Metal Fuels & City Plants

05.03.2021

Feasibility study [Final]
Shortened version for subsidy reporting

1 Summary

This report describes the feasibility study of a Metal Fuels pilot project within Uniper City Plants in the Netherlands. The study has been performed in close collaboration with all project partners, being Metalot, TU/e, Uniper, Shell, EM Group/HeatPower, Cremer, Pometon and J-tec. Each of them is a specialist in one or more topics related to the metal fuels cycle and thereby delivered valuable input.

Metal fuels as circular energy carrier is being studied by the Eindhoven University of Technology and consortium partners. The concept seems very interesting as a method for safe and compact energy transport, trading and storage and allows for applications in industrial and urban areas. It is also seen as an important enabler of the world-wide hydrogen market. Burning metal powder (in this case: iron powder) results in zero-carbon, high temperature heat, that can be used in a wide range of applications. The resulting iron oxides are recycled back to iron powder using renewable energy (via green hydrogen). This circular process can be done locally, but in the future energy import from regions with high wind and solar yield is foreseen.

The technology fits well within Uniper's strategy to become carbon neutral by 2035 without compromising in reliable energy supply. On short term, the technology can be used for peak and back-up heat supply to district heating grids and for applications with higher exergetic potential like industrial high temperature processes. It therefore fits well within the Uniper City Plants and Industrial Customer Solutions portfolio.

This pilot aims to proof that Iron Fuel technology is a safe, flexible and reliable concept for the Uniper City Plants portfolio. The pilot is not optimized on energy efficiency yet, but the consortium foresees enough potential to improve the energy efficiency and CO_2 footprint to match the Uniper City Plants requirements.

The heat capacity and site location study identified that a 5 MW_{th} combustion plant located at WSG Rotterdam is the best option for this pilot. The site is well accessible by truck for supply of iron powder. A HAZID study with all relevant project partners resulted in 94 recommendations for the design and no showstoppers were identified.

For the regeneration the Uniper Maasvlakte site has been identified as the best available option. The site manager has guaranteed a plot, but the exact location has yet to be determined due to alignment with other ongoing plans. For this pilot, (blue) hydrogen will be supplied to the regeneration plant by tube trailers. The regeneration system will be fully automated and will operate continuously to minimize the required installed capacity. A HAZID study with all relevant project partners resulted in 57 recommendations for the design and no showstoppers were identified.

The iron (oxide) powder storage and handling will be fully automated. Silo trucks will transport the iron powder from the Uniper Maasvlakte site to the Rotterdam WSG site, and the oxides back. Loading and unloading of the trucks will be done by certified drivers. Although the concept is new, standard technology can be used and no showstoppers have been identified.

A cost estimate with an accuracy of +/- 50% has been made with input from all project members. The total project cost is calculated to be 16 M€. The costs include the equipment itself, initial iron powder purchase, site integration, maintenance, operational costs, fuel costs (electricity, natural gas and hydrogen), logistics, engineering, plant optimization (R&D) and project management. Costs for overhead, land-use etc. are not included. Depending on the exact location of the regeneration plant, up to 0.7 M€ additional costs for site integration should be considered.

Within the Dutch financing instruments for innovation projects, via RVO, a DEI+ pilot subsidy has been identified to be the best fitting instrument for this pilot. However, the expected subsidy percentage and the contribution of project partners is not yet clear. Therefore, to assess the financial feasibility, the consortium will take the following steps

- Metalot will gain knowledge about the specific requirements and possibilities for private and public funding. They will propose a plan, based on the current cost estimate, how the gap between public funding and required cash expenses by partners can be minimized. This provides the project team with an overview of the required contribution.
- All project partners will jointly discuss this plan and discuss how costs can be divided over the participants. If internal funding is insufficient, the possibility of attracting additional parties will be discussed.
- With the project funding plan, the feasibility phase is finished. All parties then decide whether to continue to the next phase. This is seen as the go/no-go decision moment.
- If the result is positive, the parties will compose a collaboration agreement to start with the basic engineering phase, working towards a financial decision. The financial decision, together with submitting a project plan for subsidy, will be the final milestone before the project will start with the detailed engineering phase and realisation.
- The goal is to start the project (after FD) in Q1 2022 and to complete the project in Q3 2025.

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3 Introduction

The Metal Fuels & City Plants project is a collaboration project with several partners from knowledge institutes, industry and OEM's with the goal to install a metal fuels pilot plant in the range of several megawatts. This report summarizes the results of the feasibility study to implement the technology in the district heating grid of one of Uniper's city plants in the Netherlands.

3.1 Background and current status of technology

Metal fuels, i.e. iron, is a clean, dense and renewable fuel that enables CO_2 free heat and power with security of supply to help phasing out natural gas and coal. Iron fuel can be stored and transported safely at low costs and could be applied in many large-scale industries (e.g. power plants and heat intensive industry). It has major potential to be used as an energy commodity, like oil & gas, with ultra-low nitrous oxide (NOx) emission and inherently zero carbon dioxide (CO2) and zero sulfur oxide (SOx) emission. From an economic perspective it can be used to deal with varying renewable energy prices – due to geographical or temporal fluctuations – to build a business case for clean and renewable energy. In addition, Iron fuel can serve as a strategic energy reserve since it can be stored for longer periods of time (e.g. seasonal or yearly) with low energy losses. It therefore fits in a currently existing gap: a clean and renewable energy carrier for large scale and long-term energy storage; that is a marketable commodity; that can be transported from production sites to users and that can be implemented in existing infrastructure (retrofit).

After several years of research at the Eindhoven University of Technology the step towards a first Proof of Concept plant of 0.1 MW was made last year by the Metal Power consortium. The plant was demonstrated at the Bavaria brewery on November 27 in Lieshout, NL. Based on these results, the consortium is currently engineering a 0.5 MW plant with improved efficiency and uptime. Parallel to that, the Metal Energy Carrier consortium is assessing different regeneration technologies. The consortium plan a multi-week demo at Bavaria with some recycling of the fuel early 2022. The next step is a full cycle multi-year pilot on an industrial level.

Figure 1 Global roadmap for metal fuel development

The consortium is working on various scenarios for next steps after the Metal Fuels & City Plants pilot. One of the possible scenario's is continuation in a larger 5+5 MW pilot in 2028. The combustion plant remains at the WSG City Plant and an industrial partner (e.g. Swinkels brewery) will join, such that the technology potential can be proven in both beachhead markets (adjustable high-power loads in the energy and industrial market). International collaboration for the regeneration plant is sought. Australia (Pilbara region), for example, has unraveled solar PV potential, good iron ore infrastructure and ambition to become big in energy export[1]. In collaboration with local renewable energy corporations, cheap green hydrogen (1.5 €/kgH2[2]) can be produced. Instead of an expensive hydrogen infrastructure, the hydrogen is directly used to reduce iron oxide to iron fuel in the regeneration plant near a harbor. From there, the iron fuel is shipped in silo-bulk containers to Rotterdam. Here, part of the containers is transported to the WSG City Plants location and the other part will be transported by rail or inland shipping to the other partner. At this moment in time it is likely that there is an net negative cash flow that should be covered with subsidies. Embedding sustainable energy import in the SDE++ (or equivalent instruments) is actively pursued in the Metal Fuels & City Plants pilot.

3.2 Vision and goal

The purpose of this cooperation project is to demonstrate the technical and economic feasibility of the metal fuel technology at an industrial scale. By partnering with experts over the entire value chain the chance of a successful demonstration is optimized.

Our vision is that the metal fuels cycle, when integrated in a Uniper City plant, improves the sustainability of the district heating grid. It thereby fits well within Uniper's strategy of Energy Evolution and to generate carbon neutral power and heat by 2035. In a broader view, metal fuels are seen as an interesting technology to store energy from renewable sources over a long period of time, with a high volumetric energy density. This also allows for transport of energy over long distances and global trading. The fact that combustion of metal fuels results in high temperature heat is a strong benefit for integration in industrial high temperature processes.

Success is defined as a well-operating, safe and efficient demonstration of the metal fuels technology at MW scale and a clear view on the strategic roll-out of the technology within Uniper. Part of the pilot is to optimize the process and to improve the energy efficiency of the cycle, the knowledge and skills of project partners, the social acceptance and the attraction of other interested parties.

3.3 Brief scope

This project aims to demonstrate a MW-scale metal fuels cycle implemented in one of Uniper's City Plants in the Netherlands. Therefore, a broader value chain is involved, which is schematically shown in Figure 2. The focus of this project is on the core technology: the iron powder combustion plant, the regeneration plant and the required logistics between them. There is a strong relation with other parts

[1] https://research.csiro.au/hyresource/asian-renewable-energy-hub/
[2] https://mb.cision.com/Main/115/3271384/1361667.pdf

of the value chain which must be investigated in the feasibility study, like the iron powder production, hydrogen production and the end-users of the heat. These latter topics are essential for the operating phase as well as the set-up of the business case but are not further optimized within this project.

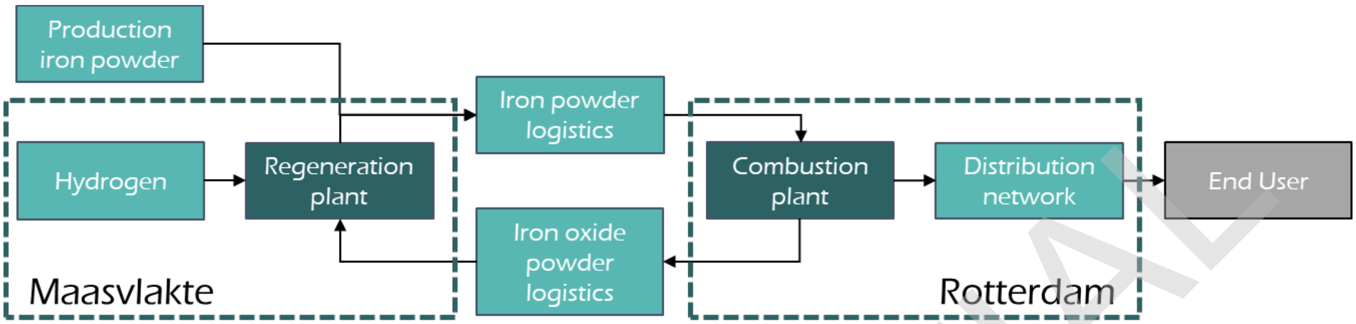

Figure 2 - Scope of the project, with focus on the core technology (combustion and regeneration)

3.4 Project partners

The following partners and suppliers have been involved in this feasibility study:

- Eindhoven University of Technology: knowledge institute, concept development
- Metalot: technology valorization, consortium building
- Uniper: end-user and site integration
- Pometon: iron powder production and regeneration development
- EM Group/HeatPower: supplier of metal fueled boilers
- Cremer: supplier of iron oxide reduction technology to regenerate fuel
- Shell: metal fuels concept development and process optimization, including application in own renewables planning for process plant decarbonization
- J-tec: material logistics, handling and storage

3.5 Feasibility study approach

In order to study the feasibility of the metal fuels pilot project, a Front End Loading (FEL) approach is used. The pilot is studied in a structured way resulting in a coherent set of deliverables, summarized in this FEL-1 report. The goal of the study is to provide decision makers with sufficient information to decide to proceed with the pilot into a next phase (conceptual design).

4 The metal fuels concept

4.1 Description of the metal fuels cycle

The concept of using metals as a fuel is nothing new. The Chinese have been burning metals in fireworks for centuries. The concept of using metals as recyclable fuels is relatively new though.

The concept makes use of the well known Redox principle. During the combustion, oxygen in the air reacts with the metal. The metal acts as a reducer, the oxygen as the oxidator. When the metal is oxidized, it loses its outer electron to give it a stable electron configuration. This electron then enters the oxygen atom exothermically, thus releasing a lot of heat. The reaction is in fact an exchange of electrons and the product is a metal oxide. In the case of iron, the equation is given as:

$$4\ \mathrm{Fe} + 3\ \mathrm{O_2} \rightarrow 2\ Fe_2O_3 + \text{heat}$$

Similarly, the metal oxide can act as an oxidizer when it reacts with a reducing agent like hydrogen. The hydrogen then reduces the metal oxide to metallic ion and the reducing agent (hydrogen) becomes oxidized (water). This equation is given as:

$$Fe_2O_3 + 3\ H_2 \rightarrow 2\ \mathrm{Fe} + 3\ \mathrm{H_2}O$$

The metal, in this case the iron, is therefore not consumed but acts as an energy carrier and can be used cyclically, in principle infinitely often. The hydrogen can also be used as an energy carrier, when water is reduced into hydrogen gas and oxygen gas using sustainable electrons in an electrolyzer, following the equation:

$$2\ H_2O = 2\ H_2 + O_2$$

The energy chain can then be displayed as:

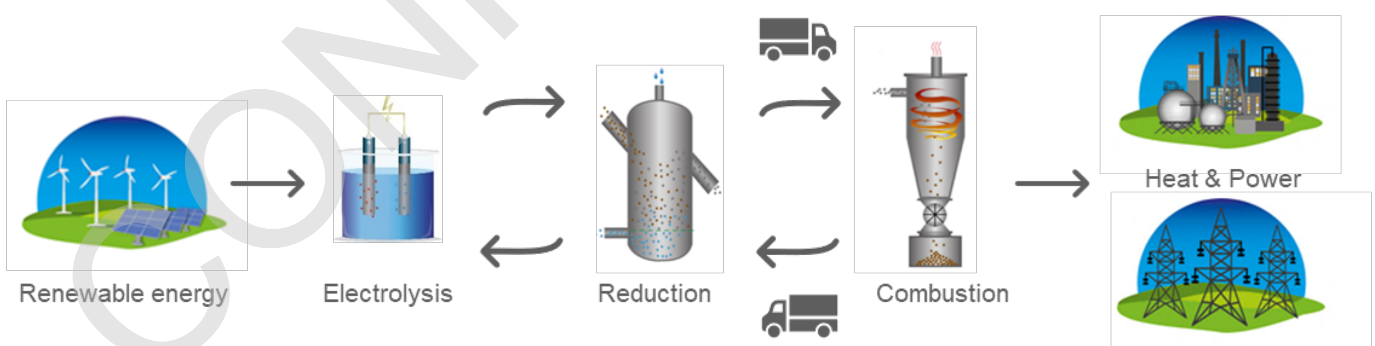

Figure 3 The iron fuel energy chain

Reducing the metal oxide using hydrogen gas as a reducing agent is called "Direct Reduction". In principle, the iron oxide can also be directly reduced in an electrolyzer cell using electricity. This technology, however, is currently still at low TRL but is expected to become important in the future. In the next decades, Direct Reduction is expected to be dominant in the iron and steel industry.

The reason that iron is used as the metal fuel is a result of several factors, including:

- Technology for reduction of iron oxides to metallic iron exists using renewable-based electricity,
- the material is durable and robust to repeated reduction-oxidation cycles,
- it has solid combustion products with low propensity for forming fumes of sub-micron oxide particles so that their capture and recycling are feasible and mass losses are minimized,
- good safety, high energy density and economical transportation characteristics,
- iron is one of the most abundant materials on earth and for the fuel production eco-friendly scrap can be used,
- low NO_x formation emissions,
- and the adiabatic temperature and the burning velocity are within traditional fossil fuel ranges which allows retrofitting existing combustion technology.

4.1.1 Block diagram

In this pilot project, the proof-of-concept of the metal fuels concept is to be demonstrated in a real-live situation at one of Uniper's sites in the Netherlands. Therefore the entire cycle including combustion, regeneration and logistics is part of the pilot scope. The link between these process steps is schematically shown in Figure 4.

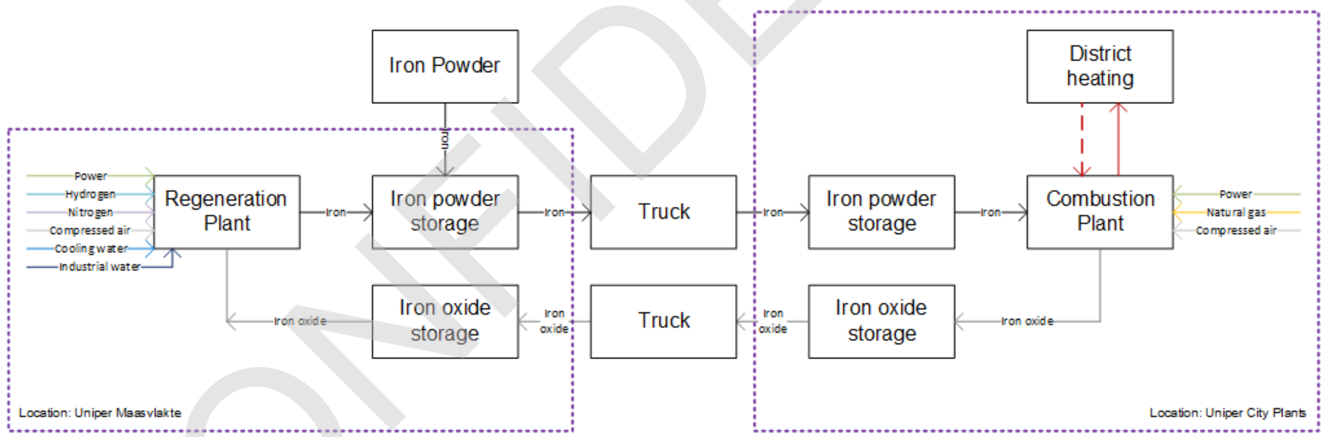

Figure 4 - Block diagram of the Metal Fuels & City Plants pilot

The combustion plant will be installed at one of Uniper's City Plant locations in the Netherlands and will be connected to the district heating grid. Thereby it can deliver 'green heat' to end-consumers. The plant requires the feed-in of iron powder, as well as a power and natural gas connection. Combustion air is directly taken from outdoors and exhaust air is filtered and released into the ambient again. Iron oxide is transported back to the storage before it is transported to the regeneration plant.

The regeneration plant will be installed at Uniper's Maasvlakte site and transforms iron oxide back into iron. Therefore it requires several utilities, starting with hydrogen for the reduction process. Electricity is needed for heating and nitrogen is used to purge the installation to prevent the formation of an explosive hydrogen/air mixture. Because the system works at a high temperature, the released water from the reduction reaction leaves the installation as steam. The steam is mixed with excess hydrogen, and thus a hydrogen recuperation unit is needed to separate the hydrogen and steam, such that the hydrogen can be re-used in the process. Therefore cooling water and industrial water are needed. Comparable as on the combustion site, the iron and -oxide are stored in silo's before being transported between both sites.

The logistics between the two sites is part of the project scope as well. It is planned to transport the metal powders with commercially available silo trucks, of which Figure 5 illustrates one of the available trucks. The logistics part of the project is a necessity for a successful pilot, but this aspect is not optimized within the project. This means that there will be no focus on reducing fuel costs for the trucks by optimizing transport routes or by testing alternative truck fuels etc. The same holds for the storage silo's and required material handling system. Although the storage size will be optimized, the storage and handling system will be industry standard.

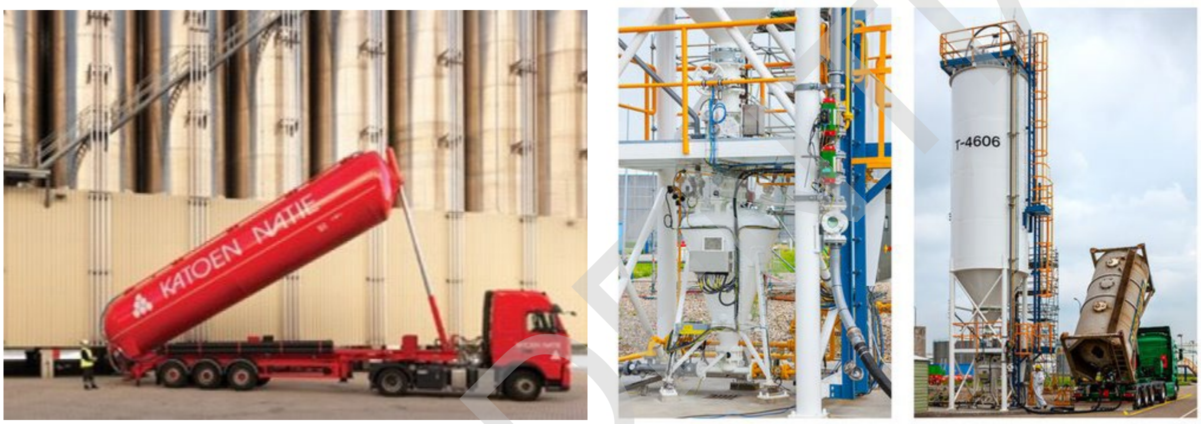

Figure 5 - Commercially available silo truck to transport metal fuels and storage silo's [Katoen Natie]

The first batch of iron powder will initially be produced by Pometon in Italy and transported to the Netherlands.

4.1.2 Simple heat and mass balance

A simple heat and mass balance is made based on the block diagram in Figure 4 and the main findings are summarized in this paragraph. More detailed information can be found in appendix A2. For the emission of CO_2, calculations are performed using the current and future CO_2 emissions of electricity according to the Dutch energy mix (currently 300 kg/MWh_e, expected to be 90 kg/MWh_e in 2030 and 0 kg/MWh_e in 2050). Although several sources of hydrogen are available, it is assumed that electrolysis is the method being used for the metal fuels process.

Calculations were performed for three scenario's:

- 2020 scenario; with current plant designs and power mix
- 2030 scenario; with improved plant design and future power mix
- 2050 scenario; with optimized plant design and zero carbon emission power mix

The energy flows (in and out) per scenario can be seen in Figure 6.This image shows that in the current plant design, almost 6 MWh of energy is required to generate 1 MWh of heat output, which equals a cycle efficiency of 17%. A lot of energy is lost as waste heat in the regeneration plant. This is due to the fact that heat recovery is hardly implemented in the current design. Improved heat recovery, however, will already be part of the engineering phase of the pilot project. Literature on direct iron reduction in steel production shows a significant heat recovery potential, which can also be incorporated in the metal fuels regeneration plant design. Besides that, additional energy consumption reduction can be achieved by reducing the required auxiliaries (nitrogen, compressed air, natural gas). When taking these optimizations into account, the cycle efficiency can improve towards 56%. Here, it is assumed that electrolyzer efficiency will not improve further, but especially the development in solid oxide electrolyzers or even direct electrolysis of iron oxide can improve the cycle further towards 69%.

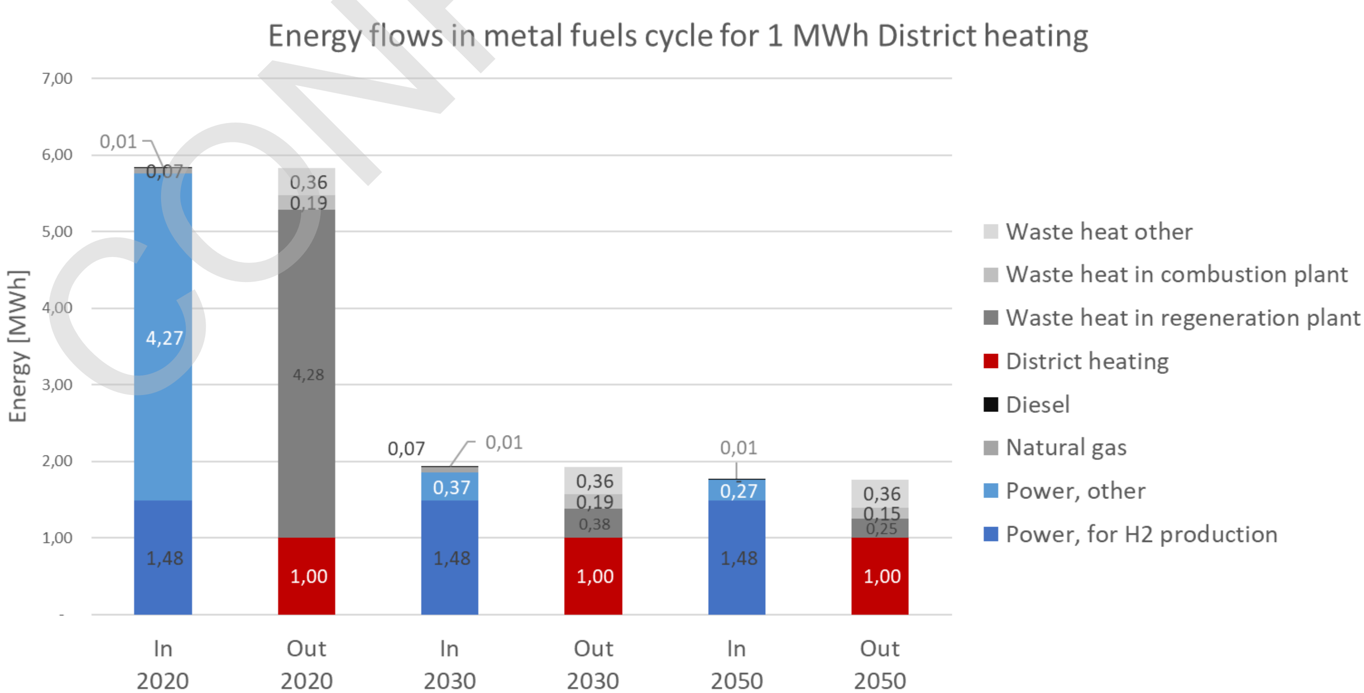

Figure 6 - Overview of energy flows in the metal fuels cycle

The expected carbon emissions related to the metal fuels cycle are shown in Figure 7. Carbon emissions are expected to decline dramatically over time, both due to an improved plant design and improved energy mix (more renewables and thus less CO_2 emission). In 2050, transportation (diesel) is the only carbon emitter left. With all developments in the transport sector in mind, one can imagine that diesel will be replaced by a CO_2 free fuel (electricity, hydrogen, biofuels) as well.

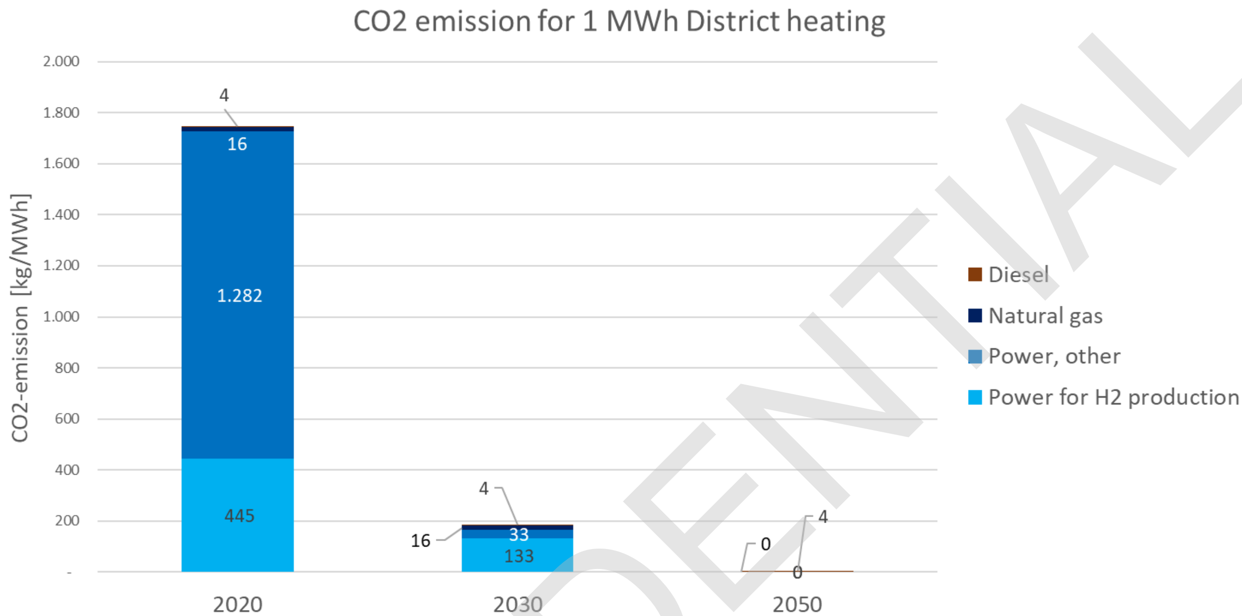

Figure 7 - Overview of expected CO2 emissions per MWh thermal output for the metal fuels cycle in 2020, 2030 and 2050

4.2 Benchmark with other technologies

In order to value the characteristics of the metal fuels, a benchmark analysis with competing storage technologies is made. The comparison is summarized in Table 1.

Table 1 - Cycle efficiencies and CO2 emissions of district heating technologies

	Cycle efficiency [%]			CO2-emissions [ton/MW_{th}]		
Year	2020	2030	2050	2020	2030	2050
Metal fuels	0,17	0,56	0,66	1,73	0,18	-
Natural gas boiler	0,94	0,94	0,94	0,22	0,21	0,21
Liquid Organic Hydrogen Carrier	0,46	0,46	0,46	0,66	0,20	-
Compressed hydrogen storage	0,46	0,46	0,46	0,65	0,19	-
Heat pump	1,43	1,43	1,43	0,21	0,06	-
Electric boiler with battery storage	0,92	0,92	0,92	0,32	0,10	-

The benchmark analysis shows that metal fuels can compete with other hydrogen technologies based on primary energy use, exergetic efficiency and CO_2-emission in 2030. It outcompetes hydrogen technologies in terms of NOx emissions, which is very beneficial in urban environments. Other low-carbon technologies like heat pumps, e-boilers (district heating) and battery electric storage (power generation) show better results on the above-mentioned criteria. This means that metal fuels should only be used in specific cases where its beneficial characteristics outscore all-electric or biobased solutions. Especially in situations where high temperature heat, long-term storage, fuel availability and safe transport are required.

From these conclusions, the following advices can be given:

Use high grade energy for high grade solutions
In any case, due to the relative low temperatures in the district heating grids, exergetic efficiencies are low. This means that it has the preference to feed the district heating grid with low grade energy (waste heat, heat pumps, geothermal etc.) as much as possible and use high grade forms of energy (hydrogen, electricity, metal fuels) for other applications (fuels, industrial and chemical). Metal fuels could for example be an interesting option to reduce carbon emissions in high temperature industrial processes.

Use metal fuels in situations where long-term and safe storage is required
An important characteristic of metal fuels compared to other hydrogen technologies is the possibility to store renewable energy safely and efficiently over a long period of time. This might be beneficial for carbon free peak and/or back-up capacity in district heating grids. It is expected that technologies like industrial waste heat, aquathermal and geothermal will be the main source of the baseload heat supply in future district heating grids. These technologies are often not suited for peak supply and have to be made redundant by installing back-up capacity. Although the peak and back-up installation will run only a limited number of hours a year, it requires a safe and reliable fuel supply. Whereas battery electric storage is very expensive and has a low energy density, biofuels might degrade and

other hydrogen solutions are less safe, metal fuels benefit from their safe, stable and energy dense storage capabilities.

Use metal fuels to transport large amounts of renewable energy over large distances
Another benefit of metal fuels is the possibility to transport it easily over long distances by truck, train or ship. This might be interesting in the case that large amounts of renewable energy have to be imported from other continents, from where no power connections or pipelines are available. For example from solar parks in the Northern African region.

4.3 Metal fuels and Uniper

Uniper's strategy is based on three interrelated components: decarbonization, customer centricity and security of supply. The main objective is to produce carbon neutral power and heat in Europe by 2035. With currently 85% of the installed capacity in Europe based on fossil fuels, this goal is very ambitious. With these three pillars Uniper will keep on reducing its carbon emissions towards 2035 without compromising the security of supply. This is what Uniper calls: Energy Evolution.

Figure 8 - Uniper's strategy: empower energy evolution with decarbonization, customer centricity and security of supply

Metal fuels can fit in this strategy in several ways: as renewable fuel for our district heating plants, as energy storage mechanism, as sustainable technology for our industrial customers' high temperature processes and as commodity for energy trading activities.

4.3.1 Retrofitting or new?

When considering introducing metal fuels in existing assets of Uniper, the question is raised whether these assets can be retrofitted or should be replaced by dedicated boilers.

It depends of course on the type of existing asset. From the fact that metal fuels require specific filter technologies for the solid particles, retrofitting of existing fire-tube auxiliary boilers is not expected to be feasible. An add-on, where iron is combusted in a water-tube boiler in front of the fire-tube auxiliary boiler, would be technically feasible. The downside is that this will double the control systems, increase complexity, issues might arise with PED, insurance and warranty, and energy efficiency might reduce due to extra heat exchanging steps. The expected overall costs will be higher than a dedicated iron fuel water-tube boiler with included convection section, and full replacement at the end-of-life is assumed to be more viable.

5 The pilot

Metal fuels show an interesting potential to decarbonize the heating demand for a wide range of applications. The technology, however, is still being developed and in between lab and pilot scale. The goal of the pilot is a proof-of-concept, of which knowledge about the technology is gained and learnings can be used for the improvement of future designs.

The proof-of-concept will be shown at MW-range in a real-live situation: by delivering heat to the district heating grid at one of Uniper's City Plants in the Netherlands. Metal fuels can play an important role as peak and back-up heat supply, due to the following characteristics:

- It is a technology that (in future) allows to decarbonize the heat supply.
- There are hardly any other low-carbon technologies for peak and back-up heat supply available. Baseload is expected to be provided by sources like industrial waste heat, heat pumps and/or geothermal energy. However, these installations require very high CAPEX investments for only a limited number of operating hours in peak/back-up moments. Besides that, heat sources are often limited in maximum capacity. Electricity grid connections are already overloaded in urban areas and more disturbances in the power supply could be expected in the future, thus all-electric heating options are less preferable for peak loads. This means that metal fuels, with relative low CAPEX (although higher OPEX) and reliable fuel availability form a good alternative.
- The fact that city plants are located in dense urban areas, requires safe and dense storage of fuel due to safety requirements and limited space availability.
- Emissions to the air, like NOx and SOx are undesirable in urban environments. Direct use of hydrogen combustion might lead to increased NOx emissions compared to the use of natural gas. Metal fuels emit fewer NOx and are thus favorable for city plant solutions.

Although the pilot is now focused on district heating, developments will bring the introduction of the technology into other applications, like industrial processes, a step closer as well.

5.1 Learning goals

The main learning goal of this pilot is the proof-of-concept of the entire metal fuels cycle (combustion, regeneration and logistics) at a MW-scale in a real-live situation.

For the combustion plant, the following subsequent learning goals are defined:

1. Proof of the working principle: the burner can deliver the designed heating capacity in a real-live situation: at a Uniper City Plant location, with respect to all safety and permit requirements, running at least for one hour continuously.
2. Proof of flexibility: the burner can be turned down from full load (100%) to part load (20%) and back to full load again.
3. Proof of reliability: the burner can deliver heat to the district heating grid for 24 hours continuously while following a heating demand curve.
4. Proof of long-term operation: the burner can be operated for approximately 800 operational hours (during the 2-year pilot).

For the regeneration plant, the following specific learning goals are defined:

1. Proof of the working principle: the system regenerates iron oxide multicyclic to iron fuel within the specs in continuous operation.
2. Proof of reliability: with respect to all safety and permit requirements, the regeneration plant runs for 8000 FLH per year during a 2-year pilot.
3. Proof of scaling potential: the technology has proven its potential and there is a design to increase the yearly output and to optimize energy efficiency to an economic feasible level.

No specific learning goals are defined for the logistics and storage, because the focus of this project is on the combustion and regeneration plant. However, the design of the pilot should be such that also the logistics and storage are safe and support the operation of both plants as required.

5.2 Project partners and demarcations

In order to succeed, the project is realized with combined effort of several project partners, each with their own specific capabilities. The demarcations between the focus areas of the project partners is indicated in Figure 9. A more detailed equipment list and scope overview is added in the high-level equipment list in appendix A5.

TU/e and Metalot are the developers of the metal fuels concept in general. Shell supports the technology development and focusses on improving the chemical processes and material handling such that it can be implemented on industrial scale. Uniper aims to proof the concept in a real-live situation at existing Dutch sites to explore the possibilities to decarbonize the heat supply for district heating. EM Group and Cremer design the combustion and regeneration plant respectively. Pometon will produce the first batch of iron powder and KatoenNatie/J-TEC is a commercial partner for logistics, material handling and storage.

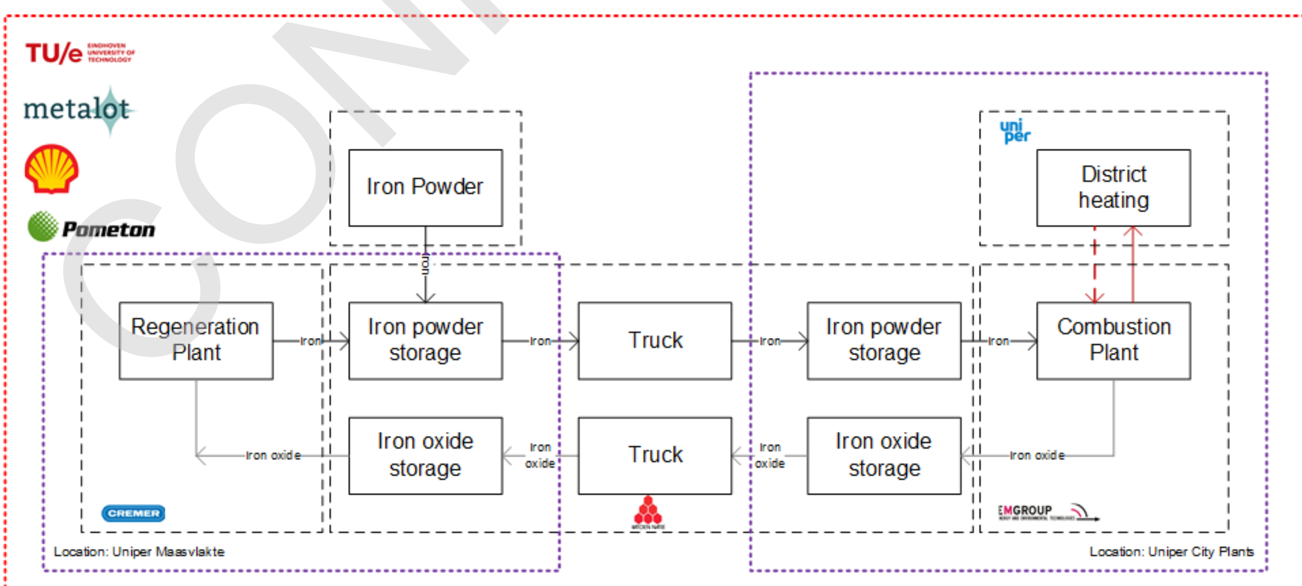

Figure 9 - Demarcations of focus areas of project partners Project planning

Currently, the project is in FEL-1 (Feasibility) phase. The next steps are globally added to the project planning as can be seen in Figure 10.

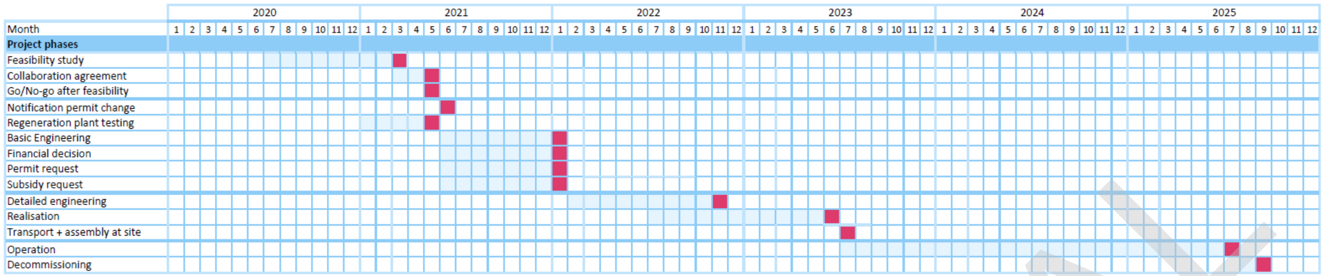

Figure 10 - High-level project planning

The project planning is divided into four main milestones:

1. Feasibility phase, including collaboration agreement, working towards go/no-go for basic engineering;
2. Preparation towards financial decision, including basic engineering, permit request and subsidy request;
3. Preparation towards realization, including detailed engineering;
4. Operation and decommissioning

The FEL-1 feasibility study is finalized with this report, giving an overview of the technical feasibility of the project and a cost estimate with an accuracy of ±50%. Before a go/no-go decision for the next phase can be made, it is important to know how much funding from subsidies is expected. This leads to a gap between required investment and public funding, which has to be closed by a contribution from all project partners. This should be discussed with all partners and, if it results in a positive financial feasibility, be described in a collaboration agreement. This collaboration agreement should form the ‘go’ decision for all project partners to start the basic engineering that results in a design accompanied with a cost estimate with an accuracy of ± 10%.

The basic design and improved cost estimate should form the basis for both the actual subsidy request and the financial decisions of all partners. Once the financial decision is made, and subsidy is granted, the detailed engineering and realization can be started.

5.3 Subsidy opportunities and requirements

There are a large number of subsidies available in the Netherlands for innovative projects related to the energy transition. Two of the options with a significant budget and a good fit with metal fuels are MOOI and DEI+. Which one of these is most interesting depends on the research phase, as can be seen in the (Dutch) image below. MOOI is focusing primarily on R&D, while DEI+ comes in the following phase of piloting and demonstration. The latter is currently seen as most viable for our project.

fase 1 Fundamenteel Onderzoek	fase 2 Onderzoek & ontwikkeling	fase 3 Demonstratie	fase 4 Opschaling & marktintroductie
NWO	MOOI	DEI+	VEKI
		Hernieuwbare Energie	EIA, MIA/VAMIL
WBSO	WBSO	Topsector Energiestudies Industrie	SDE++

Tabel 1: Illustratie van instrumenten per fase van een MMIP

The goal of the DEI+ subsidy is to gain a higher flexibility in the power market, and stimulates the storage and conversion of renewable electricity, demand response, CO2-free flexible power generation and flexibility of power grids. Large-scale conversion of electricity into other energy carriers is a primary focus point.

Projects aiming for this subsidy should be in a pilot phase and should be tested in representative environments for future roll-out.

Some facts about the subsidy are summarized below:

- Maximum duration: 4 years
- Maximum subsidy per project: 15 M€
- Available budget 2020: 86 M€
- Subsidy percentages:
  - Large companies: 25%
  - Medium size companies: 35%
  - Small size companies: 45%
  - Research institutes: 80%
- Requests are based on first come first serve, most ideal timeframe to submit project proposal is in the first quartile of the year.
- The chance to obtain the request granted becomes larger if it can be shown that serious steps have been taken to start the project, like the availability of a financial decision (also under condition of subsidy grant) and/or availability of a permit (or at least first discussions with local authorities).
- Once the subsidy is granted, the project must be started within 6 months. This can be realization, starting engineering is also acceptable. If the project doesn't start in time, the grant expires without penalty for the consortium.
- A DEI+ demo is an investment project and subsidizes investments in CO2-saving concepts. A DEI+ pilot project is a R&D project and subsidizes R&D, i.e. depreciation of capital and manhours.
  - Metalot will set up a project budget taking into account the subsidy rules of a DEI+ pilot project.

6 The combustion plant

This chapter describes the design of the combustion plant. First the possible city plant locations are compared, after which one location is chosen and being studied in more detail.

6.1 Choice for burner plant capacity

Before looking into the location for the combustion plant, it is necessary to choose a burner capacity. Typical plant sizes within Uniper's scope start at several MW's (10-20 MW), with the smallest boiler in the Netherlands having a capacity of 7 MW. From the scope of the TU/e, upscaling from 100 kW to a MW-size is a strict requirement. This leaves a range between 1 (TU/e) and 10 (Uniper) MW in which the burner capacity has to be chosen.

Due to the fact that this is a pilot project, starting with a smaller plant size has some strong benefits:

- The learning goals can be met with any size equivalent to or larger than 1 MW
- There are no significant design changes expected in upscaling the burner size from 1 to 10 MW_{th}
- Both CAPEX and OPEX are lower
- The footprint is smaller, making it easier to integrate it at the site
- Less iron/iron oxide storage is required for the same number of full load hours
- Less logistic movements are needed
- It is easier to supply smaller amounts of heat into the district heating grid due to limitations from contracts with other parties and Uniper's low position in the merit order in Rotterdam
- The total system, including logistics and the regeneration site, becomes less complex
- The system is easier to handle (during transport, commissioning etc.)

From the analysis above (smaller is better) and still being in line with Uniper's typical plant sizes, it is chosen to design the burner for a 5 MW heating capacity.

The findings from this pilot can later be translated to larger boiler sizes as well. It is expected that scaling up the boiler to 20-30 MW thermal output is possible with the same configuration. For higher capacities, parallel configurations are proposed. It is expected that the burner itself can be scaled-up towards 100 MW.

6.2 Site location study combustion plant

In this paragraph, the results of the site location study are described. More detailed analyses are added in the appendix.

6.2.1 Plot plan combustion plant and storage

The design of the combustion plant is not yet finalized, and thus assumptions are made for required footprint of the installation. The same is done for the storage silo sizes. The overview below shows the range of dimensions that is taken into account for the site location study:

Burner plant size:

- 11 MW burner: 8 x 8 x 18 m (incl. stack) (LxWxH)
- 1 MW burner: 6 x 6 x 15 m (incl. stack) (LxWxH)

Storage silo size:

- 60 m³ storage volume: Ø 3,0 m x 12 m (DxH)

6.2.2 Site location study

With the required footprints in mind, all City Plants locations in the Netherlands have been compared and the results are summarized in the decision matrix as shown in Figure 11. Maasvlakte is not considered as location for the combustion plant, because the goal of the pilot is the proof-of-concept of a hydrogen related renewable fuel that can be used and stored safely in an urban environment.

		Rotterdam					The Hague			Leiden	
		RoCa	WSG	Delftsevaart	Blekerstraat	Kop van Zuid	EDH	Bezuidenhout West	ADH	ELD	Stevenshof
Location	Maintenance space (truck/equipment)	+	+	0	0	+	0	0	0	0	+
	Installation space	0	+	0	0	-	+	-	0	+	-
	Deliver heat from this location to other locations?	0	+	+	-	-	+	+	-	+	+
	Total heat supply by boilers	+	-	-	-	0	+	+	-	+	+
Envir.	Noise limits	+	+	0	-	0	-	0	0	0	0
	Environmental permit issues	+	+	0	-	0	0	0	-	0	0
Logistics	Extra logistic movements by truck	+	+	-	-	-	0	0	+	0	+
	Connection to waterway for ship transport	-	+	0	-	-	-	-	-	-	-
	Distance to Maasvlakte (regeneration)	+	+	+	+	+	0	0	0	0	0
Ranking		2	1				2				

Figure 11 - Decision matrix combustion plant location study

From the table above one can see that WSG – Warmtestation Galileistraat in Rotterdam – comes out of the comparison best. The main purpose of this location is to distribute hot water into the city center. Besides pumps, there is also a peak boiler and two large thermal buffers. The site is located in an industrial area and is therefore good accessible by truck, although it is still close the city. There is also sufficient space to install the combustion plant. The main downsides are the relative low volumes of heat being produced here (and thereby limiting the number of operational hours of the metal fuels boiler) and the fact that it is less attractive from a marketing point of view.

6.2.3 Scenario study for heat generation throughout the year

A study has been performed to optimize between heat generation by the metal fuels burner and the required storage size and truck movements. Simulations are performed based on the assumption that the metal fuels burner should only replace natural gas peak boilers, and not to replace heat supplied by the CHP and other heat producers (AVR, WBR), because the operation of these installations is bound by contracts.

The above mentioned assumption results in a limited number of hours in which the metal fuels burner can be operated, being mainly during the winter season. This limits the flexibility of the pilot, but the earlier mentioned learning goals can still be achieved.

Typical simulation results are shown in Figure 12. The graph to the right shows the maximum heat supply by the metal fuels burner over one year, being limited by a maximum number of operating hours of 400/year. Calculations are made for 1 truck delivery per day (blue line) and for 1 truck delivery per six days (orange line). The x-axis shows the storage size in truck equivalents (max. 28 tons/truck, each truck with approx. 10 m³ of iron powder) and the y-axis shows the resulting heat delivery per year.

One can see that a higher storage volume and more truck deliveries result in larger numbers for the annual heat supply. This is caused by the fact that the heat supply is mainly limited to the winter season. During this relative short period of time, the more fuel is available (due to large storage volume or frequent delivery), the more opportunities are present to start the boiler. Once the winter season is over, there are fewer opportunities to run the boiler, even if sufficient fuel is present.

WSG		
Burner capacity	5	MWth
Max. operational hours	400	Hours/year
Trucks	6	days between truck delivery

Storage [truck equiv.]	Volume per silo [m³]	Operational hours [h/year]	Full load hours [h/year]	Heat generation [MWh]	Trucks [/year]
1	10	276	135	676	20
2	19	315	172	858	25
4	39	362	206	1.029	30
6	58	391	233	1.167	35
10	97	400	267	1.333	40
15	145	400	284	1.422	42
20	193	400	300	1.500	45
25	241	400	304	1.521	45
30	290	400	310	1.552	46
35	338	400	334	1.672	50
40	386	400	347	1.736	52
45	434	400	365	1.824	54
50	483	400	384	1.919	57
55	531	400	390	1.950	58
60	579	400	390	1.950	58

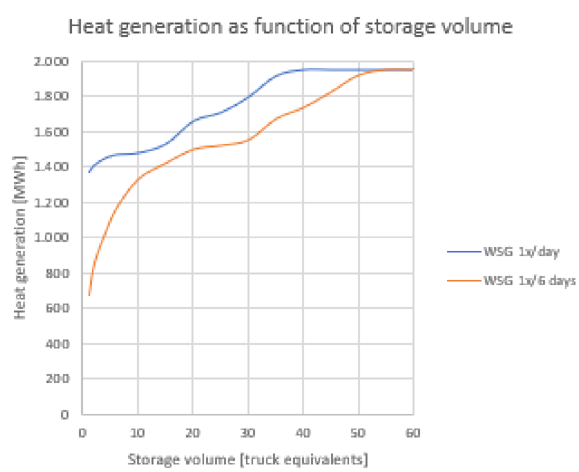

Figure 12 - Simulation results for WSG with 1 truck delivery per day or 1 truck delivery per 6 days (5 MW burner, max. 400 hrs/year)

Larger storage volumes, however, lead to higher installation costs, a larger amount of required iron powder and fewer regeneration cycles per iron particle. Therefore it was decided to design the pilot with a storage volume of 6 truck equivalents (approx. 60 m³ / 170 tons). This is the minimum volume to operate the boiler for approximately 400 hours per year. Increasing this volume does result in more heat generated by the burner, but does not further improve the results in terms of learning goals. Due to the fact that not only the iron powder has to be stored, but the iron oxide powder as well, two silos with 60 m³ storage capacity are required. When delivering new fuel once in 6 days, the number of annual truck deliveries is approximately 35.

6.3 Physical implementation at site

This chapter describes the site integration of the combustion plant in more detail. First, the possible locations at the site are discussed, as well as transport routes for truck deliveries. Thereafter, several topics, like the controls and O&M strategy are explained.

6.3.1 Locations for the combustion plant and storage at WSG

Several locations, inside of the WSG building and outside, have been compared for placing the metal fuels boiler, and at least one option seems feasible.

6.3.2 Logistics

The identified combustion plant locations at WSG can be reached by trucks, which can be seen in Figure 13. Due to the fact that WSG is located in an industrial area, it is assumed that truck movements towards the location are allowed once a day.

To fill and empty the storage silos, it is important that the truck can park close to the silos. This means that, depending on the final location, drive plates might be required for truck accessibility and parking.

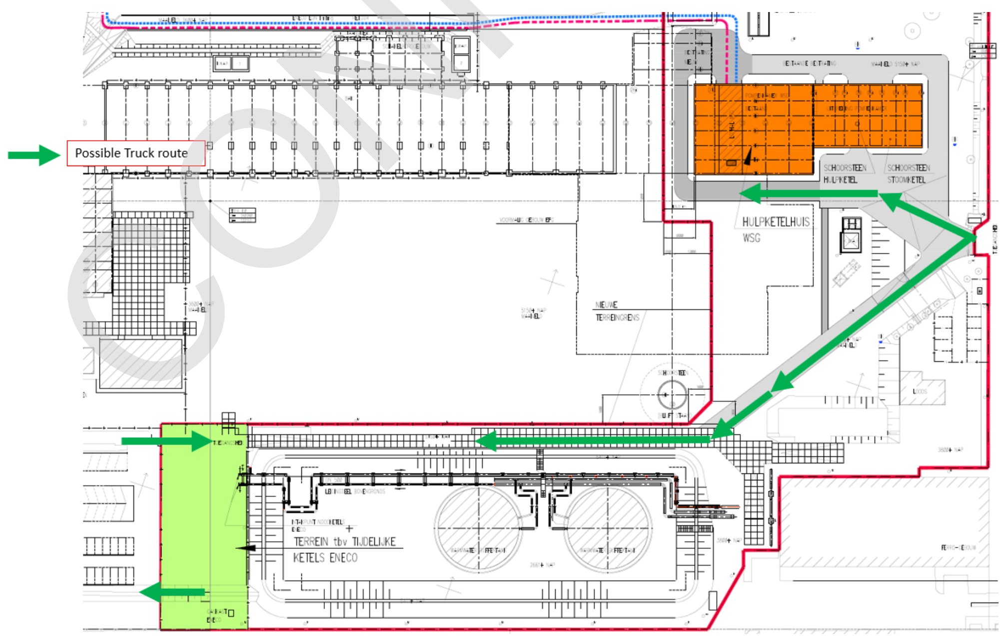

Figure 13 - Possible truck routes at WSG

6.3.3 Utility connections

The combustion plant has to be connected to a power and natural gas supply. It is assumed that the required compressed air for both the combustion plant and the iron powder transport mechanism are generated locally with own compressors, and that therefore no compressed air connection from site is needed.

Natural gas and power are available at WSG. Besides the utilities that are required for operating the combustion plant, several other systems have to be incorporated. The installation has to comply to all relevant Uniper standards, and thus has to be connected to the fire and gas detection system. A safe design also implies electrical safety (lightning protection, earthing), CCTV-covering and civil works (foundations).

6.3.4 Solids handling

In the scenario study in Chapter 6.2.3, the yearly throughput, storage buffer size and logistical movements are calculated. An overview is shown in Figure 14.

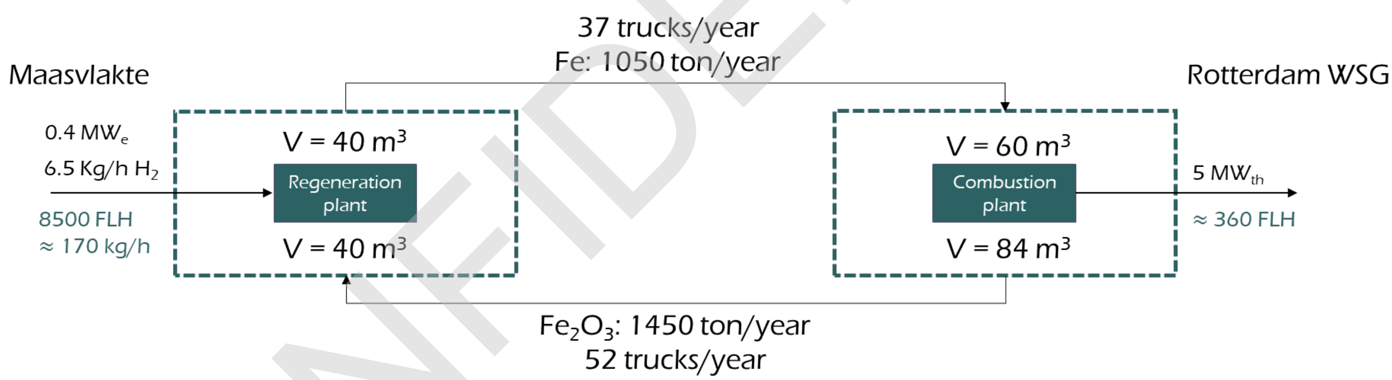

Figure 14 - Schematic of the logistical plan

Nyrstar, the zinc factory in Budel and part of the Lighthouse Metal Power consortium, is experienced in handling metal powders. Transporting incoming and outgoing metal powders at their site is handled by, amongst others, Katoen Natie. More specific, two subsidiaries of Katoen Natie. For transportation, Langen (Elsloo, NL), is contacted and for bulk flow handling equipment J-TEC (Kapellen, BE). This resulted in the following solid handling plan.

Different options have been discussed, such as storage and transportation in containers and in silo trucks. Given the pilot concept, logistics designed for containers is expected to have higher CAPEX and lower OPEX, while logistics designed for silo trucks is expected to have lower CAPEX and higher OPEX. For this project, silo truck storage and pneumatic handling is expected to have the lowest TCO.

At both sites, separate storage systems for iron powder and iron oxide powder are required. The loading/unloading is decoupled from the core process (regeneration/combustion) using a separate “day tank”. Figure 17 shows a 2D technical drawing of the design of the storage silo’s and equipment. To avoid condensation the air used for loading/unloading and pneumatic conveying is dehumidified. Transportation between the sites is handled by ADR certified bulk silo trucks and chauffeurs. Everything is standard technology using industry standard connections. An impression of a silo truck was displayed in Figure 5.

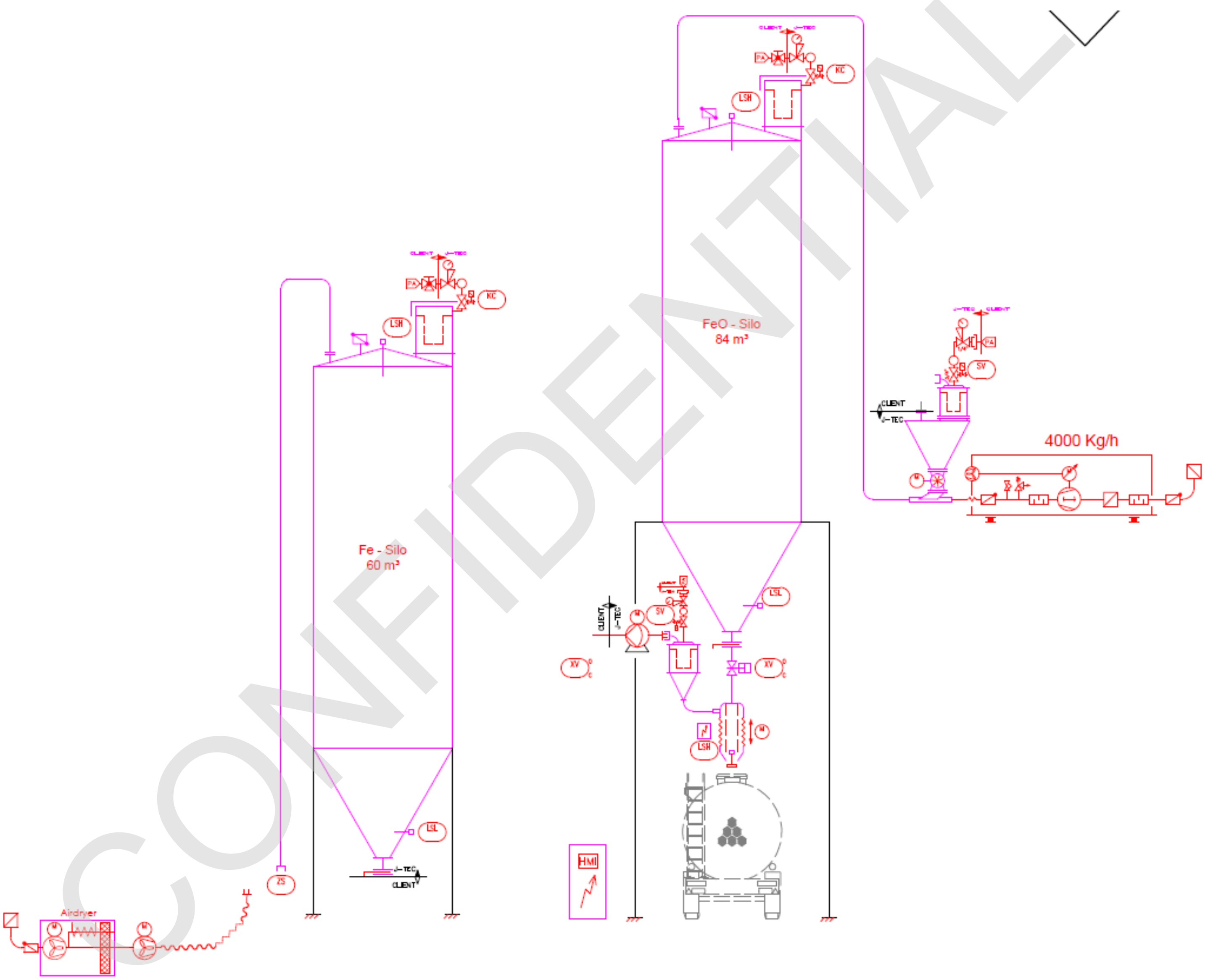

Figure 15 - CAD sketch of the storage silo's on the combustion site.

More detailed engineering of the connection between the silo’s, day tanks and combustion/regeneration system was not part of the current scope. This will be part of the next phase, basic engineering. All parties assure this is part of their standard project engineering and no fundamental challenges are expected.

6.3.5 Controls strategy

The combustion plant, storage and material handling systems have to be operated safely and are thus equipped with instrumentation and controls systems. In principle each of these installations have their own stand-alone controls systems and are only connected with each other where necessary.

The boiler installation will have its own control and safeguarding system. The HMI will be located in the control room of the WSG. To incorporate the boiler operation into the district heating, dispatch data-exchange is necessary and therefor a connection to the higher level control system is required.

6.3.6 Operation and maintenance strategy

The O&M of the combustion plant can be divided into four phases:

- Commissioning
- Start-up
- Normal operation
- Decommissioning/demolition

Each of these phases are handled separately. It is assumed that EM Group will be the manufacturer of the combustion plant and will install it at a Uniper city plants location.

Commissioning
After installation, parties will commission it according to a predefined commissioning plan. Both employees from EM group as from Uniper will attend the commissioning phase.

Start-up
During the start-up phase of the metal fuels combustion plant, both EM Group as Uniper will attend. EM Group will take the responsibility (to be discussed in detail in next design phase) for the pilot plant and will operate within the agreed working regime (depending on heating demand, supply/return water temperature etc.). Uniper employees can be trained to work with the combustion plant and metal powder transport system in the meantime. All alarms, trips, maintenance works etc. will be handled by EM Group in coordination with the Uniper site team.

Normal operation
Once the metal fuels combustion plant runs safe and steady, the installation can be switched into automatic operation and will follow the agreed working regime. From this moment on, EM Group and Uniper will discuss whether Uniper can take-over specific O&M tasks, such that EM Group employees don't have to visit the site unnecessarily. Uniper must have the possibility to overrule the metal fuels boiler plant setpoint in case the heating demand changes and to shut it down in case of emergency.

Decommissioning/demolition
After finishing the pilot project, the metal fuels combustion plant (including storage and transport system) will be safely and properly removed from the Uniper site by EM Group, except if the involved parties agree otherwise.

6.3.7 Environmental permit requirements

In summary, the following steps have to be taken for environmental permits:

- New environmental permit due to the use of new fuels. Take into account that this will take (at least) 26 + 6 weeks.
- CO_2: update CO_2 monitoring plan and include new CO_2 emitting installations
- NO_x: permitted NO_x emissions must not be exceeded
- Emissions (other): requirements will be set by DCMR in the new permit, monitoring based on periodical emission measurement will be sufficient.
- Noise emissions: must be included in existing acoustic model and be compliant with actual noise limits.
- Construction permit required.
- Soil quality assessment required when the project required hazardous activities to the soil.
- Safety risks must be determined with (at least) a HAZOP study.

An important advice for the next project phase is to start the permitting process quickly and talk to relevant authorities as soon as possible to prevent delays.

6.4 Risk identification and safety requirements

In order to challenge the metal fuels concept further, Uniper Technologies (UTL) were asked to facilitate a HAZID type study with the aim of discussing, at an early stage of development, potential major showstoppers, hazards and critical tasks that may be associated with the construction and operation of the proposed combustion plant. The results of this study provide a 'shopping list' of recommendations that should be included in the following design phases.

Hazard study sessions were held on the 2nd and 4th September 2020. Specialists attended from Uniper Benelux, EM Group, Shell, Eindhoven University and UTG.

Areas of interest in the study included:

- Fire and explosion risks of iron powder;
- Hazards of fire-fighting if the wrong medium is used;
- Fuel quality, humidity and particle size, including after regeneration;
- Weight of the fuel for transport and storage;
- Environmental compliance;
- Data and monitoring of the plant performance;
- Defining responsibilities of collaborating project partners.

There were 94 Recommendations generated which Included the following topics:

- Fire risk, emergency planning, awareness for site and local emergency services on iron fires and the correct and incorrect fire-fighting mediums (e.g. water or CO2 may react with iron to make the fire worse);
- Fuel safety measures including investigating safe fuel conveying methods and the effect of particle size on explosivity, dust control for health and explosion/fire risk, ATEX risk assessment and associated safeguards;
- Measures, due to the high fuel density, to avoid damage to underground structures during fuel transport, and checking of required silo dimensions;
- Measures to ensure fuel quality, particularly particle size after reprocessing and control of water content;
- Ensuring items such as CE marking, insurance, liabilities, ownership, intellectual property rights, coordination of research, maintenance and testing were all agreed;
- Develop stakeholder management plan;
- Monitoring of plant performance including blockages, deposits, NOx performance, running costs, erosion. Agreement of data to be measured and recorded;
- Emergency shutdown and protection needs (e.g. water breach into flue gas, off site emergencies). Need for detailed plant safety studies;
- Development of measures to cool the iron oxide for transport and recover the heat. Investigate options for managing low heat demand;
- Preferred plant design features including maintenance access points, dedicated iron unloading and oxide loading areas, fixed pipe powder transport, earthing systems, cyclone sealing plates and anti-freezing measures. Consideration of foundation requirement. Consideration of decommissioning and disposal requirements;

- Operational integration including update of site emergency response plan, access for operational and research staff, training for the new plant maintenance & operation and for the wider site staff (including involvement at commissioning);
- Development of solutions to operational issues such as maintenance, unblocking, remote operation, out-of-hours response and emergency response;
- Steps to ensure compliance with permitting requirements for e.g. noise, NOx, particulates, height restrictions;
- Clarifications of road/site transport limitations (e.g. suitable ADR routes) for iron as a heavy, combustible powder.

Although the above described recommendations will require special attention in the next design phases, no show-stoppers are seen at the moment.

7 The regeneration plant

The regeneration process is a high temperature reaction of the combustion product, iron oxide, with hydrogen.

Technology that operates with metals and high temperature hydrogen atmospheres are nothing new. Our partner, Pometon SpA (Maerne, IT) is operating this process for decades and CREMER Thermoprozessanlagen (Düren, DE) is experienced in engineering and building the hardware. However, regenerating 100% iron oxide to iron fuel within the specs with pure hydrogen is something relatively new and has never been done at this scale before.

This chapter describes the design of the regeneration plant, the site integration, what has been in and out of scope for this FEL1 report and finally the results of the HAZID.

7.1 Choice for regeneration plant capacity

The capacity of the regeneration plant is optimized based on the thermal output and the required operating hours of the combustion plant at WSG. The regeneration plant is sized such that it can operate almost 24/7,and thus its capacity is optimized for a maximum number of full load hours.

With a 5 MW_{th} burner and a maximum of 400 full load hours, the regeneration plant must be able to process 170 kg/h iron oxide. This results in a production of 120 kg/h of iron powder.

7.2 Site location study regeneration plant

It is chosen to install the regeneration plant at Uniper's site at Maasvlakte Rotterdam. This is a perfect location due to its industrial environment, 24/7 operations support and the fact that there is sufficient space available. Besides that, the site is being transformed into a future energy hub, focusing on new energy concepts (battery electric storage, blue/green hydrogen production etc.).

7.2.1 Plot plan regeneration plant, hydrogen filling station and storage

To find the right spot at the site, it is important to know the plot sizes of the required equipment. These have been estimated by the suppliers and are summarized below.

Regeneration and H2 recuperation unit
Cremer provided the sketch in Figure 16 to indicate the required plot size of the regeneration and hydrogen recuperation plant. These items, except for the chiller, have to be installed indoors (weather proof).

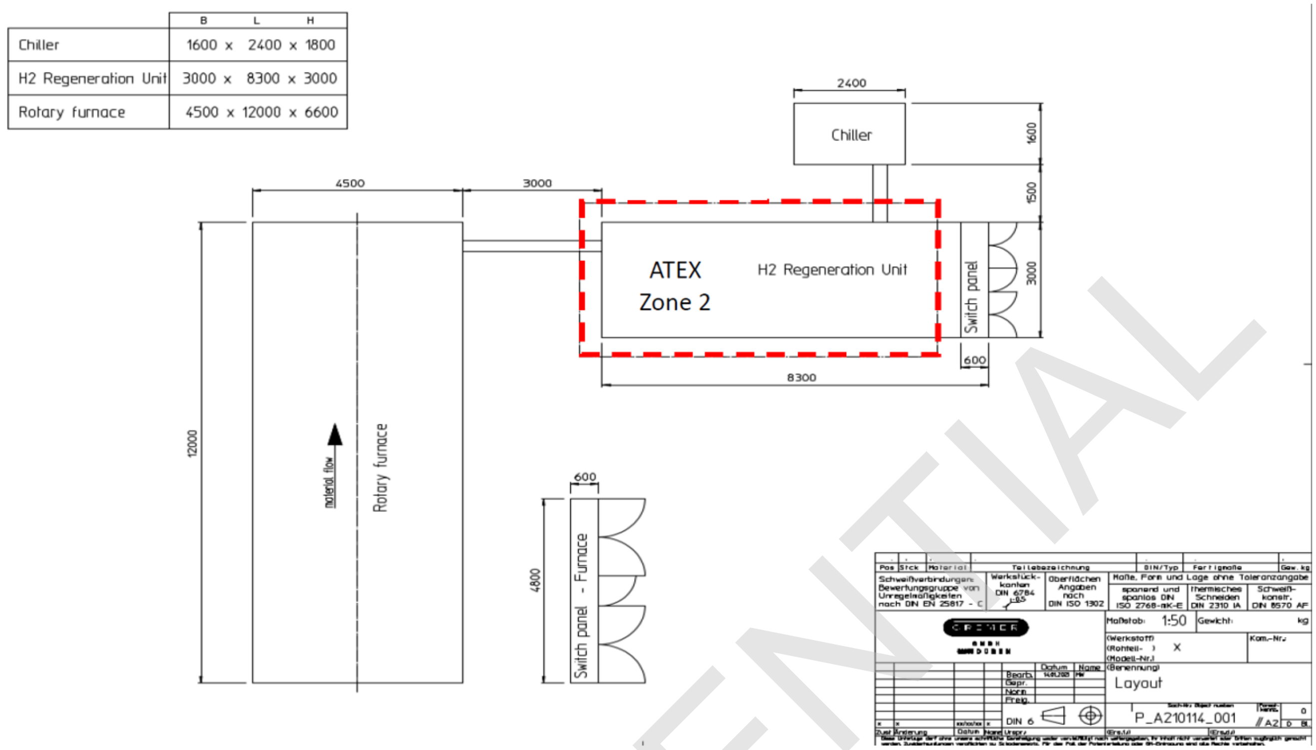

Figure 16 - Required plot size for the regeneration and H2 recuperation plant

Hydrogen filling station

A commercial hydrogen supplier provided a sketch for the required space for the hydrogen tube trailers and filling station. A total plot size of 10 x 25 meters is required. ATEX zonings are standard required within 5,5 meters of the back of the tube trailer and 1,5 meters around piping. Other distance related safety requirements must be identified during the basic engineering phase.

Auxiliaries

Auxiliary items like storage silo's (2 pcs. of 6 x 6 meters), an electrical/controls building, a nitrogen generator and air compressor have to be installed as well. Estimates for the required footprints were made.

7.2.2 Regeneration scheme throughout the year

For the dimensions of the storage silo's, a calculation was performed based on earlier calculations for the heat generation with the combustion plant throughout the year (see paragraph 6.2.3). From this calculation it is known when new trucks with iron powder are being transported from Maasvlakte to WSG, and thus at that time, sufficient powder must be available at the regeneration plant. Based on these starting points, the required storage volumes were identified as a minimum of 3 truck equivalents (30 m³ storage volume for each silo = 84 tons of FeO). The iron oxide silo should be filled with at least 1 truck equivalent to start producing iron from the beginning. To have sufficient iron powder available for transport, at least 2 truck equivalents are needed to be stored at Maasvlakte at the start of the pilot.

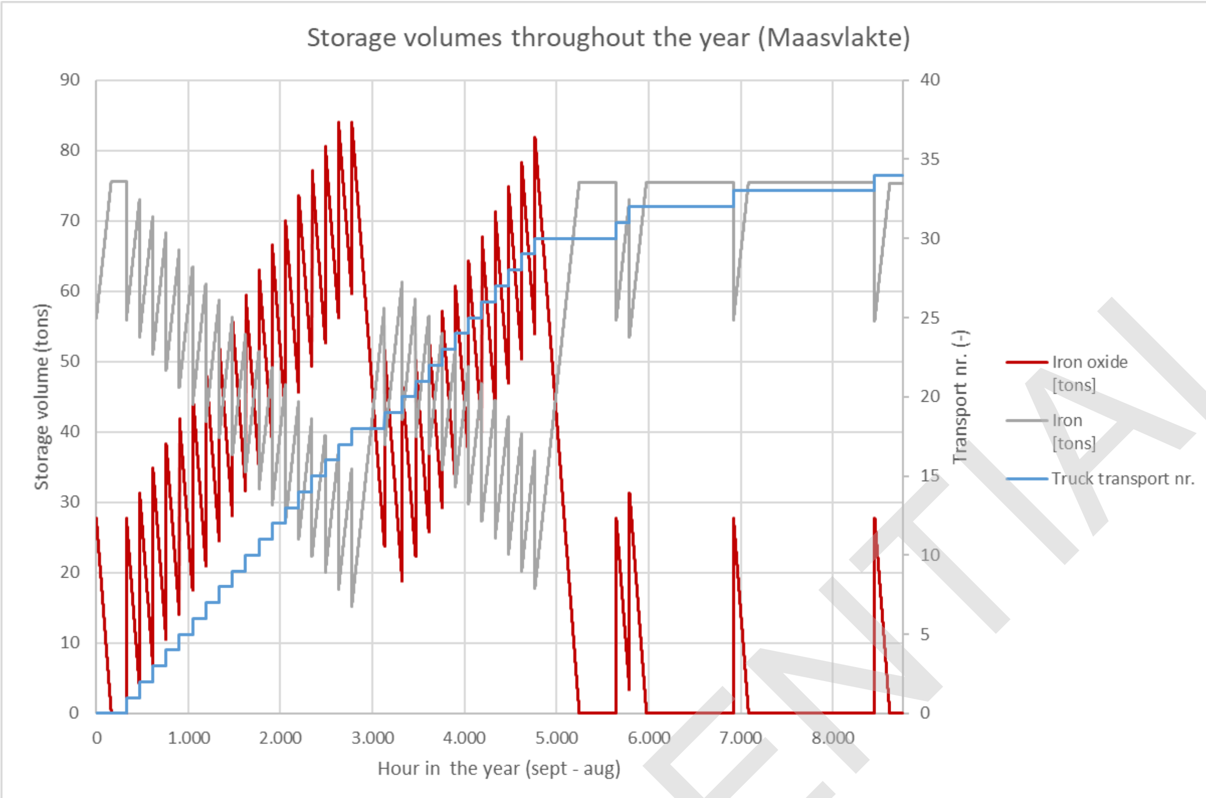

Figure 17 - Storage volumes throughout the year at Maasvlakte

7.3 Physical implementation at site

This chapter describes the site integration of the regeneration plant in more detail. First, the possible locations at the site are discussed, as well as transport routes for truck deliveries. Thereafter, several topics, like the controls and O&M strategy are explained.

7.3.1 Possible locations at Maasvlakte

The information above was the input for a site location study at Maasvlakte, where other requirements like safety, logistics and other initiatives at the site were set as well. Five locations were identified, of which several are seen to be feasible.

7.3.2 Logistics

Almost each location at the Maasvlakte site can be reached easily by trucks. Through the normal route the trucks can even pass a weighing station. Roads are in a good condition for heavy transport. In case of any road blockage, a second route can be used as well.

The number of truck transports is currently estimated as:

- 1 truck in each 5-6 days for iron powder transport
- 1 truck in each 1-2 days for hydrogen transport

On average it is assumed that one truck delivery per day is required.

7.3.3 Utility connections

The regeneration plant requires several utility connections. In summary, the following utilities are required:

- Iron and iron oxide powder storage and material handling (hand-over point between J-tec and Cremer).
- Hydrogen (delivered by a tube trailer, connected with standardized filling station)
- Power (with local transformer, Uniper scope)
- Cooling water (from site cooling water system, Uniper scope)
- Nitrogen (local generator, Uniper scope)
- Compressed air (local compressor, Uniper scope)
- Industrial water (Uniper scope)
- Drain (to site sewage system, Uniper scope)

7.3.4 Solids handling

The solids handling (from silo to plant and back) is done in the same way as at the combustion plant, and described in section 6.3.4.

7.3.5 Controls strategy

Each of the installations (regeneration plant incl. H_2 recuperation, storage & material handling, H_2 filling station, nitrogen generator and compressor) has its own control and safeguarding system. An HMI system of the regeneration plant will be installed in Uniper's control room, from which process parameters can be read and written. Also required communication between systems of different suppliers are identified in the study.

7.3.6 Operation and maintenance strategy

The O&M of the regeneration plant can be split into four phases:

- Commissioning
- Start-up
- Normal operation
- Decommissioning/demolition

Each of these phases are handled separately. It is assumed that Cremer will be the manufacturer of the combustion plant and will install it at a Uniper city plants location.

Commissioning
Installation and commissioning will be performed by the supplier of the regeneration plant. During commissioning, Uniper personnel (electrical, operations and maintenance) will be trained to operate and maintain the system. The total assembly and commissioning period is estimated to be 2 x 6 weeks.

Start-up
Start-up phase will be performed by the supplier of the regeneration. After the site acceptance test and the moment that the equipment runs stable, the equipment will be handed over to Uniper Operations.

Normal operation
In general, the system runs automatically. Data will be visualised in Uniper's control room and process operators can change the relevant parameters. The time between trips is estimated to be approx. 1-2 weeks, and trips are usually seen in the utility supply (H_2, cooling water, nitrogen etc.). The system should continuously being monitored, which can be integrated within normal operation at the Uniper site. Alarms should be investigated and being solved.

The plant needs its major maintenance once a year, with a shut-down period of approx. 2 weeks. Although Uniper maintenance personnel will be trained to perform maintenance works, it is agreed that the supplier of the equipment will perform this planned annual maintenance.

Decommissioning
Decommissioning of the equipment should be performed by the supplier, and all the utilities and buildings in Uniper's scope will be removed by Uniper. During the pilot, the consortium partners can decide to extend the pilot for a longer period. In that case, also the decommissioning date will be redefined.

7.3.7 Environmental permit requirements

Requirements related to environmental permits, as far as known at the moment, are summarized below:

- A construction permit is required.
- An environmental permit is required. Focus areas are soil, noise, emissions to the air and water, fire safety and waste handling.
    - CO_2: no additional local CO_2 emissions are expected, because no combustion process takes place.
    - NO_x: no additional local NO_x emissions are expected, because no combustion process takes place. Although high temperatures are expected in the rotary drum and N_2 might be present in the reaction chamber, the existence of oxygen should be very limited and thus NO_x formation is expected to be negligible to none.
    - Other emissions: emissions like the venting of N_2 and H_2 must be included as emission points in the environmental permit. Venting of H_2 should be checked on explosion risks.
    - It must be assured that the sewer system is not being polluted with iron powder particles.
    - Noise: noise emissions must remain within the allowable limits according to the permit.
- Nature protection act: a study should be performed to see whether the installation impacts flora and fauna.
- Water permit: no impact expected.
- Safety:
    - Explosion regulation: an ATEX assessment must be performed and findings must be implemented in the design, procedures etc.
    - Control of major-accident hazards involving dangerous substances (Brzo): the effect of hydrogen and iron powder on the Brzo legislation is assessed on high-level and no impact on current tier level is foreseen. Nevertheless, the amount of dangerous substances stored (permitted) must be properly documented and a valid material safety data sheet (MSDS) must be present.

An important advice for the next project phase is to start the permitting process quickly and talk to relevant authorities as soon as possible to prevent delays.

7.4 Risk identification and safety requirements

A HAZID has been performed for the regeneration plant, in which the following categories have been discussed:

- Hazards related to Surroundings/External
- Hazards from Facility
- Hazards for the Project

Two HAZID sessions were held on the 26th and 29th of January 2021. Attendees represented Uniper (Benelux NV and UTG), Eindhoven University of Technology, Cremer Thermoprozessanlangen GMBH and J-tec Material Handling.

The results of the discussions were covered in the HAZID report. In total, 57 recommendations were made, of which main points of attention are summarized below:

- **Integrate HSSE in the next design phases**, with for example the execution of a HAZOP, preparation of an explosion document, update of the existing site emergency response plan, update the fire protection document, update Brzo report, review noise levels, provide clean soil certificate, and assessment of requirements for CE marking.
- **Take safety into account in the technical design:** minimise the release of iron particles to the environment, ensure proper earthing to earth grid and lightning protection, take local weather conditions (salt, wind loads) into account, ensure reliefs and vents to safe locations, ensure compliance with IT security guidelines, provide Uniper specific documentations standards/procedures etc. to suppliers (safety, IT, access, etc.), assess critical components and required redundancy, review of the design by Uniper specialists (for example loads i.r.t. foundations), prevent confined spaces as much as possible, ensure frost prevention, take into account the nearby high voltage system and underground utilities.
- **Integrate maintainability and operability in the design**: prepare maintenance instructions incl. alignment with the control system, implement procedure for truck (un)loading, assess requirements for online monitoring of iron particle specifications and/or sample locations, assess automatic routing for off-spec iron particles to separate silo, align workload with Uniper operations, ensure proper training, ensure proper access/maintenance space, clarify maintenance instructions, include good housekeeping in management system Maasvlakte.
- **Ensure proper project management**: establish a project plan incl. roles, responsibilities and competences, implement stakeholder management and communication plan, include Uniper HSE guidelines in contract phase of project, take current pandemic into account, include detailed deliverable description and implement document management system.

Although the above described recommendations will require special attention in the next design phases, no show-stoppers are seen at the moment.

8 Technical feasibility

The technical feasibility of realizing the pilot at the Uniper sites WSG and Maasvlakte in Rotterdam has been assessed by studying several topics, like required capacities, corresponding equipment footprints, possible locations at the sites, utility connections and the integration within the daily operations and controls systems. Finally, findings from this study have been challenged in HAZID sessions with representatives of all relevant consortium partners and suppliers. Although there are specific points of attention in the design, no showstoppers have been identified that prevent the pilot from being technically feasible. However, some remarks and points of attentions should be noted once more:

- In general, the technology fits well within Uniper's strategy to become carbon neutral by 2035 without compromising in reliable energy supply. On short term, the technology can be used for peak and back-up heat supply to the district heating grid. In future, the technology can also be introduced for applications with higher exergetic potential like industrial high temperature processes.
- The energy efficiency of the technology, and mainly of the regeneration plant, must and will be improved compared to the proposed first design for this pilot. Because the pilot is mainly a proof-of-concept and a possibility to study the technology in an industrial environment, energy efficiency is not yet a key parameter. However, energy improvements have already been identified. When investing in this technology, future potential in energy efficiency improvement must be credible. Focus on future optimization should be part of the project.
- WSG in Rotterdam is seen as best location for the combustion plant. However, heat supply from this location is currently, due to existing heat contracts, limited to several hundreds of hours per year. This might be a project risk, because the plant cannot be operated at random moments in the year. This is not seen as a showstopper by the steering committee.
- At Maasvlakte, several locations have been compared for the regeneration plant. Because plans are not final yet, and the team has confidence that there are several other suitable locations for the regeneration plant, it is decided to postpone the final decision for the exact location of the regeneration plant to the next project phase.
- Finally, no showstoppers have been identified during the HAZID, but there is a list with many recommendations for the next design phases. These recommendations should be incorporated.

9 Financial feasibility

This chapter describes the cost estimate that has been established based on the decisions that were made in the feasibility study. Due to the fact that no real design has yet been made, the estimate only has an accuracy of ± 50%. The cost estimate should mainly be used to start the discussion within the project team to identify whether the metal fuels pilot at Uniper sites in the Netherlands is viable enough to start the basic engineering phase. If so, a collaboration agreement should be signed and all parties should commit to work towards a financial decision (go/no-go) based on a basic design and ± 10% accurate cost estimate.

9.1 Cost estimate

The cost estimate has been made with input from all project members, with each of them being a specialist for their scope. The total sum of CAPEX and OPEX is calculated to be close to 16M€, of which 15-20% is required for OPEX. Costs include the equipment itself, initial iron powder purchase, site integration, maintenance, operational costs, fuel costs (electricity, natural gas and hydrogen), logistics, engineering and project management. Costs for overhead, land-use etc. are not taken into account yet.

9.2 Financial feasibility

The financial feasibility of the project depends on the total costs, the funding through subsidies and the willingness of project partners to contribute. A first estimate of the total costs has been made in this feasibility study and sums up to approx. 16M€ (±50%).

The expected subsidy percentage and the contribution of project partners is not yet clear. Therefore, in order to assess the financial feasibility, the following steps are proposed:

- Metalot will gain knowledge about the specific requirements and possibilities for public funding. They will propose a plan how the gap between required investments and public funding can be minimized. This provides the project team with an overview of required funding from own external contribution.
- A meeting with all project partners will be scheduled to discuss whether this gap between costs and public funding can be closed by contributions from all partners, and how costs are being divided over the participants. If private funding is insufficient, the possibility of attracting additional parties will be discussed.
- If the parties agree on the total project funding, a go/no-go decision will be made. If the result is positive, the parties will compose a collaboration agreement to start with the basic engineering phase, working towards a financial decision. This financial decision will be the next milestone before deciding to start with the detailed engineering phase and realisation.