Vision document

Iron Power ecosystem

a clean and circular energy carrier

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This document is the result of a joint effort by Eindhoven University of Technology, Metalot, Pometon S.p.A., EM Group, RISE ETC, Shell, SOLID, RIFT, Veolia and HeatPower.

The consortia partners are developing the iron power technology. This vision document aims to inform about the technology and ecosystem, its application and potential, and its current status and roadmap.
More information about calculation models and data is available upon request.

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Executive summary

Climate change necessitates an energy transition from fossil fuels to renewable energy. However, there is often a temporal mismatch between demand and availability of the renewable energy source. A second factor is that the best regions in the world to generate sustainable energy are not necessarily the regions where there is the highest demand for energy. These are similar challenges to those encountered with fossil fuels: Oil and coal are easily stored and transported to make them available on demand in industrialized and populated regions. An efficient cost-competitive renewable energy carrier is required to replace fossil fuels. This would enable storage and transportation of renewable energy over long distances. A promising candidate is iron powder.

This vision document provides an overview of the iron power technology and ecosystem development. It takes a closer look at the application and potential, and its current status and development roadmap.

Iron power ecosystem

Iron is a clean, dense and renewable energy carrier based on the circular process of combustion and regeneration of iron powder, as shown in Figure 1. Iron powder can be stored and transported to energy demand locations. On demand, the iron is combusted, releasing renewable energy in the form of high temperature heat. The combustion product, iron oxide powder, is captured and regenerated to iron powder. In this regeneration step, renewable energy is stored in iron powder via reduction with green hydrogen. This closes the cycle, making it a renewable circular iron power system.

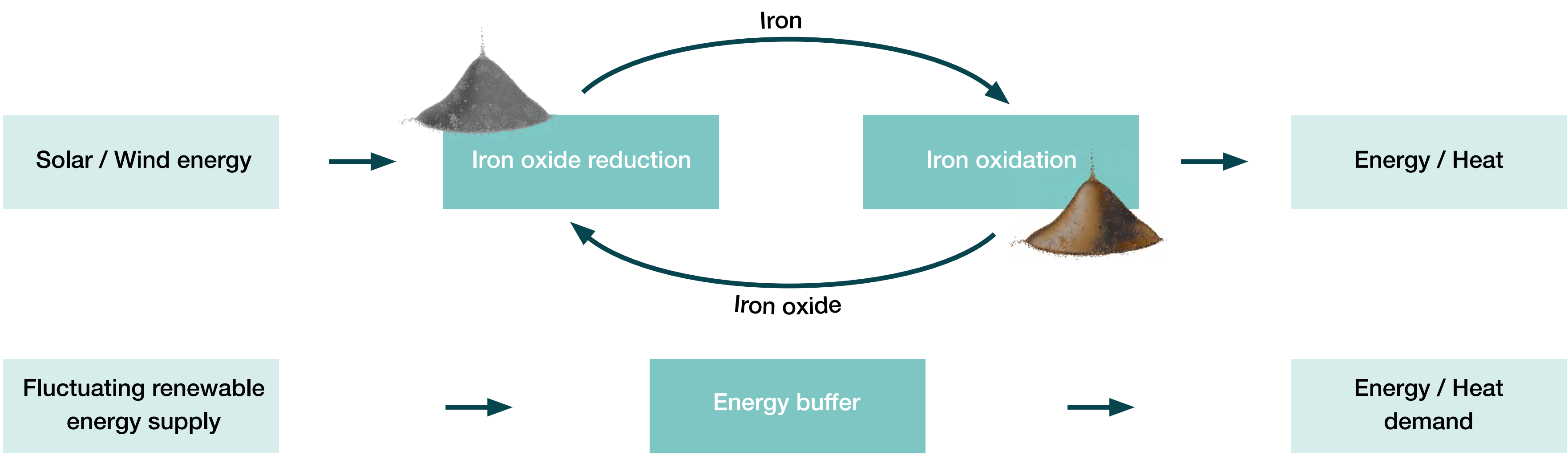

Figure 1: The iron power ecosystem

Main benefits

Iron powder will be complementary to other energy carriers in the future energy mix. The main benefits include:

- Zero carbon dioxide (CO_2), ultra-low nitrous oxide (NOx) and zero sulphur oxide (SOx) energy
- High temperature heat (200°C - 1,000°C)
- Major potential as global energy commodity, like oil and coal
- Simple infrastructure, easy storage and widely applicable.
- Security of supply and storage of strategic energy reserve
- Retrofit potential using existing infrastructure
- Competitive energy efficiency

The Levelized Cost Of Energy (LCOE) of iron power is competitive with other renewable energy carrier systems. It could soon be within the LCOE range of natural gas and other fossil fuelled systems, due to the expected price increase of fossil fuels (a.o. CO_2 penalties).

Based on the above-mentioned advantages and characteristics, iron power will be most interesting for the following applications:

1. Off grid – and grid supporting – heat intensive applications
2. High temperature industrial heat applications
3. Powerplants, e.g., retrofitting coal and biomass fired power stations
4. Maritime propulsion

The iron power concept is clean and circular. Thus, the impact on the environment is minimal. Iron itself is one of the most abundant materials available on earth. Furthermore, it can contribute to improving the position of less developed countries which are rich in renewable energy sources. The social acceptance of the technology is expected to be high.

Roadmap

The iron power concept has gained interest all over the world in the last years as research and development have moved away from it just being a curiosity. The first proof of concepts have been demonstrated. The remaining engineering challenges are soluble and will be ready for demonstration to potential end users within the next few years.

The progress of the iron power ecosystem development is marked by the following milestones:

- By 2024: Technology Development (TRL 5).
  Milestone: Full demonstration of cyclic combustion and regeneration prototypes up to 1 MW.

- By 2026: Ecosystem Development (TRL 7).
  Milestone: Full demonstration of multiple pilots including logistics on a 1 – 10 MW scale.

- By 2030: Market Development (TRL 9).
  Milestone: Mature iron power ecosystem where multiple end users are connected, and iron powder is being traded as a commodity.

Next steps

Collaboration with other industrial, logistic, and commercial partners will accelerate the development and introduction of the iron power system. Governmental participation and funding and support from institutions are critical for a successful realisation of this opportunity. In a joint effort the iron power system can become a mature solution for transport and storage of large quantities of renewable energy. This will support the worldwide energy transition program by solving the temporal and spatial mismatch of the production and demand of renewable energy. To achieve the stated ambitions, there is a need for financial support (e.g., investment fund) to finance further development and large-scale demonstration projects.

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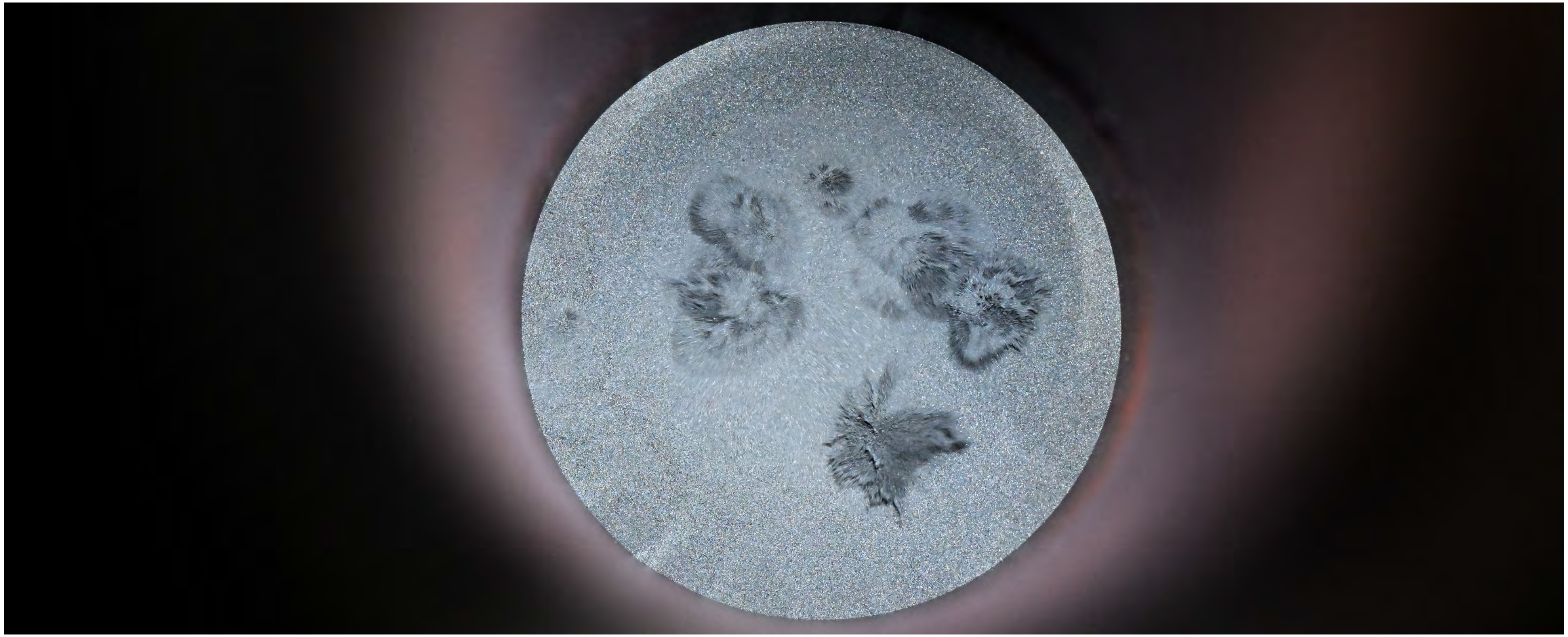
1. Future global energy system

The future energy mix will change completely when the worldwide use of fossil fuels is replaced by renewable energy sources such as sun, wind, and geothermal energy. Globally there is plenty of renewable energy available. Locally, however, there is a significant mismatch between supply and demand of renewable energy. In densely populated and industrialized regions with high energy demand, like North-West Europe, it is not viable to install all the required capacity to fully decarbonize industry. Efficient and large-scale energy storage and transportation concepts are essential to overcome the geographical and temporal (diurnal, monthly or seasonal) variations associated with renewable energy production.

Energy transportation is nothing new. Currently billions of tonnes of fossil fuels are transported all over the globe. They act as both an energy source and an energy carrier. When substituting fossil fuels with renewable energy production, a carrier is needed to transfer energy from regions where there is an energy surplus (or where a surplus can be created) to densely populated and industrialized regions.



Energy carrier concepts for long distance transport and storage of renewable energy

The most important criteria for such renewable energy carriers are:

- Easy, compact, safe storage and transportation capabilities
- Circular and low environmental impact
- Economic viability
- Tradability as a commodity
- Scalability

There are already a variety of energy carriers which all have its specific use cases. Batteries, for example, are only feasible for small scale applications, like hourly power grid balancing. Most concepts of renewable energy carriers for large scale applications are based on the use of (green) hydrogen gas. Hydrogen production costs vary widely by location worldwide. The prices for hydrogen in figure 2 are based on the long term expected production costs of hydrogen. Figure 2 shows potential energy trading routes from regions with low hydrogen production prices to regions with high energy demand and higher energy prices. Hydrogen gas, however, is not always the best option.

This document introduces the renewable energy carrier concept "iron power" as a cost-efficient alternative energy carrier system. The concept is based on the circular combustion and regeneration of iron powder. Iron powder will become part of the future mix of new energy carriers that is needed to replace fossil fuels.

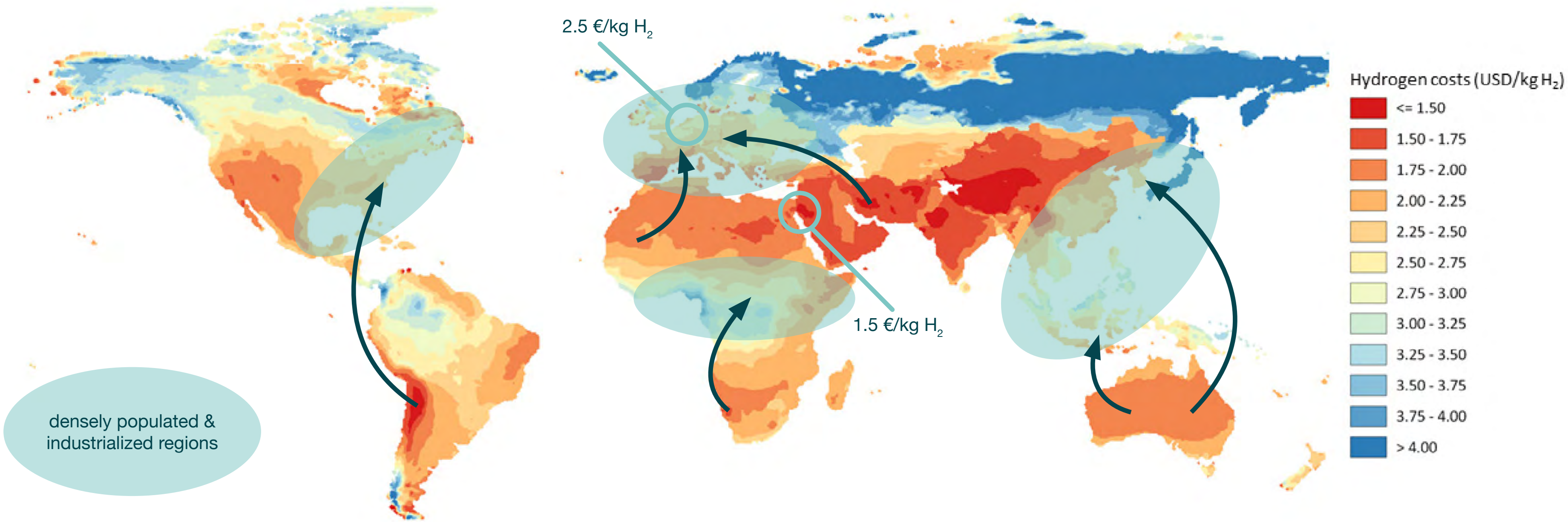


Figure 2: Potential energy trading routes based on the expected long term production cost of hydrogen from hybrid solar PV and onshore wind systems and energy demanding regions. (Source: adapted from IEA2021)

2. Iron Power System

The iron power system is a renewable energy carrier concept based on a circular process of combustion and regeneration of iron powder. When iron powder is burned, it releases energy and the iron powder is transformed into iron oxide. Iron oxide can be turned back into iron powder again by reducing it with green hydrogen. This closes the iron power cycle, making it a renewable circular system. Student team SOLID has illustrated the system in this short video.

2.1. The Ecosystem

The core of the iron power ecosystem is the use of iron powder as a medium to store and release renewable energy via combustion and regeneration. Iron powder can then be transported between energy supply and energy demanding locations. The full ecosystem is represented in Figure 3 and is explained below.

The iron power ecosystem consists of the following elements:

1. **Renewable energy** (solar, wind) is needed to produce green hydrogen and heating of the regeneration reactor. The price of the renewable energy has a strong impact on the price of the regenerated iron power. Therefore, locations with an energy surplus, or where a surplus can be realized at relatively low costs, are most viable.
2. **Hydrogen** gas is required to reduce the iron oxides into iron powder. System integration of the hydrogen production and the regeneration reactor may improve the energy efficiency. Regeneration via direct electrolysis, which would skip the hydrogen production step, is being studied but is not yet ready for demonstration.
3. **Regeneration** of the combusted iron oxide is a high temperature gas-solid reaction and comparable to the direct reduction of iron ores. The process is tailored to produce iron powder with desired specifications. Different reactor concepts are under development (see section 3.3.)

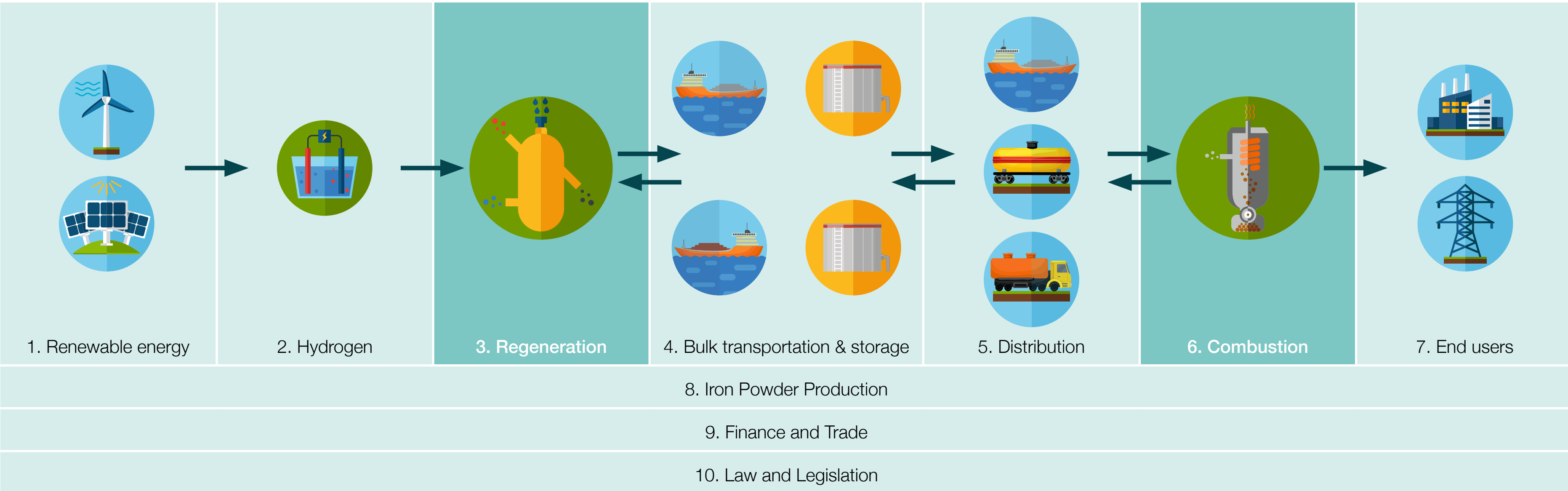


Figure 3: The Iron Power Ecosystem

4. **Bulk transportation and storage** are needed to solve the spatial imbalance of availability and demand of renewable energy. Additionally, it can serve as a strategic and seasonal energy reserve. This is comparable with the trading and storage processes of fossil fuels. Long distance transport of iron is a common practice at large scale and will be not much different for iron powder.
5. **Distribution** of iron powder is done in closed systems and in a dry atmosphere to avoid water and the associated undesirable oxidation of the iron powder. Transportation can be done by trucks, railway or inland shipping.
6. **Combustion** of iron powder is a high temperature oxidation reaction. The combustion product is solid iron oxide powder that is collected and regenerated. The current development of the combustion system is discussed in more detail in section 3.2.
7. **End users** require either direct heat, indirect heat (e.g., via hot water or steam) or electricity (via combined heat and power). Based on the characteristics of the technology, industrial end-users are the most obvious customers. The high temperatures that are obtained by combustion enable high temperature and high-pressure steam (>200°C). It would also be feasible to retrofit coal and biomass fired power stations. The energy can be delivered directly to the end user or be used in a district-heating or electricity grid to fill the intermittency gap of renewable energy sources.
8. **Iron powder production** is the starting feedstock for the iron power cycle. The production of iron powder is needed for starting up the process. It is also needed for replacing powder that might have become unusable due to attrition or agglomeration in one of the different stages of the circular process. The iron powder is currently produced by powder manufacturers for metal casting and additive manufacturing, but similar types of powders can also be used as a sustainable energy carrier.
9. **Financing and commodity trade** are essential to realize the activities and include grants, subsidies, equity, insurance, taxonomy, debt, contracting, hedging facilities etc.
10. **Law and legislation** are relevant to every element of the ecosystem. Standardization of the power characteristics will help large scale market uptake and reduce system prices.

2.2. Market applications

The most important advantageous characteristics (*) of iron power give an indication of the potential market applications. These key characteristics are summarized in the table below:

Table 1: Key characteristics of the iron powder

Area	Key Characteristics
Sustainability	
	Low NOx emission
	Low particulate matter emission
	No SOx emission
	No CO2 emission
	Fully recyclable/circular energy carrier
Safety	
	No health hazard – not toxic
	No environmental hazard and not corrosive
	Not gaseous or explosive
Economic	
	Low operational logistic costs (OPEX)
	Low storage and transportation infrastructure costs (CAPEX)
	Retrofitting possibilities
Technical	
	High output temperature (200°C - 1000°C)
	Negligible storage losses
	Energy dense (~2 kWh/kg, ~4.1 kWh/L)
	Low mass and energy losses

* As tested on lab scale

Considering these characteristics, iron power could serve:

1. Off grid – and grid supporting – heat intensive applications (study done for Uniper district heating and Swinkels brewery)
2. High temperature heat (>200°C) applications (study done for Shell Pernis steam provision and renewable methanol plant)
3. Powerplants, e.g. retrofitting coal and biomass fired power stations (>2030) (study done for Uniper MPP3 plant)
4. Maritime propulsion (>2030) (study done for ship profile and layout)

More specifically, the following applications have large global potential:

1. Peak & back-up plants for district heating networks
2. Peak & back-up plants for combined heat and power
3. Baseload plants for combined heat and power (e.g., replacing biomass stations)
4. Process heating – indirect (via steam boilers)
5. Process heating – direct (furnaces and reactors)

On a European level, the total industrial process heating demand (>200°C) is more than 1.200 TWh, and an additional 500 TWh in the range of 100°C-200°C.

For Dutch industry, Energy Innovation NL estimated that in 2050 there will be an energy demand of 11 TWh for Combined Heat and Power, 42 TWh of high temperature steam (>200°C) and 36 TWh of high temperature furnaces (Routekaart Electrificatie in de Industrie 2020). The required industrial heating capacity (>200°C) is estimated to be in the range of 7 GW, with an additional 10 GW for low temperature heat (<200°C).

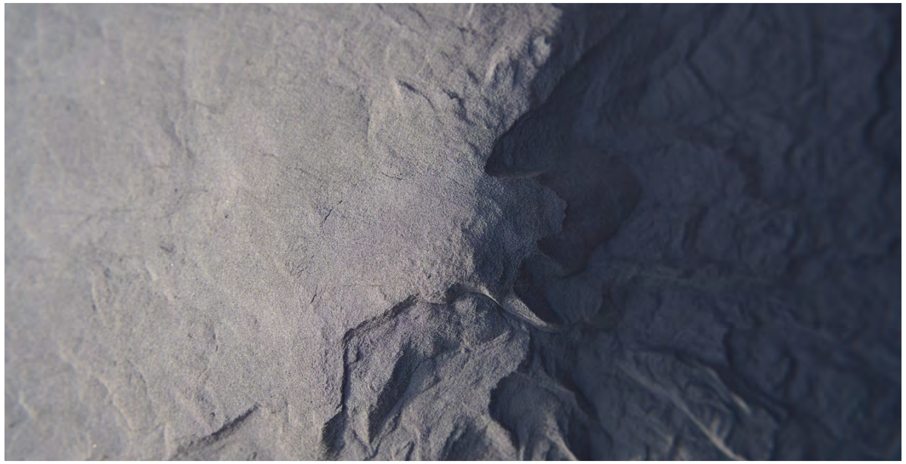
3. State of the Technology

Since 2015, research and development on iron power technology has gained global interest. The consortium authoring this document has since built up a strong and leading R&D portfolio. A unique aspect of this consortium is that is has been working on both understanding the fundamentals, and scaling the technology by developing prototype and pilot systems. So far, no technical showstoppers have been identified. The remaining engineering challenges to achieve operational competitive systems are soluble and should be ready for demonstration to potential end users within the next few years.

In this chapter we review the current state of the power specifications, combustion technology and regeneration technology, along with a discussion of social and environmental acceptance.

3.1. Power cyclicity

From both environmental and economical perspective the power cyclicity is key. Power cyclicity includes capturing all material in the handling systems and preserving the powder integrity and quality during all facets of the oxidation-reduction cycle.



The specified iron powder is easy to use and safe to handle. The average diameter is on the order of the thickness of a human hair. It has good flowability and the explosivity is lower than hydrogen, natural gas and coal. However, inadequate iron powder specifications and incorrect process conditions can have unfavourable effects. During combustion, temperature and phase-changes may lead to breaking up of particles as well as undesired nanoparticulate emissions. During regeneration attrition or agglomeration may occur. These effects are detrimental for the power integrity and cyclicity. This requires good fundamental understanding of the combustion and regeneration process, as well as the effect of the iron power specifications on the overall process.

In terms of the powder, the parameters of interest include:

1. Chemical composition (impurities)
2. Morphology (e.g., form and shape, porosity, and specific surface area)
3. Rheology (e.g., angle of repose and flowability index)
4. Particle size and size distribution
5. Bulk density

The consortium partners are studying multiple combustion and regeneration cycles for different powders and have made progress in mitigating these effects. More research is needed to accurately map the powder and process boundary conditions. The goal is to work towards standardization of the iron power cycle. This will lead to cost reduction of the components. It will also result in predictable behaviour that allows minimization of undesired emissions and energy losses in each component.

3.2. Combustion systems

The current iron power boilers are based on solid-fuel water-tube systems. During the last couple of years, the main challenges that were associated with iron power combustion in these systems have been studied:

- **Flame stabilization**
  The safety (low explosivity) of iron powder is related to the relatively low burning velocity. The consortium has demonstrated stable flames with the current 100 kW functional prototype. A boiler at MW-scale will be demonstrated in the coming two years.

- **Particulate Matter (nanoparticle) formation**
  The consortium has identified combustion regimes and powder properties to minimize emitted nanoparticles. This allows the usage of standard cyclones and bag filters to capture any escaped iron oxide particles.

- **NOx emissions**
  Initial measurements show NOx emissions below 10 mg/MJ, which makes iron power an ultra-low NOx solution.

- **Sticking and agglomeration**
  Within the flame the particles are liquid and may stick to a wall. This requires good control of the fluid dynamics within the combustion zone. After the combustion zone the particles cool down rapidly and are captured.

3.3. Regeneration systems

Iron oxide is regenerated back to iron powder by reduction with green hydrogen. While electrochemical reduction techniques such as electrowinning or molten salts are being investigated (low TRL), direct reduction systems with hydrogen gas are much more developed. Various companies have developed powdered iron ore reduction processes for the steel industry like [Hyfor] and [Circored]. These processes can produce porous powder that is very reactive and prone to oxidation while being stored. Such powders can also ignite at low temperatures, and thus require briquetting. The consortium is therefore developing new direct reduction processes that yield safe and storable iron powder.

Currently, three different reduction systems are being assessed:

1. **Fluidised Bed systems**
   Like HyFor and Circored, reactors based on fluidized bed technology are developed. They benefit from good mass transport and moderate temperatures (550-650°C). The reduction reaction rate of these systems is reasonable. The produced iron powder has a higher ignition temperature than the steel processes mentioned above, so briquetting is not required.

2. **Moving bed systems (Belt Furnace or Rotating Drum)**
   This is based on common technology in powder metallurgy. The higher operating temperature (850-1050°C) improves the reaction rate significantly. Experiments indicate that some post-processing is required to break up agglomerates. This yields a safe and easily burnable powder for subsequent cycles.

3. **Entrained Flow Reactor**
   The reduction occurs in a moving bed suspended in a gas flow at high temperatures (1300-1400°C). Regeneration is extremely fast (within seconds) and yields powders with good morphology. This concept is currently at an early stage of development but has promising characteristics.

The consortium expects to have demonstrated functional prototypes of regeneration systems by mid-2023 and to be ready to pilot these systems in an industrial setting.

3.4. Social and environmental

In the current energy landscape only countries with fossil fuel reserves can contribute to long distance energy trading with developed countries. Developing countries that have a lack of fossil energy resources but are rich in renewable energy sources, can participate in energy trading with the developed world.

No environmental harmful effects are expected from iron and iron oxide. Iron is one of the most abundant materials on earth and sources are widely spread throughout the world. Particulate matter emissions are well below acceptable limits and closed powder handling systems are used. Some powder may end up in filters within the sub-systems, but this can be recycled. This means that virtually no iron material is lost.

The iron power concept is based on the cyclic use of iron powder in closed subsystems. The combustion and regeneration (with green electricity and hydrogen) processes are carbon free. Currently, the powder that starts the cycle is produced from scrap metal. This is liquefied and purified in an electric arc furnace which has relatively low CO_2 emissions (circa 0.5 kg CO_2/GJ).

It is important that the transportation and distribution will also become sustainable. Use of current bulk carriers using fossil fuels to transport iron powder leads up to 10 kg CO_2/GJ. Sustainable fuels, like iron power, will reduce transportation and distribution emissions of bulk carriers to net-zero by 2050.

By implementing the iron power cycle the CO_2 emissions will be reduced by a factor of five compared to natural gas (11 vs 56 kg CO_2/GJ). Iron power CO_2 emissions could be further reduced to net-zero in the next decades by new powder production methods and CO_2-free shipping.

Therefore, iron power can positively contribute to the reduction of CO_2 emissions in energy intensive industries in line with sustainability goals. Next to particulate matter and CO_2, the NOx emissions are ultra-low (<10 mg/MJ) and no SOx is emitted. Finally, the iron powder combustion and regeneration processes are fully circular and thereby fits the incentives of a sustainable economy. This all contributes to social acceptance of the technology.

4. Technology benchmarking

Iron powder will be complementary to other energy carriers in the future energy mix. Each carrier has its own characteristics and purposes. For large scale transportation and storage of renewable energy, various energy carriers can be considered. In the comparison below, iron power is strategically placed in relation to these carriers.

Hydrogen

Hydrogen itself is very explosive in air comes and requires rigorous safety precautions. It has a very low energy density, even in the liquid state. Compressed storage remains bulky and expensive, while liquefaction is associated with energy losses and boil-off. Long range shipping of gaseous and liquid hydrogen is currently seen as very challenging due to the associated high costs. Onshore transport via pipelines and storage in salt caverns has potential. However, the associated requirement for an international grid is expensive and salt caverns are spatially constrained. Intercontinental pipelines through deep-sea are considered less feasible. For shipping other options are considered. These incorporate hydrogen into larger molecules such as ammonia and liquid organic hydrogen carriers.

Ammonia

Ammonia (NH_3) is a toxic and corrosive gas that requires compression and/or cooling when transporting it over long distances. There is much experience in industrial applications and transport. However, pure ammonia combustion is difficult to stabilize/operate due to the low burning velocity and is also associated with high NOx emissions or ammonia slip. Local distribution is difficult due to its high toxicity. There are government proposals to end ammonia transport by rail. Therefore, the preferred route is to crack ammonia back to hydrogen gas at central locations and distribute the hydrogen gas via pipelines. The conversion of ammonia back to hydrogen comes with losses.

Liquid Organic Hydrogen Carriers (LOHC)

LOHC's are based on the reversible catalytic hydrogenation and dehydrogenation of an organic carrier oil. Within the LOHC compounds, dibenzyl toluene (DBT) is considered as most feasible. DBT does not require cooling or compression for storage and transportation and can be done in today's fossil fuel infrastructure. However, dehydrogenation requires substantial heating and as such additional energy at the energy demanding location. Furthermore, the viscosity of hydrogenated DBT is a challenge for winter applications.

In economic models, ammonia is identified as a cheaper alternative for large scale energy trading and therefore LOHC has not been included in the technical and economical comparisons below.

Hydrocarbons

Hydrocarbons are not considered feasible for large scale energy storage and transportation. Renewable synthetic fuels are considered to be relatively expensive and require a CO_2 source. Biofuels are difficult to scale and are competitive in land use. The market applications are air and maritime transportation. Hydrocarbons are therefore not included in the technical and economical comparisons below.

Table 2: Benchmarking key technical characteristics iron powder, gaseous and liquid hydrogen, and ammonia.

	Iron Power	Gaseous Hydrogen	Liquid Hydrogen	Ammonia
Health, Safety and Environment				
	• Flammable • Irritant	• Flammable • Explosive gas • Pressurized gas	• Flammable • Explosive gas • Pressurized gas	• Corrosive • Acute toxic • Environmental hazard • Pressurized gas
Energy density (LHV, including tank)				
[MJ/L]	22 (iron power) / 16 (iron oxide)	0.9 - 4.0 (compressed)	4.9	6.3
[MJ/kg]	7.2 (iron power) / 5.1 (iron oxide)	5.7 (high pressure tank)	13.3	15.7
(Re)Conversion				
Conversion: Efficiency (LHV)	Direct Reduction 71 - 80%	Compression 85 - 93%	Liquefaction 65 - 75%	Habert-Bosch 82 - 93%
Reconversion: Efficiency (LHV)	n.a.	n.a.	Gasification 98%	Cracking 66 - 80%
Storage				
Containment:	Bulk silo (atmospheric conditions)	Pressure tank (low volumes)	Cryogenic tank (high boil-off)	Cryogenic tank (low boil-off)
		Salt & Rock caverns (geographically restricted)		
		Gas fields (uncertain)		
Transport				
National:	Inland shipping (barges)	Trucks (low volumes)		
	Railway (bulk railcar)	Pipeline (complex infrastructure)		
International:	Bulk carriers (modified bulk)	Pipeline (complex infrastructure)	L-H_2 tankers (modified LNG)	L-NH_3 tankers (modified LPG)
Intercontinental:	Bulk carriers (modified bulk)	-	L-H_2 tankers (modified LNG)	L-NH_3 tankers

Conclusion benchmarking

Table 2 shows that iron powder is a clean, dense energy carrier that can be stored and transported safely. Transportation is not restricted by borders or geography. Storage containers are simple, compact bulk silos without compression or cooling and with minimal energy losses over time. Large scale transportation is viable with bulk carriers and distribution to industrial end users can be done by for example trucks, bulk railcars or hopper barges. Iron powder can be widely applied, unless weight limitations are an issue. e.g. fuel for airplanes.

5. Financial comparison renewable energy carriers

Iron power is an economically attractive method of importing renewable energy. To illustrate this, the Levelized Cost Of Energy (LCOE) for the iron power value chain is calculated for several potential industrial end users in the Netherlands. It is then compared to alternatives.

5.1. LCOE comparison for high temperature heat

In this example we calculate the LCOE for an industrial end user in Moerdijk (NL) requiring high temperature (>200°C) steam. For the provision of the required energy, four carriers are compared:

1. Iron powder: Produced in Saudi-Arabia, imported to the Port of Rotterdam via bulk carriers, and distributed to the end user using hopper barges.
2. Hydrogen gas via ammonia: Produced Saudi-Arabia, imported to the Port of Rotterdam via liquid ammonia conversion and shipping, reconverted to hydrogen gas, and distributed via local pipelines.
3. Hydrogen gas: Produced in Saudi-Arabia, imported via transmission pipelines, and distributed via local pipelines.
4. Hydrogen gas: Produced in the Netherlands and distributed via local pipelines.

The LCOE of the four carriers is divided into five cost items:

- Hydrogen: the local green hydrogen production cost. A renewable energy source is used to produce green hydrogen via electrolysis, with an assumed production cost of € 1.50 per kg in Saudi-Arabia and € 2.50 per kg in the Netherlands in 2030.
- (Re-)Conversion: the costs related to the production of iron powder and ammonia, and reconversion of ammonia to hydrogen gas.
- Storage & Transport: the transportation, distribution, and storage costs. For iron power, this includes the transport of the iron oxide powder back to the regeneration site.
- Iron Batch: the financing costs of the initial iron powder that enters the cycle.
- Boiler: the total costs related to the steam boiler system.

In figure 4 the LCOE comparison for the four renewable energy carrier concepts is shown. It can be observed that:

- The LCOE of imported iron power is within the range of hydrogen import and local hydrogen production.
- For all cases, the hydrogen production is the major cost item of the LCOE.
- The ease of storage and transport of iron powder compared to other energy carriers outweigh the capital cost required for the iron powder batch.
- Iron powder transportation and storage contribute marginally to the LCOE, suggesting that it is cost-efficient to produce the energy carrier close to a cheap hydrogen source.

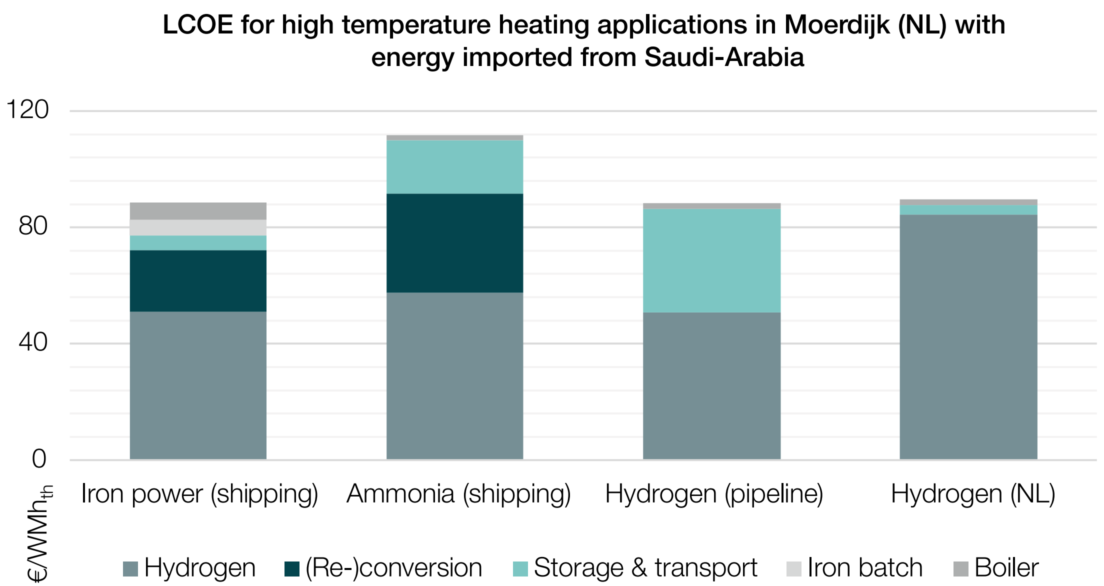


Figure 4: Financial comparison of the LCOE for high temperature processes

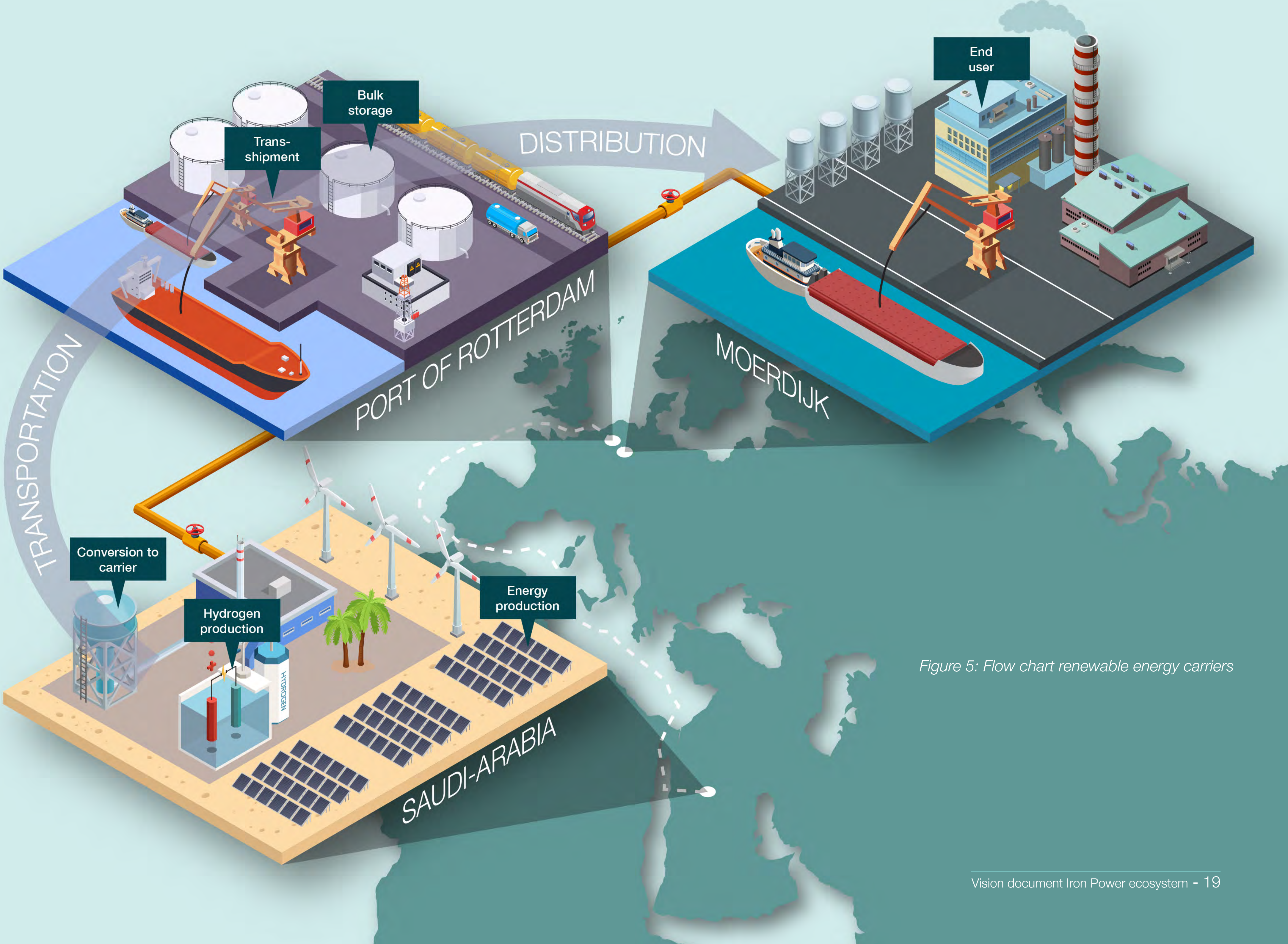


Figure 5: Flow chart renewable energy carriers

The North Sea has great potential for hydrogen production. Offshore wind is associated with high full load hours and hydrogen users are close by. However, space and storage capacity are limited so local hydrogen production will have to be complemented with energy import.

Building a pipeline from Saudi-Arabia is not trivial. The pipeline would have to pass through water and many countries that are not directly involved in the trade. This would involve significant geopolitical issues and extra unforeseen work. The transmission pipeline costs translate to circa € 0.23 per kg per 1000 km. Shipping iron powder and ammonia from Saudi-Arabia to the Netherlands would only involve a bilateral agreement between the two countries. Based on the above observations, we conclude that iron powder is an attractive addition to the future energy system and is competitive for this use case.

Comparison with fossil-based fuels

Due to the impact on climate change, governments will discourage and phase out the use of fossil fuels. To urge the industry to transition, governments will implement regulations, like the Green Deal 'Fit for 55' package, that affect the LCOE of natural gas systems. The EU taxonomy and the increasingly limited emission cap of the Emission Trading System (ETS) will cause the LCOE of natural gas systems to rise above 90 €/MWh. Therefore, the LCOE of iron power will soon be within range of the LCOE of natural gas fuelled systems.

5.2. LCOE of other applications

As discussed in the Market Analysis (paragraph 2.2) there are various potential applications for iron power. The iron power scenario in the preceding section was aimed at high temperature process heat. We also consider the LCOE of this iron power for two other applications:

- Combined Heat & Power (CHP) plant in the port of Rotterdam (near port, no distribution)
- District heating peak and back-up plant in Rotterdam city centre (distribution of iron powder via silo trucks)

In Figure 6 the LCOE of heat via iron power for these applications is shown, together with the 'High Temperature Process Heating' case described above.

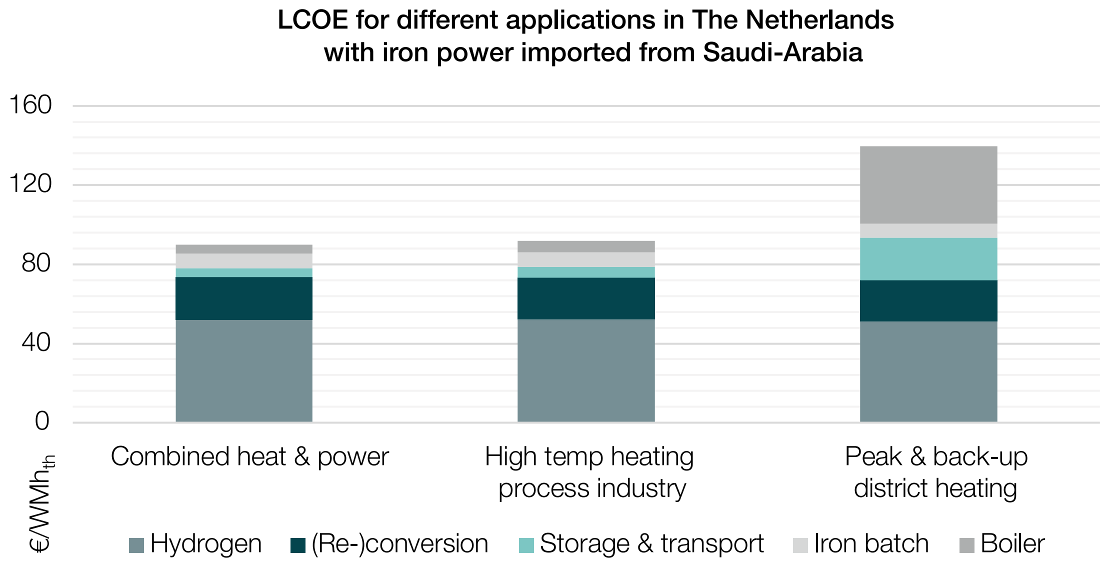


Figure 6: Total cost of energy for end-user

Combined heat and power (CHP) systems play an important role in the current energy system. If existing gas-fired or biomass-fired CHP plants can be retrofitted to iron power, there are virtually no investment costs for the power cycle. Compared to a steam boiler for process heating, scaling of the output power of the CHP boiler leads to marginal lower costs. Therefore, the LCOE of iron power heat for CHP and high temperature process heating are in the same range and the electricity can be produced at competitive prices.

At approximately 140 €/MWh$_{th}$ the example peak and back-up system for a district heating network is more expensive than the CHP and process heating applications. This is mainly due to the high transportation costs by truck to the city centre and the inherently low duty cycle of the heating system. The latter increases the investment costs per delivered amount of energy (boiler costs). The main alternative in a renewable's world is the e-boiler. (Hydrogen firing is not considered viable in city centres due to storage and safety concerns). However, during peak demand power prices often exceed 140 €/MWh$_{e}$. That, and the cost required for grid upgrading, may lead to a higher LCOE for an e-boiler in district heating networks. Therefore, iron power can also play an important role in peak and back-up plants.

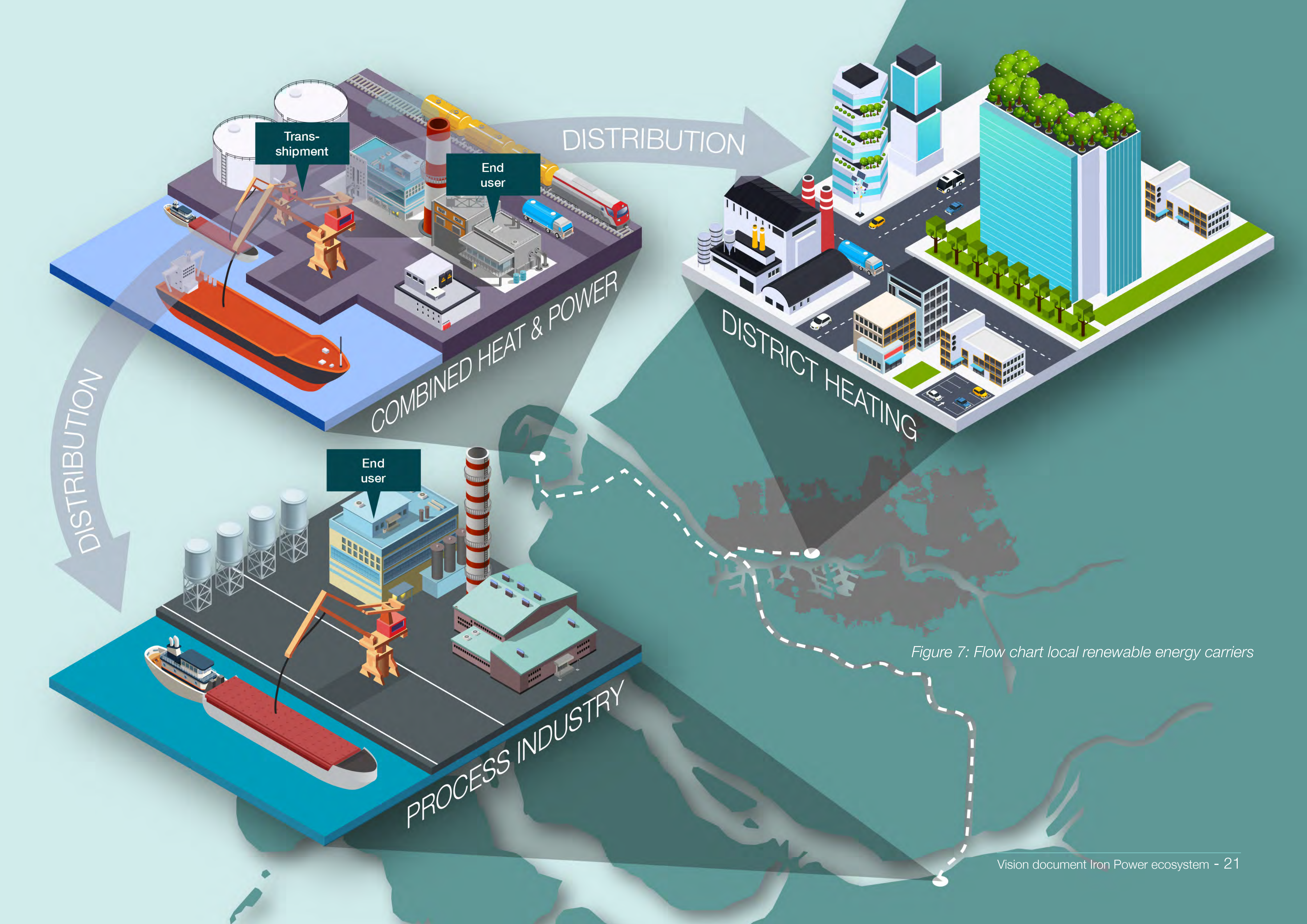


Figure 7: Flow chart local renewable energy carriers

6. Roadmap

To introduce iron power in the energy system, a new value chain needs to be set up. To achieve this, collaboration between governments, knowledge institutions, business partners from the industry, and trading companies is essential. To guide coordinated technology development and implementation efforts, we plan a roadmap as explained below.

6.1. Mature ecosystem

For a full breakthrough and wide adoption of iron power technology, we need a fully operational and efficient ecosystem. This requires the immediate and parallel development of:

- **Proof of technology value chain**
  Full demonstration of the core technology (combustion and reduction systems), auxiliary systems and system integration by pilot in real-life (industrial) conditions.

- **Participation of the hydrogen industry**
  Establish collaboration with business partners active in the hydrogen production. Ensure a surplus of cheap renewable energy at strategic locations and supply of green hydrogen.

- **Market development**
  Develop iron power supply and trading platforms by collaborating with important players in the commodity and/or energy trading market. Collaboration with energy companies is required to develop iron power demand at end users.

- **Reduction of the production cost of raw iron powder**
  Collaborate with parties in the metal powder market to reduce the cost of raw iron powder by large-scale iron powder production from scrap metal or iron ore fines.

- **Large/strong consortium**
  Active lobby towards politics, government, and the energy sector to be considered for strategic decision making and design of the energy system.

- **Laws & regulations**
  Standardized fuel properties and storage, handling and safety regulations to open up the market and financing options.

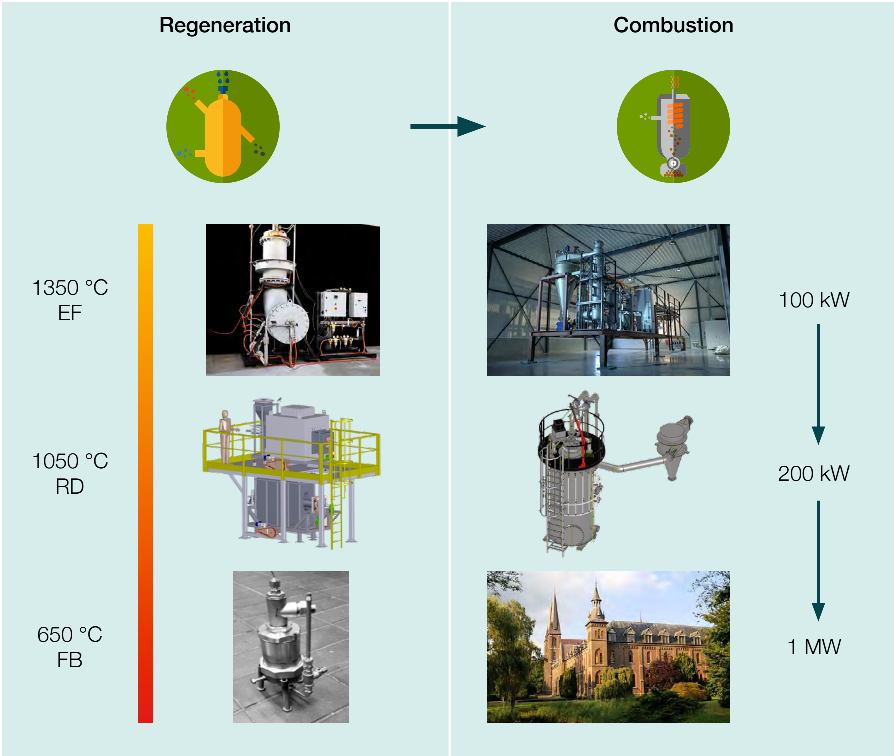
6.2. Milestones

The progress of the iron power ecosystem development is marked by the following milestones:

- By 2024: Technology Development (TRL 5).
  Milestone: Full demonstration of cyclic combustion and regeneration prototypes up to 1 MW.
- By 2026: Ecosystem Development (TRL 7).
  Milestone: Full demonstration of multiple pilots including logistics on a 1 - 10 MW scale.
- By 2030: Market Development (TRL 9).
  Milestone: Mature iron power ecosystem where multiple end users are connected, and iron powder is being traded as a commodity.

Each milestone is briefly discussed below.

Technology Development



Main deliverable: Full demonstration of cyclic combustion and regeneration prototypes up to 1 MW scale

Figure 8: Technology Development

By 2024 functional prototypes of the core technology (cyclic regeneration and combustion systems) are developed and demonstrated. Furthermore, iron powder losses will be lowered and its cyclicity will be improved.

The main developments concern:

- **Regeneration:**
  - Development and demonstration of several regeneration system prototypes: Fluidised Bed (FB), Rotating Drum furnace (RD), Entrained Flow Reactor (EF).
  - Design study for system integration of regeneration system with electrolysis for heat integration and efficiency optimization.
  - Feasibility assessment of, and connection to, alternative electrochemical reduction methods.
  - Fundamental understanding of reduction reaction to optimize particle morphology and other fuel characteristics.
- **Combustion:**
  - Demonstration that iron power can be safely applied in industry. Optimization and development of a 200 kW test-setup in a controlled environment and subsequent demonstration of ~1 MW setups at end users.
  - Directives for iron powder combustion to mitigate undesired emissions, such as volatile sub-species, and material losses.
- **Cyclicity:**
  - Proof of iron power concept: demonstrate powder integrity over multiple combustion and regeneration cycles.
  - Assessment on the effect of temperature and humidity on the storage of iron powder.
  - Directives for the chemical composition of iron powder and the iron feedstock.

Ecosystem Development

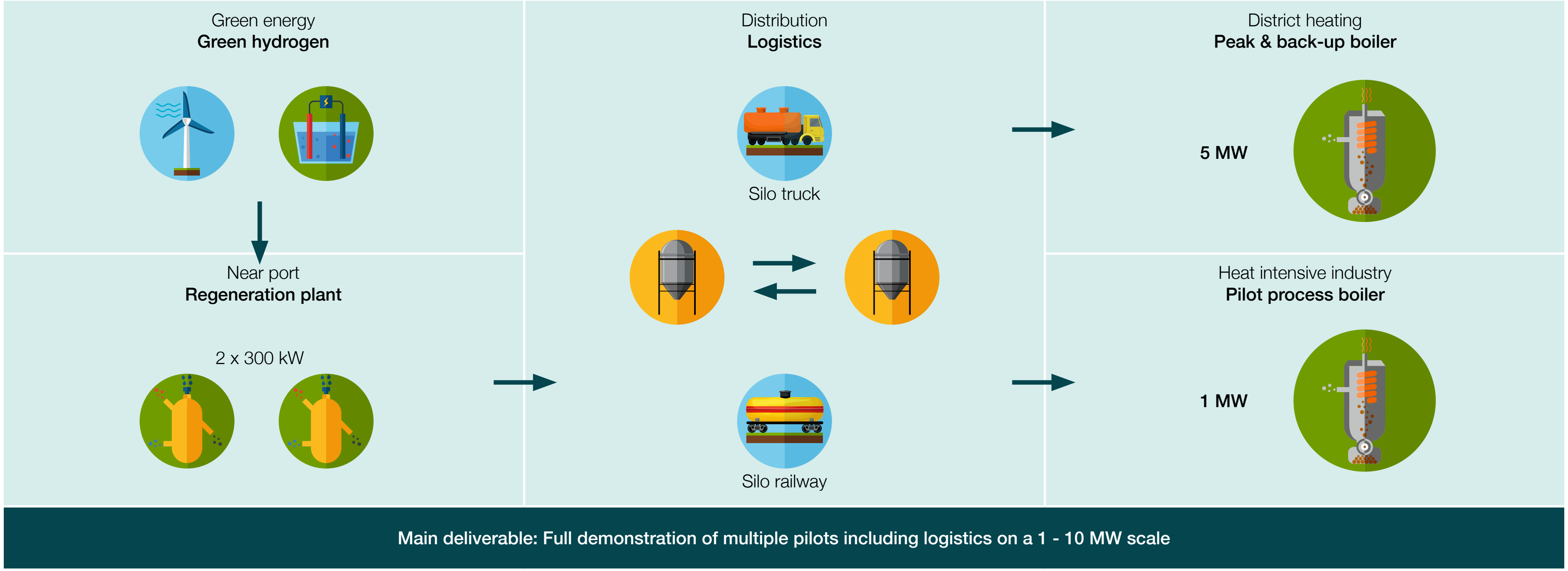


Figure 9: Ecosystem Development

In this phase, the focus will be on demonstration of the complete iron power value chain. Collaboration with hydrogen suppliers and energy consumers in industry will be required to initialize several pilot projects in this field. In these pilot projects the business case for local renewable energy storage (to overcome intermittency) is tested. Furthermore, the iron power technology is scaled and tested in industrial settings.

Potential pilot projects include:

- **Green hydrogen & regeneration plant:**
  - System integration pilot of ~300 kW electrolyser with ~300 kW reduction reactor (e.g. FB or RD) producing 1 kton (2,000 MWh) of iron power annually.
- **Hydrogen by-stream & regeneration plant:**
  - Pilot plant producing 1 kton (2,000 MWh) of iron power annually which is connected to a waste stream of reducing gas.
- **Heat intensive industry pilot:**
  - Pilot to produce steam for process industry to overcome (local and diurnal) mismatch between energy supply and demand. This pilot will demonstrate the safety and reliability of the iron power system.
- **District heating pilot:**
  - Peak and back-up boiler for district heating to overcome (seasonal) mismatch between energy supply and demand which will provide security of supply in rural areas. This pilot will demonstrate the flexibility and reliability of the iron power system.
- **Logistics:**
  - Storage, distribution and handling systems of the iron powder and spent fuel of the pilots mentioned above. Important aspects are mass and energy loss minimalization, handling safety and efficiency, logistic standardization, and other regulations.

Market Development

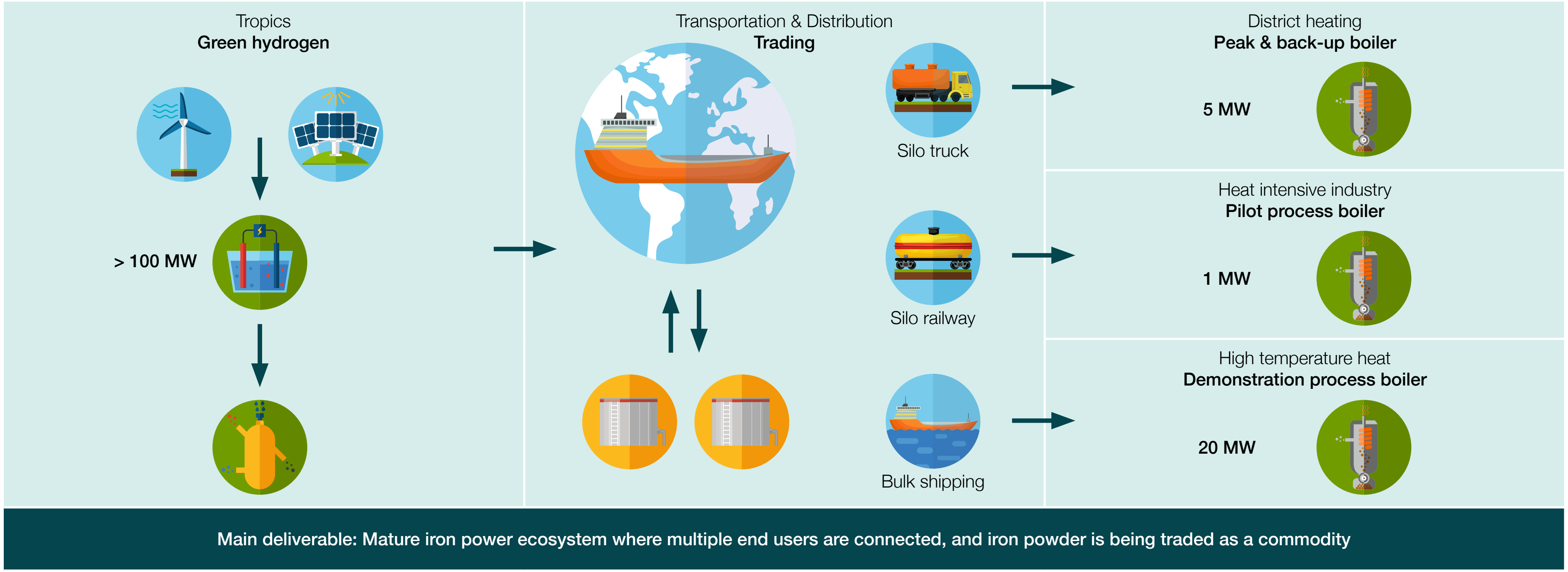


Figure 10: Market Development

In this phase, the international trade of iron powder is initiated by connecting it to existing renewable energy production sites at locations with cheap renewable energy (e.g., Northern Africa, Middle East or Australia). Transportation of iron powder by bulk carriers (or equivalent smaller scale pilot vessels), as well as transhipment at the port, are started up. Existing trade and logistic companies specialized in bulk goods and energy companies need to join efforts to develop a business model for the iron power cycle. Potential demonstration projects include:

- **Iron power regeneration plant:**
  - Be involved with international initiatives that produce abundant cheap renewable energy.
  - Realization of a 0.1 MTA (100 kton = 200 GWh) demonstration plant producing iron powder with a cost of less than 200 Euro/ton (100 Euro/ MWh).
- **Trade & Logistics:**
  - Demonstration of the (trans)shipment of iron powder and incorporation in the International Maritime Solid Bulk Cargoes code.
  - Demonstration of the business case of energy trade via iron powder.
- **Combustion plants:**
  - Expending the iron power ecosystem (internationally) by involving new end-users in heat intensive industries. This includes the demonstration of an iron power system for high temperature applications (CHP or process heating) with improved full load hours, i.e., minimal downtime.

7. Next steps

The potential of the iron power system, using iron powder as a renewable energy carrier with minimal impact on climate an environment, has been demonstrated in this document.

Iron powder can be traded and stored in large volumes and act as a strategic and seasonal energy buffer. Initial technical and economical evaluations indicate that iron power can be considered as the most attractive solution to transport energy from geographical regions with an oversupply of renewable energy to geographical (industrialized) regions with a shortage of renewable energy.

Further research and development are needed to optimize the powder cyclicity and scale the technology to industrial levels. Also, the commercial and business cases need to be proven. The current partners in the consortium are committed to develop the iron power ecosystem to a next technical and business level. Collaboration with other industrial, logistic, and commercial partners will accelerate the development and introduction of the iron power system. Governmental participation and support from institutions are critical for a successful implementation of this opportunity. In a joint effort the iron power system can become a mature solution for enabling a safe and secure renewable energy supply within the worldwide energy transition program.

Iron power not only supports the European and global climate ambitions, but it also creates a new revenue model. It gives poor countries that are rich in renewable energy sources, like the countries in Northern Africa, a large international export potential. This can improve their financial position. It is important that energy demanding and developed countries, like the Netherlands, keep their leading role and act as an international testing ground for new innovations such as the iron power technology. To achieve the stated ambitions, there is a need for financial support (e.g., an investment fund) to advance the technical development and large-scale demonstration projects.

Parties that are interested to join the next phase of the development of the iron power system are requested to contact one of the consortium partners.