per year of steam, corresponding to the production of 83 k tons of clay material. The steam from the RDF plant will be used in the SMR setup, where the steam and methane will be used to produce hydrogen (max. 4 k tons H_2 per year). This hydrogen is used by the reduction reactor ([X] MW), to convert the iron oxide to iron powder (67 k tons per year). The iron powder is transported to the iron powder boiler system, which is located at the [name of industrial partner]. The boiler system has a capacity of [X] MW and can be used to produce 134 GWh of heat energy per year. The resulting iron oxide powder is collected in [bags] and delivered back to the reduction reactor.

The entire project (4 years) is divided into three phases. In the first phase (1 year), the specifications are defined and the infrastructure dimensioned. In the next phase (1-2 years), the land is prepared for construction and the pilot setup is built. The final phase (2-3 years) involves researching and improving the performance of the entire Iron Power value chain. Important research topics include required pre- and post-treatment of iron (oxide) powder, reduction performance under different settings, and cyclicity performance of the entire chain. Performance will initially be investigated during production cycles of <100 tons of iron powder per day, and if successful, scaled up incrementally. Also, at this stage, the [indicate which knowledge] knowledge flowing from the R&D project [insert R&D project name] (if successful) will be integrated into this project. In parallel, labour market activities will be undertaken to introduce future talents to the Iron Power value chain. To this end, students and professionals will be invited (in collaboration with the Talents Service) to see and learn *hands-on* from a full Iron Power operation.

3.1.3 PILLAR III - INNOVATION INFRASTRUCTURE

The Innovation Infrastructure will be the place where the Iron Power program makes the connection between the international community (market, society and politics), and the research results, the knowledge and expertise built up within the R&D and pilot & demo projects. To this end, the Innovation Infrastructure offers four Services: Laboratories, Community, Talent, and Funding. To shape these services, six projects are set up and executed. The activities within this Innovation infrastructure pillar are aimed at obtaining and providing access to the necessary infrastructures, services, talents and networks, as well as performing network and knowledge dissemination activities. Where possible, technologies proven in both the R&D and Pilot & Demo projects will be added to the lab environments and the knowledge and expertise from these projects shared in one of the many Community events. Figure 25 provides an overview of the Innovation Infrastructure projects.

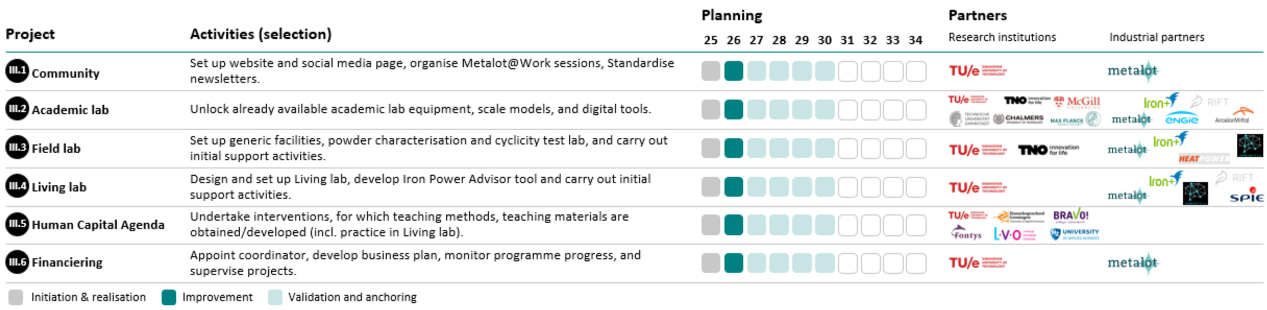

Figure 25: Innovative infrastructure – Activity plan

Community

To increase support within the ecosystem and further expand the ecosystem, the Community Service is being established. This broader Community consists of Iron Power customers and suppliers, talent & educational institutions, environmental organizations, energy companies, operators, grid operators, policy makers and *system integrators*. Members of the Iron Power Community have access to an **International Community program** to jointly realize Iron Power's value chain, set up experiments, unlock knowledge and share lessons learned as well as current state of the art and field standards. In addition, TNO is making the **concurrent engineering facility** and associated process support available to conduct physical and virtual joint engineering projects. The facility connects experts from across the field in periodic meetings (with different focuses) with the aim of working simultaneously on an innovation - accelerating the innovation process - under the guidance of experienced moderators. Community services are offered through a membership model, while *concurrent engineering* projects can be conducted on a *pay-per-use* basis.

Community Service is set up by, among other things, appointing community and communications managers who are responsible for expanding the Community through:

- **Organizing community events** such as, among others, a physical Metalot@Work event (~4 times a year) where a community is built in an interactive way (see Box 10 below)
- **Provide structured communication** to members of the Community service (and beyond), including an (eventually monthly) newsletter with activities from the Iron Power community, information on projects and industry news or communications from participants, and an annual Iron Power Community report for international dissemination
- **Representing the Iron Power ecosystem** at (inter)national symposia and trade fairs (e.g., fair X, symposium Y, Z) with the necessary promotional and marketing materials to do so
- **Create visibility within politics and society** by carrying out communication activities aimed at knowledge dissemination and necessary legislative and regulatory developments

Box 10: Metalot@Work

Metalot@Work sessions provide space for substantive presentations from the knowledge partners or business thinkers and the opportunity for all participants to pitch a new idea, concept, application or plan. Each session ends with the sharing of the agenda in which current events from the sector are highlighted. The formal part is followed by a networking part where participants can discuss, get to know and network with each other for another hour.

Agenda Metalot@Work 'Iron Power on the largest scale' March 20, 2024

13.55	Opening - Prof. Philip de Goey (chairman of the Metalot Board)
14.00	Redesign of large power plants - Aris Blankenspoor (Metalot)
14.30	Feasibility study conducted in power plant redesign - Prof. Mike Golombok (Shell)
15.00	*Pause (coffee/tea)*
15.20	Pitch: GH Power & Carlton Univ - Canadian start-up/Universiteit
15.50	Metalot Ambassador Awards
16.30	Large-scale supply of iron - Reginald Deolet (ArcelorMittal)
17.00	Closing & shared drinks

As the program progresses, more and more parties will join through membership in the Iron Power Community Service. Membership revenue will be used to cover future base costs of the Community Service.

Laboratories

To enable the necessary leaps of scale in technology for the industry, the Laboratories Service provides external users and Iron Power members access to an Academic lab, a Field lab, and a Living lab. The Laboratories Services are offered only on a *pay-per-use* basis (or through membership dues) that covers operational costs (including maintenance/renewal) on a non-profit basis. Therefore, one of the first activities is to establish a market-based expense allowance.

The **Academic lab** is available for users who want to characterize/process materials, perform small-scale oxidation/reduction experiments or do practical CFD modelling of oxidation/reduction. The lab also organizes lunch lectures, MeCRE conferences and knowledge exchange events (e.g. on safety aspects) for interested parties inside and outside the program. The various partners have already made large investments in lab equipment (e.g. *X-ray diffraction, Scanning Electron Microscopy*, LECO for material characterization), scale models (e.g. small combustion and reduction systems) and digital (techno-economic and environmental) tools. Integral access will be realized to this equipment and future equipment.

In the **Field lab**, users will have access to technical oxidation & reduction interfaces in which (newly developed / to be improved) components from the Iron Power value chain and iron (oxide) powders can be tested and characterized in a controlled environment on a larger scale of 100-500 kW. In addition, already available CFD tools (developed by TU/e) will be integrated and used to facilitate the concrete design of oxidation and reduction systems for start-ups and applications in industry, and Iron Power business cases from industry can be evaluated. To this end, access will be realized to generic facilities (e.g.H_2 lab, workshop, measurement lab), facilities for powder and cycle testing, facilities for equipment development support, and a techno-economic-assessment lab for market analysis and business case studies with the Iron Power Advisor tool. Later, the Field lab will expand to include new electrolysis equipment for hydrogen production coupled with reduction technology (SOEC), and innovative boiler/turbine serving steam/power output. Also to be added to the Field lab will be facilities from the R&D and pilot projects - such as the DER powder characterization - and eventually a DER setup, when the R&D project "DER" is successfully completed.

In the **Living** lab, not individual components take precedence, but overall system integration - to clearly integrate Iron Power technology into the value chain. Users get access to and insight into the entire Iron Power system (~1 MW) at decentralized energy hubs. The chain starts with green energy generation and ends with steam or power delivery. Among other things, the Living lab provides a monitoring and testing environment for innovation in Iron Power and access to data. The Living lab will not be set up commercially, but will serve as a means to familiarize parties with the technology (*outreach*), for education in the Talents Service "Living lab" intervention (see there), and as a demonstration of the reliability and scale-up potential of the chain. It involves talent development, knowledge dissemination to advance the sector as a whole, and developing a foundation/chain on which equipment can be validated and business cases based - in other words, making Iron Power technology investable. To this end, existing Iron Power infrastructure (including from the RIFT, Iron+) will be accessed and pooled to create a decentralized Living lab. An *electrolyser* driven by solar and wind will be linked to already existing reduction setup and at the same time a boiler and turbine will be linked to an oxidation setup to supply steam and power. The chain will be closed by transportation by electric trucks. Finally, this Iron Power system will also be made available virtually.

Talents

The national and regional labour market is tight (as also mentioned in earlier). Therefore, the Talents Service develops **Student Challenges** and **courses for students and existing professionals** (incl. lateral entry) on the essence of Iron Power technology and the working method adjustments it requires. It also focuses on innovation methods to improve labour productivity (e.g., process automation, robotization). Experience shows (see Box 11) that student team challenges are a great impetus for creating new businesses. The program is set up with impulse funding and maintained through the existing educational business models of involved institutes. Later this will also expand to new education partners.

The Talents Service undertakes interventions in the education of participating educational partners:

1. **Education Innovation and Lifelong Development Intervention:** In this intervention, the (1) existing Engineering BSc and MSc studies and professional courses are enriched with Iron Power technology focus, e.g. addition of Iron Power knowledge to the courses Combustion Technology and Thermal Energy storage (TU/e). In addition, (2) student teams will be professionalized by e.g. broadening the network, sharpening business plans and connecting with MBOs and MSc's (Fontys and Bivak). There will be (3) customized education (havo and vmbo) set up with the LVO Foundation in which students and lateral entrants will receive practical lessons in Iron Power techniques, and (4) an LLO trajectory for mbo and hbo in cooperation with the HZ University of Applied Sciences around hydrogen and safety.

2. **Intervention Living lab:** This intervention educates students/professionals in a hybrid way, in a hands-on learning environment (the Iron Power Living lab) complemented by theoretical education. It promotes mutual interaction and knowledge transfer through physical demonstrations and participations at TU/e (incl. hydrogen community) and Metalot.

Box 11: Student challenge team SOLID

Student teams are among the successes of TU/e and have often led to company spin-offs. On an annual basis, about 40 student teams are active and professionally organized in foundations with statutes and boards. Every year about 700 enthusiastic students dedicate themselves to solving challenges, with support from the TU/e and industry. These teams are innovative forms of collaboration that allow academic inventions to be regularly and quickly brought to market.

One of the consortium partners (RIFT) emerged from the student team SOLID, which was founded by TU/e in 2016 and appoints a new board every year. The team aims to develop iron powder technology and its ecosystem and work closely with other consortium partners such as TU/e and Metalot.

Team SOLID is a win-win situation: the team offers 25 talents a place to spend a year developing and broadening their skills while taking iron powder technology to the next level.

RIFT is a spin-off from team SOLID. The founders began their careers in the iron powder industry within the student team. It proves the legitimacy of team SOLID: economic (valorisation), technological and personal development have their basis in the environment created by a student challenge team.

At the same time, the Talent Service also joins the already ongoing growth fund proposals Green Power and LLO Catalyst, in which many *human capital activities* take place.

Funding

During and after the NGF period, new funding will need to be raised to pay for further developments and new technology projects. Examples of new projects are: scaling up pilots, new pilots, exploring new application domains and developing new value chains and new import/export channels. The Funding Service is set up by appointing a Funding coordinator who defines the organization and Services (incl. revenue model). The organization supports innovators in drafting business plans, and subsequently raising funding within the network of funders as well as sector funding and funding instruments (e.g. access to DEI). A flexible organization is set up whose size varies with funding demand. For new publicly funded academic (low TRL) projects, people from research-oriented organization TU/e, specifically the Research Support Office, are hired (*on-demand*), for new publicly funded pilot projects, people are recruited and appointed from the market (if possible), and for private funding, people are appointed organizing the investment platform in close cooperation with "the Gate" (TU/e), where there is a lot of experience in this field. The Gate is an information and advice platform for (deep-)tech start-ups, they help start-ups answer start-up related questions such as IP.

3.1.4 VALORISATION STRATEGY

Valorisation is an integral part of the Iron Power program. Besides the fact that all projects are commercially demand-driven defined (in collaboration with industrial partners) to maximize the valorisation potential, **the Iron Power program closes the entire TRL development chain** from concept to commercial product. It goes without saying that many successful concepts will emerge from the Iron Power program's R&D projects. Without the Iron Power program, such concepts would mostly end up on the proverbial "shelf," and only a single innovative idea will be further developed/examined. The Iron Power program goes further, testing and proving (the commercial *readiness*) these Iron Power technologies first in the Field lab and then in pilot setups. The path for potential technologies to commercialization has been concretized by the Iron Power program and is being actively promoted.

Valorisation is not only about the TRL steps made of specific technological concepts, it is additionally about building an innovation ecosystem that will continue to do so. The Iron Power program **builds, maintains and expands an Iron Power ecosystem** that will activate, enthuse and support Dutch and European activity. Knowledge, technology and infrastructure developed by the Iron Power program will be made accessible to anyone (companies, governments, educational institutions) interested in Iron Power technology and/or developing technology. On top of that, the Innovation Infrastructure offers Services to parties for testing innovations at different TRL levels (Laboratories), for building an Iron Power network and knowledge dissemination (Community), for training current and future talents (Talents), and for supporting in the search for funding (Funding). The Netherlands is and will remain the economic centre of Iron Power technology, and will attract international high-tech activity.

Finally, the Iron Power program **builds on already existing expertise and infrastructure** aimed at creating business activity - from academic concept to commercial product. During and after implementation of the Iron Power program, it is in close contact with the existing network of participating parties and the region to create business activity, such as the network of TNO, Brainport Eindhoven (including The Gate), venture capital funds and the ROMs (including BOM Brabant Ventures). It bridges existing expertise and infrastructure with the research undertaken in the program. For example, *business developers* from The Gate will participate during the R&D projects to scout spin-out opportunities and (when promising) engage and enthuse the network of funds.

The Iron Power program originates in Brainport Eindhoven, but it will be fully integrated in the Netherlands and Europe. We use existing international ecosystems and networks of our partners (such as those of TU/e, Metalot and Pometon) to continuously increase the impact of the Iron Power program. This allows us to have a broader reach and collaborate with renowned organizations around the world.

3.2 PLANNING AND PHASING

The three pillars of the Iron Power program are being developed in parallel and in conjunction with each other in three different phases over a 10-year time span.

The three phases we distinguish are:

- **Initiation & realization** - In this phase, the projects are initiated, the first-of-a-kind pilots are realized, the services and infrastructure of the Innovation Infrastructure are defined and made available. The planning phase, prior to the initiation phase, has already been completed with the submission of this program, allowing the projects to start immediately. At the end of this phase, the project portfolio is in full swing, and the Services are "live. This phase will be completed in 2025-2026.
- Research - This phase investigates the hypotheses/research questions, such as the potential of new abatement technologies, tests and optimizes the first-of-a-kind pilots, and evaluates the fit of the Services to market needs. The operational hours of the pilot setups are scaled up and the first potential technology spin-outs from the R&D projects are visible. Also in this phase, the first research results from the R&D are fed to the pilot projects. At the end of this phase, which lasts 1-5 years depending on the type of activity, a solid base of projects and Services has been formed, and the first externally funded projects have started**.**
- **Validation & anchoring** - In this phase, the first-of-a-kind pilots are further scaled up and business cases validated, system integration with industrial partners investigated and/or designed, and the R&D projects focus on anchoring their results and then completion. The NGF impulse funding is being phased out and the Innovation infrastructure is amassing more and more revenue from Services (fee-for-service, and Community contributions). At the end of this phase, the first-of-a-kind pilot setups have proven themselves in industrial settings, and the parties involved in successful pilot projects continue the further development into commercial products. The R&D projects are completed, but the technologies and knowledge are embedded in spin-outs and/or the Innovation infrastructure. The Innovation infrastructure no longer needs NGF funds to sustainably maintain it. Also, new activity has emerged as technology spin-outs or existing companies further develop the technologies near the core ecosystem in the Netherlands, or using the facilities and expertise of the Innovation infrastructure. This phase will be completed between 2030-2034, depending on the activity.

After each phase, milestones are defined for each pillar that facilitate evaluation, direction and go/no-go decision-making (see Figure 26). The phases and anticipated schedule are shown in Figure 27.

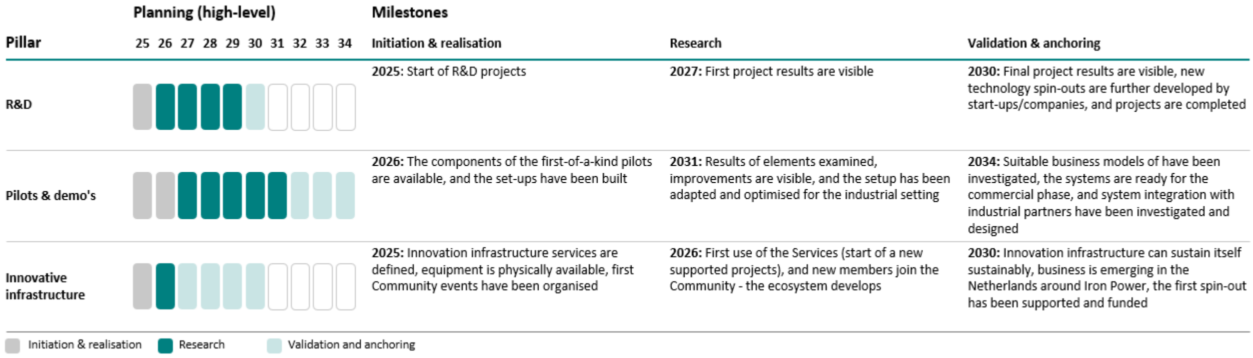

Figure 26: High-over planning and phasing including milestones

Figure 27: GANTT of the Iron Power program

3.3 MONITORING & EVALUATION

The Iron Power program has defined (Key) Performance Indicators ((K)PIs) to measure progress and success.

These are grouped into the three categories (Figure 28):

- **Process**: KPIs that reflect the activities of the program. These KPIs have time-bound objectives that follow the schedule and milestones (as defined above).
- **Outcome**: KPIs that represent key parameters against which the immediate success and future anchoring) of the project activities and Innovation Infrastructure Services are measured.
- **Impact**: KPIs representing the medium- and long-term economic, social, and sustainability impacts of the Iron Power program.

Using the KPIs, progress will be monitored, and the KPIs will form the basis on which decision-making will take place. For individual projects, KPIs linked to project-dependent milestones will be established, on the basis of which interim evaluation can take place on a project-by-project basis.

Monitoring and evaluation process

Using the KPIs, progress will be monitored, and the KPIs will form the basis on which decision-making will take place. For individual projects, KPIs linked to project-dependent milestones will be established, on the basis of which interim evaluation can take place on a project-by-project basis.

- **Annual review of the Iron Power program**: The overall progress of the Iron Power program is continuously monitored, and annually progress will be evaluated and adjusted as needed. The progress of the program is measured in the progress made within the three pillars, being the progress of the R&D project portfolio, the pilots and demos project portfolio, and the development and use of the Innovation infrastructure. The lead partners and managers involved are responsible for providing timely progress on the KPIs, milestones, phasing, as well as a plan for any adjustments towards the next year. The program board is responsible for evaluation and asks the General Assembly for a recommendation regarding progress and any directional changes. If the KPIs do not meet expectations, milestones are not achieved and/or there is insufficient visibility of success and/or confidence in an adjusted plan, the program board - in consultation with the General Assembly - can make adjustments.
- **Mid-term review after 5 years:** Halfway through (after 5 years) the program a thorough mid-term review is held. This will consider the Iron Power program and its impact on the sustainable earning capacity of the Netherlands. The evaluation process is identical to that of the annual evaluation, except for the addition that the progress and results will also be evaluated externally.

Monitoring and evaluation will be an integral part of contract partners' reporting to program management.

	Process KPI's	KPI's outcomes	KPI's Impact
R&D	• 2025 - First R&D project started • 2029 - All projects completed	• Research results published [#](Sub-) • Technologies advanced to TRL 5 [#] • Spin-outs of (sub-)technology generated [#] • Patents applied for [#] • Technologies added/tested (in pilots / Innovation infrastructure) [#]	• Total Iron Power produced by Dutch companies and companies based in the Netherlands [kg]. • Total number of Iron Power companies[1)] producing and marketing technologies, or offering services [#] • Total turnover of Iron Power companies[1)] [#; EUR] • Companies[2)] using Iron Power to de-carbonise operations [#] • Total energy generated by Iron Power solutions [MWh] • Total reduced emissions of CO2, NOx, SOx in the Netherlands and abroad by Iron Power [%] • Total number of companies established in the Netherlands where the consideration was the presence of the Iron Power ecosystem and/or access to infrastructure [#]
Pilots & demo's	• 2025 - First pilot project launched • 2027 - First pilot set-up realized • 2028 - First heat produced with iron powder in oxidation pilot set-ups • 2028 - First iron powder produced by reduction pilot set-ups • 2029 - First full Iron Power cycle demonstrated (baseline efficiency) • 2034 - All projects completed	• Pilot set-ups and value chains realised [#] • Emissions avoided during the pilots [%] • Energy generated during the pilots [MWh] • Iron powder produced during the pilots [kg] • Recyclability of iron powder [%] • Price of delivered energy [EUR / MWh] • (Sub-)Technologies (equipment & products) advanced to TRL 8 [#] • Patents applied for [#]	
Innovative infrastructure	• 2025 - Services defined (incl. infrastructure) • 2026 - First new internal user of the Laboratory • 2027 - First external Community members connected • 2029 - Start externally funded project (outside NGF scope)	• Revenue generated from fee-for-service, member contribution, and project financing [EUR] • Occupancy rate of the services [%] • Projects supported by the services [#] • Members connected to the Iron Power programme [# •]Students/professionals reached and trained [#] • Spin-out (opportunities) supported [#]	

XX Key performance indicators 1) Dutch Iron Power companies and Iron Power companies based in the Netherlands; 2) Companies served by Iron Power companies;

Figure 28: KPI's of the Iron Power program

3.4 PLAN-SPECIFIC RISKS

Table 3: Program-specific risks

Risk	Mitigation and management measures
Technical	
First-of-a-kind pilot projects do not deliver desired results	• **Experience:** The consortium parties together have broad experience in setting up pilot projects, such as the realization of the iron powder setups as an energy source at the Bavaria brewery. • **Knowledge sharing:** The parties work in partnership with parties that conduct a lot of research into Iron Power technologies • **Monitoring and adjusting:** The project will be implemented in phases, with clear Go/No-Go moments to mitigate risks in a timely manner.
R&D projects do not produce enough usable technologies for pilots and/or Innovation infrastructure	• **Project portfolio choice:** The portfolio of projects is coherent and chosen in such a way that the various value chain technologies, applications (and institutions), and industries are served • **Experience:** R&D parties have broad experience in setting up R&D projects. • **Guidance:** The Innovation infrastructure deploys capacity (where possible) to look along with the projects, to include innovations for the infrastructure as well as spin-outs • **Monitoring and adjustment**: Progress of the projects is evaluated annually during the reviews and adjustments can be made if necessary.
Commercial	
Outcomes of the Iron Power program are not converted into activity	• **Needs-driven approach:** The R&D and pilot & demo projects are defined with companies in order to concretize the route-to-market (if successful) beforehand • **Company network:** The Innovation Infrastructure establishes a network of companies interested and committed to the further development of Iron Power technology • **TRL chain approach:** The Iron Power program covers and serves with its pillars and Services the complete TRL development path - from concept to commercial product • **Guidance:** Experienced business developers from The Gate (Brainport Eindhoven) watch the R&D projects and continuously scout for spin-out opportunities
Iron Power technologies developed are too specific for the application - have little commercial value	• **Project portfolio choice:** The portfolio of projects is chosen to serve different value chain technologies, applications (and institutions), and industries • **Needs-driven approach:** The R&D and pilot & demo projects are defined with companies to concretize the route-to-market (if successful) in advance • **Guidance:** The Innovation Infrastructure deploys capacity (where possible) to watch along with the projects, for inclusion of innovations for the infrastructure
The business cases of the pilots do not improve during the projects	• **Project portfolio choice:** The portfolio of projects includes several initiatives, such as Farmsum, SOEC and DER, which focus, among other things, on improving the business case by reducing dependence on hydrogen prices • **Carefully developed**: In the project definition phase (for NGF), the business cases were carefully developed with the partners involved, including risk identification, scenario analyses and commercial due diligence • **Monitoring and adjustment:** The business cases are validated at predefined milestones, and adjustments are made where necessary.
Insufficient interest of parties in /support for	• **Strong base:** The Iron Power program builds on a strong base with 27 parties already affiliated with Metalot (core partner of this proposal)

Innovation infrastructure services	• **Open character:** The Iron Power program is open to all researchers, entrepreneurs and companies with an interest in Iron Power technology • **Active approach:** The Iron Power program will continuously and actively seek new partners to strengthen the ecosystem and start new projects with these parties • **Collaboration**: Through strategic collaborations with partners such as Veolia, Ennatuurlijk and AsfaltNu, the program has an anticipated influx of users
Ecological	
Emission targets not met	• **Monitoring:** Iron Power capacities deployed will be measured, based on which an environmental impact assessment will be made of the amount of emissions avoided • **Environmental organizations:** The Iron Power program will involve environmental organizations (e.g. the Nature and Environment Federations, Natuur & Milieu, Urgenda, etc.) and ask them to become part of the Iron Power Community
Regulation	
Delay in creation of pilots due to delayed permits	• **Experience:** The partners have extensive experience with the realization of similar physical sustainability projects • **Phasing:** The project will be implemented in phases, with clear Go/No-Go moments to mitigate risks in a timely manner. • **(Partly) Location independent:** The R&D and Innovation infrastructure projects are location independent and can start immediately.
Staffing	
The Iron Power program is insufficiently able to staff the program	*See box Staffing (human capital) of the program*

Box 12: Staffing (*human capital*) of the program

The Iron Power program relies on an average of 70-75 FTE manpower per year mobilized by more than 37 partners. Of this, about 50% is researcher (including corporate researchers, Professors, PhDs, Postdocs, assistant professors), and 45% technical staff, and 5% management and support staff (including directors, coordinators, secretary/administrative staff). Attracting the required *human capital* is estimated to be very feasible, given that within the core consortium alone (TU/e, TNO, Metalot, RIFT, Iron+) already more than 5,000 FTE researchers are employed and more than 500 FTE are hired annually.

In addition, the Iron Power program is led by strong parties (including TU/e, TNO, Metalot) and in a region with enormous international appeal. The economic growth of Brainport Eindhoven region in 2021 was more than 2%pp. higher than the economic growth in other Dutch regions (including the Amsterdam region), and last year alone 29 foreign companies settled in Southeast Brabant (source: Brainport monitor 2022) - Fuelled by the strong parties and its international network located there such as the ASML, NXP, and TU/e. The appeal of the Iron Power program and the region is further enhanced by the participation of internationally significant parties such as ArcelorMittal, TATA Steel, Pometon, Veolia, ENGIE, McGill University, TU Darmstadt, and Chalmers University of Technology.

Also, through the Innovation Infrastructure Services, the Iron Power program provides direct inflow of *human capital*. The Services are open to anyone interested and focus on training students, researchers and professionals, as well as disseminating knowledge and supporting parties interested in Iron Power technology. As a result, the Iron Power program not only accelerates the creation of an Iron Power ecosystem, but also helps increase *human capital* in Iron Power technology

3.5 LEGAL FEASIBILITY

The Iron Power program is legally enforceable, and the Iron Power program partners are familiar with, comply with and will ensure that they comply with the regulations below when conducting activities covered by them.

Overview of the applicable legal frameworks is given in Table 4.

Table 4: Legal frameworks related to the Iron Power program

Legal frameworks
General Block Exemption Regulation (GBER) - Conditions for research and development projects and investment aid for research infrastructure exempted from state aid notification requirement.
CE Marking - For industrial product groups that are traded in the European Economic Area (EEA) must be CE marked. The manufacturer hereby declares that its products have been tested against all applicable EU legislation requiring CE marking and conform to the health, safety, performance and environmental requirements relevant to those products
Foundation for Certification Maintenance and Inspection of Combustion Installations (SCIOS) - A SCIOS permit is required for industrial combustion installations to demonstrate that the installation in question is functioning properly - that an installation is safe and as environmentally friendly as possible.
Environmental Permit - Small industrial combustion plants with no standard fuel require an Environmental Permit.
Climate Act and National Climate Agreement - To combat climate change, the Dutch government wants to reduce greenhouse gas emissions in the Netherlands by 95% by 2050 compared to 1990. These goals are set out in the Climate Act of May 28, 2019.
Effort Sharing Regulation - The Effort Sharing Regulation (ESR), as adopted by the European Commission in 2018, sets national targets for emission reductions from road transport, building heating, agriculture, small industrial plants and waste management.
Environmental Management Act - Almost all national environmental legislation is included in the Environmental Management Act. This law describes an integrated approach to environmental management in the Netherlands and provides the legal framework by defining the roles of national, provincial or regional and municipal government.

Activities Decree - This decree contains general rules for environmental management that apply to all businesses, including combustion plants and storage tanks in the Netherlands.
European Industrial Emissions Directive - The Industrial Emissions Directive (IED) is the main EU instrument regulating pollutant emissions from industrial installations. This includes emissions to air, water and land, production of waste, use of raw materials and energy efficiency..
Nitrogen approach - Addressing peak loads - The Dutch government is introducing measures for industry, agriculture, transport and the construction sector, among others, to reduce nitrogen deposition and improve the quality of natural areas
Gothenburg Protocol - The protocol sets national emission ceilings for four pollutants: Sulfur (**SO_2**), Nitrogen Oxides (**NO_x**), Volatile Organic Compounds (VOCS) and Ammonia (NH3).
National Emissions Ceilings Regulations (NECR) *- The European Community has agreed new emission reduction commitments for each member state for total emissions of NOx, SOx, NMVOCs, NH3 and PM2.5 by 2030.*
Clean air program for Europe *- The clean air program for Europe outlines measures to ensure that existing targets are met and sets new air quality targets for the period to 2030 and includes a proposed directive to reduce pollution from medium-sized combustion plants.*

3.6 COOPERATION AND GOVERNANCE

3.6.1 PARTICIPATING PARTIES

The Iron Power program is led by strong core partners - who take full responsibility for the program - reinforced by public and private parties with broadening and deepening capabilities.

The core partners, consisting of TU/e, Metalot, Iron+, RIFT and TNO, take full responsibility for the Iron Power program. Together they provide the necessary expertise and capabilities for the entire program.

An ecosystem of partners with complementary expertise and/or capabilities will be established around the core partners. Together, the network of partners has all the expertise and capabilities needed to accelerate the commercialization of iron powder for the energy intensive industries. The program is open to parties from around the world who wish to participate, take advantage of the Services offered or gain knowledge about Iron Power technology.

In addition to the core partners, there are four types of partners involved in the program:

- **R&D partners** are public and private (inter)-national parties (research institutes and industrial parties) working toward a common goal of overcoming Iron Power technology challenges. One or more partners work on one project with one technological research question. For example, a researcher to investigate the efficiency gains of a new iron powder oxidation technology, or a company to investigate new iron oxide reduction technologies. These parties bring together the knowledge, expertise and methods to address and potentially overcome technological challenges. The program's R&D partners are RISE, Chalmers, Pometon, TU Delft, CSN, UM, Ferron Energy, ArcelorMittal, ENGIE, TATA Steel, TU Twente, Team Solid, Holcim, EMgroup, Iron+, RIFT, KWR, Nyrstar, HeatPower, ESA, DIFFER, Max Planck Institute for Sustainable Materials and Doosan Lentjes.
- **Pilot and demo partners** are public and private (inter)national parties (research institutions and companies) working towards a common goal to test and demonstrate the potential of Iron Power technology. For example,

several partners are working together to realize first-of-a-kind iron powder (sub-)technology setups for research and further development. The program's pilot and demo partners are Ennatuurlijk, Kingspan, Asphaltnu, Veolia, Xirqulate and Re-Forme.

- Partners in the **Innovation Infrastructure** are public and private parties who bring specific expertise to develop and implement the Services. These include:
  - **Laboratory partners** have the facilities and equipment needed to facilitate research on iron energy technology plants from 10 kW to 5 MW.
  - **Community partners** have experience building and maintaining innovation ecosystems, obtaining regulatory and concurrent engineering practices.
  - **Talent Partners** have experience developing educational programs for students (mbo, hbo & universities) and (*next generation*) professionals.
  - Funding partners have experience and a proven track-record within the innovation landscape of the Netherlands, helping start-ups, scale-ups and SMEs mobilize funding and achieve scale. These partners offer easier access to financing through their experience and network. Examples of potential partners include HighTechXL, Climate Fund Managers, FORWARD.one, InvestNL, BOM and LTO Netherlands.
- **Customers & Members** are public and private parties who want to use the services and or are part of the Iron Power community of the Innovation Infrastructure:
  - **Customers** are commercial parties who want to test technologies at pilot and demo project scale, companies/individuals who want to learn more about Iron Power and/or individuals (e.g., university researchers) to connect companies seeking growth funding with a network of funders. They use the services through a fee-for-service model.
  - **Members** are academic and commercial parties who want to jointly develop and shape Iron Power technology based on shared knowledge and insights - they become part of the Community program. All partners (committed to the Iron Power program) and parties wishing to realize Iron Power technology become part of the membership. Members gain access to *lessons learned* in the program and the current state of the art, among other things, through annual meetings, networking events and communication materials. They become part of the Community through a membership model.

There are 37 parties committed to implementing the program, including 13 large companies, 12 SMEs (together 68% of total), 7 colleges/universities and 5 research centres. A complete overview of the participating parties is shown in Figure 29. In addition to the committed parties, the Iron Power program is open to uncommitted parties through the services of the Innovation Infrastructure (users and members).

Figure 29: Iron Power programme partner types

3.6.2 GOVERNANCE AND ORGANIZATION

Iron Power's governance is structured based on the three pillars of the program and is led by a program board overseen by a General Assembly and supported by program management - Innovation Infrastructure governance builds on Metalot's existing governance structure.

The cooperation between the partners in this NGF project is defined in a consortium agreement. A **General Assembly** in which all implementing partners of the Iron Power program receiving NGF funds are represented is the highest decision-making body of the Iron Power program. It oversees the implementation of the consortium agreement and is decisive on any necessary deviations from what is included in the consortium agreement (e.g., regarding content and finances). General Assembly meetings will be organized at least once a year.

The TU/e assumes the role of **Coordinator** for the entire Iron Power program. The TU/e thus assumes responsibility as chair of the General Assembly, prepares the General Assembly meetings, is the academic representative in the program board, takes responsibility for the program management and takes care of the project administration of the subprojects in which the TU/e itself is involved.

The Iron Power program is led by a **Program Board** consisting of three people. One with an academic background (TU/e), one with a government/social background and one with an industrial background. The Program Board is responsible for the overall implementation of the strategy, external relations, preparation of General Assembly meetings and the overall *end-to-end* coordination of the Iron Power program.

The Program Board is supported by **Program Management** and consists of approximately 4 FTE. Program Management is responsible for the day-to-day coordination and administration of the program. It includes coordinating roles for each of the three pillars of the program: R&D, Pilots and Demos, and Innovation Infrastructure. These coordinating roles ensure effective collaboration between projects within and between the program pillars. They also maintain financial planning and agreements and monitor project implementation among partners. Program management also includes general secretarial and administrative functions, such as contracts and agreements, finance and secretarial support. Program Management will be responsible for cross-program issues, such as improving the Innovation infrastructure based on the results of the R&D projects.

The Program Board will be advised by a **partner meeting** and a **community advisory board**. The partner meeting consists of representatives of all parties involved in the program and meets at least twice a year. It advises the Program Board on the strategy and directions to be followed, and the quality of the projects delivered. The partner meeting consists of project partners in the R&D and pilot and demos pillars, and partners providing and receiving (sub)services as part of the Innovation infrastructure. Partners joining in new projects and new users of the Innovation infrastructure in the coming years are also welcome at the partner meeting. The Social Advisory Council is there to ensure the international and industrial relevance and acceptance of iron powder technologies and the ecosystem. The council will consist of (international) representatives from society, companies of different sizes (SMEs and large), different parts in the value chain and internationally recognized (research) institutes. The members of the Society Advisory Council also represent parties that are not part of the program: they provide an *outside-in view* to reflect on the program's strategy.

The projects within the **R&D and Pilots and demos** pillars all have their own leadership structure around the consortium of partners implementing the specific project. Each project consortium has its own leadership, determined by the lead partners of the project consortium, and supporting project management capacity appropriate to the specific project. These and other project arrangements such as contributions, activities and specific IP rules are defined in a project agreement, signed by the project partners.

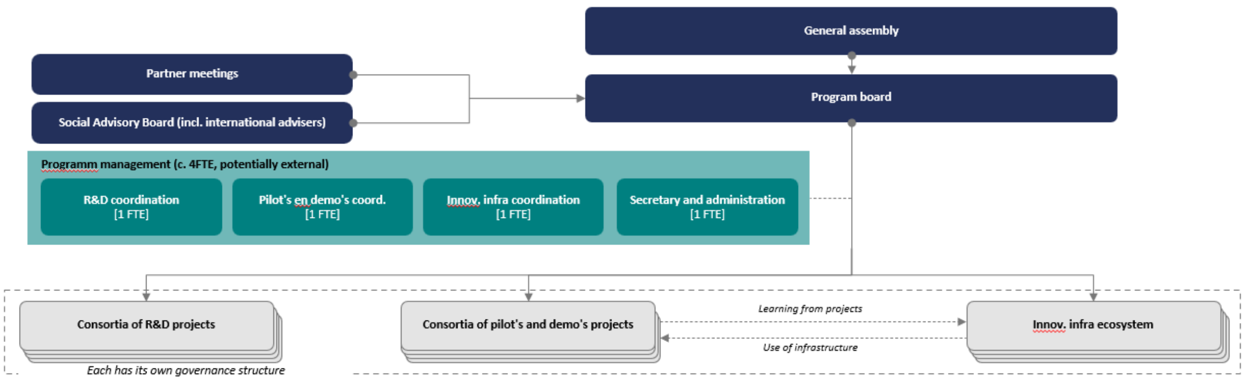

Figure 30: Governance structure of the Iron Power programme

The governance of the **Innovation Infrastructure pillar** ("Innovation Infrastructure ecosystem" in Figure 30) builds on the existing Metalot governance structure (see Figure 31). This includes expertise, people, reporting lines and legal structures already in place. The Innovation Infrastructure pillar is led by Metalot's two directors, consisting of a general operations director and a commercial director. The directors are responsible for the daily management of the Innovation Infrastructure pillar. The general operations director is the executive and directs the strategy and external relations of the pillar. He is also responsible for the maintenance and operation of the services and infrastructure. The commercial director is responsible for recruiting customers for Iron Power program services and for iron powder valorisation support. In addition, the commercial director is responsible for the continuous development of new services and all financial & legal matters of the pillar.

The directors of Metalot are all supported by different teams. The general and operations director is supported by a service management team, an infrastructure & support team and a financial, legal and secretarial team. The service management team coordinates the definition, development and operation of Iron Power program services and the organization of Community service member meetings. The infrastructure and support team provides development, maintenance and required support.

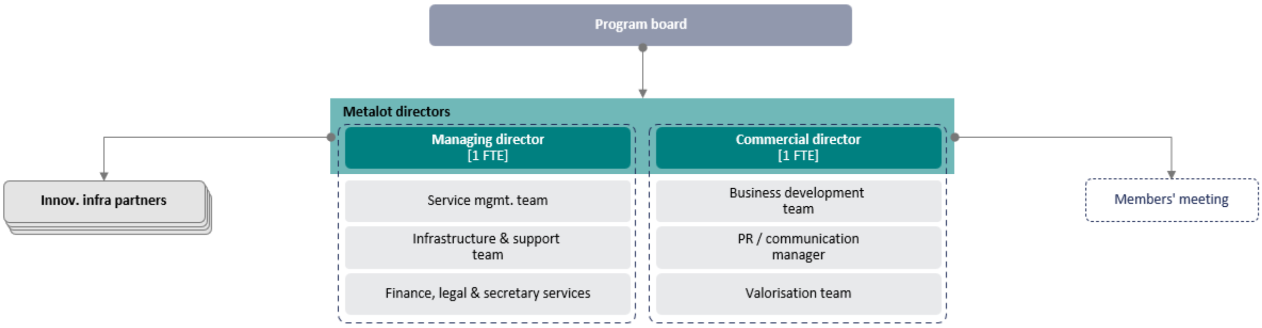

Figure 31: Governance structure of the Innovative infrastructure pillar

3.6.3 STAKEHOLDERS

The Iron Power program is a national initiative involving both public and private organizations (see Section 3.6.1). However, there are also stakeholders who are not directly involved in the program, who are indirectly involved during implementation. Below is the involvement of some of these relevant stakeholders.

Table 5: Relevant stakeholders of the Iron Power programme and relationship with other NGF proposals

Relevant stakeholders
The ministries of Economic affairs and Education, Culture and Science play an important role in regulating industrial emissions and achieving the goals described in the Climate Agreement. This is where the Iron Power program can become an appropriate complement. The long-term policies of both ministries describe industry sustainability policies and the promotion of innovation. The Iron Power program fits seamlessly with this by providing a sustainability alternative for energy-intensive industry**.**
Companies in Cluster 6 are key stakeholders. Cluster 6 includes 9 sectors: ceramic, food, chemical, base metal industry, cardboard and paper, glass, waste and recycling, ICT and oil and gas exploration. To achieve the climate goals set by the Dutch government, there are plans for the hydrogen network. However, the companies in Cluster 6 will not be connected to this network in the near future, and so they need alternative decarbonization strategies. The Iron Power program is open for these parties to participate and work with them to develop a sustainable Iron Power alternative for the energy intensive processes.
Regulatory organizations such as the EPA, IEA, IMO and ISO play a crucial role in regulation regarding the production, transportation and storage of energy/green molecules. The Iron Power program must comply with the standards and regulations set by these organizations.
Brainport Eindhoven, including The Gate, plays a vital role in attracting and uniting talent, business and finance, and stimulating new business initiatives. The Iron Power program has strong ties to Brainport Eindhoven and will work closely together to advance the *human capital agenda* (Talents) and create fertile ground for innovative ventures (Funding).
Province Noord-Brabant is one of the founders of Metalot and plays an important role in creating an innovation cluster and accelerating the energy transition by driving promising technologies and systems and making them ready for the market.
Investors have the opportunity to invest in a green energy carrier. Part of the private funds needed for the spin-out activity comes from venture capital and private investors.
Top Sectors Energy and Chemistry have formulated several ambitions, including "Mission B - Built Environment" and "Mission C - Industry" of Top Sector Energy, to which the Iron Power program fits seamlessly. Both Top Sector Energy and Chemistry strongly support the Iron Program in word and deed, and have been involved in the drafting of this program, among other things.
Relationship to other NG proposals
GroenvermogenNL aims to scale up the innovative ecosystem around green hydrogen and green chemistry. GroenvermogenNL focuses on three pillars: scale up & innovate, convert & build, retrain & educate. The Iron Power program aligns seamlessly with the goal of GroenvermogenNL. The two initiatives support each other in the areas of decarbonization, research projects and education programs, and both have their own domains that connect but do not overlap. In fact, GroenvermogenNL focuses on green hydrogen and chemistry, which is not in the scope of Iron Power. Iron Power focuses on iron powder and industries in Cluster 6 that will not have access to the hydrogen grid in the near future.
It is the ambition of **Nieuwe Warmte Nu!** to construct sustainable collective heat systems at low social costs. Economies of scale and innovations then reduce costs throughout the chain. The Iron Power program aligns with this proposal, given that district heating is an important application for the Iron Power program. Indeed, Iron Power offers a sustainable alternative to district heating, and thus there is complementarity/synergy between the programs.
Scaling up public-private partnerships in vocational education (Katapult) will invest in public-private partnerships (PPPs) between vocational education and the labour market in key sectors. The proposal focuses on talent development through educational innovation and teacher professionalization. The Talents pillar of the Iron Power program aligns well with this by developing both Student Challenges and subjects/courses for students and existing professionals that deal with the essences of Iron Power technology.
Leven Lang Ontwikkelen Katalysator aims to contribute to increasing and updating the knowledge and skills of (practical) education for better job opportunities. Within the Iron Power program, customized education (have and vmbo) is set up with the LVO foundation in which students and lateral entrants receive practical lessons in Iron Power techniques. In addition, many LLO pathways are set up for MBO and HBO in cooperation with the HZ University of Applied Sciences around energy transition.

3.6.4 INTELLECTUAL PROPERTY

The consortium lays down agreements in a cooperation agreement on dealing with intellectual property (IP), rights and licenses. The basic principle with regard to knowledge sharing within the consortium is 'open access': knowledge and innovations developed during implementation are shared. The guiding principle in knowledge sharing activities is that no information will be shared with third parties that could be detrimental to the competitiveness of the participating companies. This includes information that could lead to 'reverse engineering' of technology of the participating companies, and information that could interfere with applying for possible IP protection, such as patents. This avoids critical knowledge leakage and ensures that results benefit the participating companies.

With respect to IP, we distinguish between background and foreground knowledge. All **existing IP** background knowledge of each partner ('background'), remains the property of the partner in question at all times and is recorded in the consortium agreement. If this knowledge is used by parties other than the owner, this will be agreed upon in advance (e.g. by signing a license agreement). During projects and spin-out activities, newly **developed IP** knowledge ('foreground') will be created, for which the so-called inventor-ownership principle applies. This means that the intellectual property of the inventions in principle rests with the entity that created this invention. For **jointly developed IP** knowledge ('joint foreground'), appropriate agreements will be made in the consortium agreement.

4. FINANCIAL FOUNDATION

4.1 BUDGET

The total budget of the Iron Power program is EUR 395 m - invested over a 10-year period - of which EUR 239 m will be funded by partners and the use of the Services, and the remaining EUR 156 m will be requested from the National Growth Fund.

The implementation of the Iron Power program includes the execution of R&D and Pilot & Demo projects, the development of the Innovation infrastructure (including the four Services) and the running of the executive organization. The entire investment period of the program is 10 years, after which the Iron Power program will be self-sustaining. Table 6 shows the high-level budget and funding streams of the entire Iron Power program. The total budgeted cost of the program is EUR ~395 m over a 10-year period. The program will seek 39% impulse funding (such as from the National Growth Fund) and contributions from public and private partners and other contributions will account for the remaining 61%.

Table 6: Iron Power programme budget overview [EUR mln]

[EUR mln]	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	Total up to 2034	From 2035	% of total
Contributions	**75,3**	**75,8**	**57,3**	**58,2**	**33,2**	**34,5**	**14,3**	**14,8**	**15,5**	**15,7**	**394,5**	**1,4**	
Nationaal Groeifonds	37,7	37,7	19,4	20,3	10,4	11,7	3,8	4,3	5,0	5,2	155,8	0,0	39%
Publieke partners in-kind	3,7	3,7	3,7	3,7	1,7	1,7	0,1	0,1	0,1	0,1	18,7	0,0	5%
Publieke partners in-cash	0,9	0,9	0,8	0,8	0,6	0,6	0,4	0,4	0,4	0,4	6,0	0,3	2%
Private partners in-kind	23,4	23,4	23,4	23,4	11,1	11,1	5,4	5,4	5,4	5,4	137,3	0,0	35%
Private partners in-cash	9,3	9,3	9,3	9,3	8,6	8,6	3,5	3,5	3,5	3,5	68,3	0,0	17%
Verdienmodel	0,3	0,8	0,8	0,8	0,8	0,9	1,0	1,0	1,0	1,0	8,5	1,1	2%
Cost	**75,3**	**75,8**	**57,3**	**58,2**	**33,2**	**34,5**	**14,3**	**14,8**	**15,5**	**15,7**	**394,5**	**1,4**	
Directe loonkosten	20,2	20,4	18,9	19,4	14,7	14,7	7,0	7,0	7,1	7,1	136,6	1,1	35%
Kosten verbruikte materialen	7,5	7,6	9,7	10,2	9,8	11,2	6,1	6,6	7,0	7,2	82,8	0,2	21%
Kosten gebruik apparatuur	40,4	40,5	23,2	23,3	3,1	3,3	0,6	0,9	0,9	0,9	137,2	0,0	35%
Kosten aan derden	7,1	7,3	5,5	5,3	5,6	5,3	0,6	0,3	0,6	0,6	38,0	0,1	10%

Indicative –
1) Finances are still subject to change
2) Finances are specific for the Dutch Growth Fund

The Iron Power program requires impulse funding from the National Growth Fund of ~156 million euros, corresponding to 39% of the total budget. The remainder will be funded by public and private parties, committing 7% and 52% of the budget, respectively, and 2% by other funding instruments such as revenue (user fees).

Underpinning budget and funding lines

The budget of the Iron Power program is structured using a bottom-up approach, based on price-per-number. Costs in the program are divided into four cost types: direct labour costs, project specific costs consumed materials, project specific costs for use of equipment, equipment, machinery and project specific costs owed to third parties.

Direct labour costs for each project were determined by estimating the actual capacity required (the number of FTEs and positions) and the corresponding scale. Costs for materials consumed include iron powder, iron oxide and hydrogen costs for the oxidation and reduction processes. Costs for use of equipment, equipment and machinery include costs for setting up the oxidation and reduction processes (boiler systems) and laboratories, among others. Finally, costs due to third parties include civil works, external research, infrastructure inventories and permits.

The National Growth Fund is requested to provide an incidental grant, an impulse funding. The grant decision will be made within the EKZ grant framework, the applicable state aid frameworks and the frameworks from the Growth Fund Decision.

4.2 OPTIMAL BUDGET MIX

In addition to the funds contributed by public and private partners, the Iron Power program depends on impulse funding from the NGF - without this impulse funding, the Iron Power program (or parts of it) will get off the ground more slowly, smaller and with much lower impact. The total financial contribution from public and private partners to implement the projects within the pillars is 232 million euros (59% of total). For R&D projects the public and private contribution is 39% of the total R&D costs, for Innovation Infrastructure 34%, and for Pilots & Demos it is 66%. This funding mix is appropriate for the Iron Power program because it establishes a strong knowledge base (including with expertise development), making it a public asset for the economy and society. In addition, private input grows over time. The cost and contribution per participating party can be found in Table 8.

Table 8: Total costs borne by and contribution per participant [EUR mln]

Partner	Total costs	Total contribution	In-kind	In-cash
AsfaltNu	[redacted]	[redacted]	[redacted]	[redacted]
Xirqulate	[redacted]	[redacted]	[redacted]	[redacted]
Ennatuurlijk	[redacted]	[redacted]	[redacted]	[redacted]
Veolia	[redacted]	[redacted]	[redacted]	[redacted]
TU/e	[redacted]	[redacted]	[redacted]	[redacted]
RIFT	[redacted]	[redacted]	[redacted]	[redacted]
Ferron Energy	[redacted]	[redacted]	[redacted]	[redacted]
Kingspan	[redacted]	[redacted]	[redacted]	[redacted]
Metalot	[redacted]	[redacted]	[redacted]	[redacted]
Iron+	[redacted]	[redacted]	[redacted]	[redacted]
TNO	[redacted]	[redacted]	[redacted]	[redacted]
Re-Form	[redacted]	[redacted]	[redacted]	[redacted]
Gebruikers	[redacted]	[redacted]	[redacted]	[redacted]
TU Delft	[redacted]	[redacted]	[redacted]	[redacted]
Maastricht University	[redacted]	[redacted]	[redacted]	[redacted]
Electriffy	[redacted]	[redacted]	[redacted]	[redacted]
ArmanTech	[redacted]	[redacted]	[redacted]	[redacted]
Differ	[redacted]	[redacted]	[redacted]	[redacted]
University of Twente	[redacted]	[redacted]	[redacted]	[redacted]
Industrie	[redacted]	[redacted]	[redacted]	[redacted]
RISE	[redacted]	[redacted]	[redacted]	[redacted]

Partner	Total costs	Total contribution	In-kind	In-cash
ESA	[redacted]	[redacted]	[redacted]	[redacted]
Doosan	[redacted]	[redacted]	[redacted]	[redacted]
ArcelorMittal	[redacted]	[redacted]	[redacted]	[redacted]
Opleiders	[redacted]	[redacted]	[redacted]	[redacted]
Locaties	[redacted]	[redacted]	[redacted]	[redacted]
Pometon	[redacted]	[redacted]	[redacted]	[redacted]
Chalmers	[redacted]	[redacted]	[redacted]	[redacted]
Tata Steel	[redacted]	[redacted]	[redacted]	[redacted]
Holcim	[redacted]	[redacted]	[redacted]	[redacted]
HeatPower	[redacted]	[redacted]	[redacted]	[redacted]
SPIE	[redacted]	[redacted]	[redacted]	[redacted]
Nystar	[redacted]	[redacted]	[redacted]	[redacted]
KWR	[redacted]	[redacted]	[redacted]	[redacted]
McGill	[redacted]	[redacted]	[redacted]	[redacted]
Max Planck	[redacted]	[redacted]	[redacted]	[redacted]
Technische Universitat Darmstadt	[redacted]	[redacted]	[redacted]	[redacted]
Engie	[redacted]	[redacted]	[redacted]	[redacted]
Uniper	[redacted]	[redacted]	[redacted]	[redacted]
Emgroup	[redacted]	[redacted]	[redacted]	[redacted]
Spliethof	[redacted]	[redacted]	[redacted]	[redacted]

Public additionality

There are several public instruments that encourage research and development in the renewable energy sector, at regional, national and international levels. However, the Iron Power program stands out as a comprehensive solution for the entire value chain. This program requires cooperation at national and international levels, with parties along the entire value chain contributing to the production, transportation and storage of iron powder and iron oxide. Existing funding programs at both national and international levels typically focus on individual components within a value chain, rather than the entire ecosystem. Realizing the full potential and impact of the Iron Power program requires a broad ecosystem of companies, and thus an investment from the NGF so that companies along the entire value chain can develop. Besides the NGF, there is no other existing scheme in which an ambitious national program can be strengthened integrally and in all aspects. Subprojects could submit to other counters, such as NWO, RFO or EU, in a much smaller and adapted form, but this undermines the ambition and scale of the program and the need to implement it integrally, and then lacks the strategic direction needed for this. The table below provides an overview of public instruments that could thematically fit the goals and ambitions of this program, but are not suitable for a large-scale ecosystem program that spans the entire value chain, from basic research to technology development to application & systems integration.

Private additionality

The portion of the costs of the Iron Power program that calls on the National Growth Fund is not fundable from the private sector or through alternative forms of financing. This is first of all due to the high risks: the activities of the program are in the early stages of development, where great uncertainties prevail and the path to market is long. Moreover, these projects do not yet have positive business cases, because the value of the investments for development and scale-up will benefit the users of the ecosystem and therefore indirectly the Dutch society and economy. In short, there are a number of different forms of market failure, which legitimizes government intervention:

- **Chain collaboration:** Successful implementation of innovations impacts the entire chain, from raw material suppliers to end users. Circularity and sustainability requires a total chain approach, including all parties represented in the chain. Cooperation of all parties is a long-term process that requires strong cooperation and coordination.
- **Industrialization:** Infrastructures, knowledge and resources for transfer from laboratories to industrialization are often not available. The Iron Power cycle requires new processes and facilities developed in pilot and demo

environments. These environments are capital intensive and carry a high investment risk, which means that progression from research phase to production is often slow.

- **Timing:** Renewable energy innovations cannot compete in the short term with alternatives that are already widely produced and in use for longer. In doing so, negative environmental impact emissions are often not adequately priced. Buyers often choose cheaper solutions, while short-term innovations often impose additional risks and costs on the producer.

Potential other Dutch funding schemes

Financieringsprogramma	Uitleg
RVO	
DEI+	Alleen geschikt voor pilot projecten met investeringen EUR <15 m per project, en tijdslijn <5 jaar
SDE++	Doelstellingen voor kosteneffectieve CO_2-reductie, het Iron Power programma kan momenteel niet concurreren met alternatieve duurzaamheidsopties
Opschalingsregeling Groene Waterstof	Alleen geschikt voor waterstofprojecten
MIA-VAMIL	Gericht op investeringen om bedrijfsactiviteiten duurzamer te maken, niet het opschalen van nieuwe technologieën
EIA	Gericht op investeringen om bedrijfsactiviteiten duurzamer te maken, niet het opschalen van nieuwe technologieën
MOOI	Marginaal budget (EUR <4) m per project uitgevoerd in samenwerking met >3 partijen; onderzoeksorg. dragen minder dan <50% van de totale kosten
Vroegefasefinanciering (VFF)	Lening geschikt voor start-ups/scale-ups om commerciële levensvatbaarheid te testen; Marginaal budget EUR <3 m per business plan
InvestNL	Mogelijk geschikt voor pilot & demo projecten en/of innovatie infrastructuur, maar te hoge rendementsdoelen
MIT-regeling	Geschikt voor R&D samenwerkingen met MKB's of haalbaarheidsstudies; Marginaal budget van EUR <2 m per project
PPS-toeslag	Alleen geschikt voor R&D projecten; Marginaal budget geschikt voor kleine projecten
Thematische Technology Transfer (TTT)	Alleen geschikt voor tech transfer ondersteuning, ontoereikend voor hele Iron Power programma
SBIR	Alleen geschikt voor individuele projecten, niet voor een programma langs een gehele waardeketen
Innovatiekrediet	Alleen geschikt voor financiering van negatieve business cases van R&D en kleine pilot projecten
SEED fondsen	Alleen geschikt voor [illegible] projecten
Venture tech initiatieven	Alleen geschikt voor pilot & demo projecten
Groeifaciliteit	(Bank) leningsgarantie – Potentieel alleen geschikt voor het [illegible] negatieve business cases voor pilot projecten
Garantie ondernemersfinanciering (GO)	(Bank) leningsgarantie – Potentieel alleen geschikt voor pilot & demo projecten
Borgstelling MKB-kredieten	Onderpand voor (bank)leningen – Potentieel alleen geschikt voor pilot & demo projecten
WBSO	Alleen geschikt voor spin-out bedrijven van het programma
Innovatiebox	Alleen geschikt voor spin-out bedrijven van het programma
NWO	
NWO - Gravitation	Alleen geschikt voor samenwerkingen tussen onderzoeksorganisaties (fundamenteel onderzoek)
NWO - Perspectief	Marginaal budget EUR <5 m per project
NWO – N.R.G.W.I.	Alleen geschikt voor een deel van de onderzoek infrastructuur van het programma
NWA	Alleen geschikt voor sommige R&D projecten, kleine projecten met lage TRL
Europese financiering	
EUREKA	Alleen geschikt voor R&D en pilot & demo projecten in samenwerking met internationale partners
EFRO (OPZuid)	Alleen geschikt voor laboratoriumdiensten en enkele pilot & demo projecten; Marginaal budget EUR <6 m in totaal voor energie projecten
Horizon Europe	Alleen geschikt voor individuele projecten (EUR <10 m) en innovatie infrastructuur – vereist een internationaal consortium
Interreg	Alleen geschikt voor project samenwerkingen met internationale partijen in grensregio's; Marginaal budget per project
Innovation Fund	Alleen geschikt voor pilot & demo projecten met een hoog TRL-niveau
IPCEI - Hydrogen	Alleen geschikt voor het vergemakkelijken van financiering van het programma in een internationale context

Figure 32: Overview of national and international funding opportunities

With the impulse investment from the NGF, the government is stepping into the gap that cannot be filled by private parties. As the transition progresses and activities become less and less risky, private investors are expected to (co-)finance more and more, though. Over time, the Iron Power program will generate revenue from user fees and direct contributions from partner and the ecosystem. Contributions from the National Growth Fund have been estimated to enable this anchoring in the ecosystem and thus are precisely a catalyst for private investment.

4.3 SUBSTANTIATION FUNDING OWN SHARE

All contributions from investing parties, as described in Chapter 3, have already been confirmed by Letters of Commitment, subject to the condition that the investments described in the proposal actually take place and the National Growth Fund makes the requested contribution to them. Finally, the Iron Power program involves financial risks, which are listed in Table 9.

Table 9: Financial risks of the Iron Power programme

Financial risk	Mitigation and management measures
Cost/investment overruns in plan implementation	• **Preparedness**: Iron Power program plans have been detailed and ready for implementation in recent years - program partners have a good understanding of implementation costs. • **Committed partners**: the core consortium partners take responsibility for the realization of the Iron Power program, and ask NGF to co-fund. This responsibility translates to collaborating and resolving any changes in costs/investments. • **Adjustment:** the umbrella board will monitor and evaluate the projects to identify and mitigate financial challenges early.
A partner cannot/will not make the in-cash/in-kind contributions	• **Commitment:** all partners are committed and are reliable parties who have previously conducted collaborative projects. The largest contribution is from a number of core consortium partners who are investing in phase with the NGF. • **Supported/Guarantees:** a number of the participating parties are SMEs (also core consortium partners) who have been supported by their larger parent companies, funders and/or have received bank guarantees who/which will guarantee that they can make the necessary contributions during program implementation.
Revenues from propositions are lower than expected	• **Good acquisition**: the Iron Power partners are actively pursuing agreements with potential users. • **Building on strength:** the program has mobilized a strong base of users.

4.4 NON-STRUCTURAL

The investment from the NGF in the Iron Power program takes place from 2025 to 2034 and is temporary in nature.

The investment in the Iron Power program is intended as an impetus to start the program and build the necessary infrastructure. After the end of the NGF investment period, between 2025 and 2034, the Iron Power program will be able to be self-sustaining due to its revenue model and the continued involvement of both public and private parties. Thus, the program results in continued strengthening of the Netherlands' earning capacity. In the budget (see section 4.1), a column 'from 2035 onwards' has been included for illustrative purposes, to show how costs will be covered by partners, third parties and the revenue model (revenue from use) of the Iron Power program. Through three revenue sources, the Iron Power has an exit strategy to continue operations beyond the NGF period that will cover ongoing costs:

- **Innovation Infrastructure Community:** The Iron Power program will maintain an active central organization and Community that will continue beyond the NGF period. Members of the Community will pay a membership which will allow the access to the Community. Membership is available in five different grades, the cost ranges between EUR 3,000-75,000 per year. All implementing partners of the Iron Power program are part of the Iron Power Community (30 parties) and it is expected that the number of new memberships will increase by 1-5 per year after 2025.
- **Innovation infrastructure education**: After 2034, the Iron Power program will continue to actively invest in Iron Power education through Laboratories. These educational environments generate revenue from users through Iron Power introduction days (think courses), the operation of the Living lab and the Iron Power Advisor tool, among others.
- **Sustainable revenue model**: After 2034, the Pilot & Demo projects will serve continuous users. Through the implementation of the program, infrastructures will be developed, tested and improved. In the long run, these operational costs will be covered by user fees. The ongoing Pilot & Demo project started with a clear starting and ending point. The resulting spin-off activities will be funded through regular grant channels. These projects can claim regular grants because they stem from ongoing research and have therefore already reached a higher TRL, and the activities continue as individual projects. As a result, subsidies such as DEI+, SDE++ and MOOI are more employable and there are parties who can make a larger contribution themselves given the income from existing projects.

5. CONTRIBUTION TO SUSTAINABLE EARNING CAPACITY

The Iron Power program aims to sustainably strengthen the earning capacity of the Netherlands by contributing to the development of an Iron Power value chain with continuous innovation at every level in which the Netherlands has an essential and leading role. Thus, this program builds an Iron Power ecosystem in the Netherlands and Europe that creates economic and social value.

The economic and social impact (qualitative and quantitative) of this program was determined through a Theory-of-Change model. This section summarizes the economic impact (5.1) and social impact (5.2) of the Iron Power program.

5.1 SUBSTANTIATION OF ECONOMIC EFFECTS

Qualitative substantiation

The Iron Power consortium, financially supported by the NGF and equipped with essential knowledge, expertise and facilities, aims to further develop Iron Power technology by conducting R&D, pilot and demonstration projects and establishing an Innovation infrastructure. The activities focus on reduction, production, transportation & storage, oxidation and application & integration to make Iron Power technology suitable for industrial applications. They result in proven Iron Power equipment and new product concepts, demonstration of the value of Iron Power and associated supply chains, a sustainable and accessible Innovation infrastructure and the necessary ecosystem.

These outcomes contribute to the commercial development of Iron Power technology as a critical step toward widespread adoption and use. By demonstrating the feasibility and efficiency of Iron Power equipment and concepts in research and pilot projects, the program not only attracts investment but also stimulates the emergence of a dedicated user base willing to implement this clean energy solution. Thus, the program helps create an ecosystem of companies, researchers and stakeholders united in their pursuit of realizing Iron Power technology and its industrial applications. Moreover, the initiative places a strong emphasis on education and professional development, cultivating a talent pool of Iron Power technology experts who play an important role in driving innovation and ensuring the continued growth of the industry.

This base paves the way for creating impact in several areas. Economically, it stimulates an increase in GDP and a stronger competitive position of Dutch companies through the growth of Iron Power companies and supply of clean energy to companies in Cluster 6 (industrial locations not close to the hydrogen network). Strategically, it ensures a diverse energy mix, reduces dependence on unstable regions and promotes an attractive investment climate. Environmentally, the Iron Power program contributes to sustainability by reducing emissions from industrial activities. In addition, Iron Power increases safety in the transportation, storage and use of hydrogen. The success and speed of this impact depends in part on the development of a global hydrogen market and competitively priced hydrogen that is critical to the feasibility and expansion of Iron Power technology.

Quantitative substantiation

The magnitude of the economic effects of this program is estimated *bottom-up*, based on the *Theory-of-Change model*. By 2050, sixteen years after the end of this program, it is estimated to have contributed ~ EUR 1,800-1,900 mln in additional revenue per year, representing an additional added value for economic sectors in the Netherlands of ~ EUR 850-950 mln per year and ~ EUR 4-5 bln cumulatively until 2050. These estimates are corrected for the so-called zero alternative: Iron Power developments that are also expected to occur without the investment from the NGF. The estimated impact is in line with the results of research by the 4TU.Federation[24], which showed that EUR 1 invested in the four technical universities in the Netherlands (not corrected for zero alternative) results in an annual added value of EUR 9.

[24] 4TU.Federation - Economic Impact of 4TU (2022)

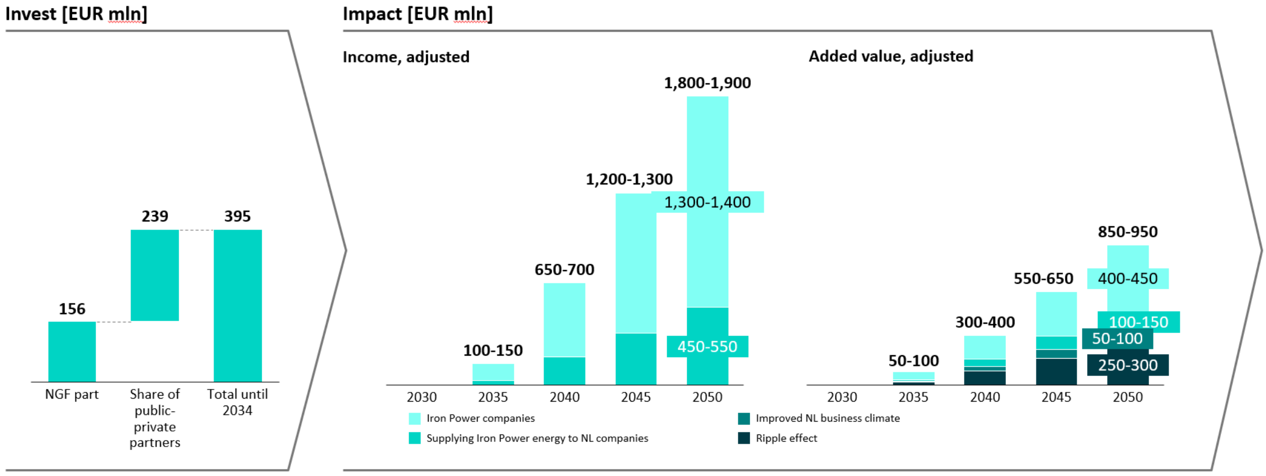

Figure 11: Investment and expected annual revenue and value added of the Iron Power programme, adjusted for the base case [EUR mln].

The impact is initiated by the direct investments of the NGF and public-private partners of EUR 395 m until 2034 and reinforced by the ongoing investments of private parties in Iron Power. The economic impact is estimated using four elements. First, **Iron Power companies generate** added value - generated by the added value of Iron Power *champions* and of the innovative concepts commercialized nationally and internationally by existing and new companies (spin-offs). Iron Power *champions* are Dutch companies that position themselves as the main suppliers of the necessary equipment/systems (e.g. oxidation and reduction equipment) for Iron Power technology in Europe. Second, the program generates added value by **supplying Iron Power energy to companies in Cluster 6.** Third, through an **increase in international investments** caused by the emerging NL Iron Power ecosystem. Finally, the so-called **"ripple effect"** on secondary industries generates added value (e.g. effects of growing industry on surrounding commerce) as a result of the direct investment in the Iron Power program.

Null alternative and external dependencies

In the above estimate of added value, adjustments have been made for risks and developments that are expected to occur even without the NGF investment. This so-called null alternative assumes that the parties behind this NGF program will continue to pursue their individual ambitions even in that case and that Iron Power developments (and associated spin-offs) will also take place then, but with a delay, a lower penetration rate, a smaller volume and less realization of effects in the Netherlands.
The impact of this program depends in part on external trends that may influence the ultimate impact of Iron Power technology evolution. Such risk factors are developments of spin-offs outside the Netherlands, drying up of investments, lagging laws and regulations and lack of development of the hydrogen value chain.

5.2 SUBSTANTIATION SOCIAL IMPACTS

The impact pathways described in the Theory of Change lead to significant strategic and sustainability value in addition to economic:

- **Strategic independence in energy supply:** By using Iron Power technology for renewable heat, the Netherlands, and consequently Europe, strengthens its position as a major player in the global energy market and significantly increases its ability to meet local energy needs. The ease of transportation and storage of Iron Power makes energy sources more diverse and flexible. This means Europe can obtain energy from more locations, thereby not only increasing energy security but reducing dependence on conventional energy imports, leading to a robust and sustainable energy mix.
- **Reducing CO_2, NO_x and SO_x emissions from industrial processes**: Iron Power's value chain, with its reduction and oxidation processes, is notable for its low environmental impact. No direct emissions of CO_2 and SO_x and minimal NO_x emissions are produced. This significant reduction of pollutants not only improves the environment near industrial sites, but also contributes to the broader reduction of overall emissions. Therefore, Iron Power positions itself as an attractive option for industries looking to reduce their environmental impact and move to more sustainable practices.
- **Improved Dutch investment climate:** The realization of Iron Power technology improves the investment climate of the Netherlands by making the country attractive from the perspective of sustainable energy development. It not only demonstrates the Netherlands' commitment to reducingCO2 emissions and addressing climate change, but also attracts the attention of investors, both local and global, eager to support innovative and environmentally friendly businesses. The growth and application of Iron Power technology generate a cascading effect that fuels a dynamic environment of startups, academic institutions and established companies united in the pursuit of sustainable energy solutions. This dynamic not only stimulates employment and economic growth, but also positions the Netherlands as a centre for green technology and innovation.

- **Improved safety in hydrogen transportation, storage and handling**: Using iron powder as a means of hydrogen storage and transportation is significantly safer than conventional methods such as methanol and ammonia. By encapsulating hydrogen in a solid state, iron powder circumvents both the hazards associated with storing and moving gaseous hydrogen under high pressure and the hazardous properties of methanol and ammonia (toxicity, flammability). The risk of spills and explosions is significantly reduced and the safety of handling, storage and transportation much greater. Since rigorous high-level safety measures are less necessary, the costs associated with safety protocols become much lower. The inherent safety benefits of iron powder make it a compelling choice for industries seeking to use hydrogen as a clean energy carrier - providing a safer work environment, lower risks to nearby workers and residents, and easier integration into current energy systems.

The expected social impacts of the proposal were also indicated through a Generational Test. For all generations, the Iron Power program contributes to improving climate & sustainability through broad access to Iron Power solutions for making industry more sustainable. This ensures the preservation and growth of this industry in the Netherlands and thus also improved income security and a healthier living environment and society (through emissions reduction). Finally, the Iron Power program sets up educational programs that are permanently offered to students and professionals in the Netherlands, thus contributing to education in the Netherlands.

It’s time for Circular energy
It’s time for **Iron Power**

TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY TNO metalot RIFT Iron+