WHEN TRUST MATTERS

Securing green hydrogen for the German power sector

Technology readiness & techno-economic feasibility study for three hydrogen value chains

30 October 2024

Introduction and background

Study background

German Power Plant Safety Act

Germany is **modernizing its electricity system** to integrate power generation from renewable energies and ensure reliability in times of low wind and solar power generation.

Hyphen project

Germany is **partnering** with countries such as Namibia to source low-cost green hydrogen.

HyIron pilot

HyIron, a collaboration between Namibian and German companies, has developed a **carbon-neutral technology for iron ore reduction** using green hydrogen.

This study

In this context, Climate Neutrality Foundation (CNF) has commissioned DNV to study the feasibility of using iron as an energy carrier to decarbonize the German power system, focusing on hydrogen-ready back-up power plants.

Basis for this study

German Power Plant Safety Act – KWSG

- Consultation opened on Sep 11 2024
- 12.5 GW of power generation
  - 5 GW H_2-ready
  - 2 GW H_2-retrofitted
  - 500 MW H_2-sprinter
  - 5 GW of “new-gas” based
- 800 full load hours is subsidized

Hyphen project

- 7 GW of renewable generation capacity in Namibia’s Tsau //Khaeb National Park, consisting of 4 GW wind and 3 GW solar
- Phase 1: 3.5 GW renewable energy
175 kt H_2 per year
1,000 kt ammonia per year
- Phase 2: 3.5 GW renewable energy
175 kt H_2 per year
1,000 kt ammonia per year

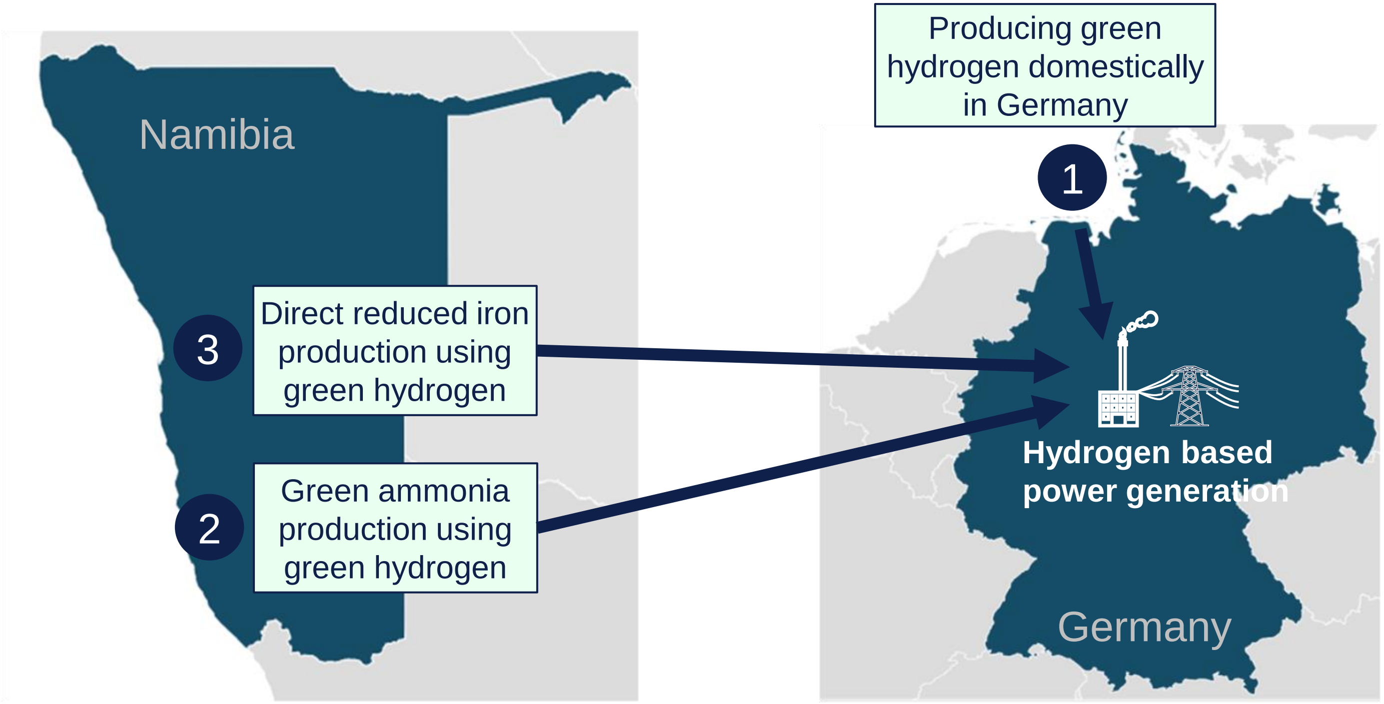
HyIron pilot

- Production of DRI in an airtight rotary kiln using hydrogen
- Pilot plant in Lingen, Germany producing 500 kg DRI per hour
- Project Oshivela - Larger 15 kt per year pilot to be implemented by the end of 2024 (construction ongoing) in Namibia

DNV assessed three different value chains

Goal

To assess the feasibility and potential benefits of alternative value chains such as importing direct reduced iron, to enable green hydrogen-based power generation in Germany.



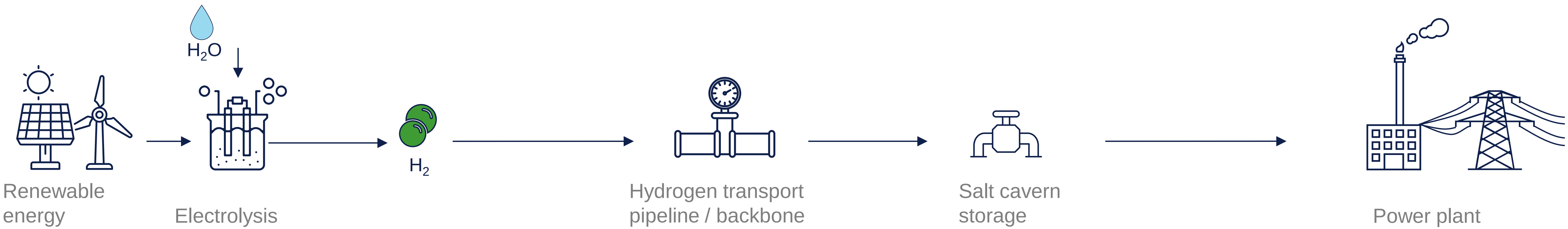
DNV assessed

- Technology readiness
- Levelized Cost
- Practicality

Value chains

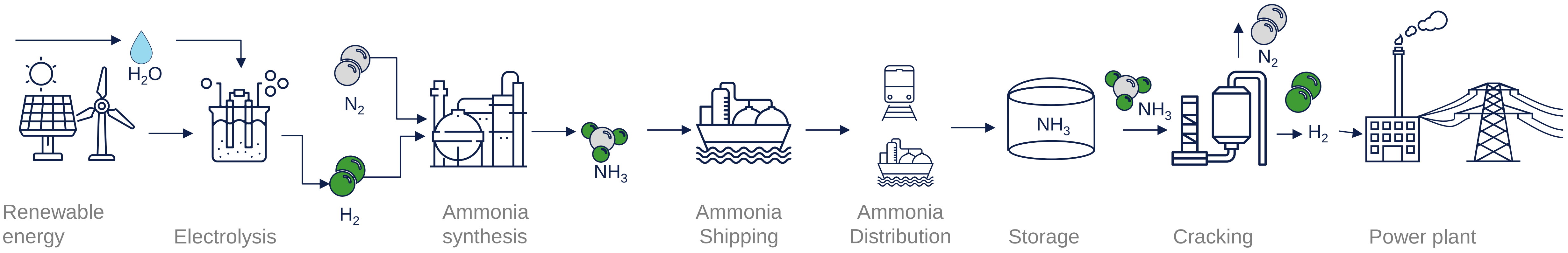
Value chain 1: Domestic Hydrogen production

1. Green hydrogen production in Germany using offshore wind energy and electrolysis
2. Hydrogen is supplied to the German hydrogen backbone and transported to the power plant
3. In most cases hydrogen is not directly transported to the power plant but stored in hydrogen salt caverns, mainly found in North Germany
4. Combustion of hydrogen in a hydrogen fired power plant to support the German electricity grid



Value chain 2: Green ammonia import

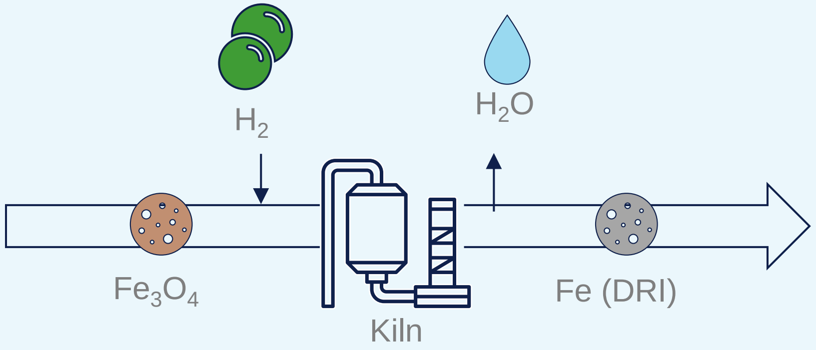
1. Green hydrogen production with abundant renewable energy in Namibia
2. Hydrogen is transported through a 50-100 km long pipeline to the harbour. The pipeline also serves as a storage/buffer vessel
3. The hydrogen is used in the Haber-Bosch process to produce ammonia
4. Nitrogen is captured from the air and sea water is desalinated to be used in both ammonia production and electrolysis. For electrolysis the water is transported to the production site (inland) by pipeline
5. Ammonia is shipped to Germany where it is further distributed or stored at the harbour
6. Ammonia is cracked centrally and injected in the hydrogen backbone to be transported to the power plant
7. Combustion of hydrogen in a hydrogen fired power plant to support the German electricity grid



Direct Reduced Iron – DRI

Basics explained

- Well known process in the steel industry and currently using coal or natural gas as reduction agent.
- Hydrogen can also be used as reduction agent to avoid CO_2 emissions – important pilar for decarbonization of the steel industry.
- The resulting product is DRI which can be transported and stored in pelletized or powder form under dry and inert conditions (e.g. nitrogen blanket).
- At oxidation (rusting) of DRI with water, hydrogen is released – for example to produce back-up power in Germany.
- DRI is not a hydrogen carrier. Hydrogen is released from the added water at reconversion.

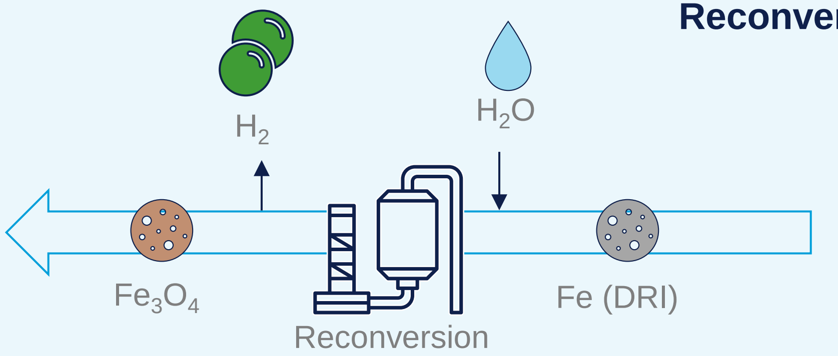


H_2 combines with the O_2 from the iron oxide (Fe_xO_x) under high temperatures in a kiln to form water (H_2O) and DRI.

$Fe_3O_4 + 4\ H_2 \rightarrow 3\ Fe + 4\ H_2O$

Reduction

Reconversion

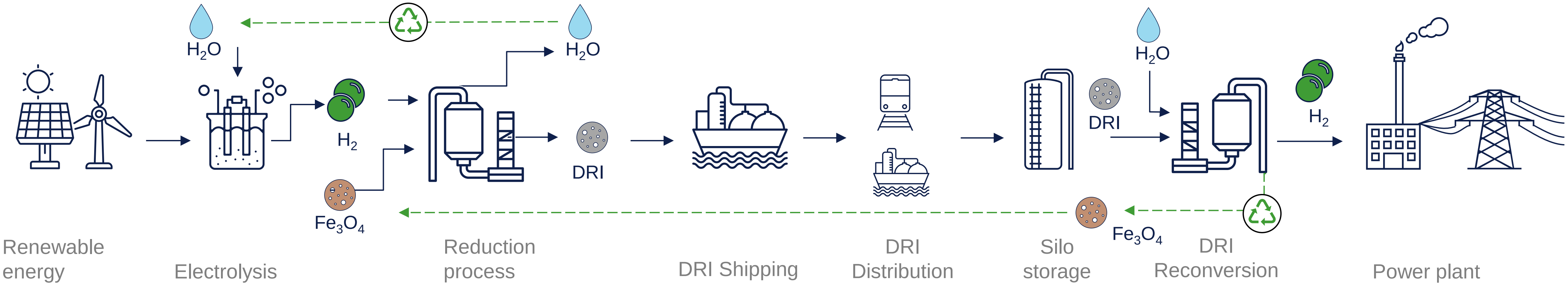


DRI is “oxidized” at ~150 ^{o}C and by adding water and a catalyst. The O_2 combines with the DRI and the H_2 from the water is released

$3\ Fe + 4\ H_2O \rightarrow Fe_3O_4 + 4\ H_2$

Value chain 3: Iron-to-Hydrogen

1. Green hydrogen production with abundant renewable energy in Namibia
2. Reduction of iron oxide using the green hydrogen to produce DRI
3. Water, formed in the reduction process, can be recycled and fed back to the electrolyser
4. Transport of DRI to Germany by ship (overseas) and distribution by ship or rail (in Germany)
5. Local storage of DRI at the power plant in silos
6. Reconversion of DRI through oxidation using water. H_2 comes from the added water, while the oxygen is combined with the DRI to form iron oxide
7. Some storage of hydrogen is likely required as a buffer while the reduction process starts
8. Combustion of hydrogen in a hydrogen fired power plant to support the German electricity grid
9. Iron oxide is transported back to Namibia to be re-used in the same process



Results of the assessments

DNV

Technology Readiness

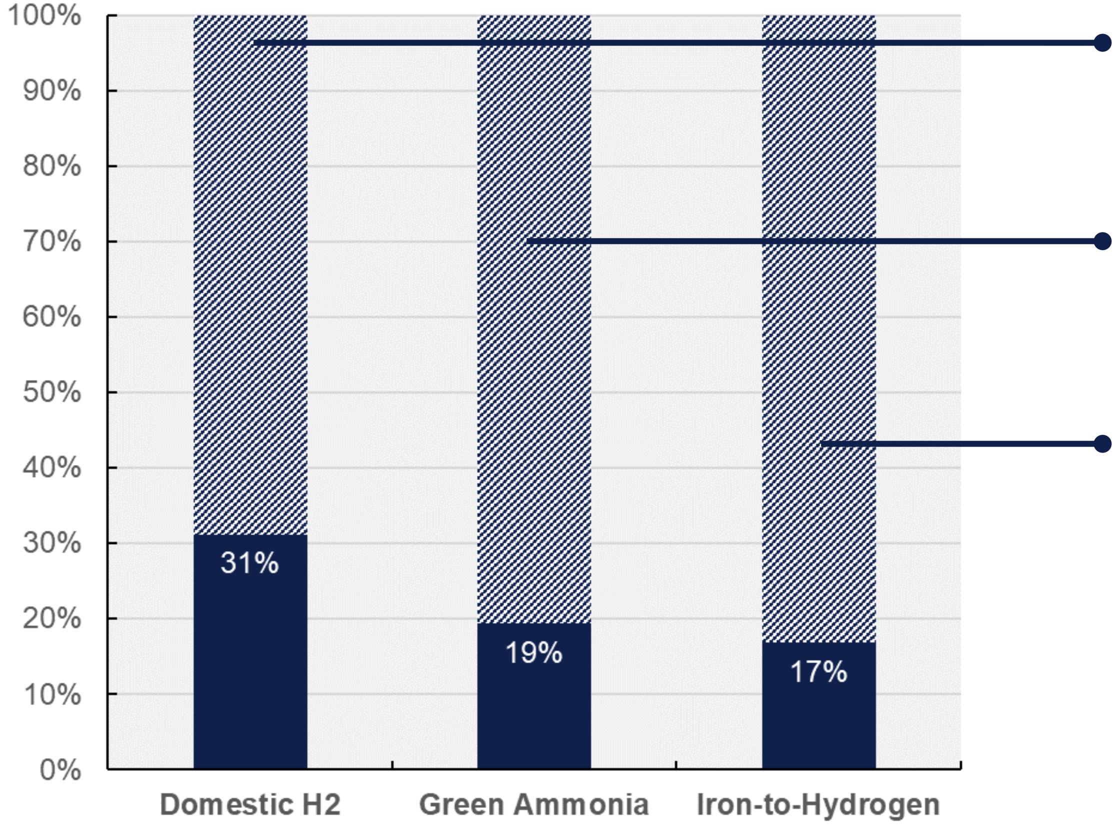
The three variants examined for the provision of back-up power generation each have **different degrees of technological maturity** with regard to the key components of generation, transportation, storage and reconversion. Iron–to-Hydrogen still needs to undergo the most development.

	Key Challenges	TRL
Domestic green hydrogen production	• Low TRL of fast cycling hydrogen salt caverns • Pressure fluctuations and impact on materials, especially steel (embrittlement)	5 – 8
Green ammonia import	• Low TRL and energy intensity of ammonia cracking at large scale • Flexibility of ammonia synthesis (intermittent renewables) and cracking (back-up power) • Toxicity	5 – 9
Iron-to-hydrogen	• Further maturing and upscaling of DRI production with green hydrogen • Low TRL of DRI reconversion technology	3 – 9

Research 1 2 3 | Development 4 5 6 | Deployment 7 8 9

DNV

Energy efficiency



Overall energy efficiency of the different assessed options

69% is lost, mainly due to electrolysis and power generation

81% is lost, mainly due to electrolysis, ammonia cracking and power generation

83% is lost, mainly due to electrolysis, DRI production and power generation

Import value chains have a lower overall energy efficiency and require more renewable energy generation in Namibia

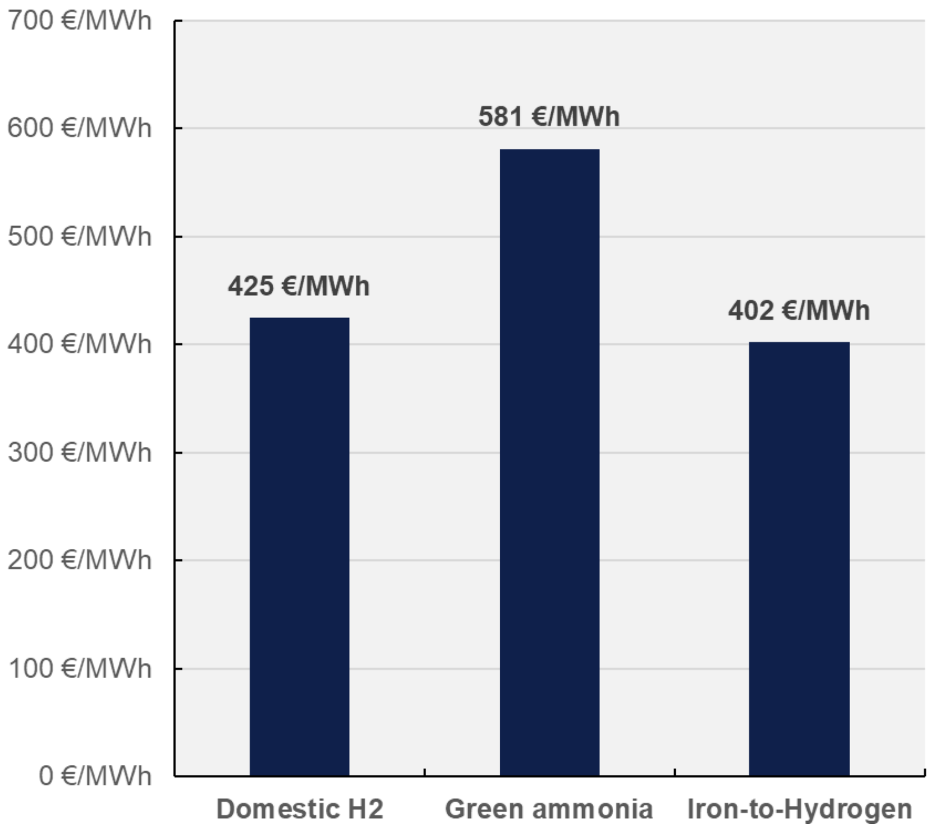
Levelized cost
1/3

- The cost assessment considers the full value chains from renewable energy production until production of peak-power in Germany.
- The **12.5 GW** and maximum of **800 full load hours**, provided in the power plant safety act, are used as a basis for scaling the different value chains and required renewable power generation. Each of the value chains provides 12.5 GW for 800 hours per year, equivalent to **10 TWh of** electricity per year. The required renewable power generation capacity depends on the efficiency of the value chain.
- No optimization was done between wind, solar and PtX capacity, but the Hyphen project was used as a starting point. The renewable energy production capacity therefore consists of **43% solar and 57% wind** (4 GW wind and 3 GW solar in Hyphen).
- The value chains have been assessed in isolation and consider dedicated renewable energy production.
- The cost assessment is performed at a **high level** to understand and compare the different value chains. No technical design and integration of the value chain, or capacity optimizations and buffer/storage calculations, were carried out.

Levelized cost
2/3

Iron-to-Hydrogen is a potentially **cost-effective** and safe option for sourcing hydrogen in Germany's Power Plant Safety Act.

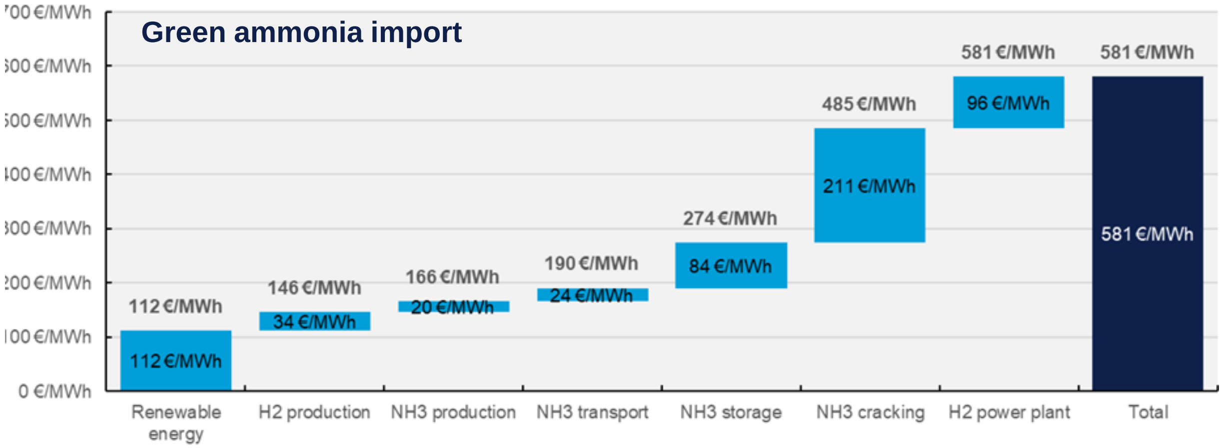
- **Domestic hydrogen** production, at 425 €/MWh, is mainly driven by costs for renewable energy generation, hydrogen production, and costs for hydrogen storage in salt caverns.
- **Green ammonia** has the highest LCOE of the three value chains, at 581 €/MWh (centralized option), mainly due to the very high cost of ammonia cracking and a higher cost of storing ammonia compared to DRI.
- **Iron-to-Hydrogen** has the potential to be the lowest cost of the three value chains studied, with an LCOE of 402 € per MWh of power generated at the German power plants (decentralized option).

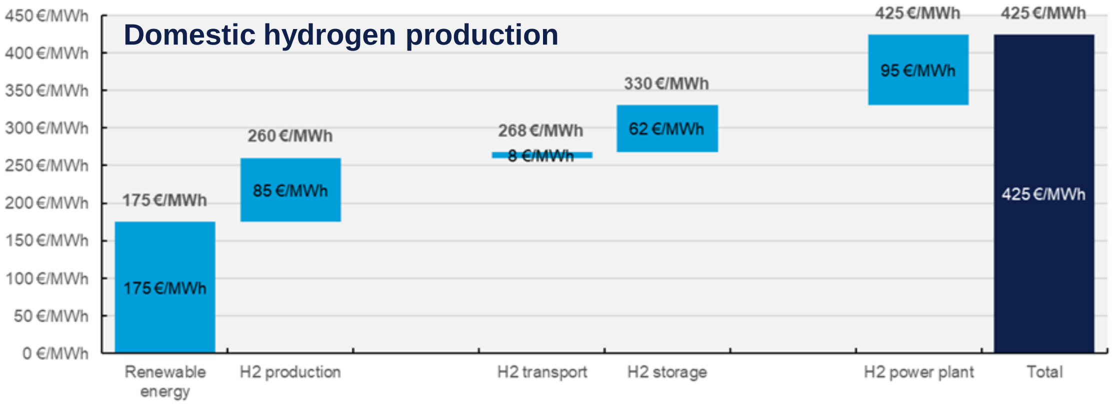


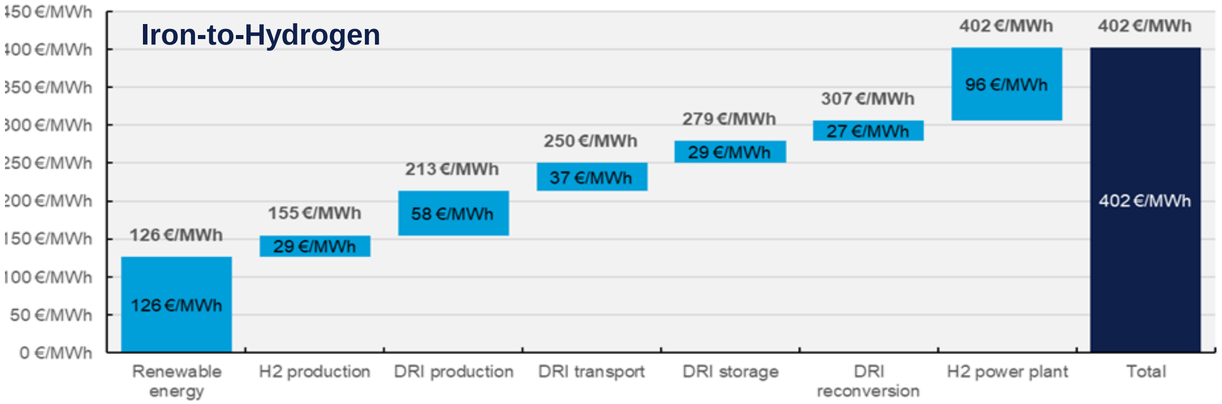
Levelized cost for production of back-up power through the different assessed options

Levelized cost
3/3

- There are different cost drivers for each value chain, depending on its particular characteristics.
- In all value chains levelized costs for producing renewable energy are a large driver:
    - Renewable energy production (offshore wind) in Germany is more expensive compared to Namibia.
    - Both import value chains have a lower efficiency and therefore more renewable energy needs to be produced in Namibia.







Strengths and weaknesses

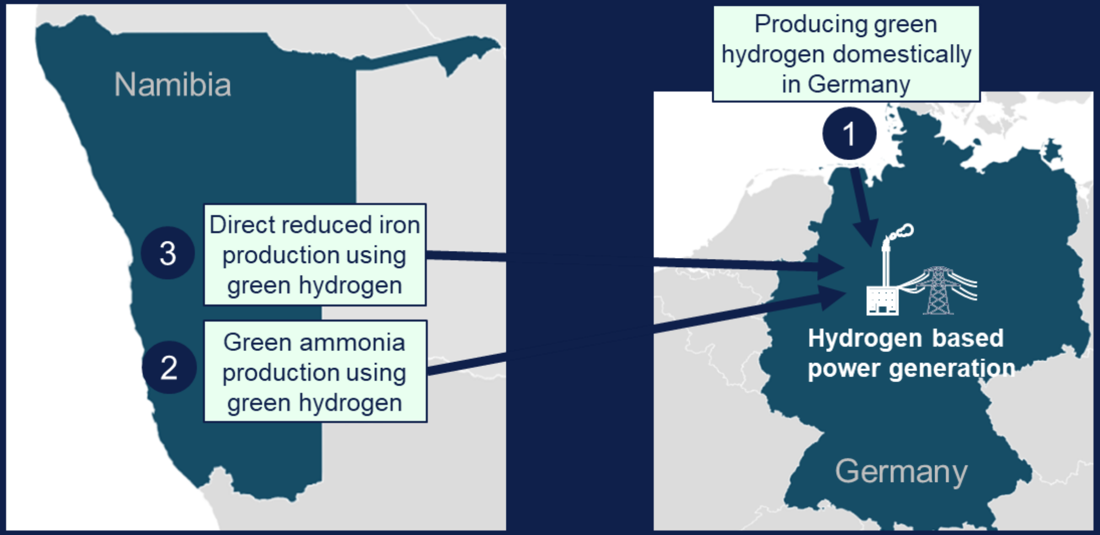
Domestic green hydrogen production	**Most secure and efficient** • Maximize energy security within Germany • Stabilize the German power market
Green ammonia import	**Momentum for large global market** • Can also be used as feedstock and is considered as a (maritime) fuel • Considerable momentum in global development • Highest cost, mainly due to cracking. Direct ammonia combustion could therefore provide potential • Toxicity needs to be carefully considered
Iron-to-hydrogen	**Versatile but requires most development** • Relatively easy and safe to store and transport • Can be used in steel industry • Suitable for decentralized back-up power generation, e.g. more remote from backbone • Lowest in TRL (reconversion) • Lowest overall energy efficiency

Main Conclusions

DNVs assessment concludes that it is worthwhile to consider Iron-to-Hydrogen as a potentially cost-effective and safe option for sourcing green hydrogen for German power plants

Goal

To assess the feasibility and potential benefits of alternative value chains such as importing direct reduced iron, to enable green hydrogen-based power generation in Germany.



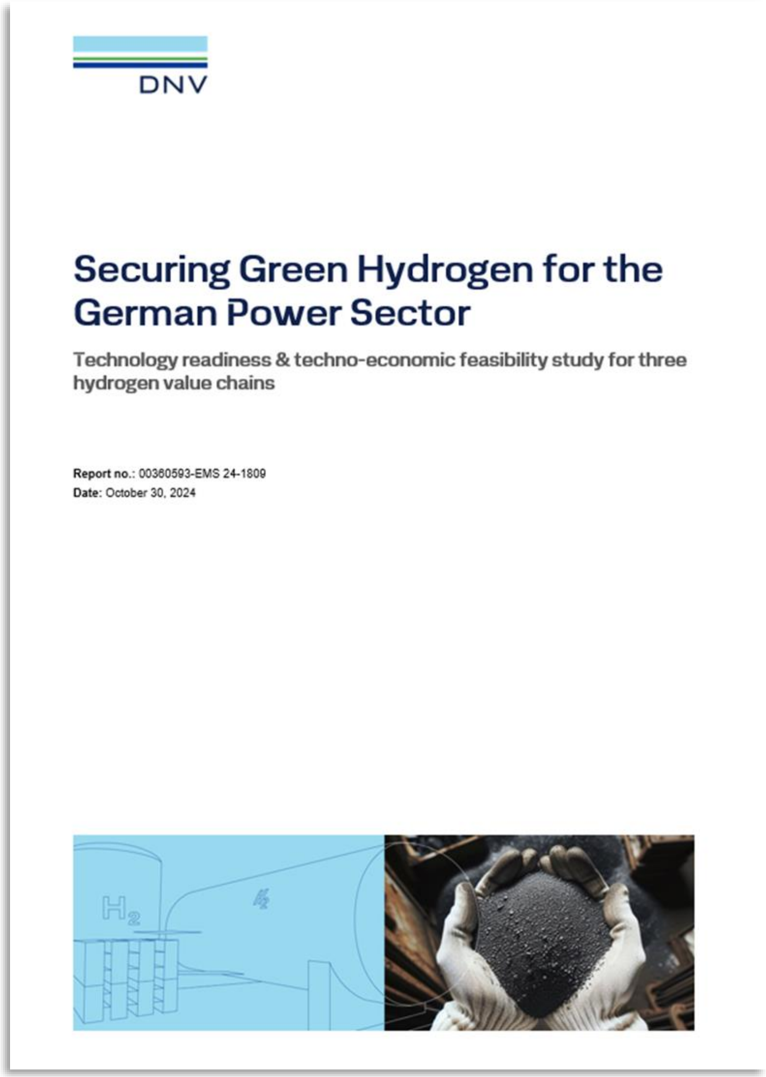
- **Technology readiness:** The three variants examined for the provision of back-up power generation each have **different degrees of technological maturity** with regard to the key components of generation, transportation, storage and reconversion. Iron–to-hydrogen still needs to undergo the most development.

- **Levelized cost:** Import of DRI and conversion to hydrogen is a potentially **cost-effective** addition to importing green ammonia or producing green hydrogen domestically in Germany.

- **Practicality:** Green hydrogen based DRI can be transported and stored relatively easily in large quantities and plays a crucial role in decarbonizing the steel industry. It could therefore provide a **versatile** medium, extending beyond a centralized hydrogen infrastructure (e.g. as a decentral solution for areas more remote from the central infrastructure).

Full technical report available in CNF repository

[link]


DNV

Securing Green Hydrogen for the German Power Sector

Technology readiness & techno-economic feasibility study for three hydrogen value chains

Report no.: 00360593-EMS 24-1809
Date: October 30, 2024

DNV

Appendix

TRL assessment continued

DNV

Appendix: TRL assessment

Hydrogen Production - General

Research 1 2 3 | Development 4 5 6 | Deployment 7 8 9

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge
Large scale renewable energy	9	• Commercially mature across the world and with a competitive business case.	• No specific technological challenges • Recycling of materials • Cannibalisation of electricity market and grid congestion
Hydrogen production from renewable energy	7-8	• Commercially available at MW scale, but no large-scale plants are successfully operated with renewable energy. • Offshore hydrogen production has a much lower TRL (<5), which is more relevant for Domestic H2 production.	• High levelized cost and a currently underdeveloped offtake market result in a challenging business case. This means there is limited incentive to boost upscaling and large-scale project development. There are a few exceptions. • Effect of fluctuating operation on lifetime and performance. • Standards, regulations and best practices for safe design and operation require further development (ongoing).
Compression	8-9	• Different technologies commercially available for hydrogen compression at both small and large scale.	• Variable drive for compression of fluctuating hydrogen production is available, but a buffer before compression is likely required. • Upscaling of the supply chain, especially for large scale and high-pressure compressors.
Water purification	9	• Commercially available at large scale. Reverse Osmosis is the most applied technology. • Other technologies like thermal desalination are less developed but allow for synergies between waste heat from electrolysis.	• Uncertainty if on the supply chain (not assessed by DNV). • Large volumes of fresh water are to be produced. This could compete with production of drinking water if the water source is limited. This could however also provide opportunities to produce additional drinking water if the water source is abundant (sea water). • Environmental challenges to expose effluent stream (higher concentration of minerals and chemicals).

Appendix: TRL assessment
Domestic hydrogen production

Research 1 2 3 | Development 4 5 6 | Deployment 7 8 9

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge

Pipeline transport	7-9	• Technically and commercially mature. Especially for new/purpose built.
		• Re-purposing (large part of backbone) still has some technical and regulatory uncertainties.
		• Maturity of complete H2 transmission pipeline system requires further development.
			• Hydrogen embrittlement is one of the key challenges, especially for re-purposing and with regard to pressure fluctuations.
			  ◦ Pressure fluctuations can promote crack formation.
			  ◦ The state of existing pipelines is uncertain
			• Good regulations/standards for assessing repurposing infrastructure are lacking. Currently ASME B31.12 is the most referred to but is conservative.
			• The operating profile of the backbone is still unclear due to undeveloped market. This means it is also not clear what pressure fluctuations can be expected and what should be the design specs or limitations for existing infrastructure.

Cavern storage (fast cycling)	5	• Only small-scale pilots to prove the concept but no complete/representative installation. • Existing H2 caverns (UK and US) are not representative for current use and scale.	• Long term gas tightness, material suitability and the effect of pressure fluctuations on material/components are uncertain. • Lack of best practices, standards and regulation. • Uncertainty on impurities from the cavern. What should be the purity at injection and what purification is needed at withdrawal. • Uncertainty on operating profile and required withdrawal rate. Withdrawal rate can however be increased by initiating multiple caverns simultaneously. • Further development is capex intensive which could be a challenge as no H2 market is in place and a business case is not easily found.

DNV

Appendix: TRL assessment
Green ammonia import

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge
Ammonia Synthesis	7	• Ammonia synthesis is a well-developed and commercially applied process. However, synthesis from renewable hydrogen provides additional flexibility requirements. • Ammonia synthesis with higher degree of flexibility is in commercial pilot phase.	• Fluctuating renewable energy and hydrogen production require the ammonia synthesis process to be run flexibly to some degree. This it a challenge to the systems that are currently in commercial operation. Turn-down capacity (<30%) and shutting down is a challenge. • Storage of H2 and/or electricity provides a solution but adds additional costs.
Ammonia shipping/export	9	• Ammonia is a globally traded commodity and ships are available.	• Higher volumes could lead to safety and environmental concerns. Especially at the harbour this could be a concern. • Higher volumes of ammonia trade could incentivize upscaling of the current fleet or ship capacity. This could lead to lower transport costs per tonne of ammonia.
Ammonia inland transport	8-9	• Ammonia is a regulated and widely transported commodity on both inland waterways and railways. • However, not at the potential future volumes	• Especially for inland transport Ammonia poses significant safety and environmental concerns due to it's high toxicity. • Current regulations are likely insufficient for a potential significant increase of transported volume. Higher volume results in a higher chance of an event. • Technological adaptations might be required to increase the safety level.
Ammonia Storage	9	Multiple methods/technologies are commercially available to store Ammonia.	• Toxicity – concerns on safety and environment • Large volumes of storage might be done in refrigerated form which can lead to additional energy consumption for re-liquefaction.
Ammonia cracking	6-7	• Commercial plant is in operation but only small scale. • Not feasible for decentralized cracking on demand	• Flexibility is a challenge, and it takes time (day) to start up. • High energy consumption and therefore reduction of value chain efficiency.

Appendix: TRL assessment
Hydrogen production

Research 1 2 3 | Development 4 5 6 | Deployment 7 8 9

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge
DRI production (reduction)	6-7	• Iron reduction has been commercially in operation for some time already in the iron/steel industry using coal or natural gas. Using only hydrogen is new. • Specific commercial systems for DRI production with Hydrogen are not yet available but are at pilot scale (e.g. HyIron project in Namibia).	• Scale-up concept is still to be developed and integrated. • Best practices for (safe) design are likely not yet in place. It is uncertain if standards or regulation needs to be put in place or should be updated. • Challenge with fluctuating operation. Flexibility is possible to some degree, but long-term effects are unknown and over-night shut-down should be avoided. Buffering/storage of H2 and/or electricity is therefore needed.
DRI Shipping/export	9	• Shipping of DRI is already done commercially and is regulated in IMSBC (International Maritime Solid Bulk Code) as DRI-C (fine powder)	• None
DRI inland shipping	8-9	• No Specific commercial system/ship identified for DRI inland shipping. It will be specialized transport but assumed to be available.	• Regulation not in place. Not included in ADN (international transport of dangerous good on inland waterways) • Transport of dry bulk and powders under protected environment is done in specialized ships but as DRI is not in the ADN it remains uncertain if this is suitable.
DRI train transport	8-9	• Commercial options are available and tested (e.g. Dry Tainer) but not yet applied.	• Scale up and application is needed in the steel market or hydrogen market. The most likely first adopter is the steel industry. • Definition or validation of regulation to assure safety should still be confirmed.
DRI storage	8-9	• No Specific commercial system identified for DRI but Storage of dry bulk under a nitrogen blanket is well known.	• Definition or validation of regulation to assure safety should still be confirmed.
DRI reconversion	3-4	• Simple process but currently no commercial system or developed prototype is in place. There is at least one system developed by HyIron for reconversion but is currently still in the phase of proving the concept.	• Low TRL and prototype is still to be established. However, no complicated technology is needed and can build on mature technology (boiler). • Controlling the process will be a challenge and is not flexible. It cannot be shut off and the reconversion rate cannot be controlled.

Appendix: TRL assessment
Iron-to-Hydrogen

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge
DRI production (reduction)	6-7	• Iron reduction has been commercially in operation for some time already in the iron/steel industry using coal or natural gas. Using only hydrogen is new. • Specific commercial systems for DRI production with Hydrogen are not yet available but are at pilot scale (e.g. HyIron project in Namibia).	• Scale-up concept is still to be developed and integrated. • Best practices for (safe) design are likely not yet in place. It is uncertain if standards or regulation needs to be put in place or should be updated. • Challenge with fluctuating operation. Flexibility is possible to some degree, but long-term effects are unknown and over-night shut-down should be avoided. Buffering/storage of H2 and/or electricity is therefore needed.
DRI Shipping/export	9	• Shipping of DRI is already done commercially and is regulated in IMSBC (International Maritime Solid Bulk Code) as DRI-C (fine powder)	• None
DRI inland shipping	8-9	• No Specific commercial system/ship identified for DRI inland shipping. Suitable ships and classification to be further evaluated, but it is assumed suitable ships are available.	• ADN (international transport of dangerous good on inland waterways) does not specify DRI and classification is to be further evaluated. • Transport of dry bulk and powders under protected environment is done in specialized ships but suitability cannot be concluded until classification of DRI in the ADN is further evaluated.
DRI train transport	8-9	• Commercial options are available and tested (e.g. Dry Tainer) but not yet applied.	• Scale up and application is needed in the steel market or hydrogen market. The most likely first adopter is the steel industry. • Definition or validation of regulation to assure safety should still be confirmed.
DRI storage	8-9	• No Specific commercial system identified for DRI but Storage of dry bulk under a nitrogen blanket is well known.	• Definition or validation of regulation to assure safety should still be confirmed.
DRI reconversion	3-4	• Simple process but currently no commercial system or developed prototype is in place. There is at least one system developed by HyIron for reconversion but is currently still in the phase of proving the concept.	• Low TRL and prototype is still to be established. However, no complicated technology is needed and can build on mature technology (boiler). • Controlling the process will be a challenge and is not flexible. It cannot be shut off and the reconversion rate cannot be controlled.

Appendix: TRL assessment

Hydrogen-fired power generation

Research 1 2 3 | Development 4 5 6 | Deployment 7 8 9

No challenges
Minor challenges
Serious challenges

	TRL	Note	Key challenge
Engines	8	• Commercially available at 1 MW scale • Suitable for quick response and back-up.	• Quick start up but requires pre-heating (stand-by costs) • Reduction of NOx emissions. Mitigating measures are however identified and applied • Retrofitting packages for existing gas engines are available but result in a reduction of capacity
	6-7	• Quickly developing and 10 MW scale is soon also commercially available.	
Combined cycle gas turbines (CCGT)	5	• >100 MW range • 20% H2 mix in NG is already possible in commercial power plants.	• Long start-up times and therefore a fully dedicated CCGT for back-up power is not feasible. • CCGT can however provide grid balancing services by reserving part of its capacity while being in operation. • Reduction of NOx emissions. Mitigating measures are however identified and applied.
Aero derivative turbines (from aviation industry)	7-8	• Derivatives from aviation industry but are currently only at concept stage. • These are suitable for quick response and back-up	• Lower efficiency compared to other solutions • Quick start up from cold state within a few minutes. However, not sufficient for primary reserve balancing services • Reduction of NOx emissions. Mitigating measures are however identified and applied.

Produced for Climate Neutrality Foundation

DNV Authors:
Jochum Douma
Daan Geerdink
Corin Taylor

30 October 2024

www.dnv.com