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

A PRE-FEASIBILITY STUDY

FEBRUARY 2022

AUTHORS

IR. T. HAJONIDES VAN DER MEULEN

CONTACT DETAILS: THOMAS.HAJONIDES@TNO.NL

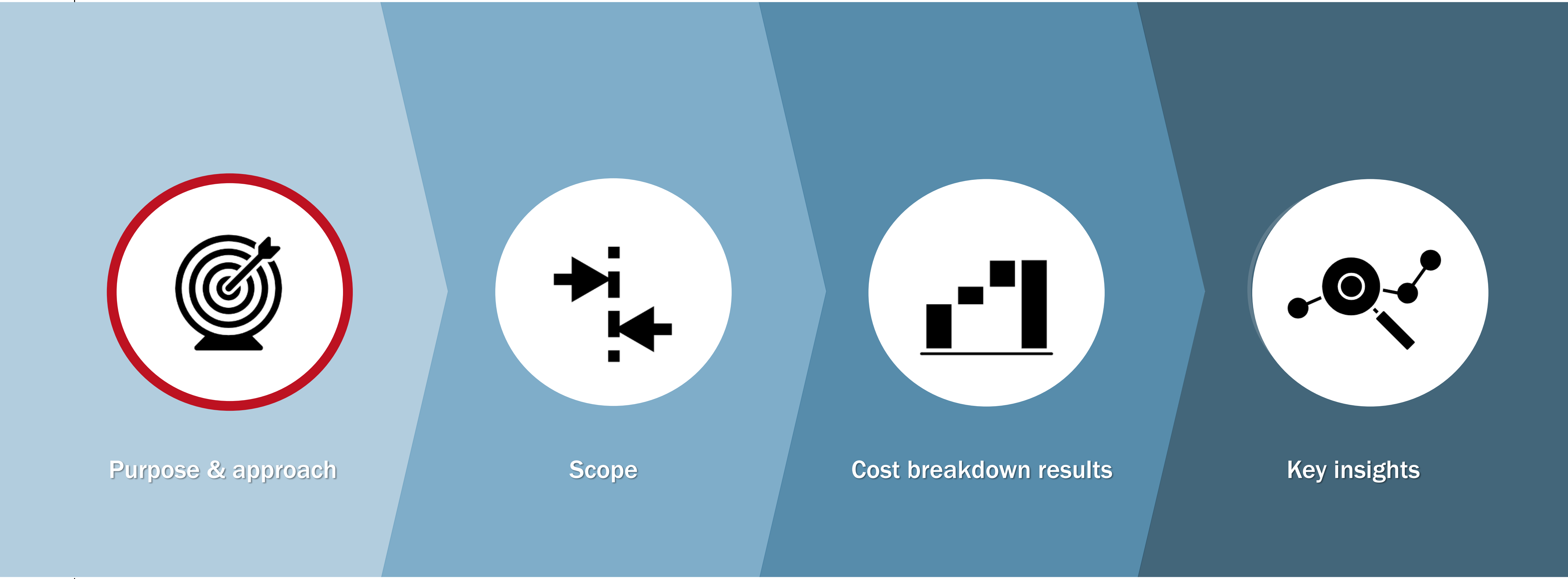
IR. T. VAN LEEUWEN

PROF. DR. H. ZONDAG

TNO innovation for life

CONTENT OF THIS DOCUMENT

STEP 1: PURPOSE & APPROACH



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-feasability 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 NH_3) chain

STEP 2: SCOPE OF THE METAL FUEL AND HYDROGEN CHAINS

Purpose & approach

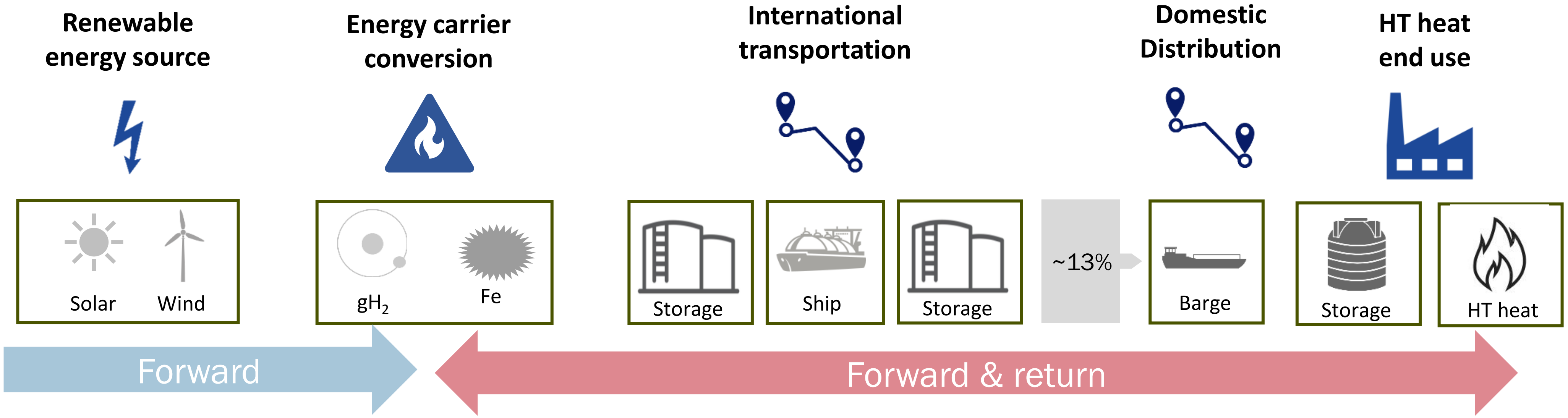
Scope

Cost breakdown results

Key insights

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:

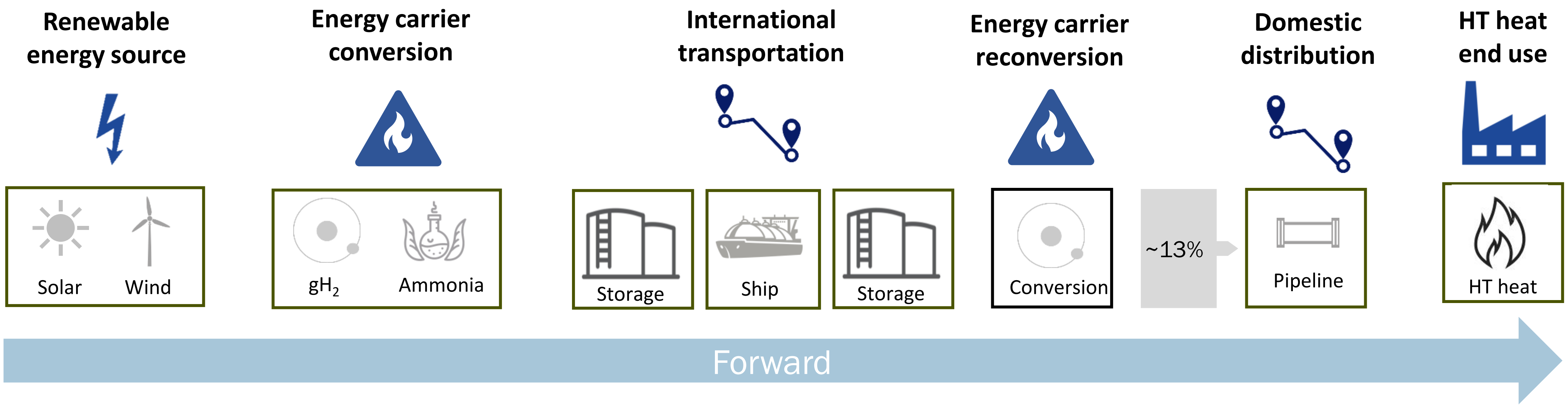
- Power-to-Hydrogen
- Hydrogen-to-Metal fuels (MF)
- MF bunker storage for export (return logistics)
- MF international ship transport (return logistics)
- MF local distribution to 1 end-user (return logistics)
- MF local storage on the site of 1 end user (return logistics)
- MF end use high temperature 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 (opereration hours based on PtH_2)
- 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 techologies in the supply chain are assumed TRL9 at large scale in 2030

SCOPE OF HYDROGEN (VIA AMMONIA) CHAIN:

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



The following chain elements will be included during the analysis:

- Power-to-Hydrogen
- Hydrogen-to-Ammonia (NH_3)
- NH_3 bunker storage for export
- NH_3 international ship transport
- NH_3 bunker storage for import
- NH_3 local reconversion to H_2
- 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 (>250ºC, 32 bar) at 1 site

Assumptions:

- 2030 time stamp
- 1GW RES locally, 99-104 ktpa PtH2 load following
- Design capacity 428,4 ktpa 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 techologies in the supply chain are assumed TRL9 at large scale in 2030

CASE DESCRIPTION: HT HEAT VIA METAL FUELS AND HYDROGEN

HT heat via metal fuel case	HT heat via hydrogen case
Fe_xO_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.	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.
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 (>250°C, 32 bar).	All the NH_3 is converted in H_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_{th} steam boiler (>250°C, 32 bar).
The oxidized MF (Fe_xO_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.	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).
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.	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.

STEP 3: PRESENTATION OF COST MODELLING RESULTS

Purpose & approach

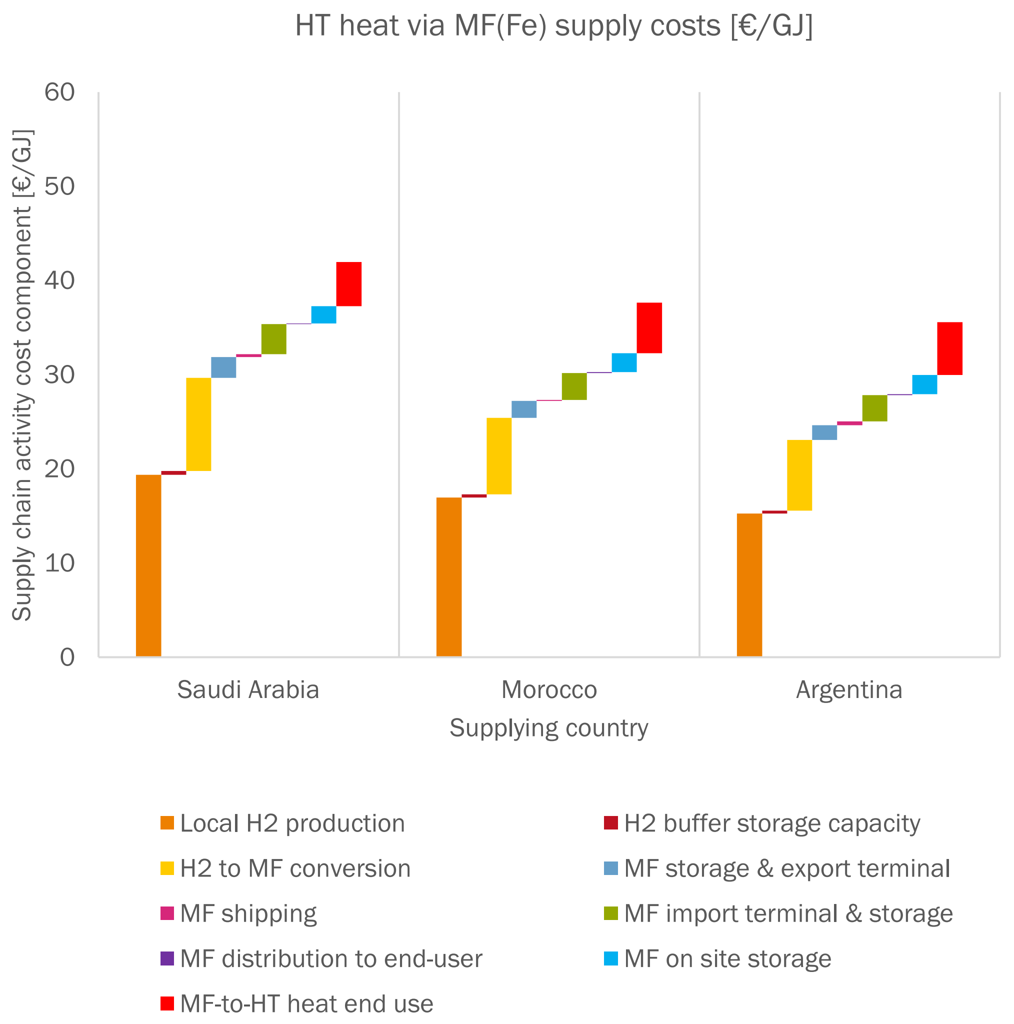
Scope

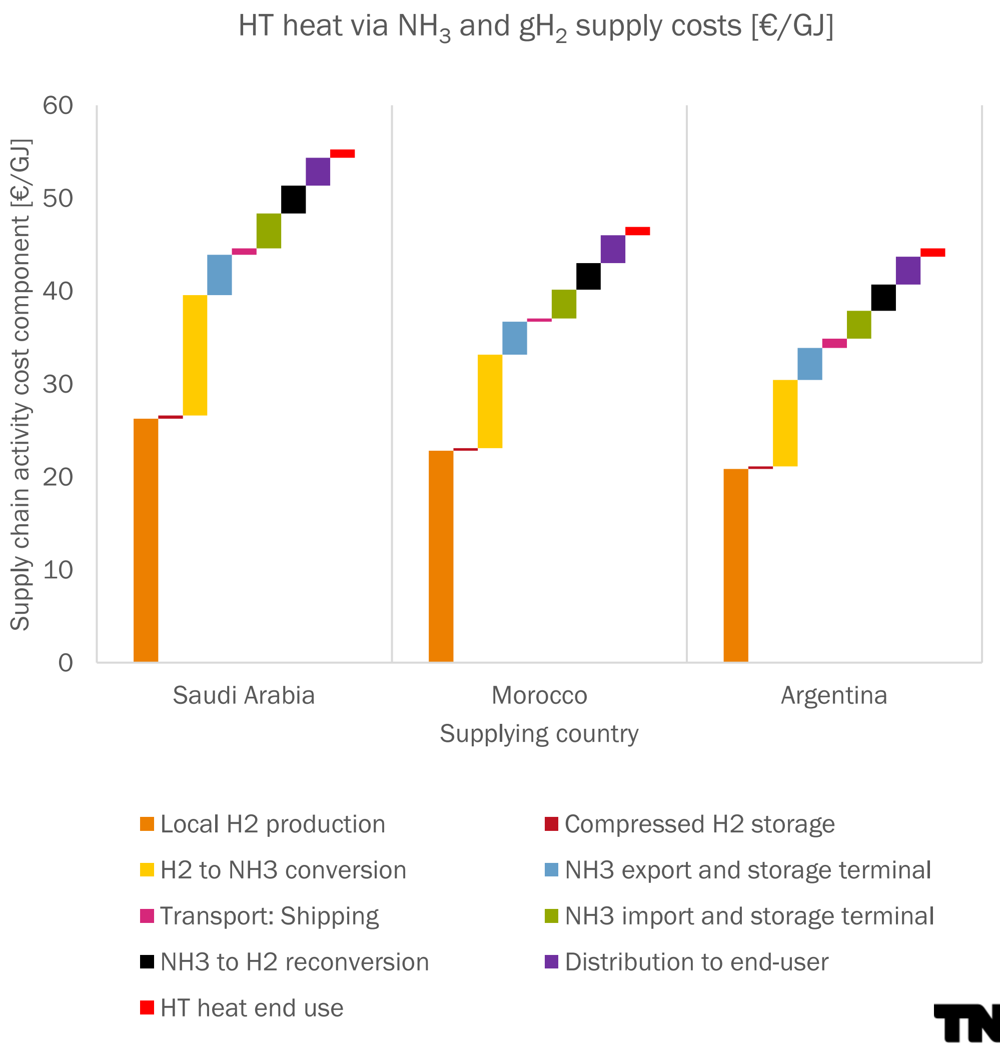
Cost breakdown results

Key insights

COST BREAKDOWN RESULTS

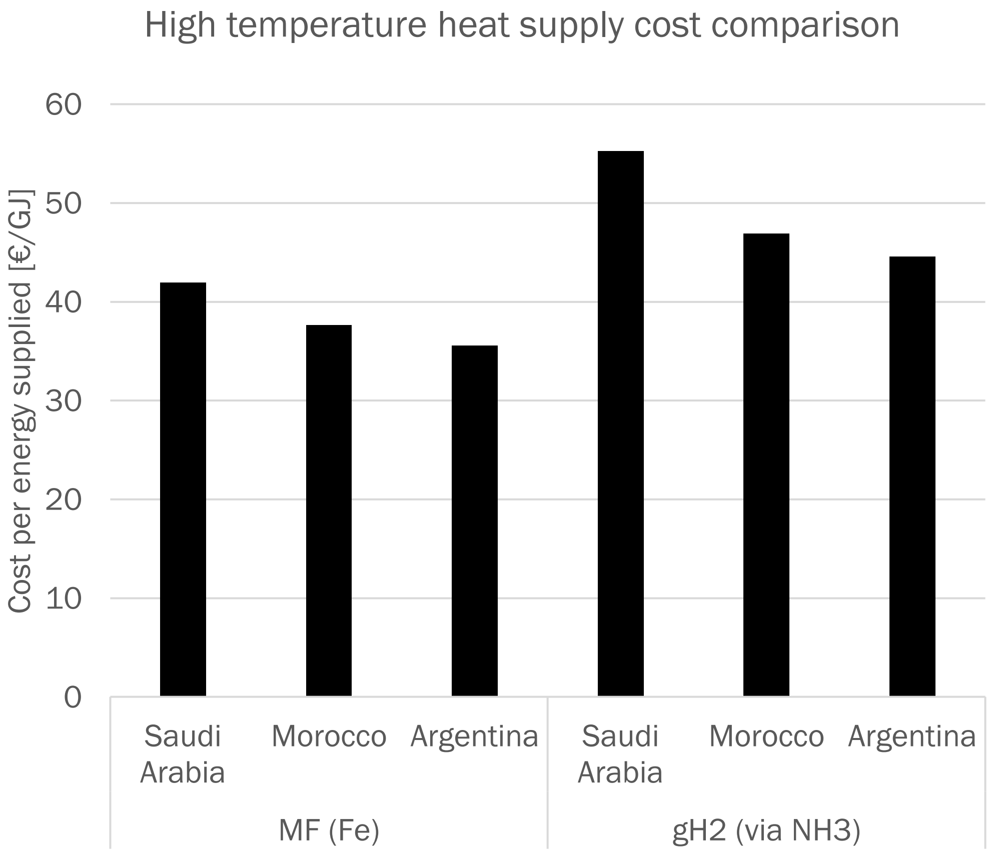
HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & H_2 (NH_3 ROUTE)

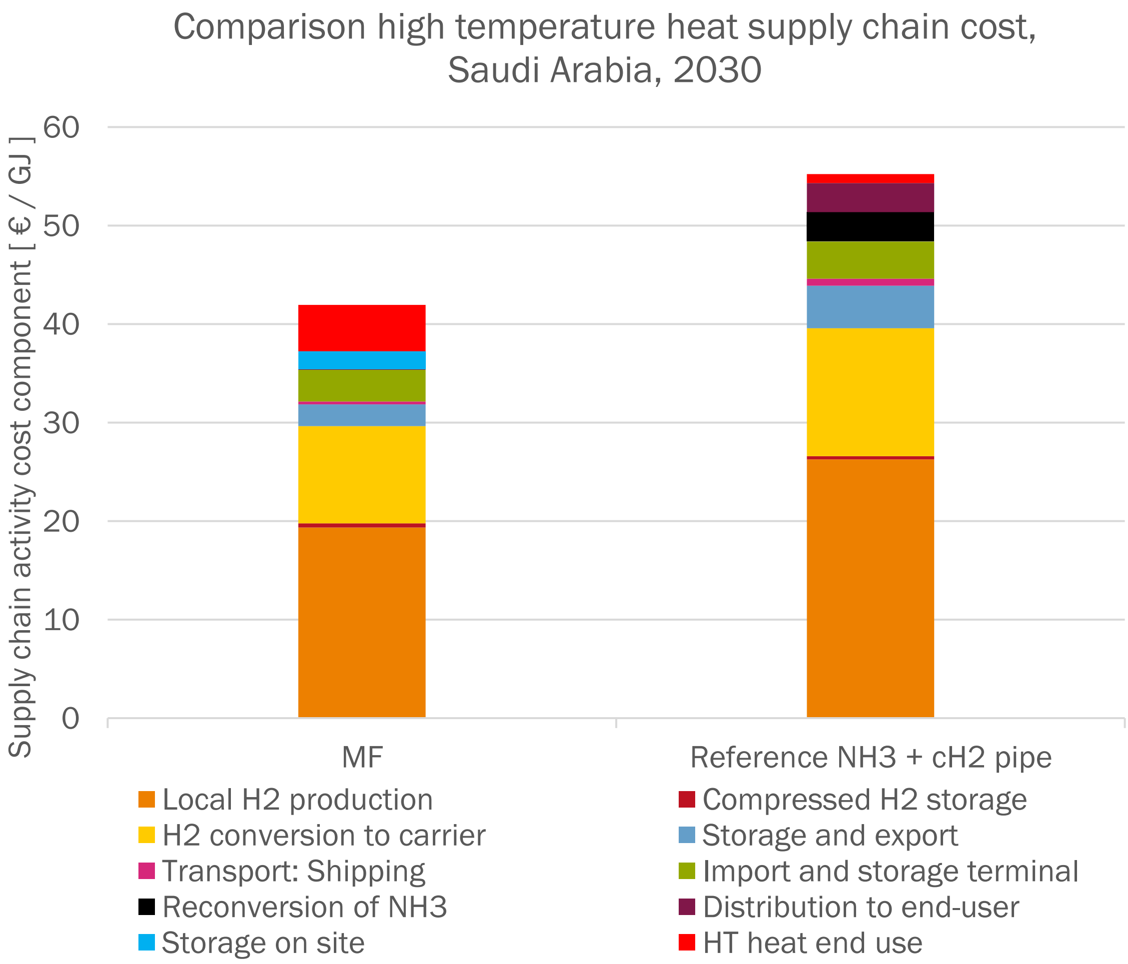




COST BREAKDOWN RESULTS

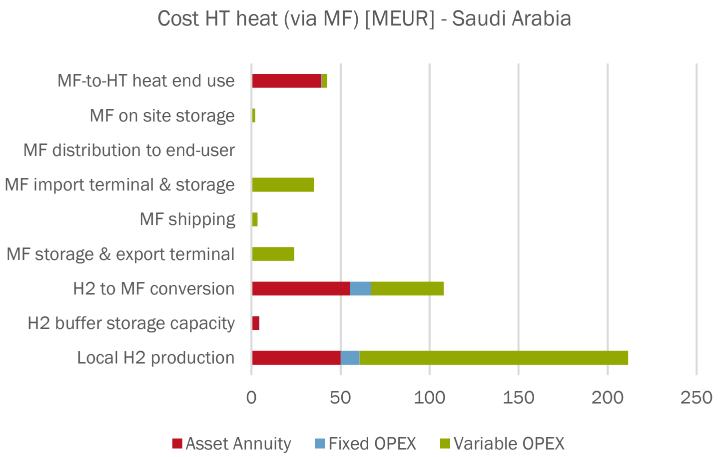
HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & H_2 (NH_3 ROUTE)

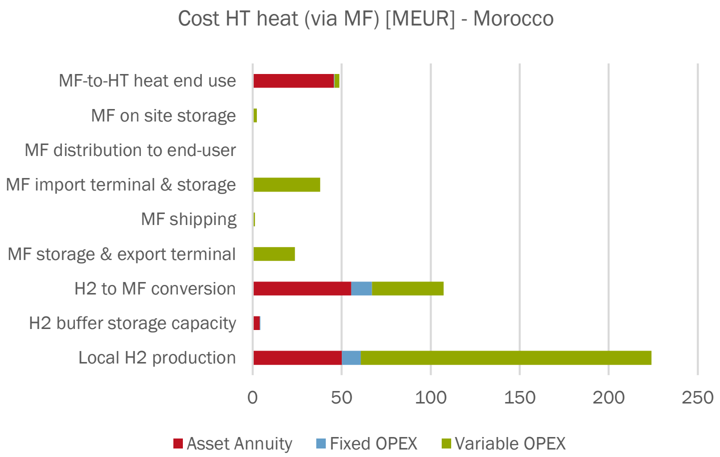


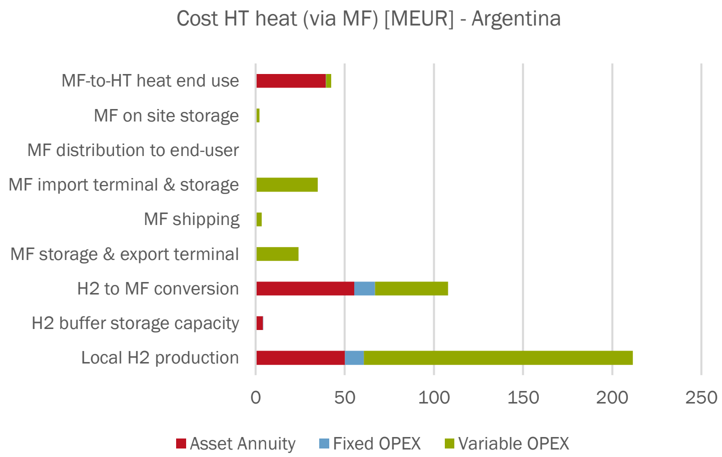


COST BREAKDOWN RESULTS (CAPEX & OPEX DETAILS)

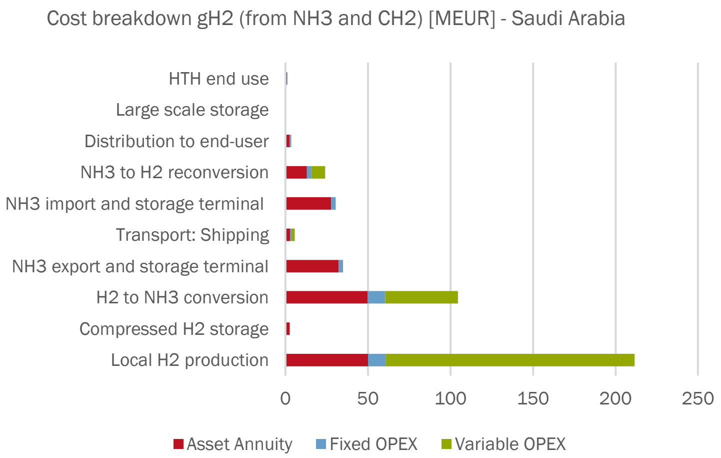
HIGH TEMPERATURE HEAT GENERATION COSTS: COMPARING METAL FUEL & H_2 (NH_3 ROUTE)

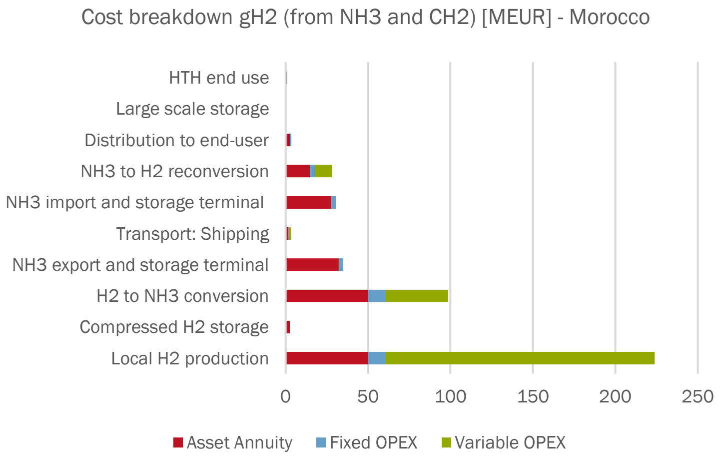


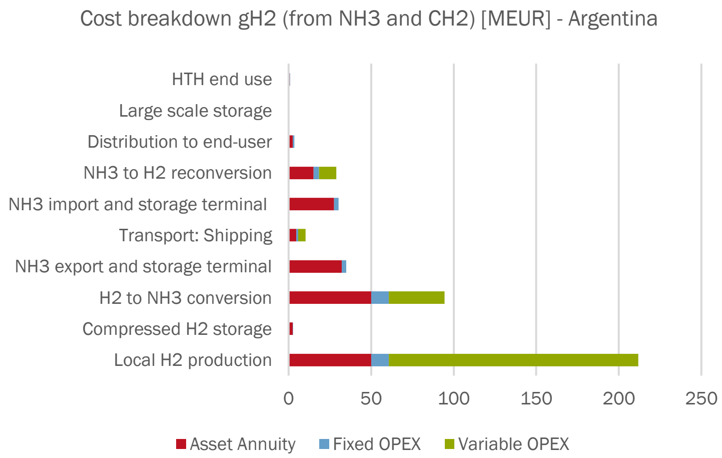




MF: The CAPEX and OPEX up and including the import terminal represent 100% mass flow. From distribution onwards, ~13% of the mass flow is assumed for one MF end-user.

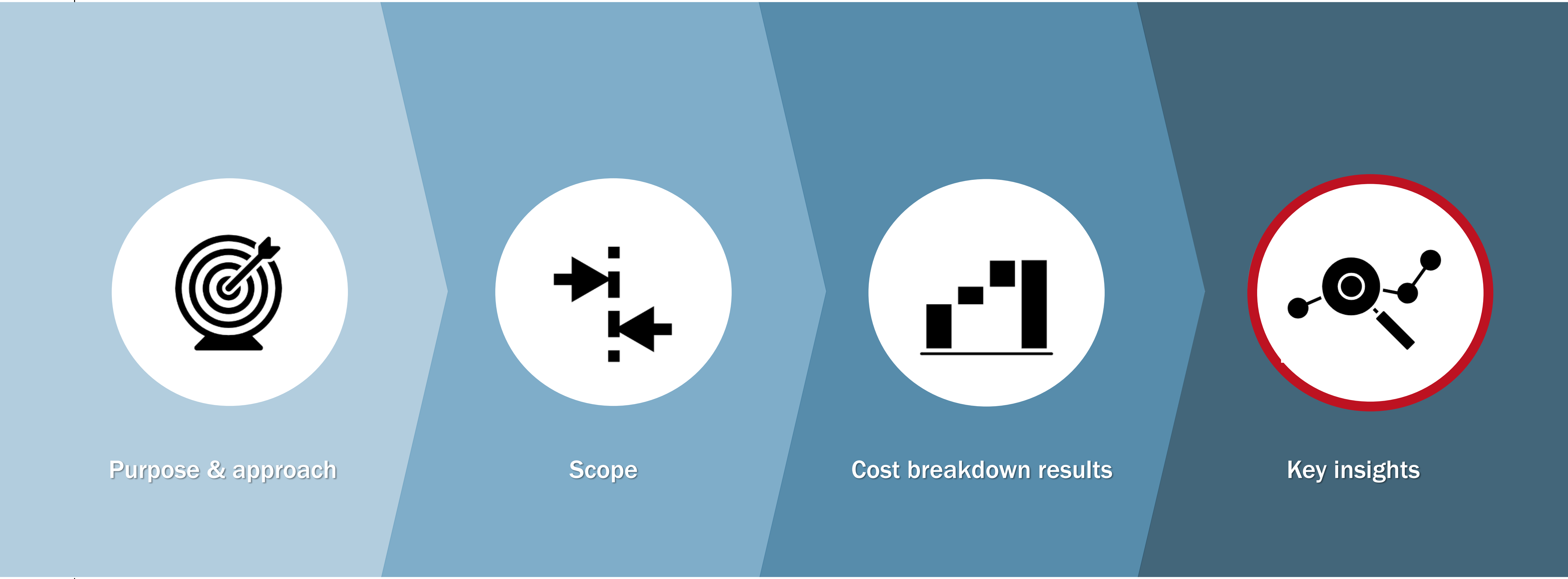






H_2: The CAPEX and OPEX up and including the H_2 reconversion represent 100% mass flow. From distribution onwards, ~13% of the mass flow is assumed for one H_2 end-user.

STEP 4: KEY INSIGHTS & FUTURE RESEARCH TOPICS



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 (>250ºC, 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 H_2 chains, the H_2 production and H_2-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 H_2 production cost constribution (in €/GJ) for the H_2 (via NH_3) 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 H_2 (NH_3) 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 accomodate 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.

H_2 (via NH_3) 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 bio-gas have not been included in this study.
- As a reference case, NH_3 as a H_2 carrier has been chosen. An additional comparison of alternative hydrogen carriers (e.g. LOHC, 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 H_2 case: it is assumed that a pipeline (connected to a H_2 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.

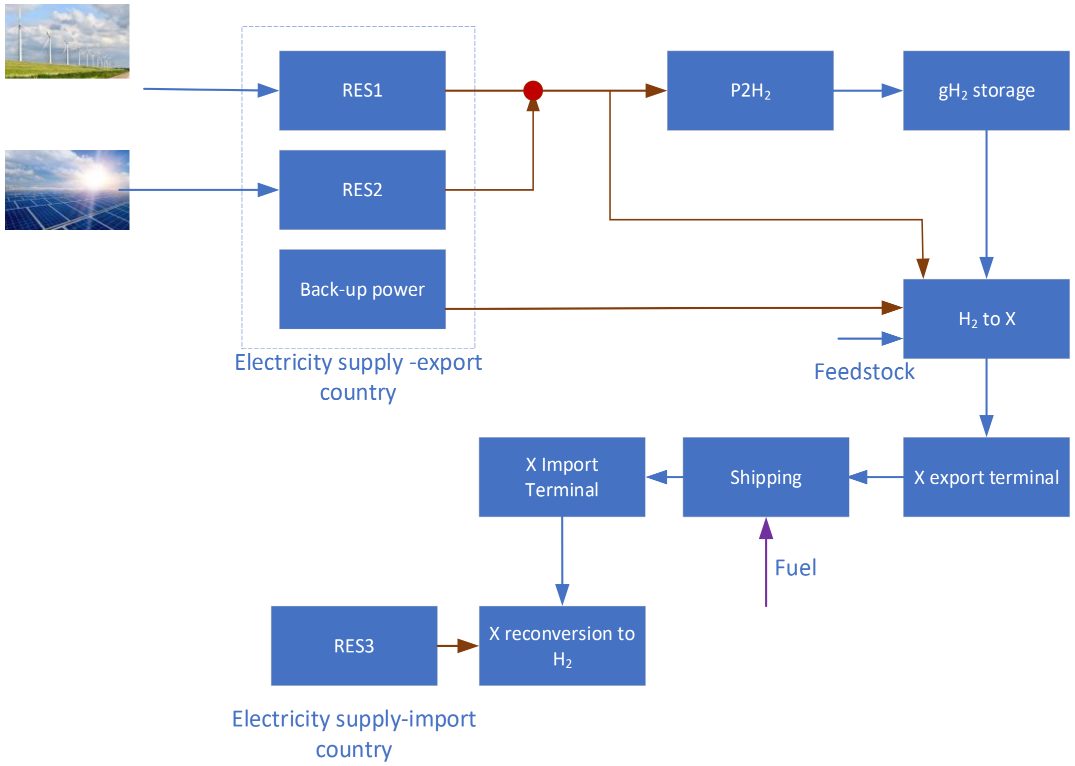
Quantification of system-level advantages of metal fuel utilization

- 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 complementory 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.

APPENDIX

TNO innovation for life

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 .

SCOPE METAL FUEL CHAIN: SAUDI ARABIA EXAMPLE

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

	Renewable energy source	Energy carrier conversion	International Transportation				Domestic Distribution	HT heat end use	
100% of MF	Solar, Wind	GH2, Fe	Storage	Ship	Storage	14% of MF	Barge	Storage	HT heat
	1 GW RES	0.9 GW AEL	35 kton Fe; 4506 m3	Up to 35 kton of Fe per ship	35 kton Fe; 4497 m3		Up to 0,5 kton of Fe per barge	1,6 kton Fe; 250 m3	46,2 MWth MF boiler
		Design capacity: 2 trains, 1484 ktpa MF each. Actual production capacity: 1540 ktpa FE	50 kton FexOy; 6338 m3	Up to 50 kton of FexOy per ship	50 kton FexOy; 6350 m3		Up to 0.8 kton of FexOy per barge	2,3 kton FexOy; 435 m3	Fuel flow: max 24 t/h Fe

MOR: 1862 ktpa FE
ARG: 1957 ktpa FE

MOR: 11% of MF
ARG: 11% of MF

RENEWABLE ELECTRICITY SUPPLY ASSUMPTIONS: HYBRID LCOE & FLH

Country-specific parameters	LCoE for **onshore wind** power in 2030	LCoE for **offshore wind** power in 2030	LCoE for **solar PV** power in 2030	LCoE for **geothermal** power in 2030	LCoE for **pumped hydro** power in 2030	LCoE for **combined RES** power in 2030	Price of **stored** electricity 2030	Average national **grid** power price 2030
Unit	*€/MWh_el*							
Argentina	27		27			30	120	
Morocco	35		23			34	120	
Netherlands								55
Saudi Arabia	46		20			38	120	

Country-specific parameters	Full-load hours (FLH) for onshore wind power	Full-load hours (FLH) for offshore wind power	Full-load hours (FLH) for solar PV power	Full-load hours (FLH) for geothermal power	Full-load hours (FLH) for pumped hydro power	Installed intermittent RES capacity	Overlap of intermittent primary and secondary RES source FLHs	Full-load hours (FLH) for combined intermittent RES power	Full-load hours (FLH) for combined intermittent RES power
Unit	*%*	*%*	*%*	*%*	*%*	*MW*	*%*	*%*	*h*
Argentina	51%		18%			2000	10%	63%	5490
Morocco	43%		23%			2000	10%	60%	5220
Saudi Arabia	30%		25%			2000	10%	49%	4320

innovation
for life