COST ANALYSIS OF HIGH TEMPERATURE HEAT SUPPLY VIA IMPORTED METAL FUEL (FE)

A PRE-FEASIBILITY STUDY

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STEP 1: PURPOSE & APPROACH

- Purpose & approach
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- Key insights
Objective & Approach of this Study

Objective of this study
➢ Understanding the import supply chain costs of Iron metal fuel as a fuel for high-temperature heat, in comparison to an alternative decarbonization option.

Approach
This pre-feasibility level study studies the techno-economic performance of metal fuels vs. hydrogen gas in high temperature steam applications through three sequential activities:

1. Technological configuration & energy/mass flows of metal fuel chain
2. Economic assessment of metal fuel chain
3. Comparison of metal fuel chain with hydrogen (via NH₃) chain
STEP 2: SCOPE OF THE METAL FUEL AND HYDROGEN CHAINS
SCOPE OF METAL FUEL (FE) CHAIN:
TOOLING: TNO ENERGY CARRIER SUPPLY CHAIN COST MODEL (SCMV1.5)

The following chain elements are included in the analysis:

- Power-to-Hydrogen
- Hydrogen-to-Metal fuels (MF)
- MF bunker storage for export (return logistics)
- MF international ship transport (return logistics)
- MF local distribution to 1 end-user (return logistics)
- MF local storage on the site of 1 end user (return logistics)
- MF end use high temperature heat generation with water-tube boiler (>250°C, 32 bar) at 1 site

Assumptions:

- 2030 time stamp
- 1GW RES locally, 99-104 ktpa PtH2 (operational hours based on RES)
- Design capacity 2000 ktpa MF conversion (operation hours based on PtH2)
- Electricity Back-up for hot-standby hours via LCoS
- Scaling factors of assets included
- Single end-user share of MF: 13% MF (Fe) mass flow
- Total MF round-trip duration (forward & return logistics): 12 weeks
- All technologies in the supply chain are assumed TRL9 at large scale in 2030
The following chain elements will be included during the analysis:

- Power-to-Hydrogen
- Hydrogen-to-Ammonia (\(\text{NH}_3\))
- \(\text{NH}_3\) bunker storage for export
- \(\text{NH}_3\) international ship transport
- \(\text{NH}_3\) bunker storage for import
- \(\text{NH}_3\) local reconversion to \(\text{H}_2\)
- \(\text{H}_2\) (compressed) transfer by pipeline transport
- No on-site storage (assumed to be covered by pipeline network)
- HTH end use for high temperature heat generation with water-tube boiler (>250°C, 32 bar) at 1 site

Assumptions:

- 2030 time stamp
- 1GW RES locally, 99-104 ktpa PtH2 load following
- Design capacity 428,4 ktpa \(\text{NH}_3\)
- Electricity Back-up for hot-standby hours via LCoS
- Scaling factors of assets included
- Single end-user share of hydrogen: ~13% mass flow
- All technologies in the supply chain are assumed TRL9 at large scale in 2030
### CASE DESCRIPTION:
#### HT HEAT VIA METAL FUELS AND HYDROGEN

<table>
<thead>
<tr>
<th>HT heat via metal fuel case</th>
<th>HT heat via hydrogen case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_x$O$_y$ is converted to Fe with green hydrogen at large-scale in foreign countries and imported by means of vessels to the Netherlands (Port of Rotterdam), where the iron metal fuel (MF) is storage centrally.</td>
<td>Ammonia is produced from green hydrogen and nitrogen at large-scale in foreign countries and imported by means of vessels to the Netherlands (Port of Rotterdam), where NH$_3$ is storage centrally.</td>
</tr>
<tr>
<td>A share of the MF is distributed towards one end-user in the Rotterdam Moerdijk region via barge transport. This end-user operates a 46 MW$_{th}$ steam boiler (&gt;250°C, 32 bar).</td>
<td>All the NH$_3$ is converted in H$<em>2$ and a share is distributed towards one end-user in the Rotterdam Moerdijk region via pipeline transport. This end-user operates a 46 MW$</em>{th}$ steam boiler (&gt;250°C, 32 bar).</td>
</tr>
<tr>
<td>The oxidized MF (Fe$_x$O$_y$) is returned to the central storage and transported to the foreign country to reuse the MF. The Fe mass circulating in each chain is: 534 (SA), 624 (MOR), 650 (ARG) kton.</td>
<td>H$_2$ storage is not taken into account as it is assumed H$_2$ is stored in the national pipeline and salt cavern infrastructure (H$_2$ backbone).</td>
</tr>
<tr>
<td>The cost of one unit of HT heat (€/GJ) is determined by summation of the costs throughout the supply chain that correspond with the total share of required MF for this one end-user.</td>
<td>The cost of one unit of HT heat (€/GJ) is determined by summation of the costs throughout the supply chain that correspond with the total share of required H$_2$ for this one end-user.</td>
</tr>
</tbody>
</table>
STEP 3: PRESENTATION OF COST MODELLING RESULTS

Purpose & approach
Scope
Cost breakdown results
Key insights
COST BREAKDOWN RESULTS
HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & \( \text{H}_2 \) (\( \text{NH}_3 \) ROUTE)

HT heat via MF(Fe) supply costs [€/GJ]

Supply chain activity cost component [€/GJ]

- Local H2 production
- H2 buffer storage capacity
- MF shipping
- MF distribution to end-user
- MF-to-HT heat end use

HT heat via \( \text{NH}_3 \) and \( \text{gH}_2 \) supply costs [€/GJ]

Supply chain activity cost component [€/GJ]

- Local H2 production
- H2 to NH3 conversion
- Transport: Shipping
- NH3 to H2 reconversion
- Distribution to end-user

Supplying country:
- Saudi Arabia
- Morocco
- Argentina
COST BREAKDOWN RESULTS
HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & H₂ (NH₃ ROUTE)

High temperature heat supply cost comparison

Comparison high temperature heat supply chain cost, Saudi Arabia, 2030
**COST BREAKDOWN RESULTS (CAPEX & OPEX DETAILS)**

**HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & H₂ (NH₃ ROUTE)**

MF: The CAPEX and OPEX up and including the import terminal represent 100% mass flow. From distribution onwards, ~13% of the mass flow is assumed for one MF end-user.

H₂: The CAPEX and OPEX up and including the H₂ reconversion represent 100% mass flow. From distribution onwards, ~13% of the mass flow is assumed for one H₂ end-user.
STEP 4: KEY INSIGHTS & FUTURE RESEARCH TOPICS

- Purpose & approach
- Scope
- Cost breakdown results
- Key insights
INTERPRETATIONS & CONCLUSIONS
THE COST ANALYSIS RESULTS OF THE METAL FUEL SUPPLY CHAIN SHOW COST-COMPETITIVE POTENTIAL TO DECARBONIZE HIGH TEMPERATURE HEAT GENERATION

Conclusions
1. The levelized costs of high temperature heat supply (>250°C, 32 bar steam) using metal fuels or hydrogen as a fuel in water-tube boilers are in the same order of magnitude: 36 – 55 €/GJ.
2. For both the MF and H₂ chains, the H₂ production and H₂-to-carrier conversion are the most dominant cost drivers.
3. For the metal fuel chain, the costs in the HT end use chain element are higher due to a required initial investment in metal fuel (Fe powder).
4. The H₂ production cost contribution (in €/GJ) for the H₂ (via NH₃) case is larger due to the Haber-Bosch process efficiency, compared to the higher conversion efficiency in the metal fuel reduction process.
5. Based on this first pre-feasibility assessment, supplying HT heat through the MF chain is, on average, 20% cheaper compared to the H₂ (NH₃) chain.

Uncertain assumptions & limitations of the study

Metal fuel chain:
- The sum of Fe fuel (530-650 kton) that circulates in the supply chain is estimated through rough estimations and is assumed to accommodate a 12 week roundtrip duration of MF. A dynamic stock-flow modelling approach is required to minimize the MF investment.
- Costs related to central export and import storage, international shipping, barge distribution and on-site storage are modelled through tariff structures, implying that assets in these supply chain elements are utilized against marginal costs.

H₂ (via NH₃) chain
- Large scale compressed hydrogen infrastructure (transmission, distribution and large-scale storage) does not exist at the moment. It is assumed that this infrastructure is operational and accessible to industry stakeholders in Rotterdam Moerdijk area to provide a continuously secured supply of hydrogen in 2030.
- More elaborated description of assumptions and logic on the hydrogen import via ammonia carriers is publically accessible via www.HyDelta.nl.
RECOMMENDED AREAS FOR FUTURE RESEARCH

**Dynamic modelling of (collaborative) supply chain logistics**
- Shifting from a static to a dynamic supply chain modelling approach can increase the understanding of the performance of the metal fuel versus hydrogen fuel chains.
- Multiple end-users can collectively use MF infrastructure assets which may lead to collaboration benefits (e.g. lower costs, security of supply redundancies).
- **Recommendation:** Modelling and simulation of collaborating MF users in interconnected and dynamic supply chains is recommended to more realistically study the transport and logistics performance and thereby quantify the benefit of collaborative utilization of metal fuels over a single-user application and supply chain.

**Expand comparison MF to more decarbonization options**
- Alternatives for HT heat such as e.g. natural gas with CC(U)S, electricity-based HT heat or biogas have not been included in this study.
- As a reference case, NH₃ as a H₂ carrier has been chosen. An additional comparison of alternative hydrogen carriers (e.g. LÖHC, LH₂) would yield a more complete view on cost ranges.
- **Recommendation:** Future research with the aim to include multiple alternatives for high temperature heat generation is recommended to create an exhaustive comparison of decarbonized HT heat fuel option.

**Diving into detail on the security of supply of HT heat fuels**
- A merit of metal fuels is their advantageous transport and storage characteristics as a solid fuel. This characteristic can be beneficial in achieving a secured supply of fuel in comparison with other high temperature heat decarbonisation alternatives.
- Storage at end user site is neglected for the H₂ case: it is assumed that a pipeline (connected to a H₂ backbone) will enable sufficient storage capacity and stable supply.
- **Recommendation:** Future research with the aim to quantify the supply chain performance of different HT heat fuels from a security of supply perspective is recommended to address the reliability of the chains.

**Quantification of system-level advantages of metal fuel utilization**
- The advantages and disadvantages of metal fuels on a local, regional, national or international system level in terms of (societal) costs, environmental impact reduction, political and social may provide complementary insights regarding the role of metal fuels in the energy system of the future.
- **Recommendation:** Model and simulate the potential effects of the introduction of metal fuels on the performance of the energy system.
SUPPLY CHAIN CONFIGURATION: FORWARD-MOVING STOCK-FLOW SUPPLY CHAIN DESIGN

The detailed description of the cost modelling logic and assumptions of the TNO Supply Chain Model V1.5 is publicly available via: [www.hydelta.nl](http://www.hydelta.nl).
## SCOPE METAL FUEL CHAIN: SAUDI ARABIA EXAMPLE

TOOLING: TNO ENERGY CARRIER SUPPLY CHAIN COST MODEL (SCMV1.5)

### Renewable energy source
- Solar
- Wind

### Energy carrier conversion
- GH2
- Fe

### International Transportation
- Storage
- Ship
- Storage

### Domestic Distribution
- Barge

### HT heat end use
- Storage
- HT heat

### 100% of MF
- 1 GW RES

### 0.9 GW AEL
- Design capacity: 2 trains, 1484 ktpa MF each.
- Actual production capacity: 1540 ktpa Fe

### 14% of MF
- 35 kton Fe; 4506 m3
- Up to 35 kton of Fe per ship
- 35 kton Fe; 4497 m3

- 50 kton Fe; 6338 m3
- Up to 50 kton of Fe per ship
- 50 kton Fe; 6350 m3

### MOR: 11% of MF
- 1.6 kton Fe; 250 m3
- Fuel flow: max 24 t/h Fe
- ARG: 11% of MF

### ARG: 11% of MF
- 46.2 MWth MF boiler
# RENEWABLE ELECTRICITY SUPPLY ASSUMPTIONS: HYBRID LCOE & FLH

<table>
<thead>
<tr>
<th>Country-specific parameters</th>
<th>LCoE for onshore wind power in 2030 €/MWh_el</th>
<th>LCoE for offshore wind power in 2030 €/MWh_el</th>
<th>LCoE for solar PV power in 2030 €/MWh_el</th>
<th>LCoE for geothermal power in 2030 €/MWh_el</th>
<th>LCoE for pumped hydro power in 2030 €/MWh_el</th>
<th>LCoE for combined RES power in 2030 €/MWh_el</th>
<th>Price of stored electricity 2030 €/MWh_el</th>
<th>Average national grid power price 2030 €/MWh_el</th>
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<th>Country-specific parameters</th>
<th>Full-load hours (FLH) for onshore wind power</th>
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<th>Full-load hours (FLH) for solar PV power</th>
<th>Full-load hours (FLH) for geothermal power</th>
<th>Full-load hours (FLH) for pumped hydro power</th>
<th>Full-load hours (FLH) for combined intermittent RES power</th>
<th>Installed intermittent RES capacity</th>
<th>Overlap of intermittent primary and secondary RES source FLHs</th>
<th>Full-load hours (FLH) for combined intermittent RES power</th>
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<tbody>
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<td>Unit</td>
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<td>Saudi Arabia</td>
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<td>10%</td>
<td>49%</td>
<td>4320</td>
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